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Detection of Targets with Small Apparent Doppler Frequencies in LFMCW Radars

Fathy M Ahmed
Radar Department, Military Technical College, Cairo, Egypt.
fkader@mtc.edu.eg

Abstract. Linear Frequency Modulated Continuous Wave (LFMCW) radars are widely used in automotive applications or borders protection because of their noticeable performance. These radars should include Moving Target Indicator (MTI) to suppress all fixed targets in urban crowded areas or open borders. MTI attenuates signals with small apparent Doppler frequencies coming from slowly moving targets, high speedy targets, or those moving with an angle near 90 or -90 degrees to the radar radial direction. In this paper, the frequency response of the MTI is modified by adding a Single Delay Line Integrator (SDLI) following it to enhance its gain for small Doppler frequencies with some degradation in detecting middle Doppler targets. A choice between the traditional structure and the proposed one through a maximum-of criterion is proposed to achieve an improved equal detection performance for all Doppler frequencies. The detection superiority of the proposed method for slowly moving or high speed targets detection over the traditional one is validated for different target scenarios through the Receiver Operating Characteristic (ROC). Implementation considerations for single delay line integrator such as complexity and stability are discussed. A suggested scheme is proposed to achieve complexity reduction as well as stable operation.

Keywords: LFMCW Radar, MTI, Integrator, Doppler frequency.

1. Introduction

Different target detection devices such as radars, cameras, ultrasonic sensors, or Light Detections And Ranging (LIDAR) are widely used in many military and civilian applications. Military applications include security requirements for country borders or important building protection. One of the famous civilian applications is the automotive field. Among these devices, radar systems are the most reliable in spite of the surrounding operating environment such as dust, bad weather, or night.

Radar systems are classified, from principle of operation view point, into pulsed or continuous wave. Continuous wave radars need to be frequency modulated to be able to measure target ranges [1]. LFMCW radar is preferable for the mentioned applications over pulse radar because of its ability to measure very small ranges and relative velocities to the target with high accuracy. FMCW radar is, also, characterized by its small weight, small energy consumption, and less hardware complexity relative to pulse radar [2].

FMCW radar extracts the information of target range and Doppler by calculating the target beat frequency and phase exchange based on a Two-Dimensional Fast Fourier Transform (2D-FFT) processing algorithm. To distinguish between fixed and moving targets, MTI filter is used. MTI frequency response varies according to its order. The main difference between MTI variants is the frequency response gain for small Doppler values [3]. The biggest gain for small Doppler frequency can be achieved by realizing the MTI as a single delay line canceller (SDLC). Even in this case, very small apparent Doppler frequency returns suffer from a great attenuation. These Doppler frequencies may be related to the following cases:

- A slowly moving target with a small Radar Cross Section (RCS), especially when this target is masked by a strong clutter.
- A target moving with any speed with an angle near 90 or -90 degrees to the radar radial direction.

In this paper, a proposed method is introduced to modify the frequency response of the SDLC MTI to improve its frequency response for small Doppler frequencies. This is achieved by adding a SDLI following the MTI.

This paper is organized as follows; after the introduction, traditional LFMCW signal processing is discussed in section 2. Modifying the MTI frequency response by adding the SDLI is explained in section 3. Application of the proposed method in LFMCW radar signal processing and comparing its performance relative to traditional one is introduced in section 4. Finally, conclusion comes in section 6.

2. Traditional LFMCW radar signal processing

Signal processing in traditional LFMCW radar system depends mainly on performing two Fast Fourier Transforms (FFTs) on the received signal for target information extraction as shown in figure (1) [4]. The first FFT is used for beat frequency (corresponds to target range) extraction and the other FFT is used for Doppler frequency (corresponds to target relative velocity) extraction. The application of MTI takes place after the first FFT as shown in the general block diagram of the traditional LFMCW radar of figure (2) [1].

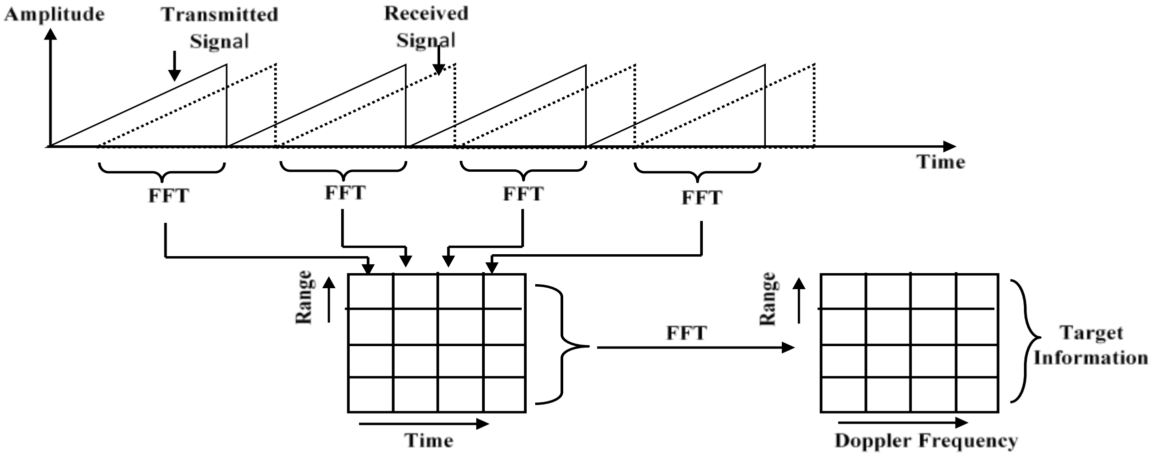


Figure 1. 2-D FFT in LFMCW radar

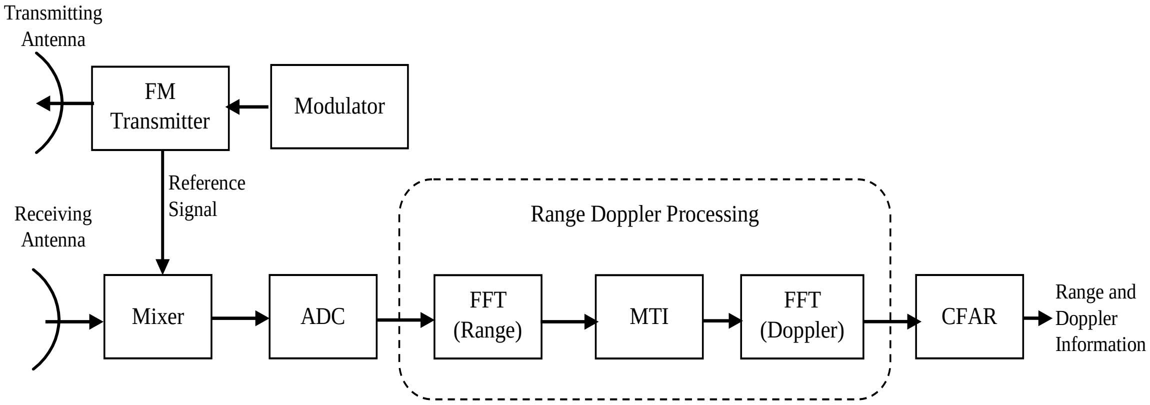
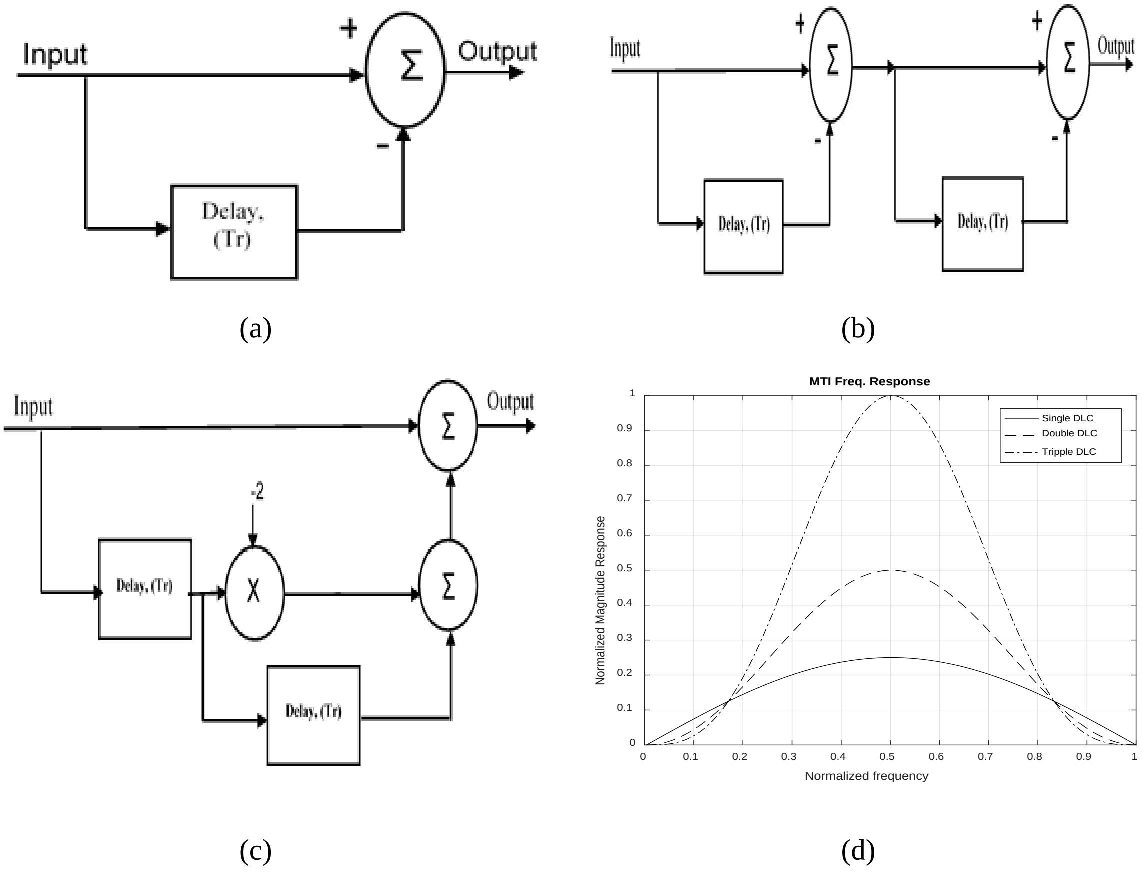


Figure 2. The general block diagram of the traditional LFMCW radar

2-D FFT processing in FMCW radar is a very good approach to distinguish between moving targets and fixed targets or clutter based on Doppler information [5]. The existence of the MTI before the second FFT not only removes fixed targets but also reduces the effect of the clutter spectrum from affecting the second FFT Doppler bins. MTI may be implemented as single, double, or triple delay line canceller as shown in figure (3-a), (3-b), (3-c). The normalized frequency responses of these MTI structures are shown in figure (3-d). Double or triple delay line cancellers are more favourable than single delay line canceller in air defence radars because they have a wider notch at the stop band to reduce the effect of slowly moving unwanted signals like chaffs. On the other hand, single delay line canceller is favourable in LFMCW radars to detect slowly moving targets like walking persons. The Constant False Alarm Rate (CFAR) processor is used to establish an adaptive threshold to achieve a constant false alarm rate [6].



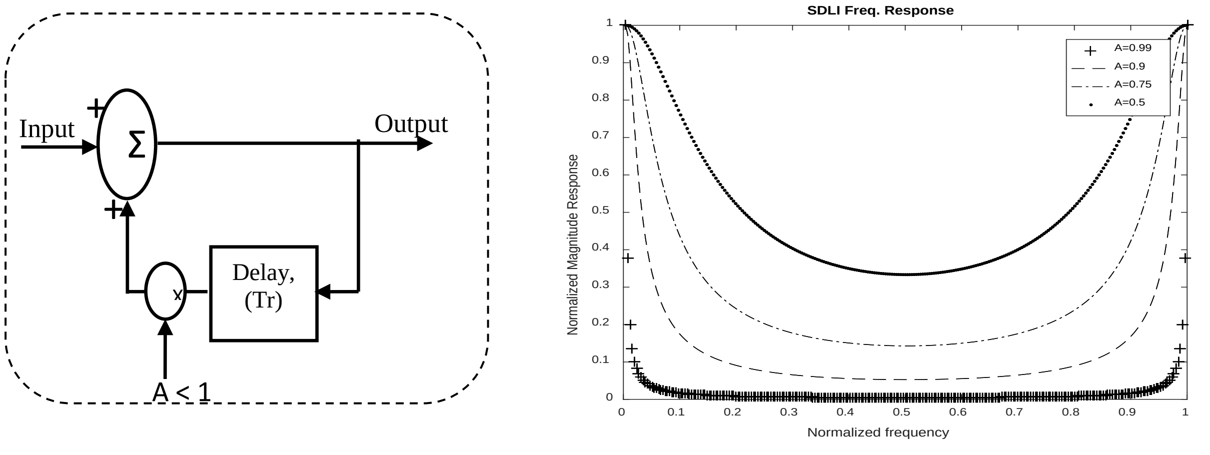
(a) (b)

(c) (d)

Figure 3. Realization and frequency response of MTI
(a) Single DLC, (b) Double DLC, (c) Triple DLC, (d) MTI Frequency Responses

3. The proposed method for modifying the MTI frequency response

The main problem of using the SDLC MTI in LFMCW radar is the attenuation of slowly moving targets due to its frequency response. If the slowly moving target with weak echo exists near strong clutter area, complete masking to this target may happen. One possible solution to solve this problem is to modify the frequency response of the SDLC MTI to improve its gain for small Doppler frequencies. This is achieved in the present work by multiplying the frequency response of the SDLC, shown in figure (3-d), by the frequency response of the SDLI, shown in figure (4-a), and whose stable realization is shown in figure (4-b) for different stabilization factor values, A.



(a) (b)

Figure 4. Stable single delay line integrator (SDLI), (a) Realization, (b) Frequency response at different values of A

The realization of the proposed SDLC/SDLI structure is shown in figure (5), while its frequency response for different values of the stabilization factor, A, is shown in figure (6). The SDLC frequency response is plotted in figure (6) for the purpose of comparison.

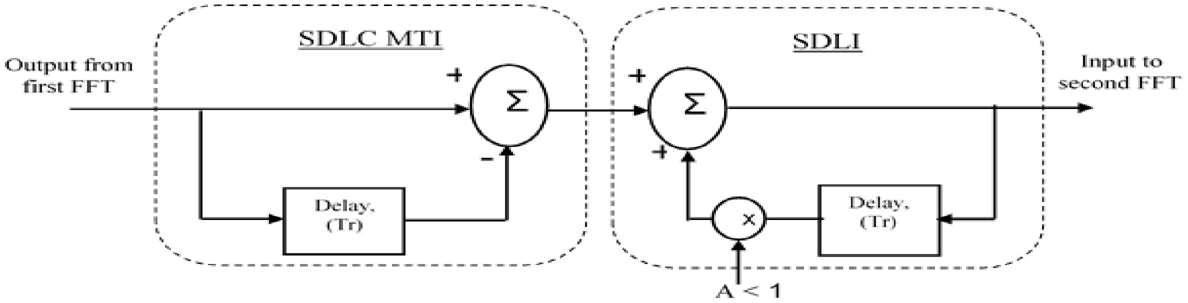


Figure 5. The proposed SDLC/SDLI structure to modify the SDLC MTI frequency response

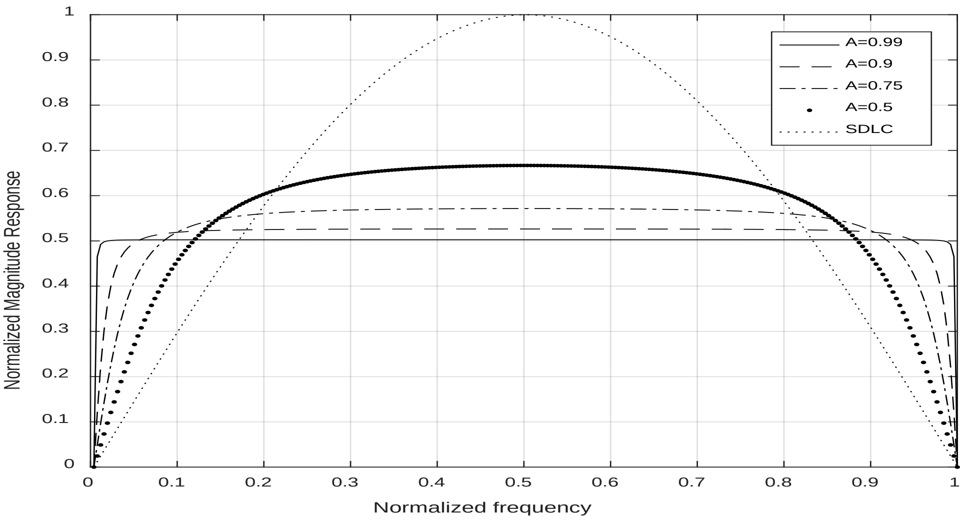


Figure 6. Frequency response of the proposed SDLC/SDLI structure at different values of A compared to that of SDLC

As shown in figure (6), the frequency response for small Doppler frequency is greatly improved relative to MTI alone. The improvement depends on the value of the selected stabilization factor, A, of the SDLI. On the other hand, for higher Doppler targets, the frequency response of the proposed structure is reduced compared to MTI. The reduction, also, depends on A. The ideal value for this factor is one which gives the greatest gain for small Doppler targets. In this case, the frequency response of the proposed structure gives the same gain for all Doppler frequencies. This structure may be used when the most concern is in detection of small Doppler targets. For A=1, the SDLI is marginally unstable. In this case, stable realization for the proposed structure in LFMCW radars is achieved as explained in the next section.

4. Application of the proposed SDLC/SDLI structure in LFMCW radar

In LFMCW radar, the total radar space, which can be explained as shown in figure (7), is divided into a large number of range, P, and azimuth, M, cells. During antenna illumination time, fixed number, N, of target returns into certain range azimuth cells can be calculated by $N= f_m \cdot \theta_b / \Omega$, where f_m is the sweep frequency, θ_b is the azimuth beam width, and Ω is the antenna scanning rate [1].

2-D FFT processing in LFMCW radar is archived for each batch of range azimuth cells called Coherent Processing Interval (CPI). In this case, and when applying the proposed SDLC/SDLI structure, the stabilization factor, A, of the SDLI can be set to one while ensuring a reset operation to the integrator summation at the end of each CPI to keep stability. However, the block diagram of the LFMCW radar incorporating the proposed SDLC/SDLI structure is shown in figure (8).

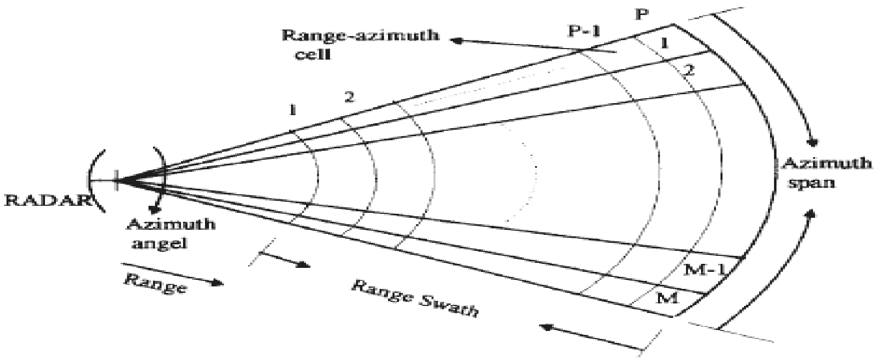


Figure 7. LFMCW radar operating space

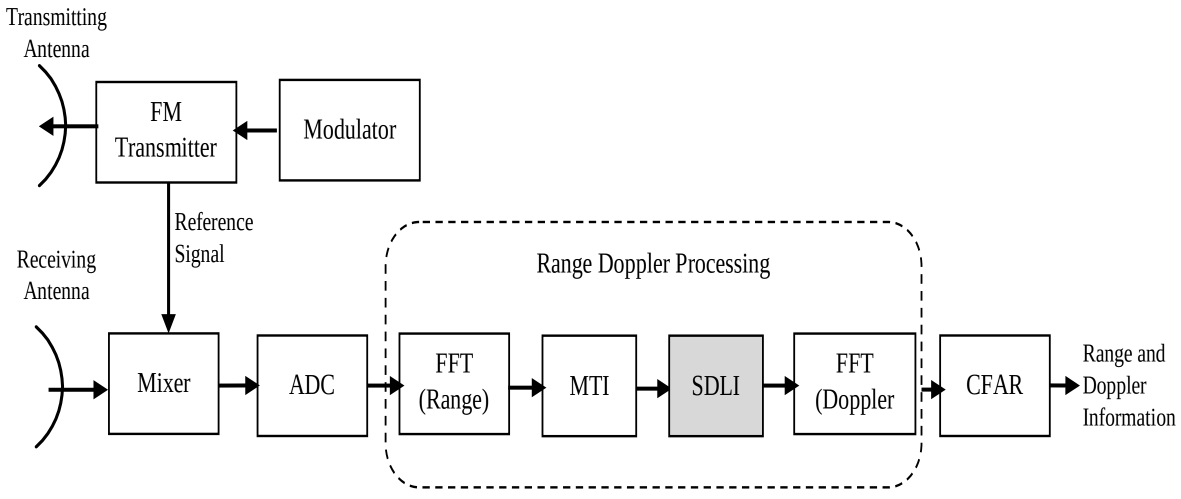


Figure 8. LFMCW radar block diagram incorporating the proposed SDLC/SDLI structure

5. Simulation results

Firstly, simulation is carried out to verify the superiority of the proposed SDLC/SDLI structure over the SDLC alone for small Doppler targets as well as for very high Doppler targets. Secondly ROC curves are plotted for the LFMCW radar using the proposed SDLC/SDLI structure and compared to the traditional one. Simulation parameters were chosen such that range cells equal 1024, while Doppler cells equal 32.

Firstly, the output of the second FFT is tested for a set of slowly moving targets with different Doppler frequencies, (1/32, 4/32, 8/32, 12/32, 16/32, 20/32, 24/32, 28/32, 31/32) x $f_{m,}$ in a noiseless environment. Figure (9) shows the output of the second FFT in the traditional LFMCW radar and the proposed one. The improvement in the amplitude of the slowly moving targets as well as very high speed targets is very clear in the proposed structure compared to the traditional one. On the other hand, the amplitudes of the middle Doppler targets suffer from some attenuation compared to the traditional one.

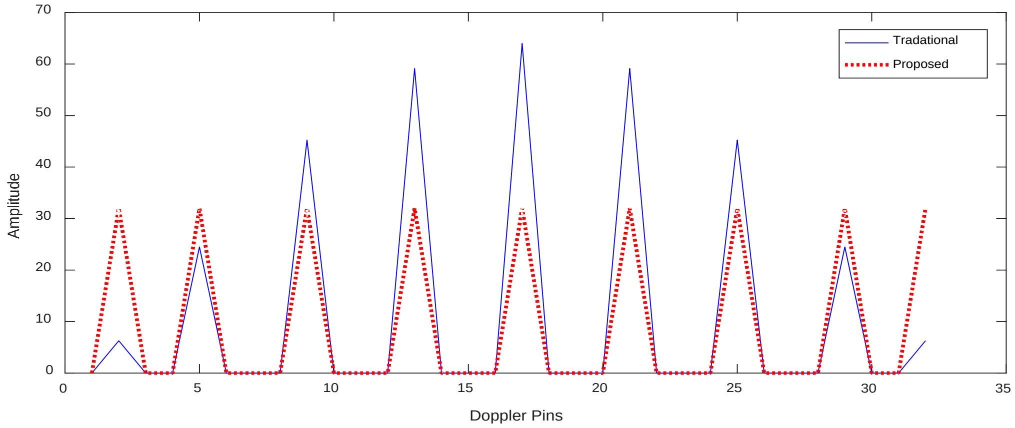


Figure 9. The output of the second FFT in the traditional and the proposed LFMCW radars for different Doppler frequencies.

Secondly, the ROC curves are calculated for the same targets. However, figure (10-a) shows the ROC curve for a slowly moving (Doppler frequency=1/32 * f_m) or the highly Doppler targets (Doppler frequency=31/32 * f_m) for both the traditional and the proposed structures. Figure (10-b) shows the ROC curve for a target with a middle Doppler frequency of 16/32 * f_m.

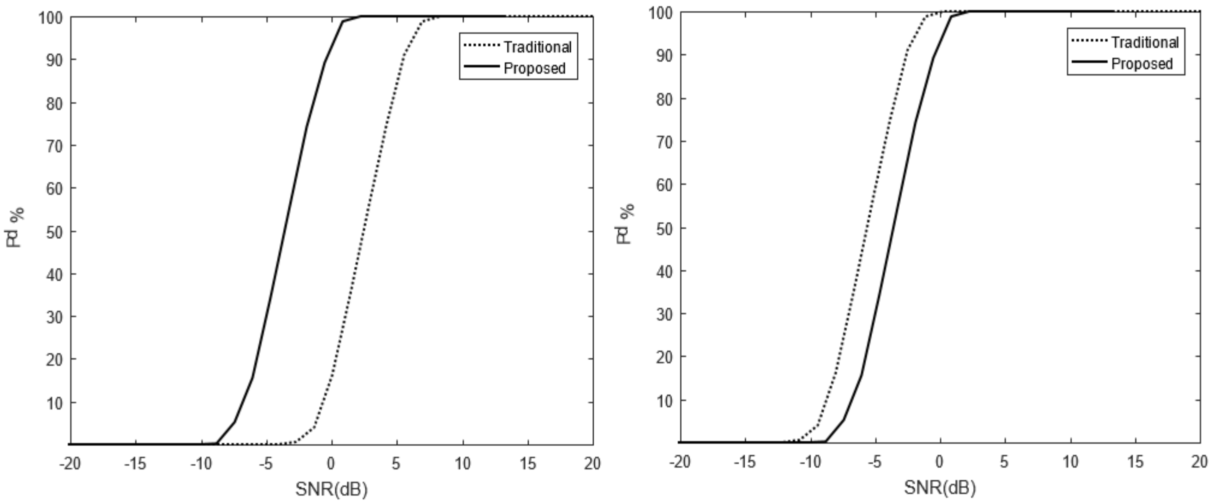


Figure 10. The ROC curves for the traditional LFMCW radar and the proposed one at P_{fa} = 10^-6
(a) Doppler frequency=(1/32)f_m or =(31/32)f_m ,(b) Doppler frequency=(16/32)f_m

Results obtained in figure (10) ensure the improvement in detection performance for slowly and very speedy moving targets (extra 80% in P_d at Signal to Noise Ratio (SNR)=0 dB), while the detection performance for middle Doppler targets is degraded (less than 30% in P_d at SNR -5dB).
To get the benefit of the proposed SDLC/SDLI structure for small and high Doppler frequencies as well as the advantage of the SDLC alone, a proposed structure combining both structures is shown in figure (11).

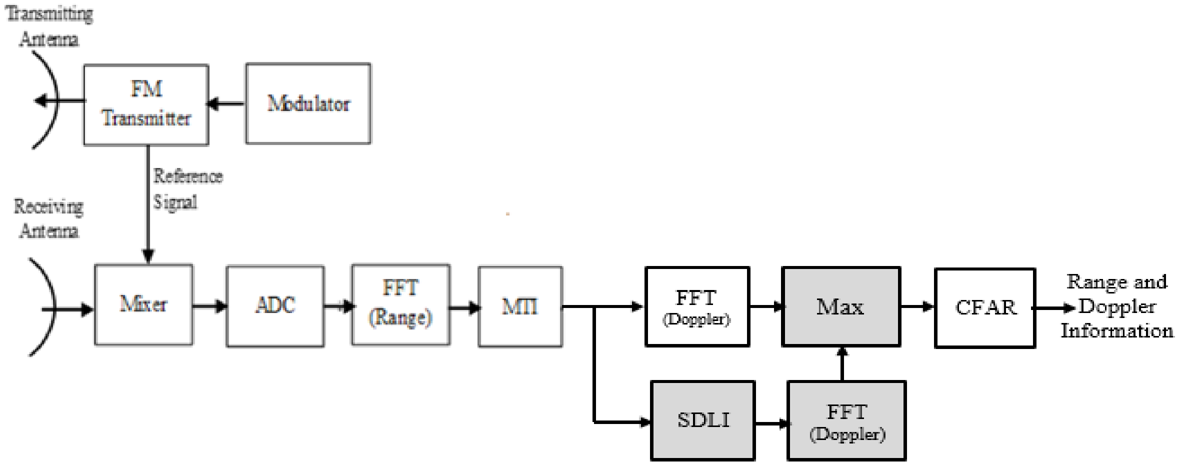


Figure 11. LFMCW radar block diagram incorporating the proposed combined structure

The proposed structure of figure (11) depends on selecting the maximum output of either the SDLC MTI channel or the SDLC/SDLI channel. The proposed combined structure contains more hardware than the traditional structure but achieves an equal improved detection performance over the traditional structure. However, figure (12) shows the output of the Max block compared to the traditional structure for different Doppler frequencies. ROC curves for the proposed combined structure compared to the traditional one for small/high Doppler and middle Doppler frequencies are shown in figure (13-a) and (13-b) respectively. It is clear that the detection performance of the proposed combined structure is better than or equal to that of the traditional one for all Doppler frequencies.

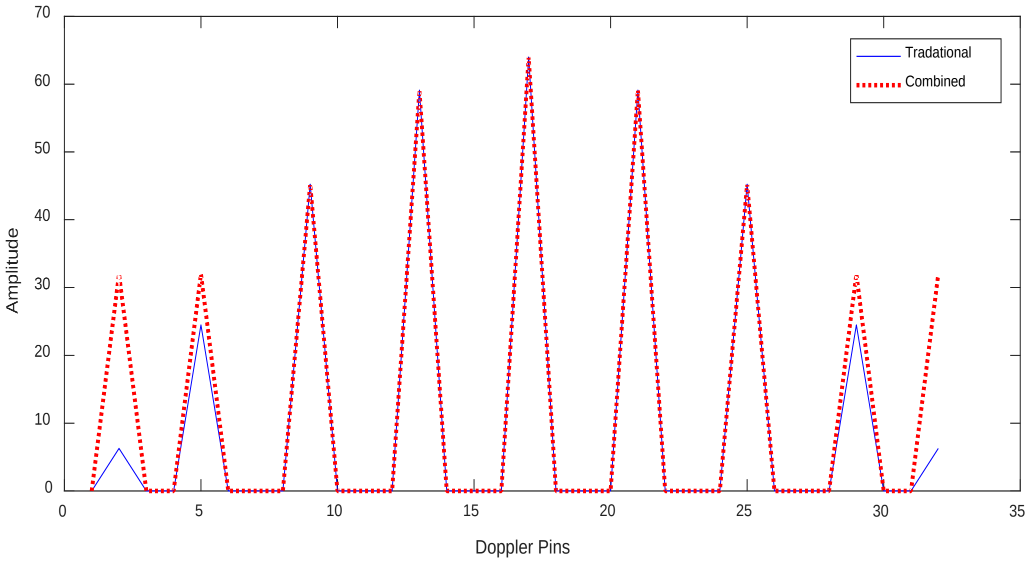


Figure 12. The output of the Max block in the proposed combined structure compared to the traditional structure for different Doppler frequencies.

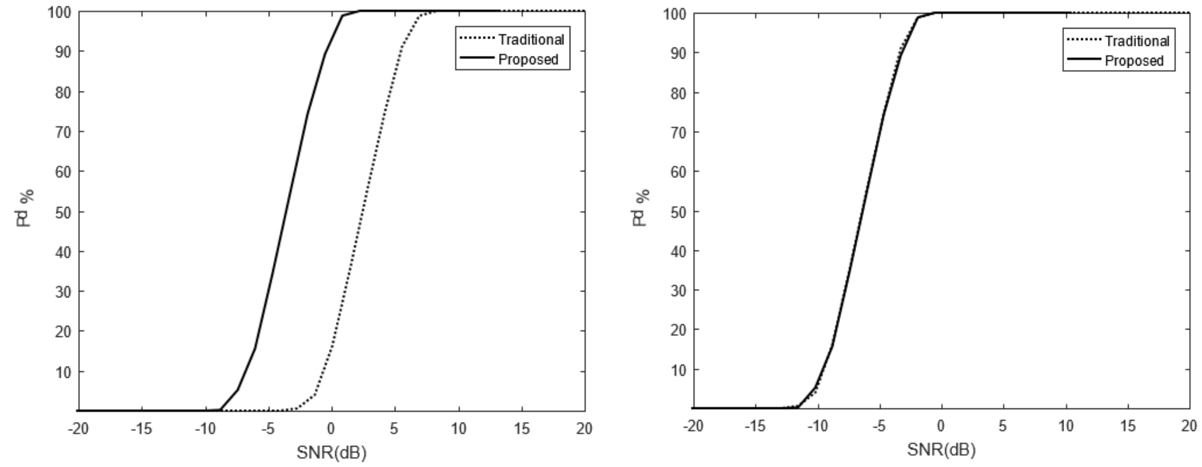


Figure 13. The ROC curves for the traditional LFMCW radar and the proposed combined one at P_{fa} = 10^-6
(a) Doppler frequency=(1/32)f_m or =(31/32)f_m , (b) Doppler frequency=(16/32)f_m

6. Conclusion

Detection of slowly moving targets with small apparent Doppler frequencies as well as very high speed targets using LFMCW radar suffers from attenuation due to MTI operation. In the present work, a proposed method is introduced to modify the frequency response of the SDLC MTI for small and very high Doppler frequencies by adding a SDLI after the SDLC. Implementation of the proposed SDLC/SDLI structure to achieve good performance with stable operation has been introduced. Using the proposed SDLC/SDLI structure in LFMCW radar signal processing enhances the detection capability for targets with small and very high apparent Doppler frequencies by 80% at SNR=0 dB over the traditional one with a detection degradation for middle Doppler targets of 30% at SNR = -5 dB. A proposed combined structure has been introduced to overcome this degradation by adding an extra FFT channel and choosing the maximum output between the FFT of the traditional SDLC channel or the SDLC/SDLI channel. The superiority of the proposed combined structure has been validated over the traditional structure through the ROC curves.

7. References

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