Detection Algorithm of Target Buried in Doppler Spectrum of Clutter Using PCA

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Abstract This paper proposes a novel technique for detecting a target signal buried in clutter signals using Principal Component Analysis (PCA) for pulse Doppler radar systems. The conventional detection algorithm is based on FFT-C-FAR (Fast Fourier Transform-Constant False Alarm Rate) approaches. However, the detection task becomes extremely difficult when Doppler spectrum of the target is completely buried in that of clutter. To enhance the detection probability in the above situations, the proposed method employs PCA algorithm, which decomposes target and clutter signals into uncorrelated components. The performance evaluation of the proposed method is investigated against the conventional FFT-CFAR based detection approach. Simulation results for both these approaches are compared in terms of the target detection probability against false alarm probability for a constant SCR (Signal to Clutter Ratio). The results of numerical simulations confirm that the proposed method improves the detection probability compared with that obtained by the conventional FFT-CFAR method, especially for the lower SCR situations.

Key words Pulse Doppler Radar, Principal Component Analysis(PCA), Constant False Alarm Rate(CFAR)

1. Introduction

Doppler radars are used to detect moving targets from the relatively slow moving or stationary clutter returns in aviation or in weather forecast to examine the motion of precipitation. It can extract much smaller target echoes from clutters using its Doppler frequency difference. The conventional Doppler radar calculates the relative velocity of the target using Fast Fourier Transform(FFT) whereas the distance of the target is measured by the time delay in the target echoes[1]. In general, there are two basic forms of Doppler radars; FMCW radars and Pulse Doppler(PD) radars[2]. We consider PD radars in this paper.

A PD radar, in general, employs CFAR (Constant False Alarm Rate) processing which detects the eminent components from the Doppler spectrum of the received signal compared with that of clutters. In the case that the velocity of target is relatively faster than that of clutter, this method accurately separates the target signal from clutter by determining an appropriate threshold [3]. However, Doppler radars often encounter a severe situation in which Doppler frequency of the target is completely buried into that of clutter. Particularly, in long range PD radar systems, when a target is moving at high speed, its Doppler spectrum is buried in that of clutter because of aliasing[1]. In such case, the detection of target with the conventional FFT-CFAR method becomes extremely difficult.

In order to overcome the above problem, this paper presents a novel algorithm of target detection in PD radars based on PCA, which decomposes the mixed Doppler spectrum of the target and clutter into uncorrelated components. Since the target component is more likely to present in the higher singular values, PCA processing can suppress a substantial level of clutter. To select the most promising Principal Component(PC), the proposed method introduces the evaluation value specifying the single sinusoidal signal detection, which measures a degree of energy concentration of reconstructed spectrum. The performance evaluation of the proposed method is investigated against the conventional FFT-CFAR method. Simulation results for both these approaches are compared in terms of the target detection probability against false alarm probability for a constant SCR (Signal to Clutter Ratio). These results verify that the proposed algorithm efficiently detects the target even in the lower SCR situations, compared to that of the conventional FFT-CFAR method.

2. System and Signal Model

Fig. 1 illustrates the schematic diagram of a PD radar. The centeral frequency of the transmitted pulse is defined as f_c and the Doppler frequency of the target is denoted by f_d. A number of pulses are transmitted after sinusoidal wave modulation. The echoes from the target are received with a time delay and its Doppler frequency is calculated by the received pulses at same range bin determined by PRI (Pulse Repetition Interval). If the verocity of the target is regarded as constant in the observation interval, the received signal with the Doppler frequency f_d can be expressed as

$$s(n) = A\exp(\mathrm{j}2\pi f_d n T_{\mathrm{pri}}), \qquad (1)$$

where T_{pri} denotes PRI, n is a number of pulse. Here, we assume that clutter signal is expressed as a moving average of signals with identical independent distribution (i.i.d) as

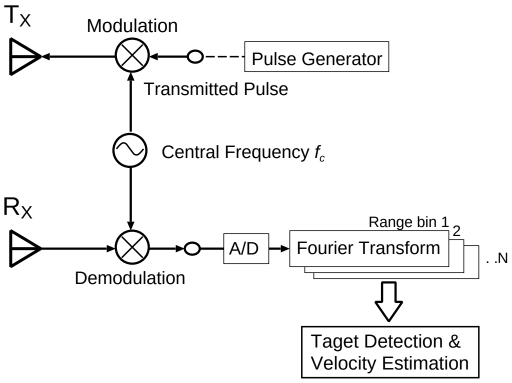

Fig. 1 Schematic illustration of a PD radar system.

$$c(n) = \sum_{l=1}^{L-1} \exp\left\{\frac{-(l-\mu_0)^2}{2\sigma^2}\right\} e(n-l), \quad (2)$$

where $e(n)$ takes a zero mean uniform distribution from -0.5 to 0.5, L denotes the length of a moving average filter, μ_0=$L/2$ and σ= $0.08L$. Then, observed signal $x(n)$ is given by

$$x(n) = s(n) + c(n). \quad (3)$$

For simplicity, we ignore a thermal noise at the receiver.

3. Conventional Method

In general, PD radars detect the target by Doppler spectrum analysis of the received signal. In the conventional detection methods, FFT is employed to determine the Doppler spectrum of target and clutter at a fixed range. Then the CFAR method is applied to the output of FFT to detect the target. Here, the existing CFAR method based on the window sliding is introduced[8]. In practice, CFAR method discriminates the target signal by comparing the intensity of frequency spectrum with preliminary determined threshold T as

$$T = \mathrm{V_{th}} \times \frac{1}{N_w}\sum_{i=1}^{N_w} x_i, \quad (4)$$

where $\mathrm{V_{th}}$ is a scaling factor used to adjust the false alarm probability and N_w denotes the length of reference window. An example of target detection by CFAR method at $\mathrm{V_{th}} = 2$ is depicted in Fig. 2. The component of the frequency spectrum which exceeds the CFAR threshold level is regarded as the target component. The FFT-CFAR method can detect target components accurately when the Doppler frequencies of the target and clutter are sufficiently separated. However, its detection ability immediately decreases when a target is buried inside clutter.

4. Proposed Method

To resolve the problem described above, this paper proposes a target detection algorithm based on PCA. PCA decomposes the observed signals into uncorrelated Principle Components(PCs). To enhance the accuracy of the target detection, the evaluation value specifying the sinusoidal wave detection is introduced in this method.

4.1 Target Detection with PCA

PCA is one of the blind source separation techniques and has been used for the suppression of ocean clutter in ground-wave radars[5] and landmines detection in Ground Penetrating Radars(GPR)[6]. A higher singular value (SV) estimated by PCA corresponds to that of desired signal, if the SV originated

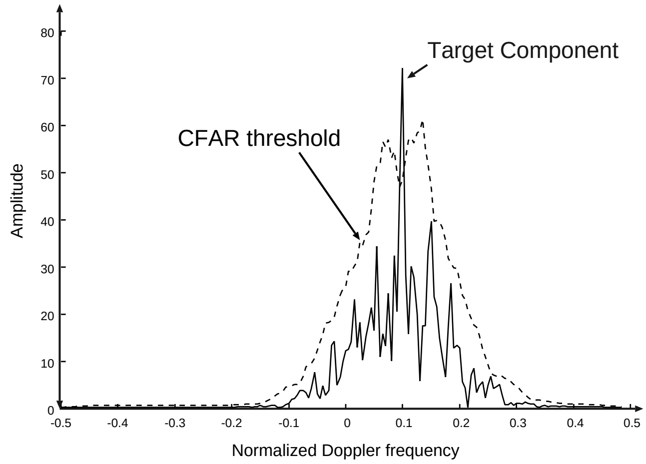

Fig. 2 Conventional target detection method using CFAR processing.

from noise is lower. In order to obtain multiple observed signals, the observed signal matrix $\boldsymbol{X}(n)$ is created with time delay as,

$$\boldsymbol{X}(n) = [\boldsymbol{x}_1(n), \boldsymbol{x}_2(n), \cdots, \boldsymbol{x}_M(n)]^{\mathrm{T}}, \quad (5)$$

where $\boldsymbol{x}_i(n) = \boldsymbol{x}(n + i\,T_{\mathrm{pri}})$ and index i denotes the channel number while T_{pri} represents the interval of time delay. Here, PCA is performed by using Singular Value Decomposition (SVD) of the observed signal $\boldsymbol{X}$. Basically, clutter components having relatively lower SVs compared to those of target, are eliminated by PCA processing. The reconstruction signal matrix $\boldsymbol{Y}$ after PCA is formulated as

$$\boldsymbol{Y} = [\boldsymbol{y}_1, \boldsymbol{y}_2, \cdots, \boldsymbol{y}_p]^{\mathrm{T}} = \boldsymbol{U}^{\mathrm{T}}\boldsymbol{X} = \boldsymbol{D}\boldsymbol{V}^{\mathrm{T}}, \quad (6)$$

where $\boldsymbol{U}$, $\boldsymbol{V}$ are orthogonal basis matrix created from the singular vectors of $\boldsymbol{X}$ and $\boldsymbol{D}$ is a diagonal matrix with singular values of $\boldsymbol{X}$. The p is the number of the dominant PCs, which have distinct SVs compared with other SVs.

To choose the desired signal assumed as a sinusoidal waveform, the following evaluation value is introduced as

$$e(\boldsymbol{y}_i) = \frac{\max|\mathcal{F}(\boldsymbol{y}_i(n))|^2}{\sum_{n=1}^{N}|\mathcal{F}(\boldsymbol{y}_i(n))|^2}, (i= 1, 2, \cdots, p), \quad (7)$$

$$\boldsymbol{y}_{\mathrm{select}} = \mathrm{argmax}_{\boldsymbol{y}_i \in \boldsymbol{Y}} |e(\boldsymbol{y}_i)|, \quad (8)$$

where $\mathcal{F}$ denotes the discrete Fourier transform and N represents the number of samples in one PC. In this case, the desired signal is sinusoidal wave, which takes an impulse distribution in the frequency domain. Then, the reconstruction signal obtaining the maximum $e(\boldsymbol{y}_i)$ defined as $\boldsymbol{y}_{\mathrm{select}}$ is regarded as the target signal.

4.2 Procedure of the Proposed Method

This section presents the actual procedure of the proposed algorithm. Figure. 3 illustrates the flow diagram of the proposed method.

Step 1). The observed signal matrix $\boldsymbol{X}$ with time delay of the data $x(n)$ is created as

$$\boldsymbol{X} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \cdots, \boldsymbol{x}_M]^{\mathrm{T}}, \quad (9)$$

where M denotes the total number of channels of $\boldsymbol{X}$.

Step 2). After applying PCA to $\boldsymbol{X}$, the reconstructed signal $\boldsymbol{Y}$ is obtained, and then, $\boldsymbol{y}_{\mathrm{select}}$ is determined in Eq. (8).

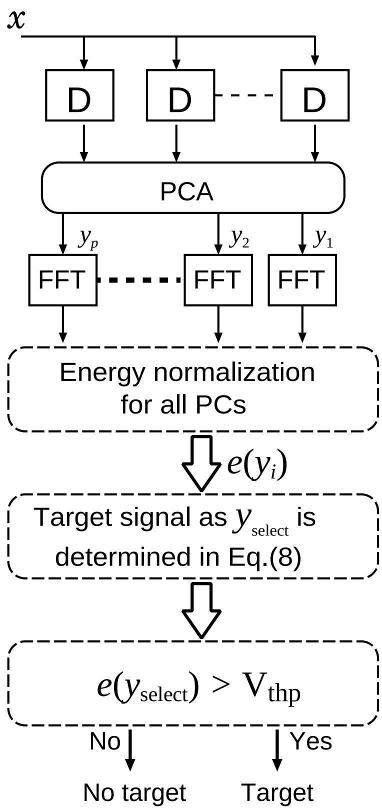

Fig. 3 Flow diagram of the proposed method(D=Time Delay).

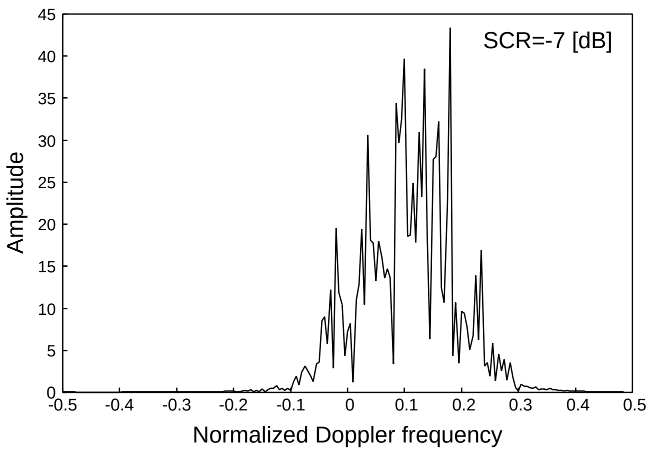

Fig. 4 Doppler frequency spectrum of the observed signal.

Step 3). The target is detected, if the following condition is satisfied,

$$e(\boldsymbol{y}_{\text{select}}) > \mathrm{V}_{\text{thp}}, \tag{10}$$

where V_{thp} is empirically determined.

The proposed method suppresses the substantial power of clutter in the reconstructed signal $\boldsymbol{Y}$. Furthermore, it provides the quantitative criteria for the detection of the single sinusoidal signal.

5. Performance Evaluation

This section presents the performance evaluation of the proposed method and conventional FFT-CFAR method in numerical simulation. Here, $M = 200$, $N = 200$ are set where N denotes the number of data samples in each channel of $\boldsymbol{X}$. The performance is investigated employing the target detection probability

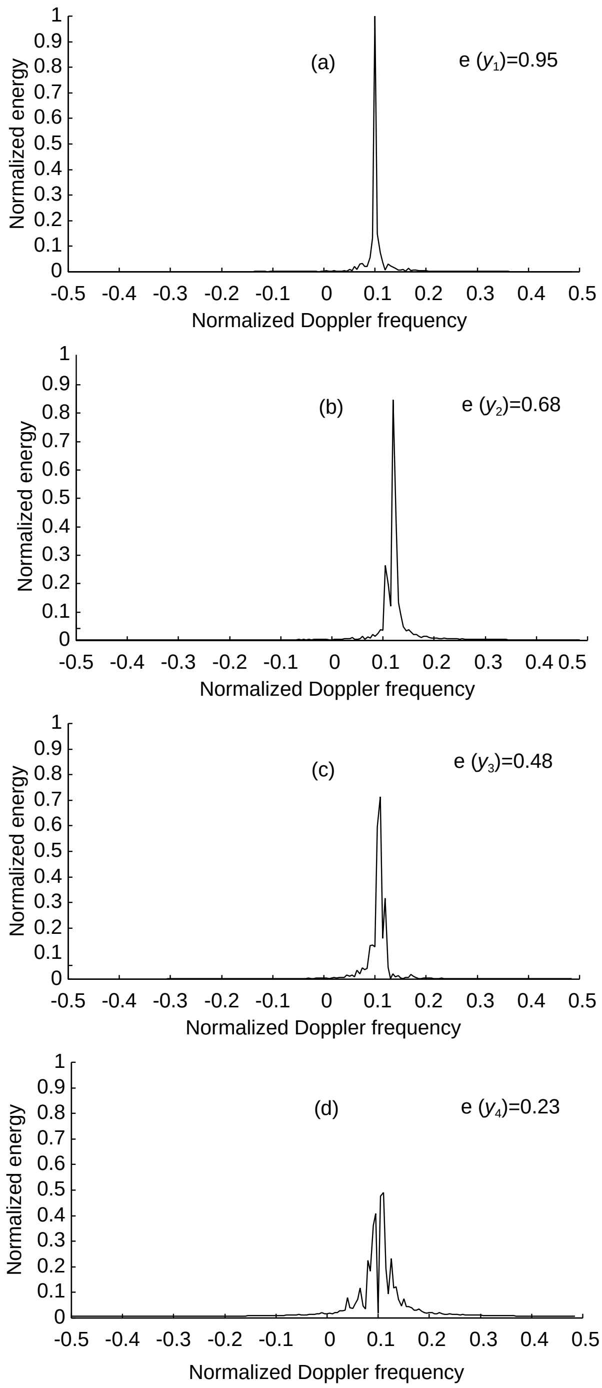

Fig. 5 The top 4 PCs and their corresponding $e(\boldsymbol{y}_i)$ values.

P_d against false alarm probability P_{fa} for a constant SCR. The SCR is defined as

$$\mathrm{SCR} = 10\log_{10}\frac{|A|^2}{E[|c(n)|^2]}, \tag{11}$$

where A is amplitude of the target and $E[*]$ denotes an ensemble averaging. Here, the SCR is averaged with 10000 which represents the total trial number used in the numerical simulation. The Doppler spectrum of the observed signal $\boldsymbol{x(n)}$ against normalized Doppler frequency at $\mathrm{SCR} = -7\mathrm{dB}$ is shown in Fig. 4. The desired target signal is located at $f_d = 0.1$ and it is completely buried into the clutter spectrum. Fig. 5 shows the reconstruction signal after applying PCA, where the top 4 components are chosen. Since Fig. 5(a) presents the PC with maximum $e(\boldsymbol{y}_i) = 0.95$, it is detected as the target signal. The com-

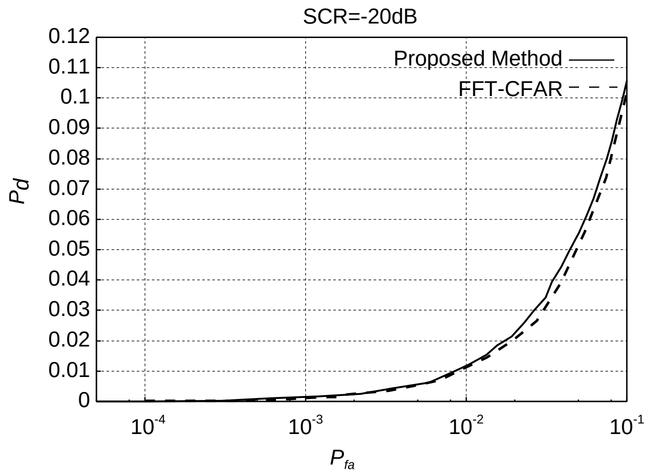

Fig. 6 Target detection probability against false alarm probability for SCR $= -20$dB.

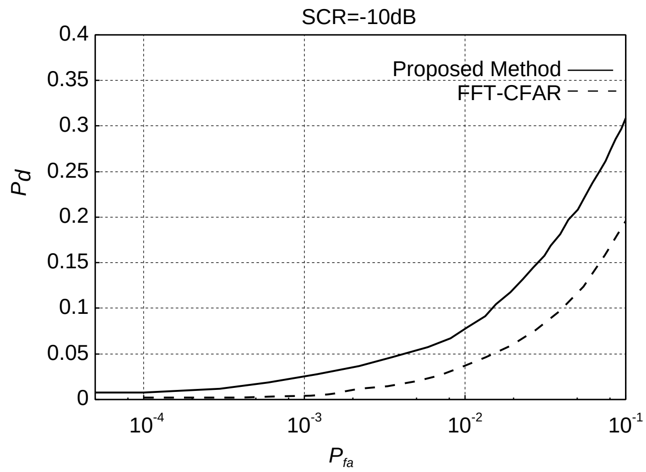

Fig. 7 Target detection probability against false alarm probability for SCR $= -10$dB.

parison of P_d verses P_{fa} is shown in Fig. 6, 7, 8, and 9 corresponding to SCR $= -20$dB, -10dB, -5dB and 0dB respectively. These figures show that the proposed method enhances the target detection probability compared to the conventional FFT-CFAR method. Even in the case of SCR $= -10$dB, where the targets are completely buried in the Doppler spectrum of observed signals, the proposed method obtains a better target detection ability with low false alarm rate. For example, at $P_{fa} = 10^{-2}$, the proposed method has $P_d = 0.08$ whereas the conventional FFT-CFAR method attains $P_d = 0.04$. Similarly, for SCR $= -5$dB at $P_{fa} = 10^{-2}$ and $P_{fa} = 10^{-3}$, the proposed method enhances P_d by 0.15 and 0.18 respectively compared to the conventional FFT-CFAR method. However, at higher SCR, the conventional FFT-CFAR method also shows an improvement in the target detection probability. Fig. 9 shows that at SCR $= 0$dB, P_d of the conventional FFT-CFAR method exceeds that of the proposed method. It is because of the strong targets which contain sufficiently high amplitudes in the Doppler spectrum of observed signals where these are easily separated by CFAR method.

Finally, Fig. 10 presents the relationship between P_d and SCR at constant $P_{fa} = 10^{-3}$ and $P_{fa} = 10^{-2}$. The figure confirms that the proposed method achieves higher P_d except at SCR $= 0$dB for $P_{fa} = 10^{-3}$ where it is slighty less than that of conventional FFT-CFAR method. However, the result suggests that for SCR $= 0$dB and higher values, both the methods show greater

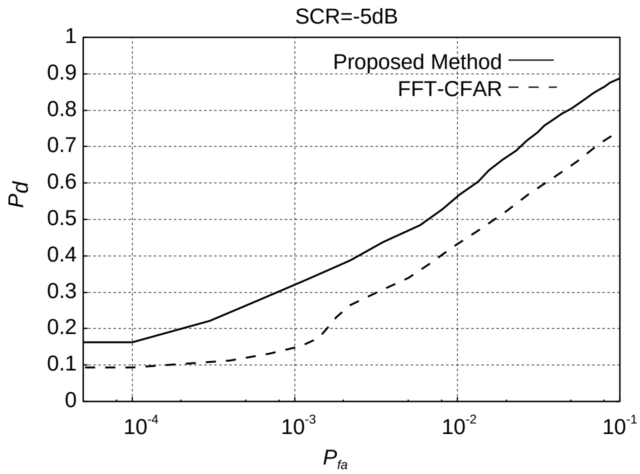

Fig. 8 Target detection probability against false alarm probability for SCR $= -5$dB.

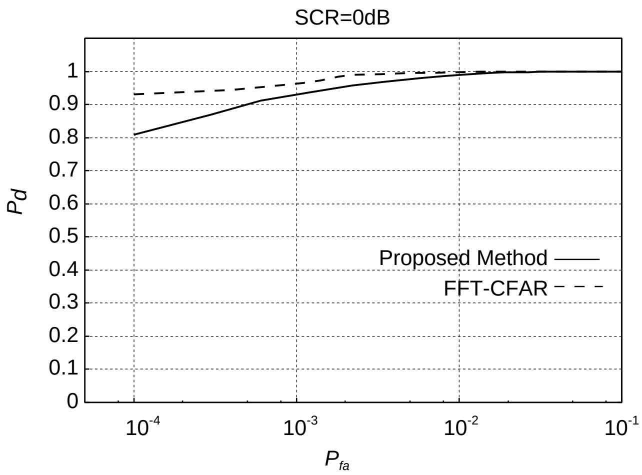

Fig. 9 Target detection probability against false alarm probability for SCR $= 0$dB.

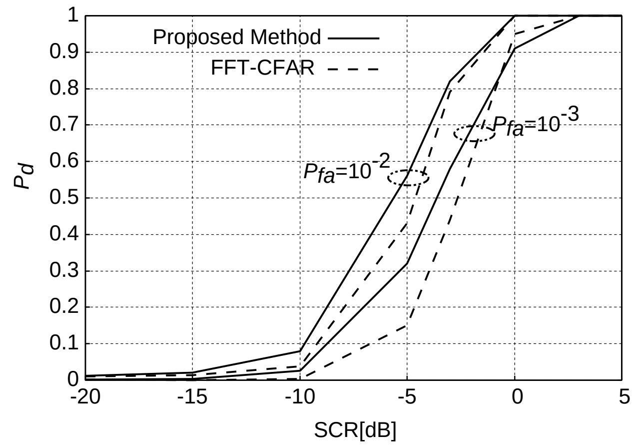

Fig. 10 Target detection probability against SCR at constant $P_{fa} = 10^{-3}$ and $P_{fa} = 10^{-2}$.

target detection tendency with $P_d = 0.9 \sim 1.0$.

6. Conclusion

In this paper, we have proposed a novel approach for the detection of a moving target in PD radar systems. In contrast to the existing approaches, we focused on the target detection when Doppler spectrum of the target is buried in that of clutter. Simulation results have shown that the proposed method based on

PCA could enhance the target detection probability compared to the conventional FFT-CFAR method. The main advantage of the proposed method is that it can detect target for the lower SCR $= -10$dB ~ 0dB more efficiently than conventional FFT-CFAR method. However, at higher SCR $= 0$dB, the conventional FFT-CFAR method also exhibits sufficient improvement in the target detection ability.

In order to keep P_{fa} lower, a higher $\mathrm{V_{thp}}$ value is adopted by the proposed method which decreases its P_d, especially at SCR $= 0$dB. Therefore, the future task of this research is to enhance the detection probability of the proposed method with an optimal $\mathrm{V_{thp}}$ value.

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