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Phased-MIMO Radar for Automotive Application

Muttaqin Hardiwansyah, Dian Neipa Purnamasari
Department of Electrical Engineering, Universitas Trunojoyo Madura, Bangkalan, Indonesia

ABSTRACT

Nowadays, radar is not only used to detect aircraft, but has been used to detect other objects such as birds, motor vehicles and others. Vehicle radar is currently one of the interesting fields to be developed. Multiple input Multiple Output (MIMO) radar systems have been widely used, with the advantages of increasing the number of targets that can be detected, wider detection angles, etc. The disadvantages of MIMO systems in radar include high gain, increasing the resolution of the object detection angle, being able to distinguish small and large objects due to differences in the radar cross section of reflected objects, etc. called phased array systems. Phased-MIMO combines the advantages of MIMO and phased-array, where PMIMO radar has diversity as well as coherent gain. PMIMO radar is an array of antenna arrays grouped into several sub-arrays that are in phase as in phased-array and between sub-arrays emit orthogonal signals. The use of PMIMO in vehicle radar in this study aims to increase the number of detected targets and be able to distinguish between small objects and large objects, for example PMIMO radar can distinguish between motorbikes, cars and trucks so that the vehicle is able to make the right decision. Whether the vehicle will braking, overtake or just shift slightly to avoid the motorcycle.

Keywords: MIMO radar, PMIMO radar, Vechicle radar.

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1. Introduction

A single antenna radar requires physical scanning all the way around dimensions, whereas the benefit of array radar means the beam be able to electronically pointed to a defined angular [1] [2]. Hence, with array radar, mechanical rotation is no longer required for the sensing.

There are several types of antenna arrays developed for radar, such as phased array radar [3] and MIMO radar [4] [5]. The main feature of MIMO radar is the possibility of using orthogonal signals, referred to as waveform diversity [5] [4]. Waveform diversity is effective in maximizing the total amount of objects that be able to tracked. The disadvantage of MIMO radar has slight directional gain, while phased array radar has the benefit of directional gain known as coherent gain.

To merge the strengths of MIMO radar and Phased MIMO radar, Phased MIMO radar was launched [6] [7] [8] [9]. In this type of radar, the antennas are organized into a few sub-arrays. Every sub-array has an equal quantity of antennas, some antennas are used in common with the neighbouring sub-arrays to create redundant sub-arrays. The antennas in a sub-array radiate the identical waveforms and thus provide coherent gain. Separate subarrays radiate signals orthogonal to one another to form diversity.

Characteristic detection capability is a key parameter in evaluating radar effectiveness [5]. Phased-MIMO radar with no overlapping subarrays be able to enhance the identification capabilities of more object parameters when comparing with phased-array radar [6]. In general, phased MIMO radar is able to enhance the signal-to-noise ratio [7] [8].

Based on the advantages of Phased-MIMO radar that have been described, this radar system is proposed to be used as a vehicle radar. The desired result is that the radar is able to improve target detection capabilities such as increasing angular resolution so that this vehicle radar is able to distinguish objects that are close together. Furthermore, with the Phased-MIMO radar system, this vehicle radar is able to distinguish small objects and large objects in the case raised is a motorcycle with a car, truck or other large vehicle.

Different types of vehicles have different reflected signals, which are called RCS. Motorcycles have the smallest RCS value of 5 m^2, cars have an RCS of 100 m^2 and trucks' RCS is 200 m^2. The biggest complication in using a MIMO system is the difficulty in distinguishing between a large target and a much smaller target when viewed from the RCS value.

The development of radar requirements for vehicles is currently a major concern, where the main purpose is driving safety [9]. To avoid unwanted accidents, a radar is needed that has the reliability to meet the needs of driving safely and comfortably.

Finally, the vehicle radar with the Phased-MIMO system has a more accurate ability to detect closely spaced targets and is able to distinguish large objects from small objects. This allows the vehicle radar to make better decisions. Whether the vehicle will maneuver to overtake the vehicle in front of it, or just shift to the right to avoid small vehicles if possible. If conditions are not possible, the vehicle will brake according to the speed of the vehicle.

2. LITERATURE REVIEW

2.1 phased-mimo radar

The basic baseband signal sent by a phased MIMO radar at subarray K could be described by:

$$\mathbf{s}_k(t) = \sqrt{\frac{M}{K}}\boldsymbol{\varphi}_k(t)\tilde{\mathbf{w}}_k^*, \quad k = 1, \dots, K \tag{1}$$

in which M is the amount of total radiating antennas, K represents the count of radiating sub-arrays, $(.)^*$ indicates the complex conjugate functions, $\mathbf{w}_k$ refer to M-element unit-norm complex weight vector for the k-th of $M-K+1$ sub-arrays in the emitted antenna. The radiating weight corresponds to the active elements in the k-th sub-array, so the number of non-zero elements in $\mathbf{w}_m$ will be exactly to $M-K+1$ and the other items as often as $K+1$ will be equal to zero [10]. In (1), M/K means the energy standardization ratio, so the power delivered in one pulse equal M.

Phased-MIMO radar produced signal matrix S(t) of $K \times M$ element has the orthogonal attribute, which means that :

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* Corresponding author
E-mail address: *muttaqin.hardiwansyah@gmail.com*

$$\int_{T_p} \mathbf{S}(t)\mathbf{S}^H(t)dt = \mathbf{I}_{MM} \tag{2}$$

T_p can be described as the pulse repetition interval (PRI), $(.)^H$ show Hermitian matrix transpose function and $\mathbf{I}_{MM}$ the M×M is Matrix of Identity.

Assuming that the accumulated power radiated by M antenna of a PRI amounts to M, the signal power of $\mathbf{s}_k(t)$ at the k-th sub-array at a PRI amounts to

$$E_K = \int_{T_p} \boldsymbol{s}_k^H(t)\boldsymbol{s}_k(t)\,dt = \frac{M}{K} \tag{3}$$

The k-th sub-array signal power from the previous expression equal M/K, therefore the signal power of an antenna on the sub-array becomes M /(K × (M-K + 1)).

The returned signal from a objects with return ratio $\sigma(\theta)$ at a given angular θ, at time t in the far field may be described as follows:

$$r(t,\theta) = \sqrt{\frac{M}{K}}\,\sigma(\theta)\sum_{k=1}^{K}\tilde{\mathbf{w}}_k^H\,\tilde{\mathbf{a}}_k(\theta)\boldsymbol{\varphi}_k(t) = \sqrt{\frac{M}{K}}\,\sigma(\theta)\sum_{k=1}^{K}\mathbf{w}_k^H\,\mathbf{a}_k(\theta)e^{-2\pi j\tau_k(\theta)}\boldsymbol{\varphi}_k(t) \tag{4}$$

where $\sigma(\theta)$ is the target return ratio at θ, $\boldsymbol{a}_k(\theta)$ is M×1 steering vector of in the kth emitter sub-array, $\tau_k(\theta) = kd_M \sin\frac{\theta}{c}$ is the time required by the emitted signal to reach the first antenna member of the k-th receiver sub-array, d_M is the range among the antenna members, and c is the velocity of light 3×10^8 m/s.

If the K×1 shown coherent processing vector on the emitter equal to:

$$\mathbf{c}(\theta) = [\mathbf{w}_{\mathbf{1}}^H\mathbf{a}_1(\theta), \dots, \mathbf{w}_k^H\mathbf{a}_k(\theta)]^T \tag{5}$$

in which

$$\mathbf{a}(\theta) = [e^{j2\pi d\sin(\theta)/\lambda}\ e^{j2\pi 2d\sin(\theta)/\lambda}, \dots, e^{j2\pi(M-K+1)d\sin(\theta)/\lambda}]^T \tag{6}$$

and K×1 waveform diversity vector [7]

$$\mathbf{d}(\theta) = \left[e^{-j2\pi\tau_1(\theta)}, \dots, e^{-j2\pi\tau_k(\theta)}\right]^T \tag{7}$$

After that, the returned signal can be easily transformed to

$$r(t,\theta) = \sqrt{\frac{M}{K}}\,\sigma(\theta)\big(\mathbf{c}(\theta)\odot\mathbf{d}(\theta)\big)^T\boldsymbol{\varphi}_{\boldsymbol{k}}(t) \tag{8}$$

In which ⊙ show the Hadamard product function.

Given that the p-th objects points in the angular of θ_p with p = 1,2, ..., P, thus the incoming complex signal vector will be

$$\boldsymbol{y}_{\mathbf{PMIMO}}(\boldsymbol{n}) = \boldsymbol{r}(t,\theta_p)\mathbf{b}(\theta_p) + \boldsymbol{z}(t) \tag{9}$$

$$\boldsymbol{y}_{\mathbf{PMIMO}}(n) = \sqrt{\frac{M}{K}}\sum_{\boldsymbol{p=1}}^{\boldsymbol{P}}\sigma(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n)\boldsymbol{b}(\theta_p) + \boldsymbol{z}(t) = \sqrt{\frac{M}{K}}\sum_{\boldsymbol{p=1}}^{\boldsymbol{P}}\sigma(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n) + \boldsymbol{z}(t) \tag{10}$$

whereabouts $\sigma_p(\theta_p)$ is return ratio of the p-th objects and **z** denotes the noise vector containing clutter that receive to radar system. It will be considered that noise and clutter is uncorrelated to the signal $\varphi_k(t)$**.**

2.2 *Parameter Identifiability*

According to the derivation of the MIMO radar capabilities in determining the object parameters [5], the baseband corresponding signal obtained from the L-antenna subarrays on the incoming array of the phased MIMO radar with the object orientation θ_p can be given by (10). The parameters that can be evaluated from $\{\mathbf{y}(t)\}_{p=1}^{P}$ are $\{\sigma(\theta_p)\}_{p=1}^{P}$. Assuming that $\boldsymbol{z}(t)$ will be uncorrelated with $\varphi(t)$ then the characteristic of the the addition term of the expression (10) will not be affected by the second equation.

The characteristic expression shall be as defined below:

$$\sqrt{\frac{M}{K}}\sum_{p=1}^{P}\check{\sigma}(\theta_p)\boldsymbol{b}(\check{\theta}_p)\left(\boldsymbol{c}(\check{\theta}_p)\odot\boldsymbol{d}(\check{\theta}_p)\right)^T\boldsymbol{\varphi}(n) = \sqrt{\frac{M}{K}}\sum_{p=1}^{P}\sigma(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n) \tag{11}$$

To determine each parameter,, (11) should contain a different formula for every parameter, i.e, $\check{\sigma}_p(\check{\theta}_p) = \sigma_p(\theta_p)$, $(\check{\theta}_p) = (\theta_p)$, $p = 1, \dots, P$. Assuming that the K emitted signals are linearly unrelated, the relationship below is satisfied:

$$\mathrm{rank}\,\{[\varphi(1)\ \varphi(2) \dots \varphi(K)]\} = K \tag{12}$$

This simplifies (11) to :

$$\sum_{p=1}^{P}\check{\sigma}(\theta_p)\boldsymbol{b}(\check{\theta}_p)\left(\boldsymbol{c}(\check{\theta}_p)\odot\boldsymbol{d}(\check{\theta}_p)\right)^T = \sum_{p=1}^{P}\sigma(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T \tag{13}$$

or

$$\check{\mathbf{A}}\,\check{\boldsymbol{\sigma}} = \mathbf{A}\,\boldsymbol{\sigma} \tag{14}$$

in which

$$\boldsymbol{\sigma} = [\sigma_{\mathbf{1}}(\theta_{\mathbf{1}})\ \dots\ \sigma_{\boldsymbol{p}}(\theta_{\boldsymbol{p}})]^T \tag{15}$$

$$\check{\boldsymbol{\sigma}} = [\check{\sigma}_{\mathbf{1}}(\check{\theta}_{\mathbf{1}})\ \dots\ \check{\sigma}_{\boldsymbol{p}}(\check{\theta}_{\boldsymbol{p}})]^T \tag{16}$$

$$\mathbf{A} = \left[\left(\mathbf{c}(\theta_1)\odot\mathbf{d}(\theta_1)\right)\otimes\mathbf{b}(\theta_1)\dots\left(\mathbf{c}(\theta_p)\odot\mathbf{d}(\theta_p)\right)\otimes\mathbf{b}(\theta_p)\right] \tag{17}$$

$$\check{\mathbf{A}} = \left[\left(\mathbf{c}(\check{\theta}_1)\odot\mathbf{d}(\check{\theta}_1)\right)\otimes\mathbf{b}(\check{\theta}_1)\dots\left(\mathbf{c}(\check{\theta}_p)\odot\mathbf{d}(\check{\theta}_p)\right)\otimes\mathbf{b}(\check{\theta}_p)\right] \tag{18}$$

Consider L describe the size of A. To determine the largest amount of objects on a phased MIMO radar, an L size should be used, such as

$$L \in [K + M_r, KM_r]. \tag{19}$$

wherever K describe the amount of sub-array which also describe the amount of orthogonal signals transmitted. Based on expression from [5]and [6], characteristic parameter is satisfied :

$$L + 1 > 2H,\ i.e,.H_{max} = \left\lceil\frac{L-1}{2}\right\rceil \tag{20}$$

whereever $\lceil . \rceil$ describe the smallest integer greater than or equal to a given number. Then the largest amount of objects on phased-MIMO radar,

$$H_{max} \in \left[\frac{K+M_r-2}{2}, \frac{KM_r+1}{2}\right) \quad (21)$$

The largest amaount H_{max} of objects for MIMO radar and phased-array radar may be calculated from the expression (20). In MIMO radar the amount of emittersr sub-arrays equals to M_t, i.e., the specific situation of M_t single-antenna sub-arrays. Therefore, expression of MIMO radar:

$$H_{max} \in \left[\frac{M_t+M_r-2}{2}, \frac{M_tM_r+1}{2}\right) \quad (22)$$

For phased-array, the amount of sub-arrays is one, i.e., the other specific situation of an array of a single M_t-antenna sub-array. Therefore, formula of phased-array radar:

$$H_{max} \in \left\lceil\frac{M_r-1}{2}\right\rceil \quad (23)$$

3. Method

3.1 least-Squares Parameter estimation

To prove object detection in vehicle radar, Least-Square (LS) estimation is used which can describe the reflected signal of the detected objet. Least-squares (LS) estimation is adopted for its simple implementation for estimating object characteristic. To achieve the LS estimation of the phased MIMO radar, the returned signal may be calculated as in (10):

$$\boldsymbol{y}_{PMIMO}(n) = \sqrt{\frac{M}{K}}\sum_{p=1}^{P}\sigma(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n) \quad (24)$$

If the two sides of (23) If the two sides of from the left and right are multiplied by the associated hermitians, then the result is:

$$\boldsymbol{b}^{\mathrm{H}}(\theta_p)\boldsymbol{y}_{\mathrm{PMIMO}}(n)\left(\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n)\right)^{\mathrm{H}} = \sqrt{\frac{M}{K}}\sum_{p=1}^{P}\sigma(\theta_p)\boldsymbol{b}^{\mathrm{H}}(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n)\left(\left(\boldsymbol{c}(\theta_p)\odot\boldsymbol{d}(\theta_p)\right)^T\boldsymbol{\varphi}(n)\right)^{\mathrm{H}} \quad (25)$$

The LS spectrum evaluation according to (24) may be approximated by:

$$\breve{\sigma}(\theta)_{\mathrm{PMIMO}} = \sqrt{\frac{K}{M}}\sum_{n=1}^{N}\boldsymbol{b}^{\mathrm{H}}(\theta)\boldsymbol{y}_{\mathrm{PMIMO}}(n)\boldsymbol{\varphi}^{\mathrm{H}}(n)\left(\boldsymbol{c}(\theta)\odot\boldsymbol{d}(\theta)\right)^* \quad (26)$$

wherever (.)* describe the complex conjugate. Based on the normalizing of MIMO, thus:

$$\breve{\sigma}(\theta)_{PMIMO} = \frac{\sqrt{\frac{K}{M}}\sum_{n=1}^{N}\boldsymbol{b}^H(\theta)\boldsymbol{y}_{PMIMO}(n)\boldsymbol{\varphi}^H(n)\left(\boldsymbol{c}(\theta)\odot\boldsymbol{d}(\theta)\right)^*}{\boldsymbol{b}^H(\theta)\boldsymbol{b}(\theta)\left(\boldsymbol{c}(\theta)\odot\boldsymbol{d}(\theta)\right)^T\boldsymbol{\varphi}(n)\boldsymbol{\varphi}^H(n)\left(\boldsymbol{c}(\theta)\odot\boldsymbol{d}(\theta)\right)^*} \quad (27)$$

The LS prediction for a phased array radar may be obtained from (26) using the phased array steering vector where the diversity $\mathbf{d}(\theta)$ is missing. The total amount of sub-arrays on a phased-array radar is 1 (K=1), to ensure that:

$$\breve{\sigma}_{PA}(\theta) = \frac{\sqrt{\frac{1}{M}}\sum_{n=1}^{N}\boldsymbol{b}^H(\theta)\boldsymbol{y}_{PA}(n)\boldsymbol{\varphi}^H(n)\boldsymbol{c}^T(\theta)}{\boldsymbol{b}^H(\theta)\boldsymbol{b}(\theta)\boldsymbol{c}^T(\theta)\boldsymbol{\varphi}(n)\boldsymbol{\varphi}^H(n)\boldsymbol{c}^*(\theta)} \quad (28)$$

Where ever

$$\boldsymbol{y}_{PA}(n) = \sqrt{M}\sum_{p=1}^{P}\sigma(\theta_p)\boldsymbol{b}(\theta_p)\left(\boldsymbol{c}(\theta_p)\right)^T\boldsymbol{\varphi}(n) + \boldsymbol{n} \quad (29)$$

For the MIMO radar [5], the LS estimation can be describe :

$$\breve{\sigma}_{\mathrm{MIMO}}(\theta) = \frac{\sum_{n=1}^{N}\mathbf{b}^T(\theta)R_{yx}\mathbf{a}(\theta)}{\|\mathbf{b}(\theta)\|^2\mathbf{a}^*(\theta)R_{xx}\mathbf{a}(\theta)} \quad (30)$$

whereever :

$$\mathbf{R}_{yx} = \frac{1}{N}\sum_{n=1}^{N}\boldsymbol{y}_{MIMO}(n)\boldsymbol{\varphi}^H(n) \quad (31)$$

$$\mathbf{R}_{xx} = \frac{1}{N}\sum_{n=1}^{N}\boldsymbol{\varphi}(n)\boldsymbol{\varphi}^H(n) = I \quad (32)$$

$\mathbf{R}_{yx}$ denotes the correlated matrix between the incoming and outgoing signals, in which $\mathbf{R}_{xx}$ represents the correlation matrix between the transmitted signals and itself, resulting in the identity matrix.

4. RESULT AND DISCUSSION

Simulations were performed using equation (27) for PMIMO radar, and equation (30) for MIMO radar. This simulation shows the backscattered signal based on each vehicle type, namely the RCS value of motorcycles is 5 m^2, car is 100 m^2 dan truck is 200 m^2.

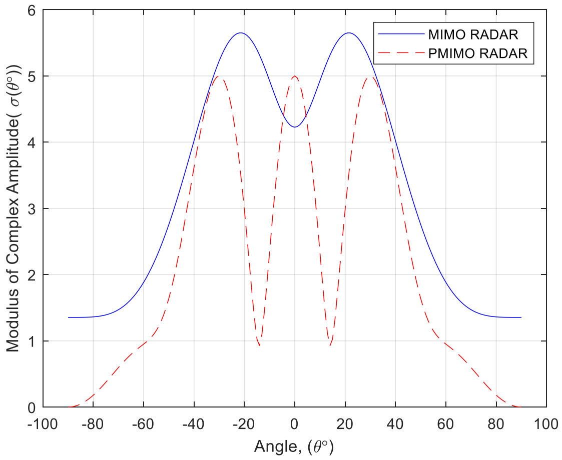

Figure 1. MIMO vs PMIO

Let a 4×4 MIMO radar system with ULA configuration, i.e., $M_t = M_r = 4$. For MIMO radar, the number of sub-arrays has equal amount of antenna (K=M). Every antenna emits an orthogonal signal. Assuming a phased-MIMO radar uses two sub-arrays, K=2, in which case the amount of antenna of each sub-array (M-K+1) is three. The emitted signal are generated using Hadamard codes depend on the amount of subarray [8] [10].

The first experiment of the radar system will detect 3 motorcycles located at angles of -30°, 0°, 30°. From figure 1, the MIMO radar is only able to detect 2 targets located at angles of -20° and 20°. There are 2 detection errors by the MIMO radar, the first is an error in reading the number of targets. In reality, the number of targets in front of the radar is 3 targets, but it only reads 2. This is due to the MIMO radar having less than maximum angular resolution. The second error is the location of the target, which should be located at an angle of -30°, 0°, 30°. This is caused by the presence of a target at an angle of 0° that cannot be detected. So it is as if some of the target RCS is read to other targets, resulting in a shift in target location.

Unlike MIMO radar, PMIMO radar is able to detect the location and number of targets accurately because PMIMO radar has better angular resolution due to the coherent gain property. From this case, it can be seen that PMIMO radar is able to improve MIMO radar in terms of angular resolution.

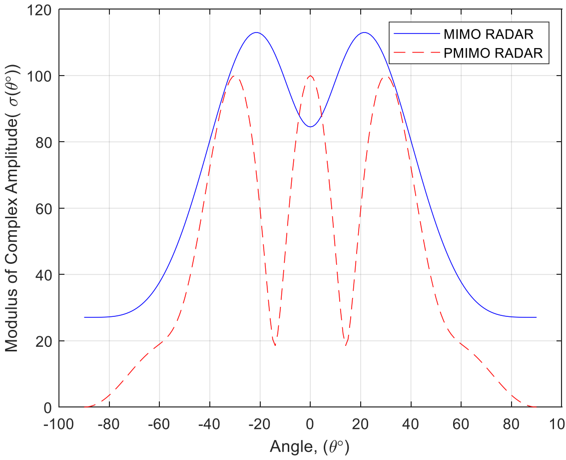

Figure 2 MIMO vs PMIMO Radar for car detection

In the second experiment, the radar system will detect a car object with the same number of antenna elements as in the first experiment. In Figure 2, once again the MIMO radar is not able to detect the car object correctly both from the number of targets and the location. Another error that occurs is that the RCS value is greater than it should be, i.e. the RCS of the car is 100. This is caused by the leakage of the RCS value of the target at 0°, so that the RCS of the target at angles of -20° and 20° is increased.

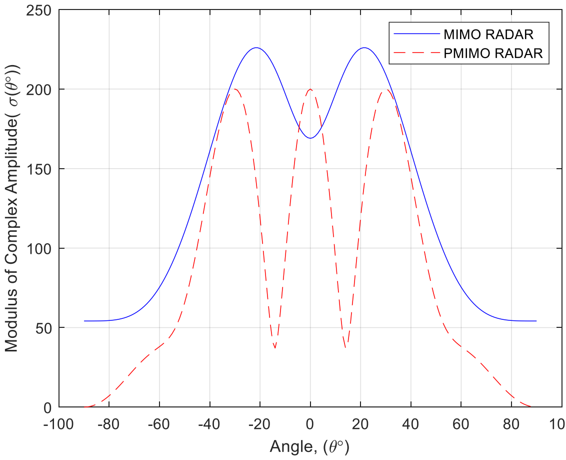

Figure 3 MIMO vs PMIMO Radar for truck detection

In the third experiment, the number of antenna elements is the same as before, namely 4×4, except that detection is carried out on a truck with an RCS of 200 m^2. In Figure 2, once again the MIMO radar was unable to detect the car object correctly both in terms of target number and location. Another error that occurs is that the RCS value is larger than it should be, i.e. the RCS of the truck is 200. This is caused by the leakage of the target RCS value at 0°, so that the RCS of the target at the angles of -20° and 20° is increased.

In the last experiment, the radar system will detect the difference between the three targets, namely motorcycles, cars and trucks. Due to the large difference in RCS between motorcycles and cars and trucks, a 10×10 antenna element is used.

In Figure 4, the MIMO radar can detect cars at an angle of 0° and trucks at an angle of 30° with RCS values of 100 and 200. However, for motorcycles at an angle of -30°, the MIMO radar is unable to detect due to white Gaussian noise. The RCS of the small motorcycle is not read due to the same level as the noise, as a result the motorcycle object is read as noise on the MIMO radar.

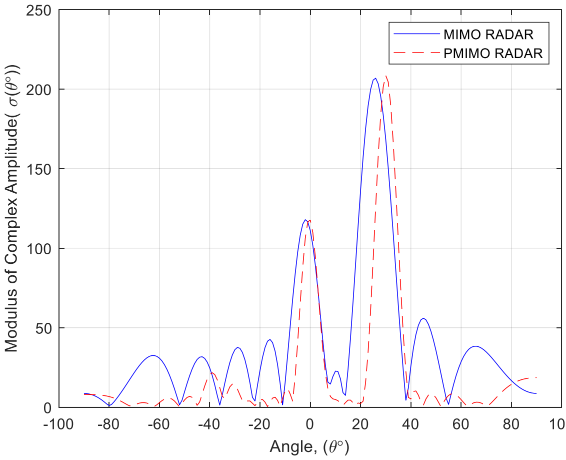

Figure 4 Capabilities of MIMO radar vs PMIMO radar to detect motorcycle, car and truck

The number of subarrays in PMIMO radar is K = 4, because the best number of subarrays in PMIMO is less than half the total number of antenna elements. In contrast, PMIMO radar can still detect motorcycles with a much smaller RCS because the noise produced is still smaller than the target RCS. PMIMO radar can also detect cars at an angle of 0° and trucks at an angle of 30° with RCS values of 100 and 200. Again, the advantage of PMIMO radar is that it can distinguish between small objects and larger objects.

5. Conclusions

Conclusions that can be taken from this research:

- PMIMO radar can be used for vehicle
- PMIMO radar is able to improve the shortcomings of MIMO radar in terms of angular resolution.
- PMIMO radar is more accurate in reading RCS objects compared to MIMO radar.
- PMIMO radar is able to distinguish small objects from large objects, which MIMO radar is not capable.

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