Modified Variability-Index CFAR Detection Robust to Heterogeneous Environment

Jong-Woo Shin, Young-Kwang Seo, Dae-Won Do, Sang-Moon Choi, and Hyoung-Nam Kim

***Abstract*—**Since a variability-index (VI) constant false alarm rate (CFAR) detector dynamically selects one of the mean-level CFAR algorithms based on VI and mean ratio (MR) test, it is robust to various noise environments. However, the VI CFAR still suffers from low detection accuracy in heterogeneous environments. To overcome this problem, we modify the conventional VI CFAR processor by adding a TM (trimmed mean) CFAR for the improved robustness and involving a sub-windowing technique for the enhanced selectivity. Computer simulation results show that the proposed method is superior to the conventional VI CFAR or any single CFAR algorithm in terms of a detection probability.

Keywords—CFAR, variability index, target detection, composite CFAR

I. Introduction

IN RADAR and SONAR systems, it is desirable to maximize a detection probability while maintaining a constant false alarm probability [1]. To achieve this principal goal, lots of CFAR (constant false alarm rate) algorithms have been studied [2], [3]. The key factor of CFAR algorithms lies in setting the threshold adaptively by estimating the background noise power included in a test cell. A mean-level CFAR algorithm is the simplest one and uses arithmetic averaging to estimate the noise power. The most well-known mean-level CFAR algorithm is the cell averaging (CA) CFAR which averages all cells in the reference window. This property of the CA CFAR yields the optimal performance in homogeneous environment [2]. However, it does not work well for heterogeneous cases which are frequently produced by masking targets and clutter edges. For this reason, many alternative CFAR algorithms have been proposed to cope with such diverse heterogeneous environments but do not still succeed in combatting robustly to environment changes.

The difficulty in finding a solution based on a single CFAR algorithm to deal with diverse noise environments has led to the development of composite CFAR algorithms [3]. The VI CFAR, one of intelligent CFAR algorithms, is the most popular composite CFAR algorithm. The VI CFAR dynamically selects one of the mean-level CFAR algorithms based on a variability index and a mean-ratio test to perform robustly in heterogeneous environments. Despite of its good robustness, it exposes an inevitable problem of performance degradation in terms of detection probability when interfering signals arise on the both side of the test cell. In addition, the existence of the clutter edge in the reference window may also lower the detection probability of the VI CFAR although the false alarm probability is below the designed target value.

To overcome these problems, we have approached by two directions; the robustness to diverse environments and the appropriateness of the algorithm selection. The first one is achieved by adding a trimmed–mean (TM) CFAR which plays a key role in coping with the case of multiple interferences existing on the both sides of the test cell [7]. To improve the selectivity of an algorithm, a sub-windowing technique is incorporated for finding the location of the clutter edge. This helps avoiding the biased estimation caused by the existence of the clutter edge in the reference window.

This paper is organized as follows. In section II, a brief overview of a CFAR detector is presented. In section III, a composition of the CFAR algorithms is introduced with the focus on VI CFAR. Our main idea to improve the VI CFAR is dealt with in section IV. Simulation results for verifying the efficiency of the proposed algorithm are given in section V. Finally section VI concludes this paper.

II. Constant False Alarm Rate Detector

The signal window of a CFAR detector consists of a test cell, guard cells, and the reference window as shown in Fig. 1. The CFAR detector adaptively sets the detection threshold based on local information of the noise power. The noise power of test cells is estimated from the reference window, and then the constant factor (T) that is calculated from the design factors such as false alarm probability and window size is multiplied to obtain detection threshold (TZ). Finally, target decision is realized by comparing the value of the test cell with detection threshold as follows

$$\begin{cases} \text{No target}\,(H_0)\,, & \text{if } Y < TZ \\ \text{Target present}\,(H_1)\,, & \text{if } Y \geq TZ \end{cases} \quad (1)$$

where Y is the value of the test cell. When the reference window only contains background noise, the noise environment is denoted as a homogeneous environment. Since the input signal

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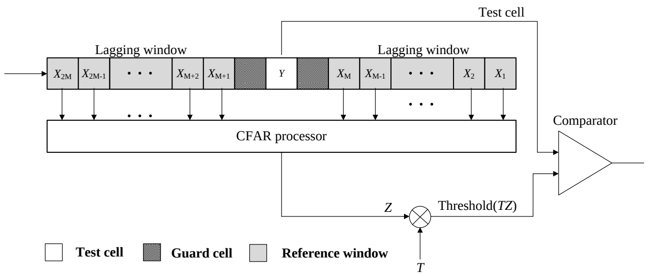

Fig. 1 The structure of a conventional CFAR detector

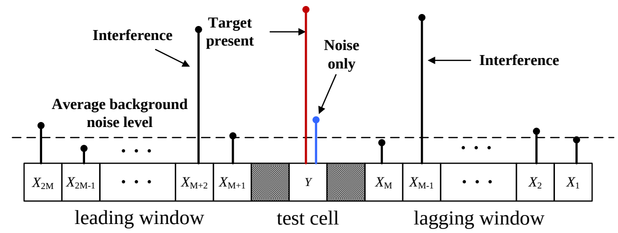

Fig. 2 Target masking environment

of the CFAR detector is the square-law detected outputs, the value of each cell in the reference window is exponentially distributed in homogeneous environment as follows, [2]

$$f_X(x) = \frac{1}{2\lambda} e^{-\frac{x}{2\lambda}}, \ x \geq 0 , \tag{2}$$

$$\lambda = \begin{cases} \mu , & if\ H_0 \\ \mu(1+S) , & if\ H_1 \end{cases} , \tag{3}$$

where μ is an average noise power and S is an average signal-to-noise ratio(SNR). The false alarm probability and the optimum detection probability can be expressed as follows, respectively

$$P_{fa} = P[Y > Y_0 \mid H_0] = e^{-\frac{Y_0}{2\mu}} , \tag{4}$$

$$P_d^{opt} = P[Y > Y_0 \mid H_1] = e^{-\frac{Y_0}{2\mu(1+S)}} . \tag{5}$$

If we have knowledge of the average noise power, we can obtain the optimum threshold (Y_0) from (4). However, we cannot know the average noise power and usually have to estimate it from only N cells of the reference window. Moreover, the noise environment cannot be described by a single probabilistic model. In other words, it would not always homogeneous but sometimes heterogeneous. As a result, the noise distribution does not follow a single exponential distribution.

The heterogeneous noise environment is also modeled as two different situations [3]. If the reference window contains large interfering signals, the target signal will be masked by them. Fig. 2 describes an example of the situation which is called *target masking*. Since large interfering signals increase the estimated noise power, the detection threshold will also increase. As a result, the detection probability will be lowered.

If there is a clutter signal or different kinds of clutter signals in the reference window, the edge will be appeared due to the difference of the average power level as depicted in Fig. 3. This situation is called *clutter edge*. When the test cell is in the higher clutter power area, the clutter yields a decreased detection probability due to the lowered SNR of the target signal. The false alarm probability is also increased due to the clutter. On the contrary, the clutter yields a decreased detection probability

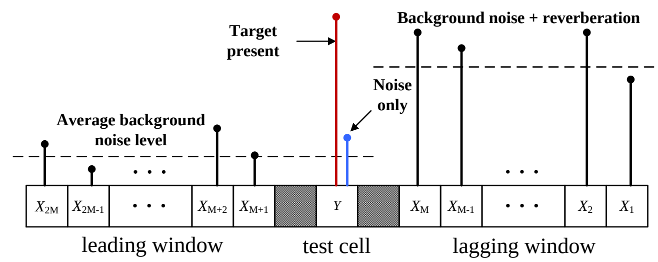

Fig. 3 Clutter edge environment

due to the increased noise estimate when the test cell is in the lower clutter power area.

When we employ the CFAR detector for determining detection threshold, it is desirable to estimate average noise power of the test cell by only using homogeneous noise and removing heterogeneous noise in the reference window. In the past, numerous CFAR algorithms such as OS (ordered statistics) CFAR and switching CFAR have been proposed for achieving the purpose [2],[6]-[9]. However, none of single CFAR algorithms can simultaneously deal with three kinds of noise model described in this paper, i.e. homogeneous, target masking, clutter edge environment. In this reason, the composite CFAR techniques were proposed for recent years [3], [10], [11].

III. Variability Index Constant False Alarm Rate Detector

The VI CFAR is the composite CFAR algorithm and the structure of the VI CFAR is described in Fig. 4. [3]. The VI CFAR selects one of the mean-level CFAR algorithm based on the real time test of the reference window. The reference window is divided into the leading window and the lagging window. Mean and variance of each window are calculated to determine the noise environment condition of the each window. By comparing the mean ratio (*MR*) and the variability index (*VI*) with predetermined threshold K_{VI}, K_{MR}, the state of the noise environment is determined as follows [3]

$$MR = \sum_{i=1}^{M} X_i \Big/ \sum_{j=M+1}^{2M} X_j \ , \tag{6}$$

$$\begin{cases} K_{MR}^{-1} \leq MR \leq K_{MR} \ , & \text{same mean} \\ \text{otherwise} \ , & \text{different mean} \end{cases} , \tag{7}$$

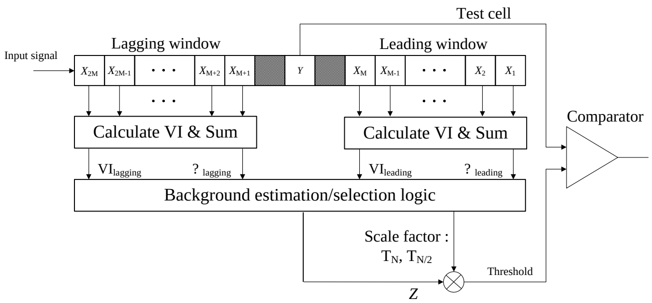

Fig. 4 The structure of the VI CFAR [3]

TABLE I. THRESHOLD DECISION METHOD FOR VI CFAR [3]

$VI \geq K_{VI}$ leading	$VI \geq K_{VI}$ lagging	MR	adaptive threshold
No	No	same	$(\sum_{leading}+\sum_{lagging})\cdot T_N$
No	No	different	$\max(\sum_{leading},\sum_{lagging})\cdot T_{N/2}$
Yes	No		$\sum_{lagging}\cdot T_{N/2}$
No	Yes		$\sum_{leading}\cdot T_{N/2}$
Yes	Yes		$\min(\sum_{leading},\sum_{lagging})\cdot T_{N/2}$

$$VI = 1 + \hat{\sigma}^2 / \hat{\mu}^2 , \tag{8}$$

$$\begin{cases} VI \geq K_{VI}, & \text{variable} \\ VI < K_{VI}, & \text{invariable} \end{cases} . \tag{9}$$

The threshold decision method in the VI CFAR is shown in table I. If there is a variable window, the noise environment is regarded as the target masking environment. Otherwise, the existence of the clutter edge will be tested based on the mean ratio.

In the clutter edge environment, the VI CFAR will become a GO(greatest-of) CFAR [3]. When the interfering signals are on the both side of the test cell, the VI CFAR will become a SO(smallest-of) CFAR [3]. In other cases, the VI CFAR will operate as a CA CFAR, equivalently.

IV. Proposed Method

In general VI CFAR algorithms, the noise power is estimated by excluding the cells which contain heterogeneous noise to keep the state of estimated noise environment being homogeneous when the heterogeneous noise exists in reference window. However, the VI CFAR cannot maintain high detection probability and desired false alarm probability in the following two noise environment conditions. First, when the interfering signals are present on the both sides of the test cell as depicted in fig. 2, the VI CFAR selects a window that contains the lower power of the estimated noise than the other. Since both windows contain interfering signals, the estimated noise is heterogeneous. Second, when the clutter edge is present in the reference window and the test cell does not contain the clutter signal as depicted in fig. 3, the VI CFAR selects a window that contains the higher power of the estimated noise than the other. Since the selected window contains the clutter signal while the

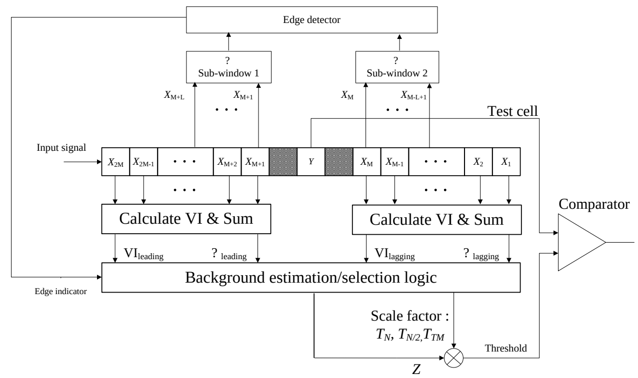

Fig. 5 A modified structure of VI CFAR

test cell does not contain clutter signal, the estimated noise power is heterogeneous. As a result of these two conditions, the detection threshold is unnecessarily increased and therefore the detection probability is too much lowered.

To cope with these problems, we substitute the SO CFAR with the TM (trimmed mean) CFAR [5] when the interfering signals are present on the both side of the test cell. A sub-windowing technique is also used when the clutter edge is present in the reference window. The TM CFAR estimates the noise power by using the rest of total window after the amplitude values of the reference window are rank-ordered according to increasing magnitude, then the k_1 largest cells and k_2 smallest cells are removed. The detection threshold is given by [5]

$$TZ = T_{TM} \cdot \sum_{j=k_1+1}^{N-k_2} X_{(j)} . \tag{10}$$

T_{TM} is a constant factor which can be obtained using a formulation expressing false alarm probability of the TM CFAR and $X_{(j)}$ denotes a j_{th}-smallest value in the reference window. Therefore, the interfering signals existing on the either side of the reference window can be effectively excluded when determining the detection threshold.

If there is a clutter edge in the reference window, the L-length sub-windows on the both side of the test cell with a smaller size than $N/2$ is added to determine whether the edge is close to the test cell or not through the additional mean ratio test as follows

$$MR^{'} = \sum_{i=M-L+1}^{M} X_i \Big/ \sum_{j=M+1}^{M+L} X_j , \tag{11}$$

$$\begin{cases} K_{MR}^{'-1} \leq MR^{'} \leq K_{MR}^{'}, & \text{same mean} \\ \text{Otherwise} & \text{, differenct mean} \end{cases} . \tag{12}$$

Fig. 5 describes the structure of the proposed CFAR detector and table II shows threshold decision method using sub-windowing technique when the clutter edge exists in the reference window. The location of clutter edge can possibly exist one of the four locations as depicted in fig. 6. The location ‘a’ and ‘d’ of the fig. 6 are not close to the test cell. Therefore, if the edge exist on the location ‘a’ or ‘d’, the mean values of each sub-window are nearly same. In this case, the detection

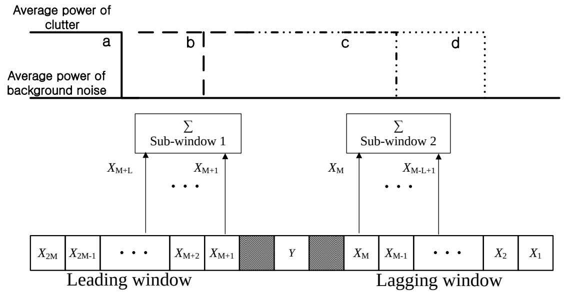

Fig. 6 Possible location of the clutter edge

TABLE II. THRESHOLD DECISION METHOD USING SUB-WINDOW

$\min(VI_{\text{leading}}, VI_{\text{lagging}})$	MR'	adaptive threshold
VI_{leading}	same	$\sum\text{leading}\cdot T_{N/2}$
VI_{lagging}	same	$\sum\text{lagging}\cdot T_{N/2}$
	different	$\max(\sum_{\text{lagging}},\sum_{\text{lagging}})\cdot T_{N/2}$

threshold is determined by a half of the reference window that has lower *VI* than the other because the clutter edge yields the higher *VI*. On the other hand, the location 'b' and 'c' are close to the test cell, and therefore additional mean ratio test will indicate that the mean values of each sub-window are different. In this case, we adjust GO CFAR to determine the detection threshold as VI CFAR. Finally, we can obtain more homogeneous noise power estimate using sub-window than VI CFAR in the clutter edge noise environment.

V. SIMULATION RESULT

To verify the strength of the proposed CFAR algorithm, we compared a detection probability (P_d) and a false alarm probability (P_{fa}) of each CFAR algorithm through the 1,000,000 Monte-Carlo simulations. We assumed the size of reference window (N) equal to 48 and the size of sub-window (L) equal to 12. The threshold values which determine the state of noise in the reference window were set as K_{VI} = 4.76, K_{MR} = 1.806 and, K'_{MR}=1.6 for yielding very small value of probability of determining error [4]. The desired P_{fa} was 10^{-4} and the simulation was performed for a state of homogeneous, interfering signals on both side of the test cell, and clutter edge environment. Fig. 7 shows the P_d versus SNR of the CA-CFAR, the OS-CFAR, the VI-CFAR, and the proposed method in homogeneous environment. The performances of all kinds of simulated CFAR algorithms are similarly close to the optimum value. However, the heterogeneous noise gives rise to the performance degradation. Fig. 8 and fig. 9 show the P_d and the P_{fa} versus SNR, respectively, when an interfering signal is contained in the either side of the reference window. In this case, we can find that P_d and P_{fa} of the proposed method and the OS-CFAR are less degraded than that of the VI-CFAR and the CA-CFAR from optimum value. We can confirm from the result that rank-ordering CFAR algorithm is more efficient than averaging method, when the interfering signals exist in the reference window. In fig. 10 and fig. 11, P_d and P_{fa} are described according to the location of clutter edge, when the clutter with 10dB of CNR(clutter-to-noise ratio) is present in the

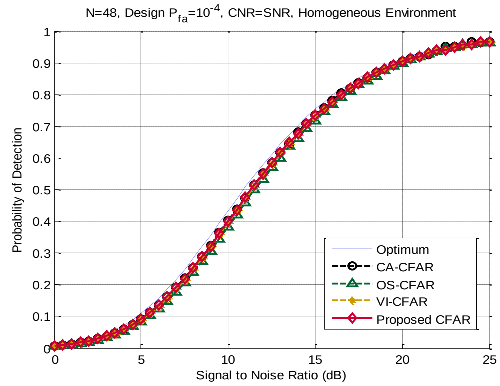

Fig. 7 Detection probability in homogeneous environment

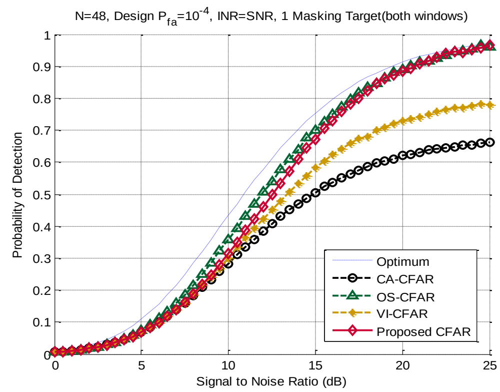

Fig. 8 Detection probability when the interfering targets are included in both side of window

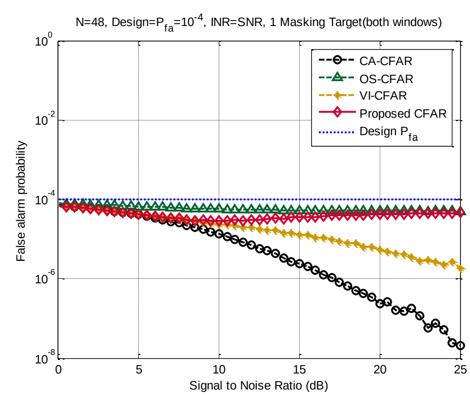

Fig. 9 False alarm probability when the interfering targets are included in both side of window

reference window. We can find that if the test cell contains clutter, the CA-CFAR and the OS-CFAR show much higher P_{fa} than the VI-CFAR and proposed method in clutter edge environment. In addition, if the test cell does not contain clutter P_d and P_{fa} of the VI- CFAR is much decreased than the proposed method. Therefore, the proposed method is most efficient when the clutter edge is present in the reference window.

VI. CONCLUSION

To overcome the lowered detection accuracy of the VI CFAR in heterogeneous environment, we added a TM CFAR for the robustness to diverse environments and incorporated a

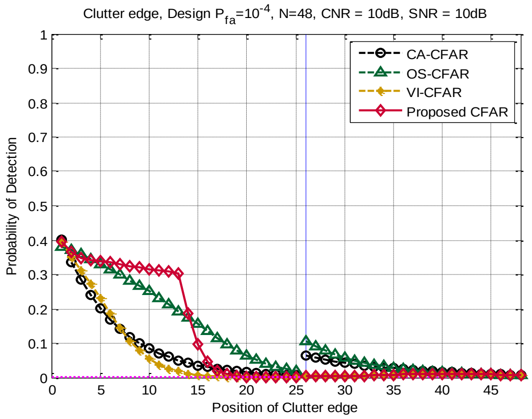

Fig. 10 Detection probability in the clutter edge environment

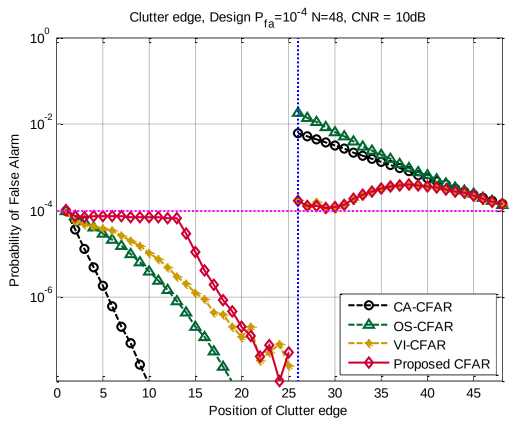

Fig. 11 False alarm probability in the clutter edge environment

sub-windowing technique for the efficient selectivity of an algorithm. The proposed method shows the better performance than VI CFAR and other single CFAR algorithms in terms of a detection probability without any overshooting the target value of a false alarm probability, especially in heterogeneous environment. It is expected that the proposed CFAR algorithm can provide an effective solution to detect targets in complicated environments, such as underwater SONAR systems and RADAR systems.

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