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Adaptive Thresholding using Improvised CFAR Algorithm for Wind Turbine Clutter Mitigation in Homogeneous Environment

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Abstract: In this decade, wind farms have piqued the interest of a significant number of scholars and policymakers all around the world. At the dawn of 21st century, researchers especially environmentalist are concerned about global warming, deterioration of climate, particularly ozone layer thinning. Today green energy is a need of hour. Quest for green energy has caused rapid growth of wind farm installations all over the world. Installations of wind farms obstructing line of sight of communication systems causes interference to receiver. The interference due to Doppler shift generated by the wind Farm having thousands of wind mills are a cause of concern for Communication systems. Specifically, wind turbines and its rotating blades cause adverse effects on the performance of such devices particularly radar. It can cause receiver saturation. The secondary data derived using primary measurement can go erroneous if primary data i.e. Doppler data is not corrected. It is pertinent to design a detector having robustness to interference. In this work, various thresholding algorithms are experimented and novel CFAR architecture is proposed and results are discussed. The performance of variability index CFAR and ordered statistics CFAR method are analyzed. Comparative analysis through the Receiver Operating Characteristics (ROC) is presented to understand the superiority of OS CFAR in the context of mitigation of interference caused by wind turbines /wind farms. Novel strategies for detecting and mitigating wind turbine clutter are addressed in this research article. Results are discussed in detail in further sections.

Keywords*: CFAR Processor, Doppler shift, Interference, Order Statistic, Wind Farms, Wind Mills, Wind Turbines, Wind Turbine Interference.*

1. Introduction

An essential resource for a country's development is energy. Fossil fuel is predominantly consumed in the generation of conventional energy. It creates Environmental concerns, particularly global warming. Quest for non-conventional energy sources has explored other forms of energy sources such and wind, solar bio fuels etc. The sources of conventional energy are depleting faster. Wind farms (both on-shore and off- shore) are witnessing faster growth over the decade. It has potential to fulfil the need of clean energy.

Renewable energy has a share of 32% of total electrical energy production in Germany with wind energy contributing about a third [1, 2]. The German legislation plans to further extend renewable energy and sets the target to generate 80% of electrical energy from renewable sources by 2050 [1, 2]. Wind energy generation is growing rapidly in India, US and EU nations. India has set a target of 60 GW for generation of wind energy whereas it has potential to generate 302 GW. [3, 4]. India is continuously increasing the capacity wind power generation [3, 4]. UK has issued specific guidelines to installation of wind farms. Almost all European countries are facing concerns while augmenting the renewable energy capacities. At the same time national security requirements can't be compromised. Radars are extensively used for in airspace, air defence, tracking and surveillance, even for weather forecasting applications.

The development of several thousand MW of wind energy has been halted by the FAA and the DOD by refusing permissions for installation of new wind farms which are in line of sight of radars stations. A significant number of these denials pose a concern to the country's mandated increase in the goal of sustainable energy. Wind Farms falling in the Line of sight of communication systems causes interference to communication systems, particularly radars. One particular class of radars, Doppler radars are severely affected. It causes Doppler shift in received signal. The secondary estimations based on primary data are distorted. The problem requires robust clutter mitigation algorithms. Any unwanted echo is referred as Clutter. Wind turbine interference degrades the detection capability, eventually saturating the receiver. Wind farms are easily recognized as real targets by weather radar due to their large radar cross section (RCS). The tower, nacelle, rotor, and fins are the parts of a wind turbine generating interference proportionately, as depicted in Figure 4.

Since the primary Doppler information is biased, the secondary moment's data is affected. And thus output of algorithms depending on observations for quantitative precipitation estimation (QPE) can be biased if wind turbine clutter (WTC) interference caused by the wind mill/ wind farms /wind turbines are not minimized [5, 6]. After detailed deliberations on interference components, attempts are made to develop an algorithm exploring these features. Subsequently various classifiers are analysed to see applicability and suitability. It is reported in one of the manuscript about fuzzy classification. Support vector machine (SVM) has unique ability to classify in homogeneous background. The SVM technique uses spectral properties to divide wind turbine interference data into two categories. Based on the moment estimates, it constructs the band pass filter. Brief of above work is discussed in subsequent section.

The main contributions of this papers are listed below:

Aim of this research proposal is to identify and refine detection of moving objects among clutter generated by rotating blades of wind turbine by solving problems like desensitisation, shadowing effects, poor frequency resolution, clutter map. We have implemented CFAR algorithms and proposed OS CFAR assisted with variability index based Background estimation to improve quality in the context of wind turbine interference. The algorithm is simulated for various environmental conditions such as multiple targets situations, clutter edges, reverberation edges and for homogeneous and nonhomogeneous environments.

Section II deals with problem formulations and their solutions reported in literature, section III deals with design methodology ,section IV deals with algorithmic developments to identify and mitigate clutter caused by wind turbine interference by improving probability of detection and finally section. Secondly, the detection algorithms are implemented and analysed for usefulness in case of detection problem suffered with interference from wind farm. The various CFAR algorithms including statistical methods such as OS CFAR are implemented and results are analysed for suitability in case of WTC. Section 5 deals with results and its analysis coupled with conclusion and reference used as above.

2. Literature Review

In this section, the shadowing effect, desensitization effect are resolved by proposing a novel algorithm based on statistical attributes of data. Results are discussed in further sections for the OS CFAR coupled with background estimation based on variability Index. The current architecture adapts the detection threshold depending on the background environments.

Wind farm consists of thousands of wind mills spread across wide geographical area in a specific spatial pattern .The purpose of distributing wind mills in a particular spatial pattern is to harness maximum wind energy w.r.t. to Benz's Law. Wind energy harvesting using wind farm/ turbine (WF/WT) is governed by Betz's Law. WF/WT can capture 59.3% of kinetic energy of wind flowing. So the trend is to erect turbines taller and taller at specific geographical locations.Vestas wind mill has capacity of 8 MW each, having height of 200 mtrs and fin diameter of 164 mtrs. This is even bigger than A380 Aircraft. Cluster of WT forms wind farm. Wind turbine consists of stationary tower, Nacelle, Hub and Fins.

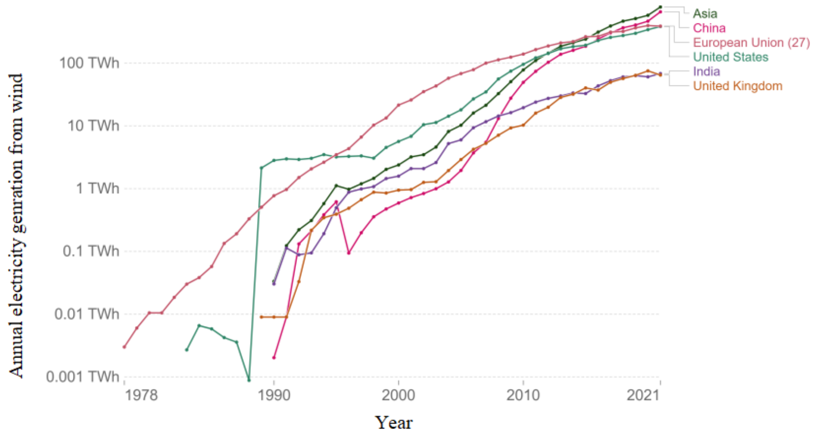

Figure 1. Annual wind power generation: country specific. [27, 2]

Fig.1 depicts the annual production of wind energy. The growth rate is increasing every year. The size of turbines, height of wind mill, locations of wind farms, directivity are the influential parameters governing the generation of wind energy form wind farms .The Kansas city wind farm covers 200 sq. miles of area [7]. The Benz's Law governs the selection of site and directivity. Few of parameter such as height of wind turbines, radar cross section has dominating effect on wind energy generation as well the interference caused to communication systems. Particularly, more the height of wind turbines, more will be energy generated, also more will be interference caused to radar systems. The increasing size of rotating fins and height of the installation is increasing day by day, as it suffices the generation of larger wind energy as depicted in Figure 2. Today each wind mill can generate 8 MW of energy [2]. This approach is resulting in greater susceptibility to radars. Radar cross section (RCS) of wind farm, particularly wind, mill, and then its constituent parts wind turbine, tower, nacelle, plays an important role in interference problem, particularly rotating blades. Receivers are saturated because of the powerful reflections from the WT structure. Concerns are manifold.

A basic wind turbine interference signal is mainly composed of reflections from three pieces of a wind turbine: a tower, fins, and a hub. The wind turbine's immovable towers generate a zero velocity signal. Many features are investigated and examined, with a focus on temporal and spatial methodologies. Few of these are discussed further.

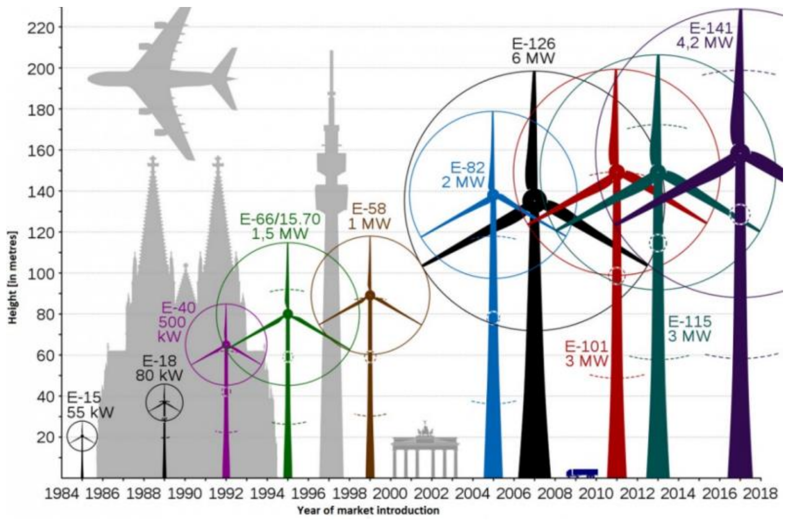

Figure 2. Contextual evolution of wind Turbine [2]

The Doppler spectrum consists of targeted reflections, interference from unintended objects such as wind mills, clutter from foliage, clutter generated from fixed targets, receiver noise, thermal noise, etc. The zero velocity filter works on clutter generated from fixed targets. CFAR algorithm plays vital role in governing dynamic threshold with balance between P_d vs.P_{fa} for stated environment conditions as depicted in Figure 6.The receiver input is a composite signal. It can consists of reflections from combinations of homogeneous, non-homogeneous environment having reverberation edges.

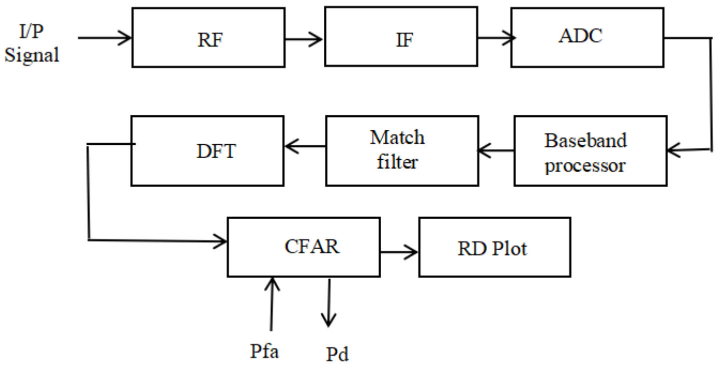

Figure 3. Signal Processor block diagram with CFAR

CFAR processor is a backbone of adaptive threshold detection algorithm. The detector estimates background noise power by averaging the amplitudes of reference cells from input data. This estimated noise power Z is then multiplied with scaling factor T, which is a function of required probability of false alarm (P_{fa}). However, this method faces detection problem, particularly in two cases; clutter edge and multiple targets environment.

We have analysed an automatic filtered cell averaging CFAR detector based on ordered data variability. Censoring technique uses variability index that distinguishes between homogeneous and non-homogeneous population. Ordered data variability based statistics has been used to determine set of ranked thresholds according to desired probability of false censoring [8, 9]. Main idea is based on selecting p lowest cells representing initial estimation of the background level. More generalized approach of OS scheme was proposed by You He [9, 10, 11], which combines cell averaging, with trimmed mean (TM) CFAR. An ordered reference cells in leading and lagging windows are trimmed at upper end and then the averaging of remaining cells is performed for background estimation. Another approach to this was added which discards the smallest cells T2 and greatest cells T2 before averaging.

It has been suggested by U. Jie et al. [12] to use coherent accumulation for double threshold target detection. In this paper, we examine the properties of radar clutter distribution and a coherent accumulation technique for LSS target recognition in a complex electromagnetic environment. Dai et al. has discussed on interference mitigation [13]. In paper [14], they have proposed the Neural Network based CFAR. We note that conventional CFAR architecture requires modification since the maximum function is nonlinear. Based on second order neural networks, they have offered neural solutions [14]. It is claimed that with real-time operations, it can achieve reduced computational costs.

Second group presents algorithms which are the combination of above mentioned approaches. He et al. [8, 9, 15, 16] proposed ordered data variability CFAR technique which offers better false alarm regulation property with enhanced interference mitigation for large CNR situations. One of the advancement is ODV CFAR. Depending on the outcome of VI hypothesis test, the ODV CFAR dynamically shifts to one of CFAR algorithms, the lowest ranked cells, or the larger ranked cells CFAR. Reference [11] presents the model cell averaging trimmed mean (CATM) CFAR, which combines the methods of cell averaging and trimmed mean.

Artificial intelligence based approaches are used to find small moving targets in areas with maritime congestion. In composite hypothesis testing situations, neural detectors are thought to be close to the Neyman Pearson criteria (NP). Constrained generalised likelihood ratio (CGLR) based sub optimal methods together with Constant False Alarm Rate and Doppler based methods are examined to have improved signal to interference ratio as well as interference rejection.

Jing Liang has proposed usefulness of STFT to detect target obscured by foliage [17]. According to reference number such as [18], the small coherent processing interval makes it difficult to resolve the wind turbine micro Doppler signature. In actuality, the wind turbine clutter spectrum resembles a noise signal with a high zero Doppler return. Jian Xue has proposed a prior knowledge of clutter locations can be can be utilized to improve detection performance [19], Further it can be extended to use locations of wind farm region to have localized adaptive threshold, rather than having a single threshold.

It is further proposed to utilize multiple beam approaches and each beam should have distinct exclusive threshold. This approach can solve the cascading effect of background noise on threshold. In [20], Baiqiang Zhang has introduced Bayesian methodology. Baiqiang Zhang has proposed the use of weighted likelihood and its usefulness to devise a novel CFAR based on it [21].

Authors has proposed application of moment's space to improve detection quality while keeping constant probability of false alarms [5]. In this context, they have proposed SM CFAR (statistical moments) CFAR. The procedure outlined for CFAR is based on estimation of boundary and detection of double threshold. Maokai Wu et al. has proposed two stage detection algorithm to identify suspicious targets in cluttered and as well as in Interference region [22]. In preprocessing stage, highly dominated regions of clutter and interference are identified in the range Doppler spectrum using artificial intelligence based algorithms such as CNN. In second stage i.e. target detection, extrenum algorithm is applied followed by a classifier algorithm. Atef Farrouki and others has proposed optimal selection of censored mean level proportional to the background environment [23]. This concept has potential to discard outlier from the data set. Tao Liu suggested using truncation to weed out any statistically significant outliers. Prior knowledge of the interfering targets is not necessary for this algorithm to function [11].

Zhuhai Cao has advocated use of compressed sensing based CFAR to overcome shadowing effect in multi target scenario [24]. J. S. Ahmed has proposed estimator based on weighted likelihood [25]. It is effective in the estimating parameter of exponential distributions where a large portion of observations are outliers. This hypothesis fits in our case where reflections from rotating blades of wind turbine are vastly outliers for radar detection point of view and difficult to discriminate among the real targets of interests.

The interfering targets are modeled and their effect is minimised using the Bayesian detector. In [20] authors has proposed usefulness of linear SVM in nonhomogeneous environment where clutter edges, reverberation edges and multiple targets are of concern. It is robust in above conditions. To detect targets in nongaussian noise, the k nearest neighbours (KNN) method is frequently utilised [26].

Literature survey has clearly pointed out that no specific solution does exist to carry out mitigation of wind turbine clutter in Radars. In future, Concurrent High and Low Beam Processing, Clutter Maps for each Doppler Filter, Enhanced Constant False Alarm Rate (CFAR) processing will see progress further. Even though Holographic Radar has claimed a total solution, it is a completely new systems and concept based on multiple projections. It can not be applied to existing radars.

3. Design Methodology

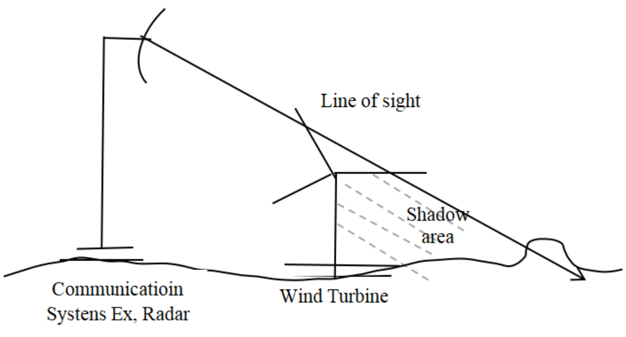

Figure 4. Interference caused by wind turbines

Ref No. / Author	Approach	Observations
Angulo I et al. [7 &10],	Two stage detection	Better detection capability in clutter edges.Processing delays, latency requires addressal
W. Zhou et al.[28]	Grubbs Criterion	I[st] stage: Background estimation, II[nd] stage: Thresholding. Used for background estimation
Zhou et al.[5]	Iterative process, Sorting and weighting average	I[st] stage: Sorting, II[nd] stage: Weighted average. Used for background estimation
A. Farrouki et al.[14]	Ordered Data Variability based censoring	I[st] stage : Censoring, II[nd] stage : Thresholding
Zhao et al.[7]	ODV based	ODV detector performs better than that of the VI-CFAR only when iinterfering targets are not confined to a single half of the reference window.
Jie Yu et al.[10]	Based on mean and variance	Iterative two stage process
T. R. Saeed et al.[29]	Use of classifier,	SVM classifier used as feature extraction algorithm.The results shows the approach outperforms to the conventional classifer SVM by 1.6 %. Better to use in tracking phase.
Bhang et.al.[18]	Bayesian predictive	Need tests w.r.t. wind turbine Interference
B. Zhang et al.[19]	maximum likelihood criterion	Fits well in targets following weibull distribution with known shape parameters.
Proposed ATI CFAR with VI based Background estimation	Proposed ATI CFAR with variability index based background estimation and censoring	Performs better in multiple target situations. Can minimise outliers caused by wind turbine interference.

Table 3: Comparative analysis of research papers

The interference by wind farms causes shadowing effect. The interference by wind farms causes shadowing effect, desensitization effect, poor visibility in cluttered regions, poor detection performance to list a few. Figure 4 depicts interference caused by wind turbines. Several such are arranged in wind farm in a particular positions to harness and optimize generation of wind energy. Base equation governing the received contaminated returns f_r is expressed below.

$$F_r = \frac{1}{2\pi}\frac{d}{dt}\left(2\pi f_t\left(t+\frac{2r}{c}\right)+\emptyset_1\right) = f_t + \frac{2f_t}{c}\frac{dr}{dt} = f_t + \frac{2f_t vr}{c} = f_t + f_d \quad (1)$$

where

f_r denotes received signal

f_t denotes transmitted signal

f_d denotes Doppler returns from intended and unintended objects.

4. Proposed Algorithm

Based on the requirements, the robust algorithm based on CFAR processor augmented with estimation of background environment using variability index is proposed as below.

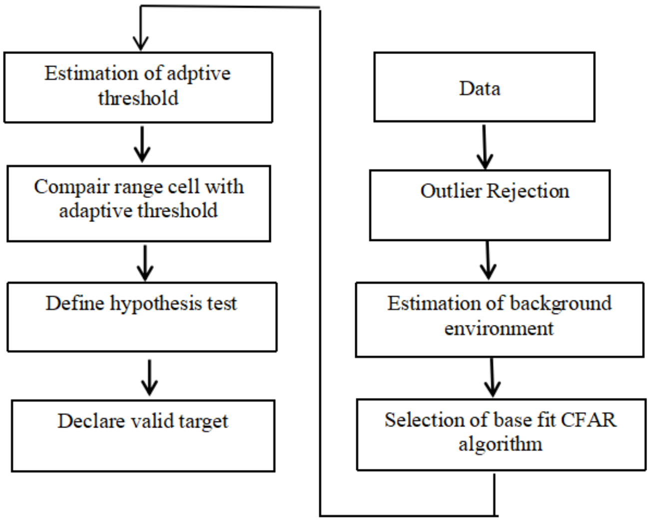

Figure 5. Flowchart of proposed algorithm

When the environment is homogeneous, the cell averaging constant false alarm rate (CA CFAR) performs well; but, when there are presence of non homogeneity, such as spiky outliers, Interference, multiple closed targets or reverberation edges, etc. in reference window, its performance suffers. CFAR architecture is depicted in Fig. 7. The parameters that have been considered for simulation are given in Table 1. The values of KVI and KMR are chosen such that it assures the VI hypothesis test of both the reference windows.

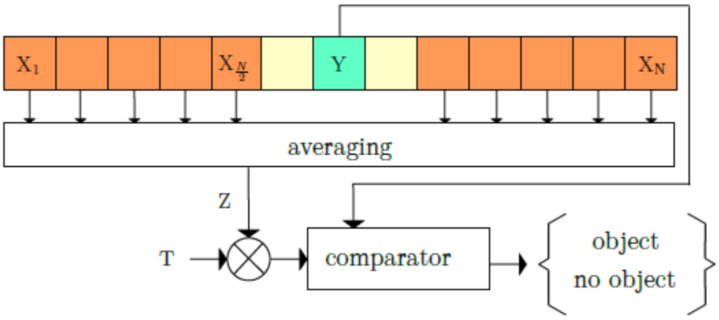

Figure 6. Architecture of CFAR detector

When there is no target [H0], signal detection consists solely of noise. When there is a target [H1], it consists of both signal and noise. The detection performance is determined by the probability of detection (P_d) and the probability of false alarm rate (P_{fa}). Noise estimation is obtained by calculating average mean of all reference cells as given in Eq. (2),

$$Z = \frac{1}{N} \sum_{i=1}^{N} X_i \qquad (2)$$

where N belong to number of reference cells and X_i is a reference cell at i^{th} position. Being a function of probability of false alarm, threshold multiplier T is calculated as,

$$T = N\left({P_{fa}}^{-1/N} - 1\right) \qquad (3)$$

P_{fa} is a desired probability of false alarm.

Hypothesis test for target detection can be given as,

$$H = \begin{cases} H1, \; if\ Y \geq T, & Target \\ H0, if\ Y \leq T, & No\ target \end{cases} \tag{4}$$

There are two situations that could occur when there is a change from a clean to a clutter region.When the test cell is in a clear location and the reference cell group is in a cluttered area, as in the first situation, the adaptive threshold floats above the noise floor which lowers the likelihood of false alarms and increases the likelihood of detection. In the second situation, the adaptive threshold is comparatively small due to clean background will affects the likelihood of false alarm.Especially when the set of reference cells are in a clear area while the Cell under test (CUT) is submerged in clutter even though guard cell are placed. To increase the likelihood of a detection, the greatest of constant false alarm rate (GO CFAR) is suggested. It is attempted here to refine parameter to improve quality of detection. Few of the design parameter are listed as below.

Table 1: Parameters for ATI CFAR

No of range cells	50
P_{fa}	10^-4
K-VI	1.46
K-MR	1.8060
Reference window size	16

Figure 7 describes architecture for one dimensional OS CFAR. This paper proposes CFAR Processor based on ordered statistics (OS CFAR) coupled with background estimation for wind turbine interference mitigation problem. It fares better across homogeneous and nonhomogeneous environment will multiple conditions such as multiple targets in range cell etc. However we have restrained ourselves from describing it in detail.

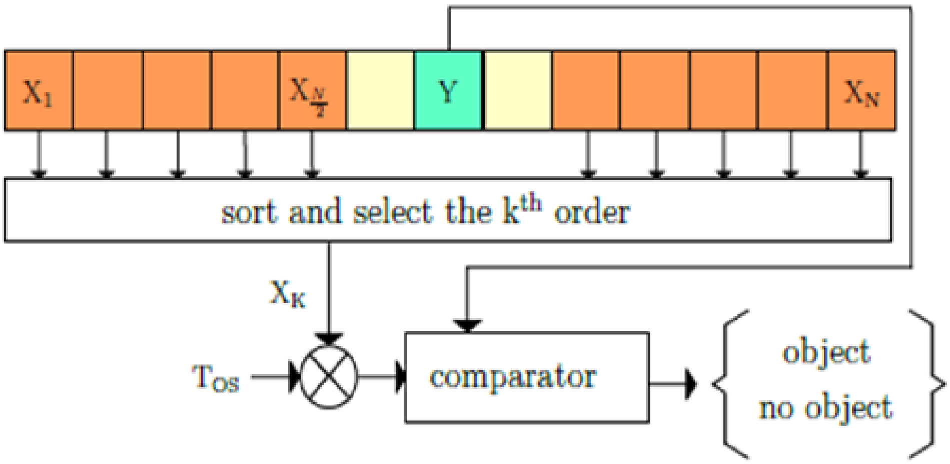

Figure 7: Architecture for OS CFAR

5. Results

From Literature survey, it is inferred that concerns of renewable energy industry requires to be addressed to fulfil the societal need for energy in this 21st century. But in turn, there are various challenges that need to be address, such as interference with communication systems, receiver saturation, increased false alarms in radar, poor detection and tracking capability. Since Radars are used for various civilian and strategic purposes, ignorance can be catastrophic. One simple argument to justify above is stated below. Since the Doppler data is contaminated with interference from wind farms, it affects the secondary moments data which are used to derive moments. These moments governs the weather forecasting parameter such rain rate, precipitation… For military requirements, since the detection process itself in question, the subsequent tracking of targets can be erroneous. The proposed algorithm is implemented in MATLAB software with system specification having windows 10 operating system, Intel Core i5 processor and 16 GB RAM. The proposed method utilized a number of performance metrics to estimate the system performance. Performance is measured in terms of parameters like ROC curve, P_d, $P_{fa.}$ Curve are plotted specifying their dependencies. The test conditions such as multiple targets, clutter edges, reverberation edges etc. evaluated for homogeneous environment conditions. Background estimation is obtained using special characteristics of variability index. Further the traditional CFAR and Ordered Statistics CFAR are implemented.

Performance of CA CFAR, GOCA, SOCA and OS CFAR are compared over detection probabilities using ROC curve in all three environment such as uniform background, nonuniform background and interfering targets.

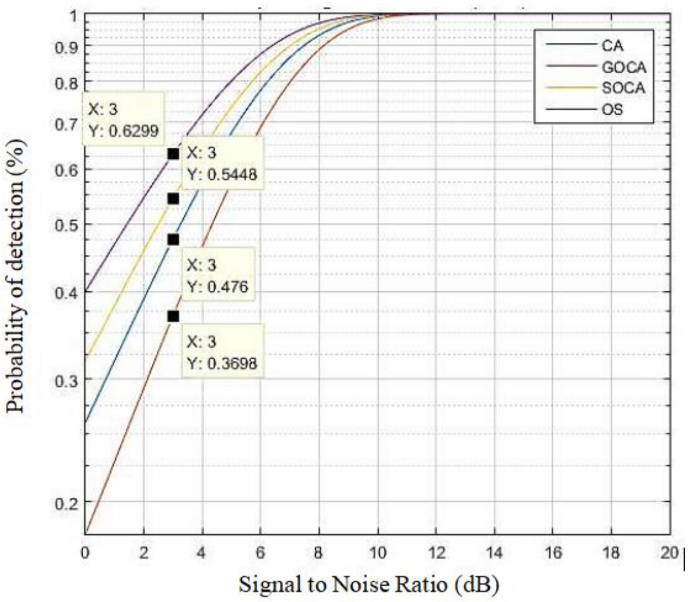

Figure 8. Probability of detection vs signal to noise ratio

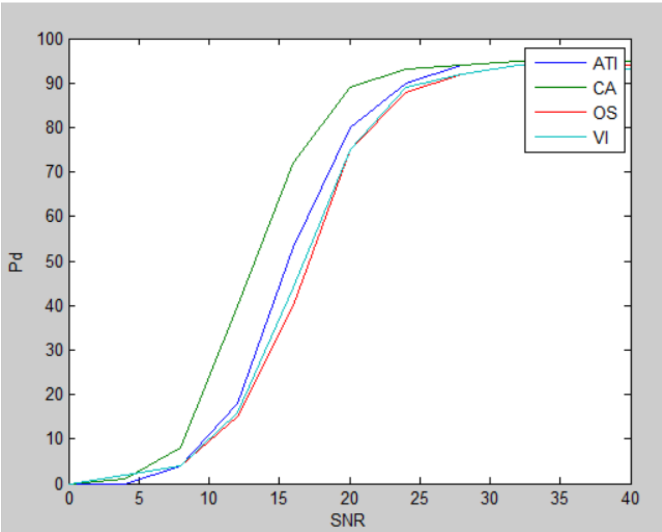

Figure 9. ROC curve for ATI, CA and OS CFAR in a homogeneous environment.

The results are obtained by using Monte Carlo simulation. Calculated values of VI and MR statistics are compared with thresholds K_{VI} and K_{MR}. As variability indices of both the reference windows are less than threshold value K_{VI}

which is set to 1.46, hypothesis test shows each half of the reference cells is homogeneous. MR hypothesis find both windows have different means. Hence algorithm uses GOCA CFAR scheme to calculate adaptive threshold.The performance of detectors is analyzed by plotting a graph of detection probabilities of each detector to the designed SNR.The performances of detection probabilities of CA CFAR, GOCA, SOCA, and OS CFAR are compared in figure 8 for VI CFAR where as figure 9 and 10 shows detector performance for proposed ATI CFAR processor. When compared to CA CFAR, SOCA CFAR provides 58% Pd at 3dB SNR, while OS CFAR provides 66% P_d, which is 10% better than SOCA and over 20% better than CA CFAR. Hence algorithm uses GOCA CFAR scheme to calculate adaptive threshold. In a nonuniformly distributed noise over the length of reference windows, GOCA and SOCA performs better than CA CFAR, while OS CFAR detector detects target with P_d of 70%.

The performance of ATI, CA, VI and OS CFAR in the presence of three interfering objects within the reference window is shown in figure 10. ATI CFAR processor performs better in homogeneous environment compared to OS, VI and CA CFAR algorithms.

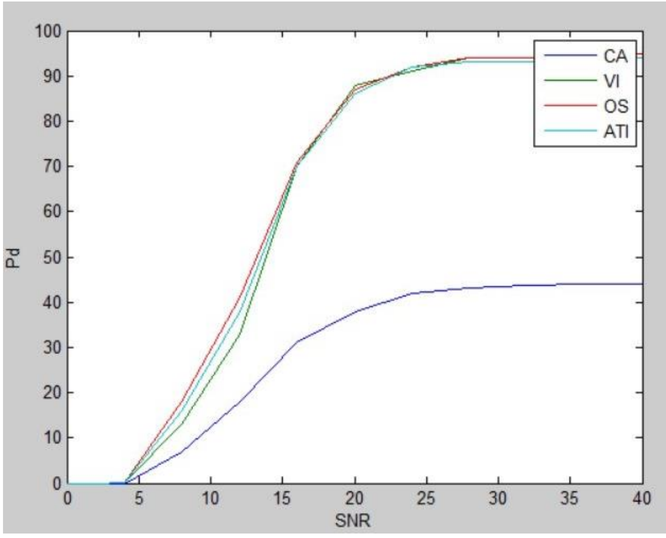

Figure 10. ROC curve for ATI, CA, VI and OS CFAR for multiple targets conditions.

6. Conclusion

An essential resource for a country's development is energy. Wind farms (both on shore and off shore) are witnessing faster growth over the decade. It has potential to fulfil the need of clean energy. With an emphasis on wind turbine clutter mitigation, the proposed method is devised with the expectation of improving detection capability in homogeneous environment condition.

We have implemented cell averaging CFAR algorithms and proposed OS CFAR assisted with variability index based background estimation to improve quality of detection in the context of wind turbine interference. The algorithm is simulated for various environmental conditions such as multiple targets situations, clutter edges, reverberation edges. Aim of this research work is to identify and refine detection of moving objects among clutter generated by rotating blades of wind turbine by solving problems like desensitisation, shadowing effects. Shadowing effects are addressed by proper refining of parameters such as range cells, having localised thresholds, adaptive threshold based on background environment.

It is observed that variability Index algorithm selects appropriate threshold routine based on the type of environment. The effectiveness of thresholding algorithms is examined in homogeneous environments for multiple targets and clutter edges scenarios. GOCA CFAR and SOCA CFAR improvises the performance in variable noise condition and interfering target situation respectively but GOCA fails to maintain false alarm at desired level. OS CFAR offers 63% detection probability where CA CFAR performs to 48%. Probability detection of detector increases as SNR is increases.

As per reference number [14], neural network based thresholding is proposed. Two stage detector process is also reported [12]. However it is observed that it is computationally heavy to implement neural network based detector or two stage detector on real time data. Table 3. shows comparative analysis. ATI CFAR processor performs better in homogeneous environment compared to OS, VI and CA CFAR algorithms. A robust classifier can be roped in the subsequent stages after centroiding.

In future work, the computational complexity can be taken into account. Radar cross section is a dominant parameter which influences interference to communication systems. In future, proposed method can be applied on different environment conditions. The wind turbine interference radar problem required efforts on larger scale with emphasis on specific requirements of systems and conditions in which it has to function. A generous effort has been made to address the impending problem in the path of green energy.

6. Contributions

This research work conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing, original draft preparation, writing , and editing, visualization, have been done by 1st author. The supervision has been done by 2nd author and review and project administration have been done by 3rd author.

7. Approval

The Research work is funded and approved.

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