

EFFECT OF THRESHOLD VALUE ON THE PERFORMANCE OF NATURAL FREQUENCY-BASED RADAR TARGET RECOGNITION

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Abstract—In this paper, the performance analysis of the natural frequency-based radar target recognition in the time domain is considered. We investigate the dependence of the probability of correct classification on a specific threshold value, and determine the optimum threshold value for two targets, and the sub-optimal threshold for multiple targets to maximize the probability of correct classification. Based on the probability density function (PDF) of some quantity consisting of the projections of the late time response onto the column spaces of the matrices constructed using the natural frequencies of the specific targets, we propose how to determine an optimum threshold in the sense that the probability of correct classification of two targets is maximized. By extending the scheme for two targets, we show how to determine a threshold value close to the optimal threshold for multiple targets. The scheme is validated by comparing the performance using the analytic method with that using the Monte-Carlo simulation.

1. INTRODUCTION

Radar [1–25] has been widely used as a sensor for detection [26–46] and tracking [17, 47–49] of radar target. The range to the target and the velocity of the target can be measured using radar. Doppler shift can be used to estimate the velocity of moving target [26–28, 50, 51]. The radar cross section (RCS) [52–59] of radar target can be estimated from the strength of the signal reflected from the target. The reflected signal of the radar target can be simulated using scattering analysis of the radar target [60–69]. In addition to radar detection and tracking, there have been many studies on radar target recognition [70–80, 159–166].

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There are many radar signatures which can be used for radar target recognition: Natural frequencies of radar target [159–166], high resolution range (HRR) profiles [72, 75–80] of radar target, microwave image [101–123] of the radar target [1, 26, 31, 50, 55, 70, 73, 81–100], and inverse synthetic aperture radar (ISAR) [55, 86–100, 125, 126] image proved to be useful features for target recognition. Jet engine modulation and helicopter modulation [127, 128] have also been known as useful features for target recognition.

It has been shown that the performance of radar target recognition can be improved by exploiting the polarization characteristics [1, 31, 71, 84, 129]. In the viewpoint of the anti-stealth technology, detection of low RCS target has been an interest. Multiple-input and multiple-output (MIMO) radar, bistatic radar and multi-static radar [51, 84, 85, 124, 130–137] have been employed to detect low-RCS target. Pulse compression proved to be an effective way to enhance the performance of radar target detection and recognition [138–140]. In addition, ultra-wideband (UWB) radar [71, 89, 141–146] has been employed to improve the performance.

There have been many studies in the literature about radar target detection [148–155, 169] and recognition [70, 159–166]. The first set of works presents how different techniques have been successfully applied to detect radar targets in different environments such as sea [152, 153] and ground [154, 155]. The typical techniques are neural-network based detectors [148, 149] and constant false alarm rate (CFAR) detectors [150, 151]. The works of the second set [148–164] present how the above-mentioned or other techniques have been successfully applied in radar target recognition tasks. Natural frequency is a commonly used radar signature for radar target recognition [159–162, 163–167].

In [160, 161], the authors presented the natural frequency-based radar target recognition scheme in the time domain [160] and in the frequency domain [161]. In [162] and [168], performance of natural frequency-based target recognition has been analyzed in the time domain and in the frequency domain, respectively. The schemes are based on the binary hypothesis testing and a numerical evaluation of a probability density function (PDF).

In this paper, based on the results in [162], we consider how to improve the probability of correct classification by properly selecting the threshold value used for the classification.

2. LATE TIME RESPONSE AND NATURAL FREQUENCIES

Let $y_{n|k}$ represent a sampled response with sampling interval of Δt , and define $z_{m|k} = \exp[s_{m|k}\Delta t]$, where $s_{1|k}, \dots, s_{M_k|k}$ are the natural frequencies of the k -th target. M_k is the number of the natural frequencies of target k . It can be easily shown that, based on the late time representation using the natural frequencies, the late time response can be written as [160], for the k -th target,

$$y_{n|k} = u_{n|k} + g_{n|k} = \sum_{m=1}^{M_k} c_{m|k} z_{m|k}^n + g_{n|k} \quad n = 1, 2, \dots, N \quad (1)$$

where N is the number of the sampled frequency response.

$g_{n|k}$ is the zero-mean Gaussian distributed with variance of σ^2 , associated with $y_{n|k}$. $s_{m|k}$, $m = 1, \dots, M_k$, is the natural frequency of the k -th target. $u_{n|k}$, $n = 1, \dots, N$, is the noiseless late time response of the k -th target.

If we define

$$\mathbf{y}_k = [y_{1|k} \ y_{2|k} \ \dots \ y_{N|k}]^T \quad (2)$$

$$\mathbf{c}_k = [c_{1|k} \ c_{2|k} \ \dots \ c_{M_k|k}]^T \quad (3)$$

$$\mathbf{g}_k = [g_{1|k} \ g_{2|k} \ \dots \ g_{N|k}]^T \quad (4)$$

$$\mathbf{u}_k = [u_{1|k} \ u_{2|k} \ \dots \ u_{N|k}]^T, \quad (5)$$

Equation (1) can be written as

$$\mathbf{y}_k = \mathbf{B}_k \mathbf{c}_k + \mathbf{g}_k = \mathbf{u}_k + \mathbf{g}_k \quad (6)$$

where $\{\mathbf{B}_k\}_{nm}$ is defined as

$$\{\mathbf{B}_k\}_{nm} = z_{m|k}^n. \quad (7)$$

3. MOTIVATION

In [162], the authors chose zero for the threshold for the classification. Assume that we try to recognize target 1 and target 2 based on the PDF of

$$Z_{21|k} \equiv \|\mathbf{P}_2 \mathbf{y}_k\|^2 - \|\mathbf{P}_1 \mathbf{y}_k\|^2 = \mathbf{y}_k^H \mathbf{P}_2 \mathbf{y}_k - \mathbf{y}_k^H \mathbf{P}_1 \mathbf{y}_k \underset{\text{target 1}}{\overset{\text{target 2}}{>}} 0 \quad k = 1, 2 \quad (8)$$

where k denotes that the noisy late time response is from the k -th target and the projection matrices \mathbf{P}_1 and \mathbf{P}_2 are defined as

$$\mathbf{P}_2 = \mathbf{B}_2 (\mathbf{B}_2^H \mathbf{B}_2)^{-1} \mathbf{B}_2^H \quad (9)$$

$$\mathbf{P}_1 = \mathbf{B}_1 (\mathbf{B}_1^H \mathbf{B}_1)^{-1} \mathbf{B}_1^H. \quad (10)$$

Eigendecomposition of $\mathbf{P}_2 - \mathbf{P}_1$ results in

$$\mathbf{P}_2 - \mathbf{P}_1 = \mathbf{V}\mathbf{\Lambda}_{21}\mathbf{V}^H. \quad (11)$$

\mathbf{w}_k is defined from

$$\mathbf{w}_k = [w_{1|k} \quad \dots \quad w_{N|k}] = \mathbf{V}^H \mathbf{y}_k. \quad (12)$$

The mean of \mathbf{w}_k is denoted as

$$\text{mean}(\mathbf{w}_k) = [\mu_{1|k} \quad \dots \quad \mu_{N|k}] = \mathbf{V}^H \mathbf{u}_k. \quad (13)$$

$Z_{21|k}$ in Eq. (8) can be written as [162, 170]

$$Z_{21|k} = F_{21|k} + G_{21|k} \quad (14)$$

where

$$F_{21|k} = \sum_{l=1}^{M_2-M_1} w_{l|k}^2 \quad \text{and} \quad G_{21|k} = \sum_{l=1}^{2M_1} \lambda_l w_{M_2-M_1+l|k}^2. \quad (15)$$

The characteristic functions of $F_{21|k}$ and $G_{21|k}$ are [162]

$$\Phi_{F_{21|k}}(j\omega) = \frac{1}{(1-j2\omega\sigma^2)^{(M_2-M_1)/2}} \exp\left(\frac{j\omega \sum_{l=1}^{M_2-M_1} \mu_{l|k}^2}{1-j2\omega\sigma^2}\right) \quad (16)$$

$$\Phi_{G_{21|k}}(j\omega) = \prod_{l=1}^{2M_1} \frac{\lambda_l}{|\lambda_l| (1-j2\omega\lambda_l\sigma^2)^{\frac{1}{2}}} \exp\left(\frac{j\omega \mu_{M_2-M_1+l|k}^2 \lambda_l}{1-j2\omega\lambda_l\sigma^2}\right). \quad (17)$$

Finally, the PDF of $Z_{21|k}$ is

$$p_{Z_{21|k}}(z) = F^{-1} \left\{ \Phi_{F_{21|k}}(j\omega) \Phi_{G_{21|k}}(j\omega) \right\}. \quad (18)$$

The cumulative distribution function (CDF) of $Z_{21|k}$ is obtained from

$$F_{Z_{21|k}}(z) = \int_{-\infty}^z p_{Z_{21|k}}(z') dz'. \quad (19)$$

The performance analysis of the natural frequency-based radar target recognition in the frequency domain is considered in this paper. In the scheme presented in [162], the authors set the threshold for the classification to zero. In this paper, we propose to change the threshold value to see what threshold value results in the maximum probability of correct classification.

In addition, we show how to determine the optimum threshold from the analytic PDF's and CDF's for two targets. For more than

two targets, we propose how to choose a threshold value which is very close to the optimum threshold $\gamma_{\text{opt}}^{\text{simul}}$ maximizing Eq. (25).

$\mathbf{P}_2\mathbf{y}$ should be a vector on the column space of \mathbf{B}_2 since $\mathbf{P}_2\mathbf{y}$ is a projection of \mathbf{y} onto the column space of \mathbf{B}_2 . Similarly, $\mathbf{P}_1\mathbf{y}$ should be on the column space of \mathbf{B}_1 .

For $M_1 < M_2$, the dimension of the column space of \mathbf{B}_2 is greater than that of the column space of \mathbf{B}_1 .

Note that the ranks of \mathbf{B}_1 and \mathbf{B}_2 are M_1 and M_2 , respectively. For $M_1 < M_2$, the constraint that the projection should be on the column space of \mathbf{B}_2 is less demanding than the constraint that the projection should be on the column space of \mathbf{B}_1 .

For $M_1 < M_2$, $\|\mathbf{P}_2\mathbf{y}\|$ tends to be larger and $\|\mathbf{P}_1\mathbf{y}\|$ tends to be smaller both for $\mathbf{y} = \mathbf{y}_1$ and $\mathbf{y} = \mathbf{y}_2$.

$\|\mathbf{P}_2\mathbf{y}\|$ gets smaller for smaller M_2 , and vice versa, and $\|\mathbf{P}_1\mathbf{y}\|$ gets smaller for smaller M_1 , and vice versa.

The constraint that the projection should be on the column space of \mathbf{B}_2 gets stricter resulting in smaller $\|\mathbf{P}_2\mathbf{y}\|$ as M_2 gets smaller, and vice versa. Similarly, the constraint associated with $\mathbf{P}_1\mathbf{y}$ gets stricter resulting in smaller $\|\mathbf{P}_1\mathbf{y}\|$ as M_1 gets smaller, and vice versa.

$\text{Prob}(\|\mathbf{P}_2\mathbf{y}\| > \|\mathbf{P}_1\mathbf{y}\|)$ for $M_2 > M_1$ becomes larger than $\text{Prob}(\|\mathbf{P}_2\mathbf{y}\| > \|\mathbf{P}_1\mathbf{y}\|)$ for $M_2 = M_1$, and $\text{Prob}(\|\mathbf{P}_2\mathbf{y}\| < \|\mathbf{P}_1\mathbf{y}\|)$ for $M_2 > M_1$ becomes smaller than $\text{Prob}(\|\mathbf{P}_2\mathbf{y}\| < \|\mathbf{P}_1\mathbf{y}\|)$ for $M_2 = M_1$.

What we suggest in this paper is to improve $P_I(\gamma)$ by defining

$$P_{I|1}(\gamma) = \text{Prob} \left(\left(\|\mathbf{P}_2\mathbf{y}\|^2 - \|\mathbf{P}_1\mathbf{y}\|^2 \right) < \gamma \mid \text{1st target is present} \right) \quad (20)$$

$$P_{I|2}(\gamma) = \text{Prob} \left(\left(\|\mathbf{P}_2\mathbf{y}\|^2 - \|\mathbf{P}_1\mathbf{y}\|^2 \right) > \gamma \mid \text{2nd target is present} \right) \quad (21)$$

$$\begin{aligned} P_I(\gamma) &= \sum_{k=1}^2 P_{I|k}(\gamma) \text{Prob}(k\text{-th target is present}) \\ &= \frac{1}{2} \sum_{k=1}^2 (P_{I|1}(\gamma) + P_{I|2}(\gamma)). \end{aligned} \quad (22)$$

The simulation performance can be written as

$$P_{I|1}^{\text{simul}}(\gamma) = \text{Prob} \left(\left(\|\mathbf{P}_2\mathbf{y}_1\|^2 - \|\mathbf{P}_1\mathbf{y}_1\|^2 \right) < \gamma \right) \quad (23)$$

$$P_{I|2}^{\text{simul}}(\gamma) = \text{Prob} \left(\left(\|\mathbf{P}_2\mathbf{y}_2\|^2 - \|\mathbf{P}_1\mathbf{y}_2\|^2 \right) > \gamma \right) \quad (24)$$

$$P_I^{\text{simul}}(\gamma) = \sum_{k=1}^2 P_{I|k}^{\text{simul}}(\gamma) \text{Prob}(k\text{-th target is present})$$

$$\begin{aligned}
&= \frac{1}{2} \sum_{k=1}^2 P_{I|k}^{\text{simul}}(\gamma) \\
&= \frac{1}{2} \left[\text{Prob} \left(\left(\|\mathbf{P}_2 \mathbf{y}_1\|^2 - \|\mathbf{P}_1 \mathbf{y}_1\|^2 \right) < \gamma \right) \right. \\
&\quad \left. + \text{Prob} \left(\left(\|\mathbf{P}_2 \mathbf{y}_2\|^2 - \|\mathbf{P}_1 \mathbf{y}_2\|^2 \right) > \gamma \right) \right] \quad (25)
\end{aligned}$$

where $\|\mathbf{P}_2 \mathbf{y}_1\|^2$, $\|\mathbf{P}_1 \mathbf{y}_1\|^2$, $\|\mathbf{P}_2 \mathbf{y}_2\|^2$ and $\|\mathbf{P}_1 \mathbf{y}_2\|^2$ are obtained from the Monte-Carlo simulation in the sense that the noises in \mathbf{y}_1 and \mathbf{y}_2 are Gaussian random vectors.

By setting $\gamma = 0$ in Eq. (23) and Eq. (24), we get $P_{I|1}$ and $P_{I|2}$ defined in the scheme presented in [162].

4. DEPENDENCE OF \mathbf{P}_I ON γ FOR TWO TARGETS

Let $P_{I|2}(\gamma)$ be the probability of correct classification with the specified threshold value of γ given that the second target is present and $P_{I|1}(\gamma)$ be the probability of correct classification with the specified threshold value of γ given that the first target is present.

The probability of correct classification with threshold value γ is obtained from the PDF as follows:

$$\begin{aligned}
P_{I|1}^{\text{analy}}(\gamma) &= \text{Prob}(Z_{21|k} < \gamma | k = 1) \\
&= \int_{-\infty}^{\gamma} p_{Z_{21|1}}(z) dz = F_{Z_{21|1}}(\gamma) \quad (26)
\end{aligned}$$

$$\begin{aligned}
P_{I|2}^{\text{analy}}(\gamma) &= \text{Prob}(Z_{21|k} > \gamma | k = 2) \\
&= \int_{\gamma}^{\infty} p_{Z_{21|2}}(z) dz = 1 - F_{Z_{21|2}}(\gamma) \quad (27)
\end{aligned}$$

$$\begin{aligned}
P_I^{\text{analy}}(\gamma) &= \sum_{k=1}^2 P_{I|k}^{\text{analy}}(\gamma) \text{Prob}(k\text{-th target is present}) \\
&= \frac{1}{2} \sum_{k=1}^2 P_{I|k}(\gamma) = \frac{1}{2} (F_{Z_{21|1}}(\gamma) + 1 - F_{Z_{21|2}}(\gamma)) \quad (28)
\end{aligned}$$

where $F_{Z_{21|1}}(z)$ and $F_{Z_{21|2}}(z)$ represent the CDF of $Z_{21|k=1}$ and $Z_{21|k=2}$, respectively. Refer to Section 3 to see how to numerically evaluate the PDF's and the CDF's of $Z_{21|1}$ and $Z_{21|2}$ [162].

As we change γ in Eq. (28) with respect to γ , the optimum threshold value, γ_{opt} can be determined from the threshold value at which $P_I(\gamma)$ is maximized.

From Eq. (26) and Eq. (27), $P_{I|1}^{\text{analy}}(\gamma)$ and $P_{I|2}^{\text{analy}}(\gamma)$ are monotonic increasing and decreasing functions of γ , respectively. Since $P_I^{\text{analy}}(\gamma)$ is a sum of monotonic increasing and decreasing functions, it is quite intuitive to see that $P_I(\gamma)$ tends to have a local maximum at $\gamma = \gamma_{\text{opt}}$.

γ_{opt} can also be analytically found by differentiating $P_I(\gamma)$ with respect to γ :

$$\begin{aligned} \frac{d}{d\gamma} P_I^{\text{analy}}(\gamma) &= 0 \\ \frac{d}{d\gamma} \left(\frac{1}{2} (P_{I|1}^{\text{analy}}(\gamma) + P_{I|2}^{\text{analy}}(\gamma)) \right) &= \frac{1}{2} \frac{d}{d\gamma} (1 - F_{Z_{21|2}}(\gamma) + F_{Z_{21|1}}(\gamma)) \\ &= \frac{1}{2} (-p_{Z_{21|2}}(\gamma) + p_{Z_{21|1}}(\gamma)) = 0 \\ p_{Z_{21|2}}(\gamma) &= p_{Z_{21|1}}(\gamma). \end{aligned} \quad (29)$$

Therefore, γ_{opt} can be found from γ value satisfying Eq. (29).

Let ζ_1 and ζ_2 denote the limit above which the values of $p_{Z_{21|1}}$ and $p_{Z_{21|2}}$ can be practically set to be zero, respectively, which can be given, for $k = 1, 2$, [162]

$$\begin{aligned} \zeta_k &= \mu_{Z_{21|k}} + 6\sigma_{Z_{21|k}}, & \mu_{Z_{21|k}} &> 0 \\ \zeta_k &= -(\mu_{Z_{21|k}} - 6\sigma_{Z_{21|k}}), & \mu_{Z_{21|k}} &< 0. \end{aligned} \quad (30)$$

Using Eq. (30), the range of γ over which $P_I(\gamma)$ should be calculated is given by

$$-\max(\zeta_1, \zeta_2) < \gamma < \max(\zeta_1, \zeta_2). \quad (31)$$

5. DEPENDENCE OF P_I ON γ FOR THREE TARGETS

For simplicity, we assume that there are three targets. We can extend the results to more than three targets.

For three targets, we tabulate the decision strategy for nonzero threshold γ in Table 1: Notation I is the convention used for two targets and Notation II and Notation III are the conventions used for more than two targets.

Note that in Table 1, for derivation of Notation II from Notation I, we use the fact that, for example, $Z_{31|1} < \gamma$ is equivalent to $Z_{13|1} > -\gamma$ due to $Z_{31|1} = -Z_{13|1}$. In general, $Z_{ik|k} < \gamma$ is equivalent to $Z_{ki|k} > -\gamma$ because of $Z_{ik|k} = -Z_{ki|k}$.

If we define

$$t_{kl|k}(\gamma) = \begin{cases} \gamma, & k > l \\ -\gamma, & k < l, \end{cases} \quad (32)$$

Table 1. Decision strategy for three targets.

targets	Notation I	Notation II	Notation III
1 2	$Z_{21 2} > \gamma,$ $Z_{21 1} < \gamma,$	$Z_{21 2} > \gamma$ $Z_{12 1} > -\gamma$	$Z_{21 2} > t_{21 2}(\gamma)$ $Z_{12 1} > t_{12 1}(\gamma)$
1 2	$Z_{31 3} > \gamma,$ $Z_{31 1} < \gamma,$	$Z_{31 3} > \gamma$ $Z_{13 1} > -\gamma$	$Z_{31 3} > t_{31 3}(\gamma)$ $Z_{13 1} > t_{13 1}(\gamma)$
1 2	$Z_{32 3} > \gamma,$ $Z_{32 2} < \gamma,$	$Z_{32 3} > \gamma$ $Z_{23 2} > -\gamma$	$Z_{32 3} > t_{32 3}(\gamma)$ $Z_{23 2} > t_{23 2}(\gamma)$

we get Notation III from Notation II in Table 1.

From Table 1, the probability of correct identification can be written as

$$P_{I|1}(\gamma) = \text{Prob} \{ Z_{12|1} > t_{12|1}(\gamma), Z_{13|1} > t_{13|1}(\gamma) \} \quad (33)$$

$$P_{I|2}(\gamma) = \text{Prob} \{ Z_{21|2} > t_{21|2}(\gamma), Z_{23|2} > t_{23|2}(\gamma) \} \quad (34)$$

$$P_{I|3}(\gamma) = \text{Prob} \{ Z_{31|3} > t_{31|3}(\gamma), Z_{32|3} > t_{32|3}(\gamma) \}. \quad (35)$$

Using Eq. (32) in Eq. (33)–Eq. (35), we have

$$P_{I|1}(\gamma) = \text{Prob} \{ Z_{12|1} > -\gamma, Z_{13|1} > -\gamma \} \quad (36)$$

$$P_{I|2}(\gamma) = \text{Prob} \{ Z_{21|2} > \gamma, Z_{23|2} > -\gamma \} \quad (37)$$

$$P_{I|3}(\gamma) = \text{Prob} \{ Z_{31|3} > \gamma, Z_{32|3} > \gamma \}. \quad (38)$$

6. DEPENDENCE OF P_I ON γ FOR MULTIPLE TARGETS

Equations (33)–(35) are valid for three targets. It is straightforward to extend Eq. (33)–Eq. (35) to more than three targets. Assume that there are Q targets.

Assuming that the k -th target is present, the probability of correct classification can be written as, for $k = 1, \dots, Q$,

$$P_{I|k}(\gamma) = \text{Prob} (Z_{k1|k} > t_{k1|k}(\gamma), \dots, Z_{k,k-1|k} > t_{k,k-1|k}(\gamma), \\ Z_{k,k+1|k} > t_{k,k+1|k}(\gamma), \dots, Z_{k,Q|k} > t_{k,Q|k}(\gamma)). \quad (39)$$

Using Eq. (32) in Eq. (39), we have

$$P_{I|k}(\gamma) = \text{Prob} (Z_{k1|k} > \gamma, \dots, Z_{k,k-1|k} > \gamma \\ Z_{k,k+1|k} > -\gamma, \dots, Z_{k,Q|k} > -\gamma). \quad (40)$$

$Z_{kl|k}$ and $Z_{lk|k}$ are defined as

$$Z_{kl|k} \equiv \|\mathbf{P}_k \mathbf{y}_k\|^2 - \|\mathbf{P}_l \mathbf{y}_k\|^2 \quad (41)$$

$$Z_{lk|k} \equiv \|\mathbf{P}_l \mathbf{y}_k\|^2 - \|\mathbf{P}_k \mathbf{y}_k\|^2. \quad (42)$$

Note that Eq. (41) and Eq. (42) are consistent with Eq. (8).

Using Eq. (41) and Eq. (42) in Eq. (40), the probability of classification can be expressed as

$$\begin{aligned} P_{I|k}(\gamma) &= \text{Prob} [\mathbf{y}^H \mathbf{P}_k \mathbf{y} > \mathbf{y}^H \mathbf{P}_1 \mathbf{y} + \gamma, \dots, \mathbf{y}^H \mathbf{P}_k \mathbf{y} \\ &> \mathbf{y}^H \mathbf{P}_{k-1} \mathbf{y} + \gamma, \mathbf{y}^H \mathbf{P}_k \mathbf{y} > \mathbf{y}^H \mathbf{P}_{k+1} \mathbf{y} - \gamma, \dots, \mathbf{y}^H \mathbf{P}_k \mathbf{y} \\ &> \mathbf{y}^H \mathbf{P}_Q \mathbf{y} - \gamma | k\text{th target}]. \end{aligned} \quad (43)$$

Since evaluating Eq. (43) is quite challenging, we try to get the upper bound and the lower bound of the probability of correct classification.

Assuming that the correct target is the k -th target, the upper bound and the lower bound of correct classification are given by [137]

$$\begin{aligned} P_{I|k}^{\text{up}}(\gamma) &= \min_{i \neq k} \left\{ \int_{t_{ki|k}(\gamma)}^{\infty} p_{Z_{ki|k}}(z) dz \right\} = \min_{i \neq k} \left\{ 1 - F_{Z_{ki|k}}(t_{ki|k}(\gamma)) \right\} \quad (44) \\ P_{I|k}^{\text{lo}}(\gamma) &= \max \left\{ 0, 1 - \sum_{\substack{i=1 \\ i \neq k}}^Q \int_{-\infty}^{t_{ki|k}(\gamma)} p_{Z_{ki|k}}(z) dz \right\} \\ &= \max \left\{ 0, 1 - \sum_{\substack{i=1 \\ i \neq k}}^Q F_{Z_{ki|k}}(t_{ki|k}(\gamma)) \right\}. \end{aligned} \quad (45)$$

where $F_{Z_{ki|k}}(z)$ denotes the CDF of $Z_{ki|k}$.

Note that, the PDF's and the CDF's in Eq. (44)–Eq. (45) are evaluated using the scheme in Section 4.

Simulation performance based on the Monte-Carlo simulation is

$$\begin{aligned} P_{I|k}^{\text{simul}}(\gamma) &= \text{Prob} [\mathbf{y}_k^H \mathbf{P}_k \mathbf{y}_k > \mathbf{y}_k^H \mathbf{P}_1 \mathbf{y}_k + t_{k1|k}(\gamma), \dots, \mathbf{y}_k^H \mathbf{P}_k \mathbf{y}_k \\ &> \mathbf{y}_k^H \mathbf{P}_{k-1} \mathbf{y}_k + t_{k,k-1|k}(\gamma), \mathbf{y}_k^H \mathbf{P}_k \mathbf{y}_k > \mathbf{y}_k^H \mathbf{P}_{k+1} \mathbf{y}_k \\ &+ t_{k,k+1|k}(\gamma), \dots, \mathbf{y}_k^H \mathbf{P}_k \mathbf{y}_k > \mathbf{y}_k^H \mathbf{P}_Q \mathbf{y}_k + t_{k,Q|k}(\gamma)]. \end{aligned} \quad (46)$$

The upper bound and the lower bound of correct classification,

considering all Q targets, are given by [162]

$$P_I^{\text{up}}(\gamma) = \frac{1}{Q} \sum_{k=1}^Q P_{I|k}^{\text{up}}(\gamma) \quad (47)$$

$$P_I^{\text{lo}}(\gamma) = \frac{1}{Q} \sum_{k=1}^Q P_{I|k}^{\text{lo}}(\gamma). \quad (48)$$

Simulation performance considering all Q targets is

$$P_I^{\text{simul}}(\gamma) = \frac{1}{Q} \sum_{k=1}^Q P_{I|k}^{\text{simul}}(\gamma). \quad (49)$$

Using Eq. (45) in Eq. (48), we can plot $P_I^{\text{up}}(\gamma)$ as we change γ . From the plot, we can easily identify the optimum threshold, $\gamma_{\text{opt}}^{\text{lo}}$, at which $P_I^{\text{lo}}(\gamma)$ is maximized:

$$\gamma_{\text{opt}}^{\text{lo}} \equiv \arg \max_{\gamma} P_I^{\text{lo}}(\gamma). \quad (50)$$

Similarly, using Eq. (44) in Eq. (47), we can calculate $P_I^{\text{up}}(\gamma)$ for various γ values and the optimum threshold value, $\gamma_{\text{opt}}^{\text{up}}$, can be found from the threshold value at which $P_I^{\text{up}}(\gamma)$ achieves the maximum.

$$\gamma_{\text{opt}}^{\text{up}} \equiv \arg \max_{\gamma} P_I^{\text{up}}(\gamma). \quad (51)$$

7. PROCEDURE ON HOW TO DETERMINE THE OPTIMAL THRESHOLD

7.1. Two Targets

What makes the scheme in this paper very useful in practical implementation of radar target recognition is that the optimal threshold $\gamma_{\text{opt}}^{\text{simul}}$ for practical implementation of Eq. (25) can be calculated analytically from $\gamma = \gamma_{\text{opt}}^{\text{simul}}$ using Eq. (28) or Eq. (29).

The procedure for getting the optimal threshold for two targets can be summarized as follows:

- (i) Given σ^2 of $g_{n|k}$ in Eq. (1), calculate $\gamma_{\text{opt}}^{\text{analy}}$ from γ value satisfying Eq. (29) or γ value maximizing Eq. (28).
- (ii) Use $\gamma = \gamma_{\text{opt}}^{\text{simul}} = \gamma_{\text{opt}}^{\text{analy}}$ in Eq. (25) to get the maximum probability of identification in practical implementation.

The procedure is essentially based on the fact that the simulation performance in Eq. (23), Eq. (24) and Eq. (25) do agree with the analytic performance in Eq. (26), Eq. (27) and Eq. (28) respectively, for all γ values in Eq. (31).

Accordingly, $\gamma = \gamma_{\text{opt}}^{\text{simul}}$ maximizing Eq. (25) can be found from $\gamma = \gamma_{\text{opt}}^{\text{analy}}$ maximizing Eq. (28) or $\gamma = \gamma_{\text{opt}}^{\text{analy}}$ satisfying Eq. (29).

Note that the PDF's and the CDF's in Eq. (28) and Eq. (29) can be analytically obtained, given the variance of σ^2 of $g_{n|k}$ in Eq. (1). We do not have to know specific realization of $g_{n|k}$ and \mathbf{y} to get the PDF's and the CDF's in Eq. (28) and Eq. (29), from which we can get the optimum threshold $\gamma = \gamma_{\text{opt}}^{\text{analy}}$.

That is, we do not have to perform the Monte-Carlo simulation in Eq. (25) to get $\gamma = \gamma_{\text{opt}}^{\text{analy}}$. $\gamma = \gamma_{\text{opt}}^{\text{analy}}$ from Eq. (28) or Eq. (29) can be used in direct evaluation of Eq. (25) with $\gamma = \gamma_{\text{opt}}^{\text{simul}} = \gamma_{\text{opt}}^{\text{analy}}$ via the Monte-Carlo simulation.

7.2. Multiple Targets

For more than two targets, we can not calculate $P_I^{\text{analy}}(\gamma)$ analytically, and only get the upper bound $P_I^{\text{up}}(\gamma)$ and the lower bound $P_I^{\text{lo}}(\gamma)$ of the probability of classification [162]. The threshold values, at which $P_I^{\text{up}}(\gamma)$ and $P_I^{\text{lo}}(\gamma)$ are maximized, are denoted as $\gamma_{\text{opt}}^{\text{up}}$ in Eq. (51) and $\gamma_{\text{opt}}^{\text{lo}}$ in Eq. (50), respectively. We define $\gamma_{\text{opt}}^{\text{analy}}$ using $\gamma_{\text{opt}}^{\text{lo}}$ and $\gamma_{\text{opt}}^{\text{up}}$ as follows:

$$\gamma_{\text{opt}}^{\text{analy}} = \begin{cases} \gamma_{\text{opt}}^{\text{lo}}, & P_{I|1}^{\text{simul}}(\gamma_{\text{opt}}^{\text{lo}}) > P_{I|1}^{\text{simul}}(\gamma_{\text{opt}}^{\text{up}}) \\ \gamma_{\text{opt}}^{\text{up}}, & P_{I|1}^{\text{simul}}(\gamma_{\text{opt}}^{\text{lo}}) < P_{I|1}^{\text{simul}}(\gamma_{\text{opt}}^{\text{up}}) \end{cases} \quad (52)$$

where $\gamma_{\text{opt}}^{\text{lo}}$ and $\gamma_{\text{opt}}^{\text{up}}$ are obtained from Eq. (50) and Eq. (51), respectively.

Note that $\gamma_{\text{opt}}^{\text{lo}}$ and $\gamma_{\text{opt}}^{\text{up}}$ should be obtained for each signal-to-noise ratio (SNR), which results in different $\gamma_{\text{opt}}^{\text{analy}}$ for each SNR.

8. NUMERICAL RESULTS

We use two straight wires of length = 1.0 m and 1.2 m for two targets. For three targets, the three straight wires of length = 0.8 m, 1.0 m and 1.2 m are used.

When we only consider two targets, we compare the analytic results in Eq. (28) with the simulation-based performance. For multiple targets, the analytic results in Eq. (48) and Eq. (47) are compared

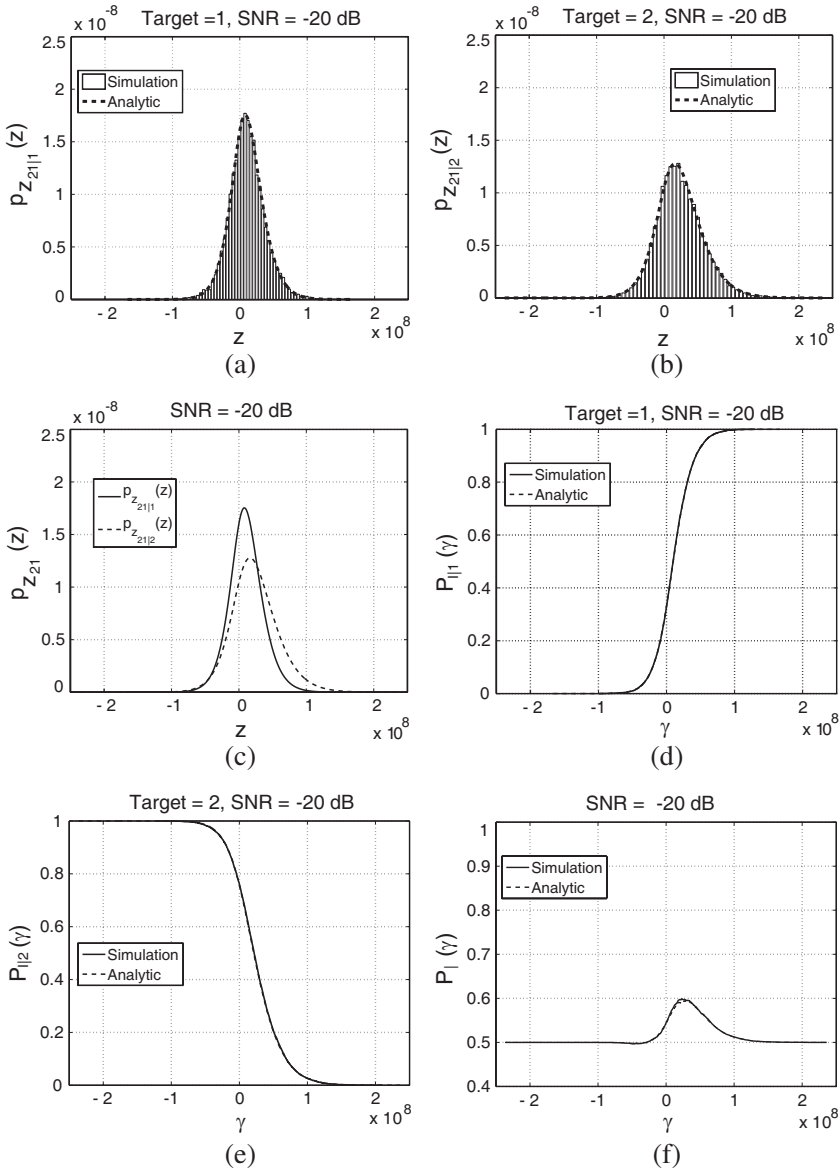


Figure 1. Dependence of $p_{Z_{21|1}}(z)$, $p_{Z_{21|2}}(z)$, $P_{I|1}(\gamma)$, $P_{I|2}(\gamma)$ and $P_I(\gamma)$ on the value of γ for two straight wires of length = 1.0 m and 1.2 m (SNR = -20 dB).

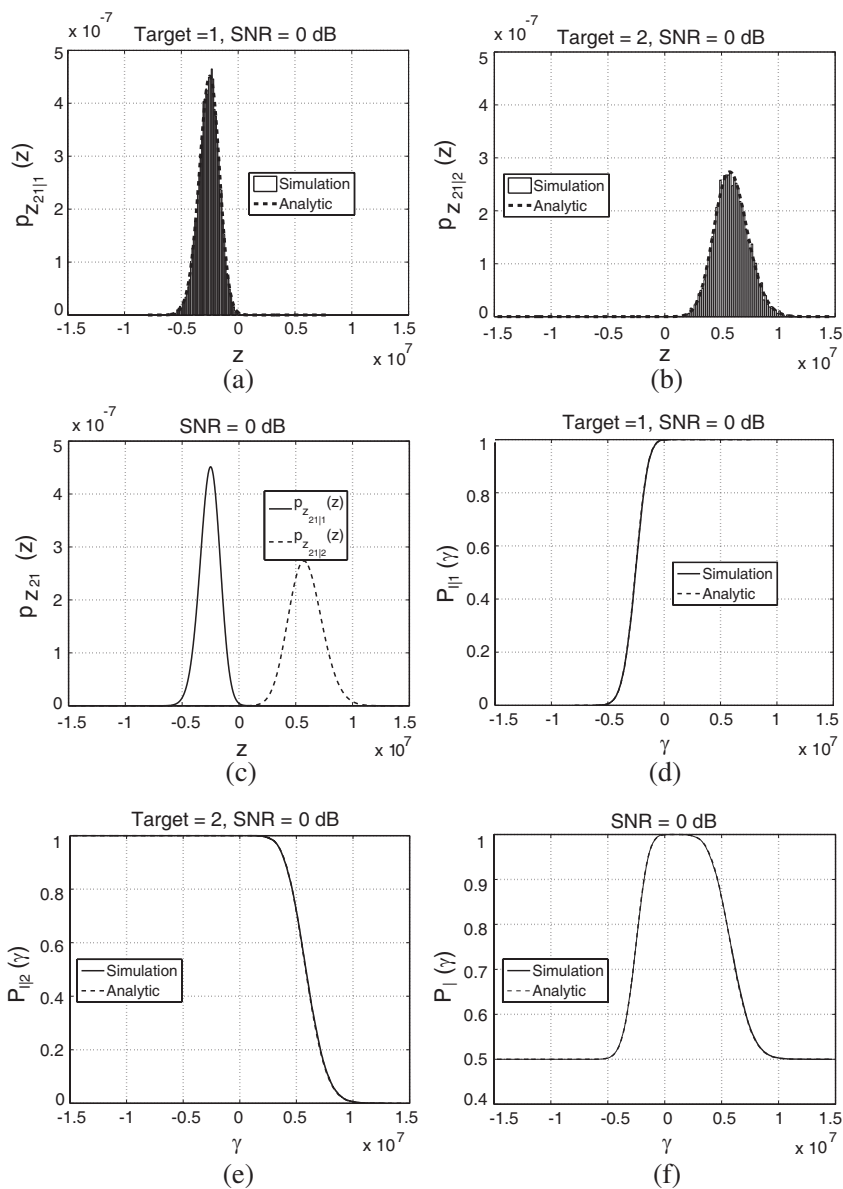


Figure 2. Dependence of $p_{Z_{21|1}}(z)$, $p_{Z_{21|2}}(z)$, $P_{I|1}(\gamma)$, $P_{I|2}(\gamma)$ and $P_I(\gamma)$ on the value of γ for two straight wires of length = 1.0 m and 1.2 m (SNR = 0 dB).

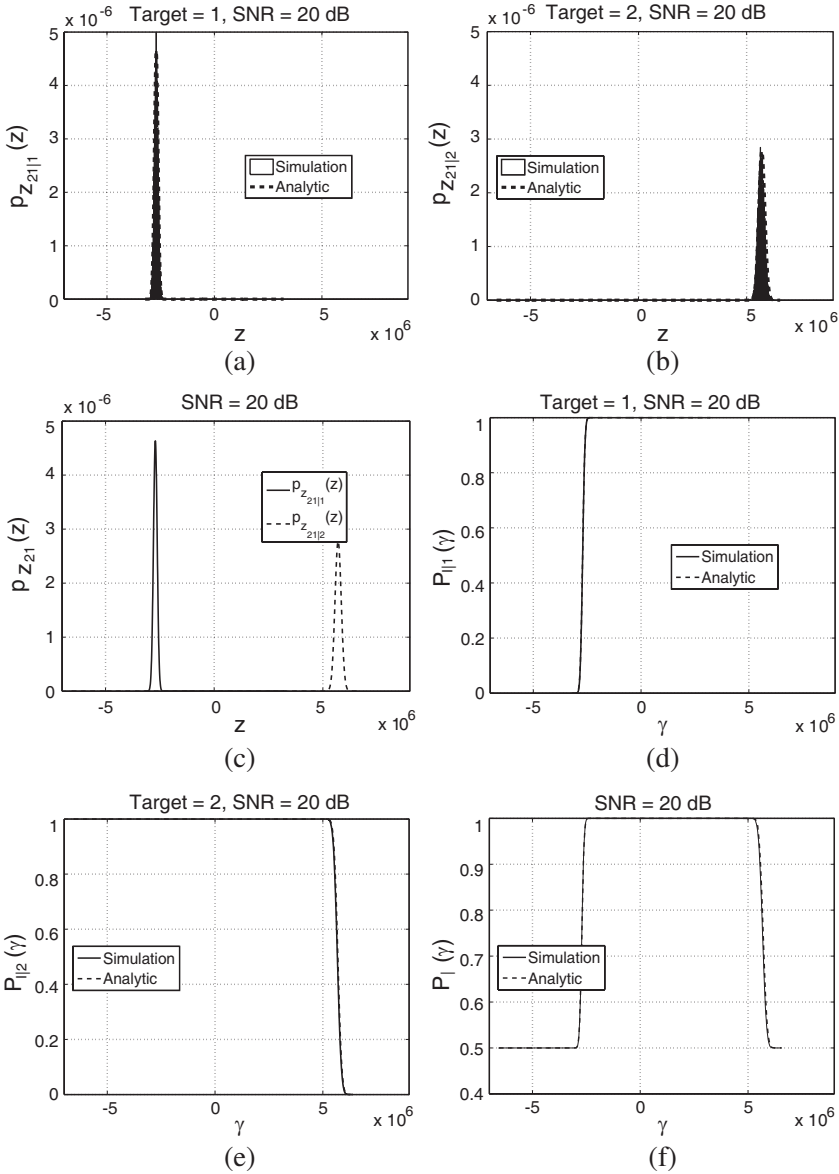


Figure 3. Dependence of $p_{Z_{21|1}}(z)$, $p_{Z_{21|2}}(z)$, $P_{I|1}(\gamma)$, $P_{I|2}(\gamma)$ and $P_I(\gamma)$ on the value of γ for two straight wires of length = 1.0 m and 1.2 m (SNR = 20 dB).

with the results based on the Monte-Carlo simulation. In getting the simulation-based performance, the probability of correct classification is obtained from 10,000 repetitions.

The noiseless frequency response is obtained via the method of moments (MoM). We calculated the back-scattered field. The frequency response up to 0.5 GHz is obtained in increments of 7.8 MHz. The incident angle for all the numerical examples is $\theta = 30^\circ$. The frequency response is inverse Fourier transformed to obtain the time domain response.

The numbers of the natural frequencies for two targets

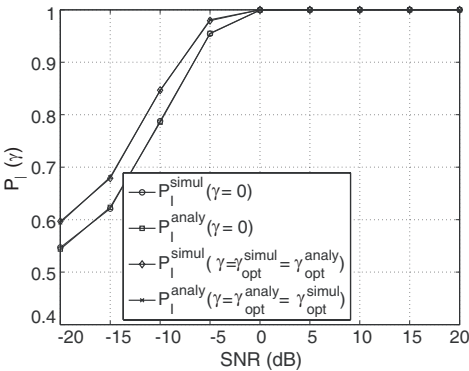


Figure 4. The performance improvement at $\gamma = \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}}$ over the performance at $\gamma = 0$ for two straight wires of length = 1.0 m and 1.2 m.

Table 2. The optimal threshold values in Fig. 4 for various SNR values.

SNR (dB)	$\gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}}$
−20	2.97×10^7
−15	0.72×10^7
−10	0.25×10^7
−5	0.11×10^6
0	$-0.79 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}} < 2.95 \times 10^6$
5	$-1.66 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}} < 4.07 \times 10^6$
10	$-2.14 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}} < 4.74 \times 10^6$
15	$-2.39 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}} < 5.11 \times 10^6$
20	$-2.53 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}} < 5.35 \times 10^6$

corresponding to the frequency range up to 0.5 GHz are $M_1 = 6$ and $M_2 = 8$ [162].

In Figs. 1–3, we illustrate how $p_{Z_{21|1}}(z)$, $p_{Z_{21|2}}(z)$, $P_{I|1}(\gamma)$, $P_{I|2}(\gamma)$ and $P_I(\gamma)$ look for various SNR's.

In Figs. 1(a)–3(a) and Figs. 1(b)–3(b), we confirm that the analytic PDF's $p_{Z_{21|1}}(z)$ and $p_{Z_{21|2}}(z)$ agree quite well with the empirical PDF's obtained from the histogram using $Z_{21|1}$ values and $Z_{21|2}$ values in Eq. (8) from the Monte-Carlo simulation for each SNR value. Refer to Section 3 to see how to obtain the analytic PDF's of $p_{Z_{21|1}}(z)$ and $p_{Z_{21|2}}(z)$ [162].

In Figs. 1(c)–3(c), we overlap the analytic PDF's of $Z_{21|1}$ and $Z_{21|2}$ to graphically check at what γ value Eq. (29) holds. $P_{I|1}(\gamma)$ in Eq. (26), $P_{I|2}(\gamma)$ in Eq. (27) and $P_I(\gamma)$ in Eq. (28) are shown in Figs. 1(d)–3(d), Figs. 1(e)–3(e) and Figs. 1(f)–3(f), respectively. Note that γ values

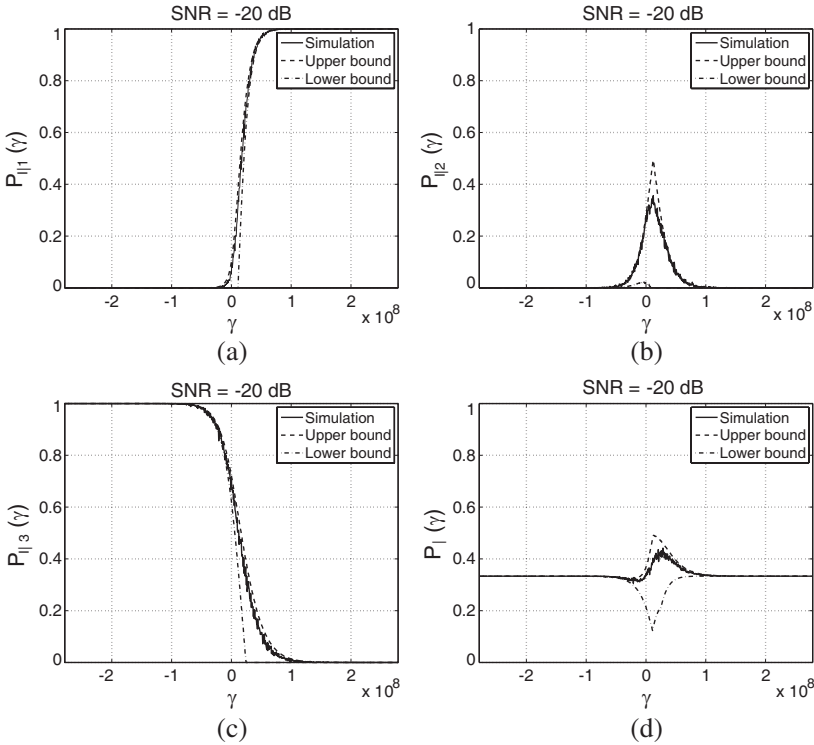


Figure 5. Analytical and simulated results as a function of γ value for three targets (SNR = -20 dB, $\gamma_{\text{opt}}^{\text{analy}} = 1.28 \times 10^7$, $\gamma_{\text{opt}}^{\text{simul}} = 2.84 \times 10^7$). (a) $P_{I|1}(\gamma)$, (b) $P_{I|2}(\gamma)$, (c) $P_{I|3}(\gamma)$ and (d) $P_I(\gamma)$.

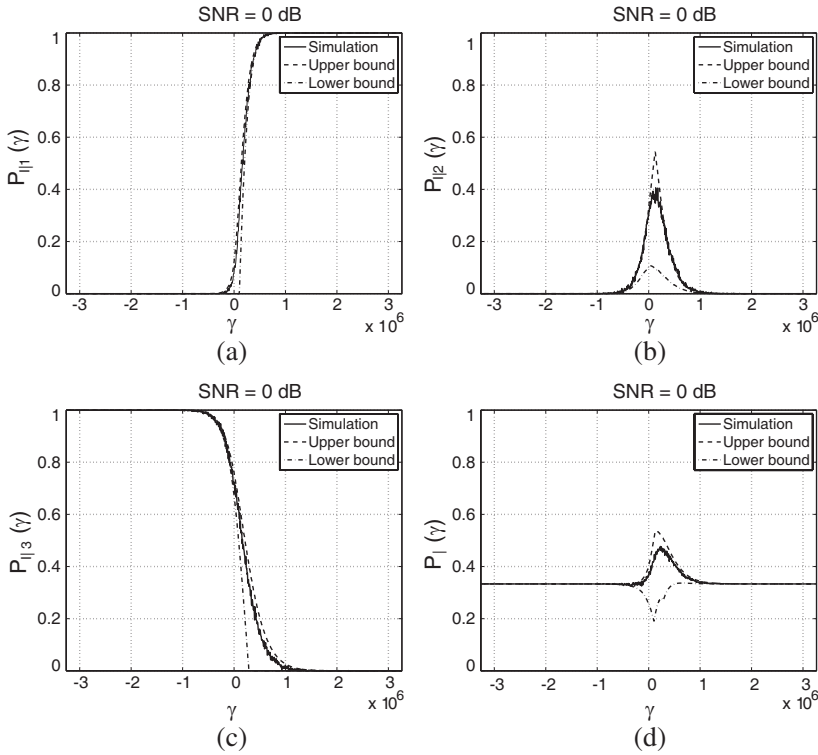


Figure 6. Analytical and simulated results as a function of γ value for three targets (SNR = 0 dB, $\gamma_{\text{opt}}^{\text{analy}} = 0.15 \times 10^6$, $\gamma_{\text{opt}}^{\text{simul}} = 0.22 \times 10^6$). (a) $P_{I|1}(\gamma)$, (b) $P_{I|2}(\gamma)$, (c) $P_{I|3}(\gamma)$ and (d) $P_I(\gamma)$.

maximizing Eq. (28) coincide with γ values satisfying Eq. (29) for all SNR's, which can be graphically checked by comparing γ value at which the PDF's of $Z_{21|1}$ and $Z_{21|2}$ in Figs. 1(c)–3(c) overlap with γ value at which $P_I(\gamma)$ is maximized in Figs. 1(f)–3(f). The optimal values of the thresholds are $\gamma_{\text{opt}}^{\text{analy}} = 2.97 \times 10^7$, $-0.79 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} < 2.95 \times 10^6$ and $-2.53 \times 10^6 < \gamma_{\text{opt}}^{\text{analy}} < 5.35 \times 10^6$ for SNR = -20 dB, SNR = 0 dB, and SNR = 20 dB, respectively.

For SNR = 0 dB, since $p_{Z_{21|1}}(z)$ is almost zero for $z > -0.79 \times 10^6$, and $p_{Z_{21|2}}(z)$ is nearly zero for $z < 2.95 \times 10^6$, the probability of correct classification is nearly constant for the threshold value of $-0.79 \times 10^6 < \gamma < 2.95 \times 10^6$. Similarly, the optimal threshold for SNR = 20 dB can be expressed as $-2.53 \times 10^6 < \gamma < 5.35 \times 10^6$.

It is also shown in Figs. 1(d)–3(d), Figs. 1(e)–3(e) and Figs. 1(f)–3(f) that analytic $P_{I|1}^{\text{analy}}(\gamma)$, $P_{I|2}^{\text{analy}}(\gamma)$ and $P_I^{\text{analy}}(\gamma)$ show agreements

with simulated $P_{I1}^{\text{simul}}(\gamma)$, $P_{I2}^{\text{simul}}(\gamma)$ and $P_I^{\text{simul}}(\gamma)$ for all γ values in Eq. (31).

In Fig. 4, we illustrate how much improvement we can get by adopting the optimal threshold $\gamma = \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}}$ in comparison with $\gamma = 0$. In Table 2, the optimal threshold values are explicitly shown. Note that the $\gamma_{\text{opt}}^{\text{analy}}$ value should be calculated using Eq. (28) or Eq. (29) for each SNR value. Since we have more performance improvement at low SNR than high SNR, the proposed scheme is useful at low SNR. It is also shown that analytic performance shows an excellent agreement with simulation performance at $\gamma = \gamma_{\text{opt}}^{\text{analy}} = \gamma_{\text{opt}}^{\text{simul}}$ as well as at $\gamma = 0$.

In Figs. 5–7, we illustrate the results for three targets. The three targets are straight wires of length = 0.8 meter, 1.0 meter, and

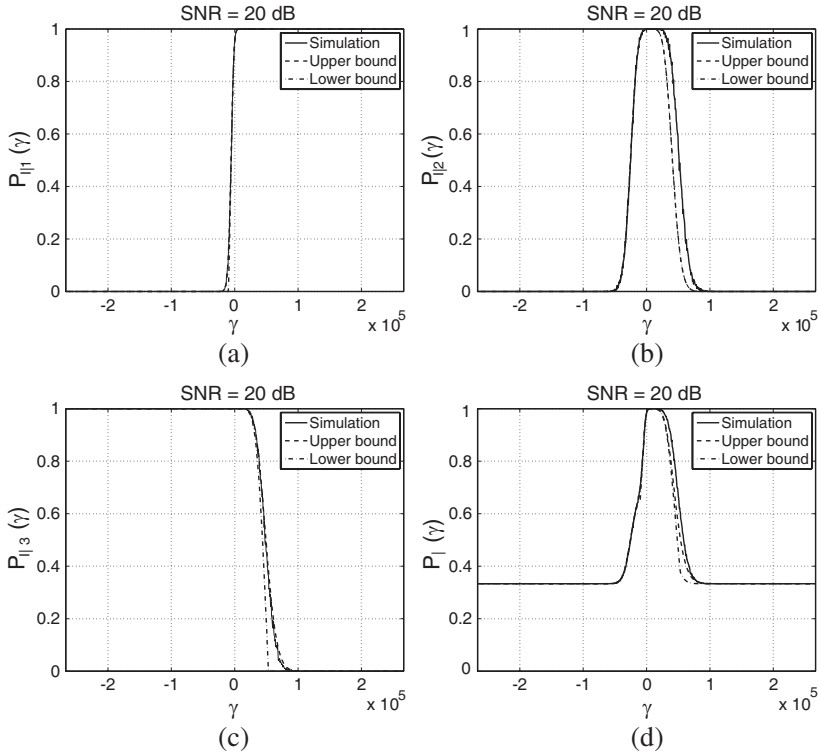


Figure 7. Analytical and simulated results as a function of γ value for three targets (SNR = 20 dB, $0.10 \times 10^4 < \gamma_{\text{opt}}^{\text{analy}} < 2.13 \times 10^4$, $0.10 \times 10^4 < \gamma_{\text{opt}}^{\text{simul}} < 2.08 \times 10^4$). (a) $P_{I1}(\gamma)$, (b) $P_{I2}(\gamma)$, (c) $P_{I3}(\gamma)$ and (d) $P_I(\gamma)$.

1.2 meter with $M_1 = 4$, $M_2 = 6$ and $M_3 = 8$, respectively [162].

In Figs. 5–7(a), we show $P_{I|1}^{\text{simul}}(\gamma)$, $P_{I|1}^{\text{up}}(\gamma)$ and $P_{I|1}^{\text{lo}}(\gamma)$ as γ varies for various SNR values. Note that, in Figs. 5–7, the simulation performance is actually between the lower bound and the upper bound for all γ values:

$$P_{I|k}^{\text{lo}}(\gamma) \leq P_{I|k}^{\text{simul}}(\gamma) \leq P_{I|k}^{\text{up}}(\gamma).$$

(53)

Similarly, the results assuming that the true targets are target 2 and target 3 are shown in Figs. 5–7(b) and Figs. 5–7(c), respectively.

The results from Eq. (44) and Eq. (45) are used for an upper bound and a lower bound in Figs. 5–7(a), Figs. 5–7(b) and Figs. 5–7(c). The simulation performance in Figs. 5–7(a), Figs. 5–7(b) and Figs. 5–7(c)

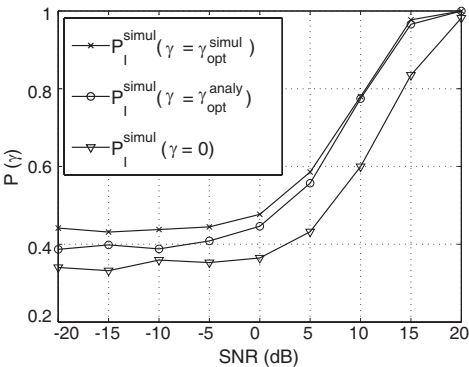


Figure 8. The performance improvement at $\gamma = \gamma_{\text{opt}}^{\text{simul}}$ and $\gamma = \gamma_{\text{opt}}^{\text{anlay}}$ over the performance at $\gamma = 0$ for three straight wires of length = 0.8 m, 1.0 m and 1.2 m.

Table 3. The optimal threshold values for three targets.

SNR (dB)	$\gamma_{\text{opt}}^{\text{anlay}}$	$\gamma_{\text{opt}}^{\text{simul}}$
−20	1.28×10^7	2.84×10^7
−15	0.40×10^7	0.53×10^7
−10	0.12×10^7	0.21×10^7
−5	0.40×10^6	0.74×10^6
0	0.15×10^6	0.22×10^6
5	0.05×10^6	0.08×10^6
10	0.03×10^6	0.02×10^6
15	0.01×10^6	0.01×10^6
20	$0.10 \times 10^4 < \gamma_{\text{opt}}^{\text{anlay}} < 2.13 \times 10^4$	$0.10 \times 10^4 < \gamma_{\text{opt}}^{\text{simul}} < 2.08 \times 10^4$

Table 4. The performance improvement at $\gamma = \gamma_{\text{opt}}^{\text{simul}}$ and $\gamma = \gamma_{\text{opt}}^{\text{analy}}$ over the performance at $\gamma = 0$ for three straight wires of length = 0.8 m, 1.0 m and 1.2 m (Numerical values).

SNR (dB)	-20	-15	-10	-5	0	5	10	15	20
P_I^{simul} ($\gamma = \gamma_{\text{opt}}^{\text{simul}}$)	0.44	0.43	0.43	0.44	0.47	0.58	0.77	0.97	1.00
P_I^{simul} ($\gamma = \gamma_{\text{opt}}^{\text{analy}}$)	0.38	0.39	0.38	0.40	0.44	0.55	0.77	0.96	1.00
P_I^{simul} ($\gamma = 0$)	0.34	0.33	0.35	0.35	0.36	0.43	0.60	0.83	0.98

are obtained from Eq. (46).

The upper bound and the lower bound in Figs. 5–7(d) are obtained from Eq. (47) and Eq. (48). The simulation performance in Figs. 5–7(d) are from Eq. (49). $\gamma_{\text{opt}}^{\text{analy}}$ and $\gamma_{\text{opt}}^{\text{simul}}$ values are also specified in the captions of Figs. 5–7.

In Fig. 8, we illustrate $P_I^{\text{simul}}(\gamma = 0)$, $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{simul}})$ and $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{analy}})$ for various SNR values. In Table 3, we also tabulate $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{simul}})$, $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{analy}})$, and $P_I^{\text{simul}}(\gamma = 0)$ in Fig. 8.

Although we get $\gamma_{\text{opt}}^{\text{lo}}$ and $\gamma_{\text{opt}}^{\text{up}}$ from Eq. (50) and Eq. (51), respectively, using the PDF's and the CDF's without the Monte-Carlo simulation, we can not get $\gamma_{\text{opt}}^{\text{simul}}$ analytically. We do have to perform the Monte-Carlo simulation as γ value varies to see what γ value results in the maximum $P_I^{\text{simul}}(\gamma)$.

How to choose the sub-optimal threshold without exhaustive search over γ value is given in Eq. (50)–Eq. (52). $\gamma_{\text{opt}}^{\text{analy}}$ and $\gamma_{\text{opt}}^{\text{simul}}$ values in Fig. 8 are indicated in Table 4. In Fig. 8, we illustrate how close $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{analy}})$ is to $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{simul}})$, and how much $P_I^{\text{simul}}(\gamma = \gamma_{\text{opt}}^{\text{analy}})$ has improved in comparison with $P_I^{\text{simul}}(\gamma = 0)$.

9. CONCLUSIONS

We considered the dependence of the probability of correct identification on the value of the threshold in the radar target recognition using the natural frequency. We illustrated how to determine the optimum threshold for use with the natural frequency-based radar target recognition of two targets. For multiple targets, we show how to determine the sub-optimal threshold.

We extended the formulation in [162] by adopting a nonzero threshold. How the probability of correct identification is dependent on the threshold value is addressed by numerical evaluation of the PDF.

The derivation is validated by comparing the analytical performance with the performance based on the Monte-Carlo simulation. To show the agreement between the analytic results and the simulation results for nonzero threshold value, the late time responses of simple targets are used. The results for two targets show that the scheme presented in this paper can be used to determine the optimum threshold for use with the performance analysis of the natural frequency-based radar target recognition in the time domain. For more than two targets, we show how to choose the threshold which is very close to the optimum threshold.

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