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CAPON-LIKE METHOD FOR DIRECTION OF ARRIVAL ESTIMATION USING TDM MIMO RADAR

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Abstract

This paper presents a novel measurement method and briefly discusses the basic properties of direction of arrival (DoA) measurement in a multiple-input multiple-output (MIMO) radar system by using orthogonality with time-division multiplexing (TDM), where only one transmitting antenna element is active in each time slot. This paper presents the mathematical model of the TDM-MIMO radar operating at 10 GHz, transmitting a string of pulses, the method of transmitting and receiving the signal, and the method of measuring the angle of arrival of the signal based on the use of the Capon algorithm and its modifications. Finally, the correctness of the theory, algorithm and method of measuring the direction of arrival of the signal is verified by experimental simulation. The work discussed in this paper is of great significance to practically demonstrate the capabilities of the TDM MIMO radar sensor in practical implementations like reconnaissance and electronic warfare systems.

Keywords: direction of arrival measurement, Capon algorithm, multiple-input multiple-output radar, time-division multiplexing, signal processing.

1. Introduction

Recently, an increased number of publications on *direction of arrival* (DoA) estimation algorithms for *Multiple-Input-Multiple-Output* (MIMO) radars can be noted. Taking into account the current geopolitical situation, the measurement of the signal from an unknown emitter location by means of a MIMO radar fits into the tasks of electronic intelligence systems. Knowing the direction of the incoming signal, the next step is to measure the parameters of the received signal and analyse it, which leads to the recognition and identification of the emitter.

Each element of the antenna array of a MIMO radar transmits a different signal and it is possible to distinguish them in individual receiver channels. Therefore, a virtual antenna array

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with an extended aperture is created, which significantly improves angular resolution of the system without adding more antennas to the arrays [1]. In the literature, the MIMO radar is often presented as a very good technical solution that can find application in various fields of technology, not necessarily only in radiolocation. If the MIMO radar design is such that the transmitter and receiver are located in the same place, such a radar system is called monostatic. In the case the two are placed in different locations, we call the radar bistatic [2–4].

The key technical challenge in designing a MIMO radar system is to develop suitable transmit signals that can be separated at each receiving antenna [5]. There are three techniques to achieve full signal separation: time division, frequency division and code division. While frequency division and code division techniques require a set of orthogonal signals that can be transmitted simultaneously, *time division multiplexing* (TDM) provides serial transmission [6–10]. The work presented here extends the authors' previous publications and shows a specific application of DoA measurement using orthogonality with a time-division multiplexing MIMO radar [11]. TDM is often used because of its simplicity and low cost in practical implementations. What is most important among the three methods is that TDM provides perfect orthogonality [12–14]. Different multiplexing approaches have been studied in great detail in the context of pointing out moving ground targets (*Ground Moving Target Indication* – GMTI) in [15, 16].

In the literature, a clear division of DoA estimation algorithms into quadratic type algorithms and algorithms based on eigendecomposition can be detailed. The Capon algorithm can be assigned to the first group of algorithms [17–20]. The MUSIC (*Multiple Signal Classification*) and ESPRIT (*Estimation of Signal Parameters via Rational Invariance Techniques*) algorithms should be classified into the second [20–24]. A comparison of the indicated DoA algorithms is presented by the authors of this publication in [11].

Current analysis of the literature and the resulting sizable number of new DoA algorithms show that they have not been yet widely used in radiolocation and signal arrival angle measurements. In [25], the authors propose a MIMO radar using TDM with signals optimized for an automotive radar. DoA is measured by evaluating the received signals using a three-dimensional *discrete Fourier transform* (DFT). In this work, a special linear *frequency modulated continuous wave* (FMCW) radar waveform was used, which allowed simultaneous measurement of range and Doppler frequencies even in a multi-target situation, and could be extended to MIMO radar applications using the *time deviation technique* (TDM).

The paper [26] proposes a reduced dimension polynomial root multiple signal classification (RC-root-MUSIC) that reduces the high computational complexity of the traditional MUSIC algorithm in MIMO radar DoA estimation. The reduction in computational complexity was achieved by reducing the dimensions of the matrix of the matched filter output signal. In conclusion, in this article the authors do not indicate at all the frequency range in which the described algorithm works and what type of transmitted signal was used for simulation. The authors focus their attention on hardware implementation and reducing the computational complexity of the proposed algorithm.

In the article [27], the authors showed that the angular resolution limit depends on the chosen TDM scheme of the MIMO radar and can be better than that of the SIMO radar, despite the unknown Doppler frequencies. This article discussed the MIMO radar, while its operating bandwidth and type of signal orthogonality were not specified. It is only known that the radar transmitted a string of pulses.

The paper [28] presents the use of MIMO radar operating at 77 GHz for accurate DoA determination. The paper describes a MIMO radar with TDM orthogonality and a special linear frequency modulated continuous wave (FMCW) radar.

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The application of neural networks can already be seen in the literature. For example, the article [29] presents an architecture consisting of *denoising convolutional autoencoders* (DCAEs) and *conventional neural networks* (CNNs) called the DCAE-CNN architecture. DCAEs are used to restore data before DoA estimation, and CNNs are used to measure DoA by mapping the restored data to appropriate angles. The proposed solution shows more satisfactory performance in terms of accuracy under low *signal-to-noise ratio* (SNR) conditions and significantly reduces computation time compared to the standard MUSIC algorithm. This article referred to a MIMO radar, while its operating bandwidth and type of signal orthogonality were not specified. It is only known that the radar transmitted a string of pulses.

The main purpose of this paper was to present a method of signal arrival angle measurement based on the adapted Capon method from the paper [11] and its application in a TDM MIMO system. The essential novelty is that a model of a TDM-MIMO radar operating at 10 GHz, transmitting a string of pulses, with a built-in Capon algorithm as described in [11], had to be developed. So far, one can find in the literature applications of TDM-MIMO radars at 77 GHz and simultaneously operating on a continuous wave, just as cited in [15] and [28]. We are filling this gap by pointing out how the DoA is measured by a TDM-MIMO radar operating in the X-band. The radar system and DoA measurement method presented in the article are a proposal for a radar system that at least an enemy radio reconnaissance unit can be equipped with. It is noteworthy that the design of reconnaissance and electronic warfare stations in use around the world indicates that a radar operating in the X-band will provide greater DoA measurement accuracy than in lower frequency bands.

The remainder of this paper is organized as follows. In Section 2 a TDM MIMO radar system is described. Section 3 focuses on presenting a method for measuring the angle of signal arrival in the proposed system. Computer simulation studies are presented in Section 4. The paper is concluded in Section 5.

2. Signal and system model

2.1. TDM MIMO radar system – technical aspects

Consider a MIMO radar system operating at 10 GHz, transmitting a string of pulses. A radar system consists of an M-element transmit array and N-element receive array, both of which are collocated and uniform linear arrays with isotropic antennas, with the interelement distances of d_t and d_r, respectively. The MIMO technique uses the existing transmitting and receiving antennas to obtain the virtual antenna aperture to achieve the expansion of the antenna aperture, and improve the DoA estimation performance.

In a MIMO radar system, each antenna of the transmit array transmits an orthogonal waveform. Because of this orthogonality, it is possible to recover the transmitted signals at the receive array. The measurements at the physical receive array corresponding to each orthogonal waveform can then be stacked to form the measurements of the virtual array, as shown in Fig. 1.

Assume that there are P targets located in the far field, and the pth target DoA is denoted by θ_p ($p = 1, 2, \ldots, P$). The problem of measurement the DoA of a signal from a target as well as the phase shift between different signals arriving at successive antennas is shown in Fig. 2.

A simple way of using the TDM in the MIMO case is a sequential activation of the transmitters. Each Tx element transmits a complete frequency slope before the next transmitter is activated. In each time step only one transmitter is active. Considering a MIMO radar with M transmit and N receive antennas, in this way the signal at each receive antenna is divided into M virtual

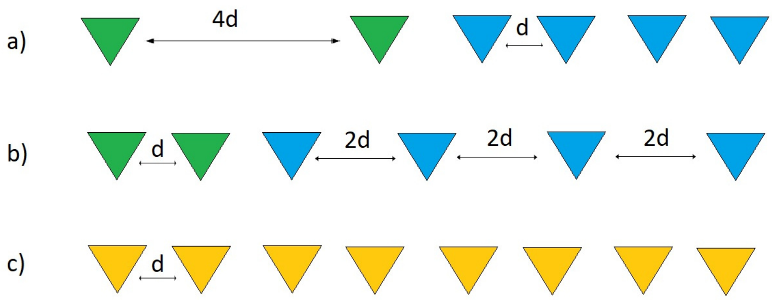

Fig. 1. Different configurations that realize same MIMO virtual array a) and b). Full MIMO virtual array obtained via $M = 2$ and $N = 4$ antennas c).

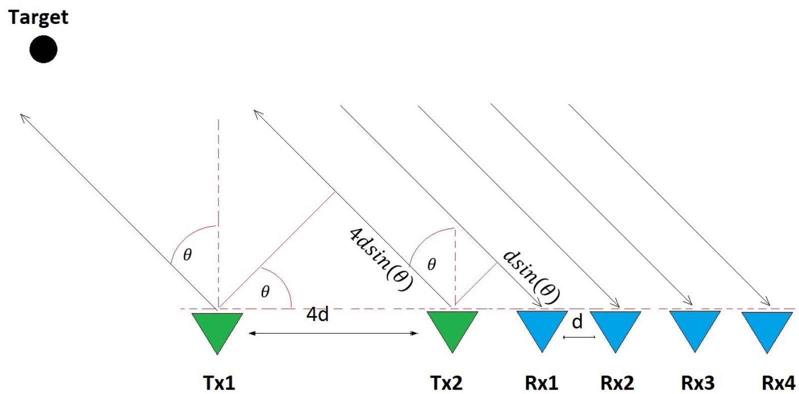

Fig. 2. Phase shift of signals arriving at individual antennas.

signals. As the number of receive antennas is N, the total number of virtual signals is MN. Now, each virtual signal corresponding to a specific transmitter-receiver pair m and n is processed independently as for a single antenna system.

Different colors in Fig. 3 stand for individual time-slots of different transmit antennas with duration of T_{slot}. At each receive antenna the echo signal is sampled by the rate of $1/T_{\text{slot}}$.

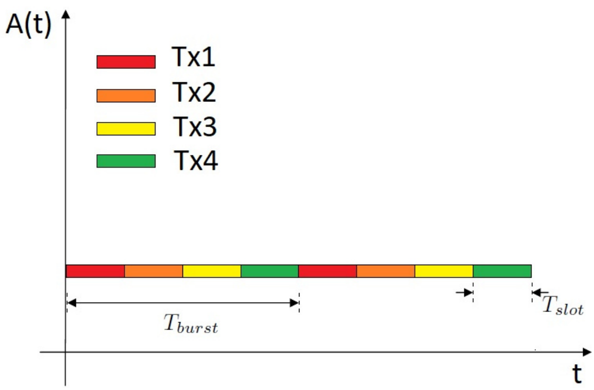

Fig. 3. TDM signal waveform for $M = 4$ transmit antennas.

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The received array signals are matched by each of the transmitting waveforms and the output of the matched filters after collecting a total of Q pulses can be written as [11]

$$\boldsymbol{Y} = \boldsymbol{A}\,\boldsymbol{S} + \boldsymbol{Z}, \tag{1}$$

where

$$\boldsymbol{A} = \boldsymbol{A}_r \odot \boldsymbol{A}_t \tag{2}$$

is known as the virtual array matrix, $\boldsymbol{A}_r$ is the receive steering matrix with the pth receive steering vector $\boldsymbol{a}_r(\theta_p)$, $\odot$ denotes a Hadamard product, and $\boldsymbol{A}_t$ is the transmit steering matrix with the pth transmit steering vector $\boldsymbol{a}_t(\theta_p)$, where λ is the wavelength.

$$\boldsymbol{A}_r = \left[\boldsymbol{a}_r(\theta_1), \boldsymbol{a}_r(\theta_2), \ldots, \boldsymbol{a}_r(\theta_p)\right] \tag{3}$$

$$\boldsymbol{a}_r(\theta_P) = \left[1,\, e^{-j2\pi\frac{d_r \sin\theta_P}{\lambda}}, \ldots, e^{-j2\pi(N-1)\frac{d_r \sin\theta_P}{\lambda}}\right]^T \tag{4}$$

$$\boldsymbol{A}_t = \left[\boldsymbol{a}_t(\theta_1), \boldsymbol{a}_t(\theta_2), \ldots, \boldsymbol{a}_t(\theta_p)\right] \tag{5}$$

$$\boldsymbol{a}_t(\theta_P) = \left[1,\, e^{-j2\pi\frac{d_t \sin\theta_P}{\lambda}}, \ldots, e^{-j2\pi(M-1)\frac{d_t \sin\theta_P}{\lambda}}\right]^T \tag{6}$$

$\boldsymbol{S}$ denotes the target coefficient matrix, $\boldsymbol{Y}$ is the data matrix corresponding to a virtual array with $y_{m,n}$ being the output data of the $(n-1)\times M + m$th virtual array element, where $m = 1, 2, \ldots, M$ and $n = 1, 2, \ldots, N$. Z represents the white Gaussian noise matrix with $z_{m,n}$ being the noise vector of the $(n-1)\times M + m$th virtual element.

$$\boldsymbol{S} = \left[\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_Q\right] \tag{7}$$

$$\boldsymbol{Y} = \left[\boldsymbol{y}_{1,1}, \ldots, \boldsymbol{y}_{M,N}\right] \tag{8}$$

$$\boldsymbol{y}_{m,n} = \left[y_{m,n}(1), y_{m,n}(2), \ldots, y_{m,n}(Q)\right] \tag{9}$$

$$\boldsymbol{Z} = \left[z_{1,1}, \ldots, z_{M,N}\right] \tag{10}$$

$$z_{m,n} = \left[z_{m,n}(1), z_{m,n}(2), \ldots, z_{m,n}(Q)\right] \tag{11}$$

The covariance matrix of the received data is given as:

$$\boldsymbol{R}_x = E\left\{\boldsymbol{Y}\boldsymbol{Y}^H\right\} \tag{12}$$

$$\boldsymbol{R}_x = \boldsymbol{A}\,\boldsymbol{R}_s\,\boldsymbol{A}^H + \boldsymbol{R}_N \tag{13}$$

$$\boldsymbol{R}_s = E\left\{\boldsymbol{S}\boldsymbol{S}^H\right\}, \tag{14}$$

where $\boldsymbol{R}_S$ is the covariance matrix of the received signal and $\boldsymbol{R}_N$ is the noise covariance matrix.

2.2. Method for estimating the DoA in a TDM MIMO radar

For precise measurement of the angle of arrival of the signal in the presented TDM MIMO radar, the Capon algorithm was used, taking into account the properties of TDM and the MIMO technique and considering modifications as in [11].

The goal of the Capon algorithm is to achieve the minimum power at the output of the array of receiving antennas, except in the direction of the incoming signal. It can be written as [11]:

$$\min_{\boldsymbol{w}} \boldsymbol{w}^H \boldsymbol{R}_x \boldsymbol{w} \tag{15}$$

considering the condition that:

$$\boldsymbol{w}^H \boldsymbol{A} = 1, \tag{16}$$

where $\boldsymbol{w}$ is a weight vector. Equation (15) represents an optimization task that can be solved with the method of Lagrange multipliers. This is a method of calculating the conditional extremum of a differentiable function, which is very often used in optimization theory. Thus, using the Lagrange method, the solution of the optimization task above will be given by the relation:

$$\boldsymbol{w}_{\mathrm{LAG}} = \frac{\boldsymbol{R}_x^{-1}\boldsymbol{A}}{\boldsymbol{A}^H \boldsymbol{R}_x^{-1}\boldsymbol{A}}, \tag{17}$$

where $\boldsymbol{R}_X^{-1}$ denotes the inverse covariance matrix of the received data equal only to the upper triangular matrix $\boldsymbol{R}$ resulting from the QR decomposition of matrix $\boldsymbol{R}_X$:

$$\boldsymbol{R}_x = \boldsymbol{Q}\boldsymbol{R} \tag{18}$$

$$\boldsymbol{R}_x = \begin{bmatrix} \boldsymbol{q}_1, & \boldsymbol{q}_2 & \ldots, & \boldsymbol{q}_{MN} \end{bmatrix} \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1N} \\ 0 & R_{22} & \cdots & R_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R_{MN} \end{bmatrix}. \tag{19}$$

The power at the output of the array of the receiving antennas can be represented as:

$$\boldsymbol{R}_y = E\left\{|\boldsymbol{Y}|^2\right\} = \boldsymbol{w}^H \boldsymbol{R}_x \boldsymbol{w}. \tag{20}$$

Finally, by substituting matrix $\boldsymbol{R}$ from equation (19) into equation (20), the signal power at the output of the array of receiving antennas can be determined as a function of the signal arrival angle:

$$P_{\mathrm{CAPON}}(\theta) = \frac{1}{\boldsymbol{A}^H \boldsymbol{R}^{-1} \boldsymbol{A}}. \tag{21}$$

The measured angle of arrival of the signal from the object will be equal to the maximum value of the function (21), which can be easily found by drawing its graph for the entire range of angles θ. Then, for the maximum value of the function $P_{\mathrm{CAPON}}(\theta)$, the corresponding angle θ is determined.

3. Algorithm for estimating the DoA in a TDM MIMO radar

The following figure shows a flow chart of signal arrival angle measurements starting from the generation and transmission of signals by the transmitting antennas of a TDM MIMO radar system.

After sampling and pulse compression, as well as Doppler filtering of the received signal, a raw data cube is shaped. Based on the raw data cube, estimation of the clutter covariance matrix is carried out. The interference covariance matrix is the main factor in the process of determining the weight vector. On the basis of the obtained vector of weights, an adaptive beam is formed. The main lobe of the adaptive beam contains information about the location of the object; hence it is possible to estimate the parameters of the object such as the angle of arrival of the signal, the angle of elevation and the azimuth angle of the radar with respect to the object and the radar-object distance.

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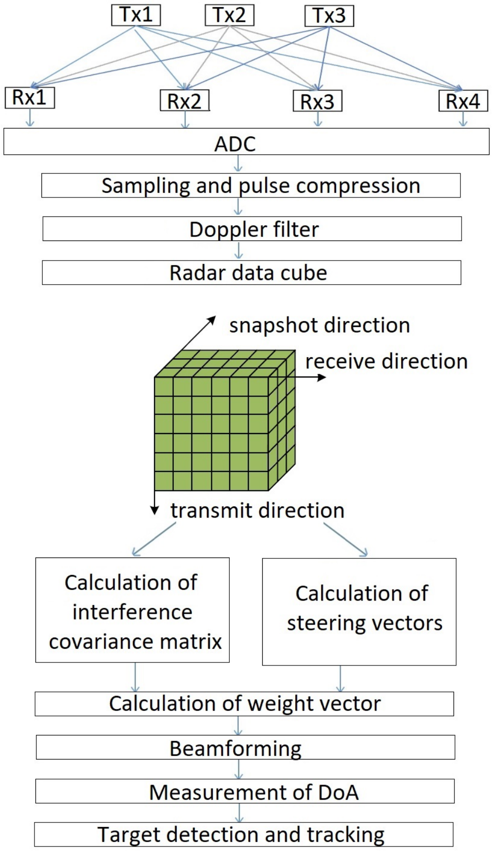

Fig. 4. Flow chart of the algorithm of DoA measurement.

The inputs of the core processing are the data contained in the radar data cube. This is the raw data received by the antenna array. In the literature on the subject, one can find various methods of estimating the clutter covariance matrix. The general division into statistical and non-statistical methods is applied. In the first case, the estimation of the clutter covariance matrix is derived from data from training distance cells surrounding the target cell being tested. As it turns out, in real conditions it is difficult to determine the clutter covariance matrix and its inverse in this way. Furthermore, statistical algorithms fail when the data contained in training cells do not reflect the statistical clutter properties of the test cell, especially in a non-uniform clutter environment.

The paper [30] presents a new method of estimating the clutter covariance matrix based on the use of the *Multiple Input, Multiple Output* (MIMO) radar geometry model, as well as the *orthogonal matching pursuit* (OMP) algorithm. The developed technique allows suppression of interferences and detection of an object in a heterogeneous environment.

4. Simulation results

In order to validate the mathematical model of the DoA measurement method presented in this paper, computer simulations were developed in MATLAB.

4.1. Application of the MIMO technique

This section shows the effect of antenna system design on the precision of DoA measurements. The use of the MIMO technique has a practical justification.

Figures 5–6 show the antenna characteristics for two cases. The first case shows a situation where an antenna array was built with 5 antennas spaced from each other by a fixed distance equal to half the wavelength (*uniform linear array* – ULA), and the same array of antennas in the MIMO technique, *i.e*. different distances in the array between transmit and receive antennas

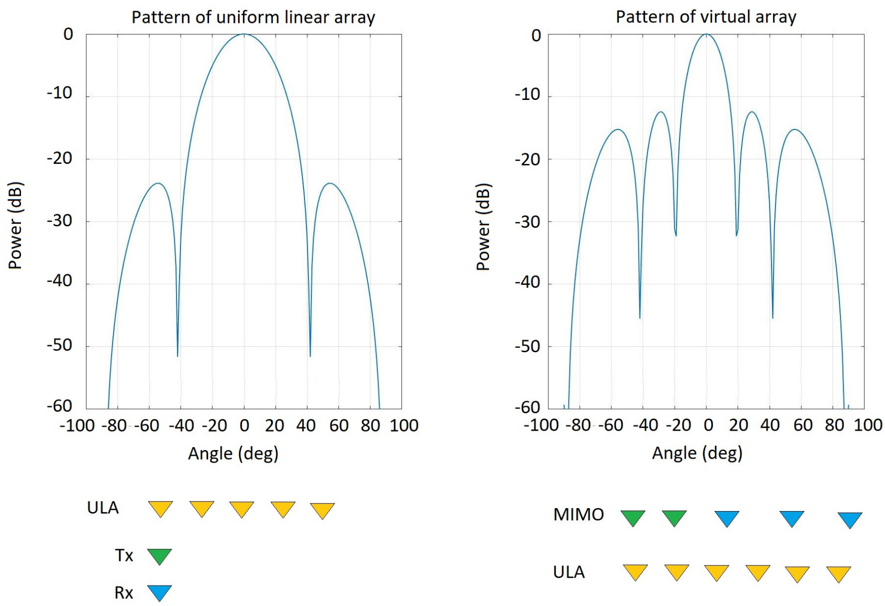

Fig. 5. Comparison of ULA and MIMO radar systems (2 transmit antennas and 3 receive antennas).

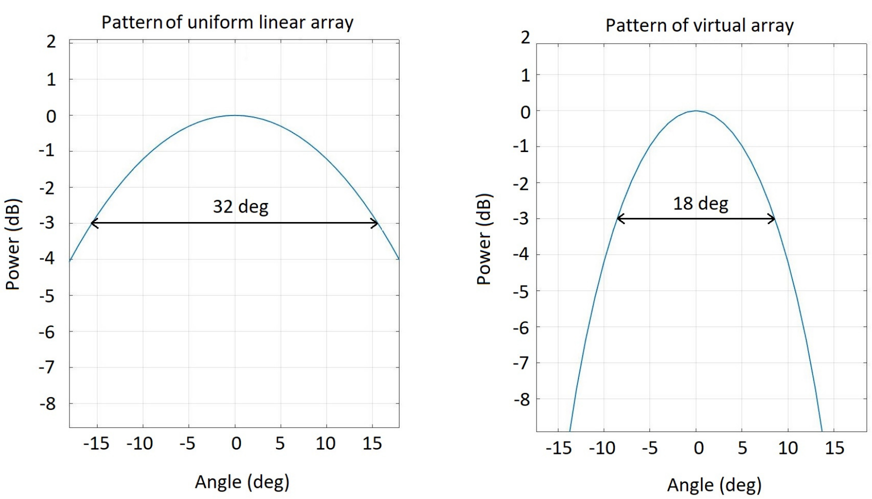

Fig. 6. Comparison of ULA and MIMO radar systems (2 transmit antennas and 3 receive antennas) – width of the main lobe at – 3 dB.

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were applied. In this case, the MIMO radar system was equipped with 2 transmit antennas and 3 receive antennas. The difference in performance is shown in Fig. 5. In addition, Fig. 6 shows the width of the main lobe at – 3 dB for both cases.

The second case shows a situation where an antenna array was built with 7 antennas spaced from each other by a fixed distance equal to half the wavelength (uniform linear array), and the same array of antennas in the MIMO technique, *i.e.* different distances in the array between transmit and receive antennas were used. In this case the MIMO radar system was equipped with 3 transmit antennas and 4 receive antennas. The difference in performance is shown in Fig. 7. In addition, Fig 8 shows the width of the main lobe at – 3 dB for both cases.

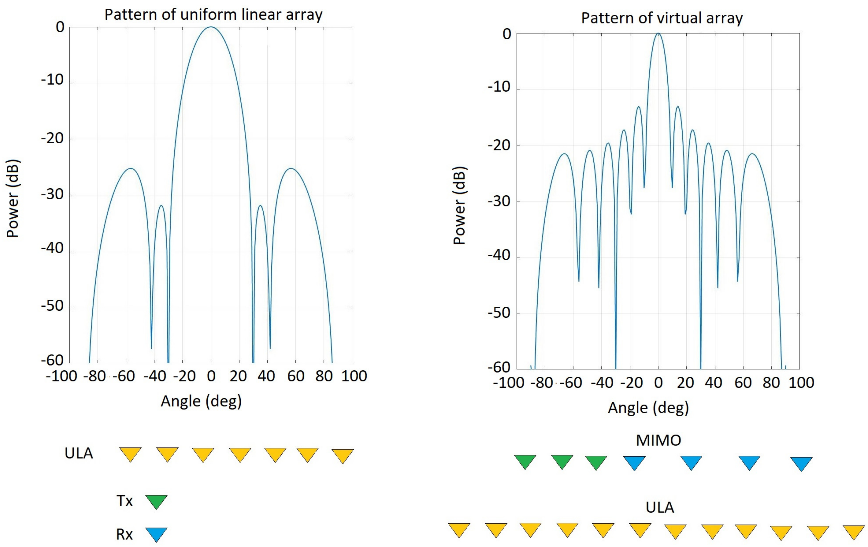

Fig. 7. Comparison of ULA and MIMO radar systems (3 transmit antennas and 4 receive antennas).

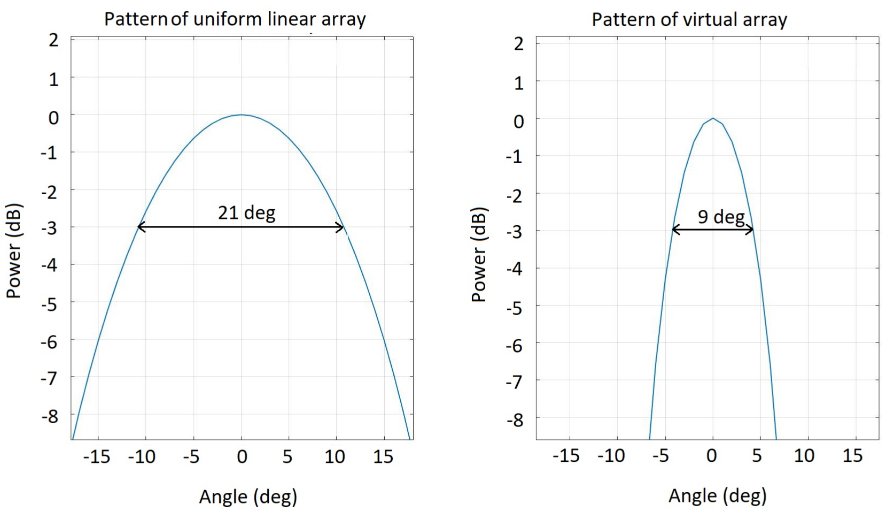

Fig. 8. Comparison of ULA and MIMO radar systems (3 transmit antennas and 4 receive antennas) – width of the main lobe at – 3 dB.

As can be observed, with the MIMO technique it is possible to obtain a much more accurate measurement of the angle of arrival of the signal, which directly means narrower antenna characteristics and thus greater distance discrimination of the radar. The second conclusion to note is the reduction in the cost of building an antenna system. By using the MIMO technology, it is possible to achieve the same or better angular measurement performance, but with fewer antennas. This leads to a reduction in the cost of building an antenna array.

To conclusively prove the validity of the MIMO technique and confirm the conclusions above, Fig. 9 shows the case where the same accuracy of DoA measurement in a MIMO radar system of 4 transmit and 8 receive antennas requires the construction of a ULA array of as many as 32 antennas. This case is shown in Fig. 9. In addition, Fig. 10 shows the width of the main lobe at – 3 dB for both cases.

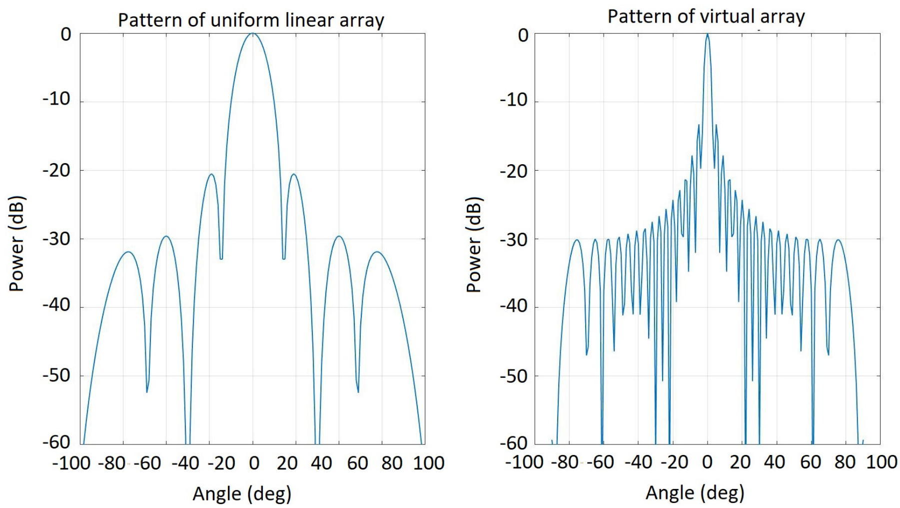

Fig. 9. Comparison of ULA and MIMO radar systems (4 transmit antennas and 8 receive antennas).

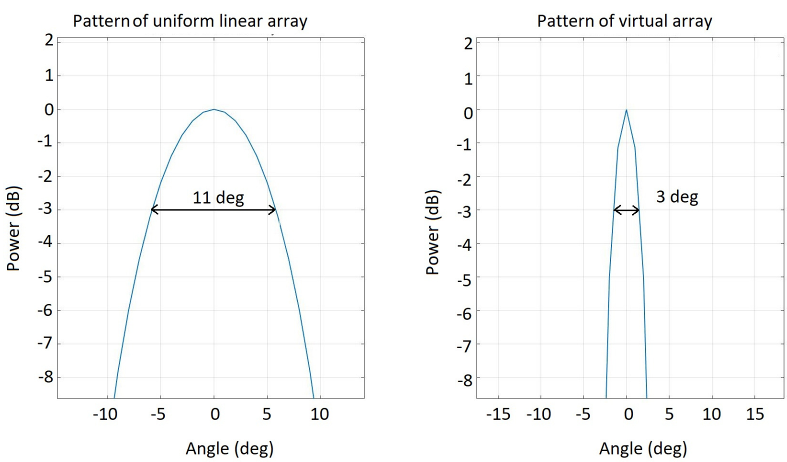

Fig. 10. Comparison of ULA and MIMO radar systems (4 transmit antennas and 8 receive antennas) – width of the main lobe at – 3 dB.

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Table 1. Parameters assumed for the simulations.

Parameter	**Simulation Fig. 5**	**Simulation Fig. 6**	**Simulation Fig. 7**
ULA antennas	5	7	32
Transmitting antennas	2	3	4
Receiving antennas	3	4	8
Carrier frequency of the radar system	10 GHz		
Wavelength	0.03 m		
Interelement distances of ULA	0.015 m	0.015 m	0.015 m
Interelement distances d_t	0.015 m	0.015 m	0.015 m
Interelement distances d_r	0.03 m	0.045 m	0.06 m

4.2. Performance comparison of different DoA measurement algorithms

This section presents simulation results of signal arrival angle measurements for the proposed TDM MIMO radar model using several fundamental algorithms, indicated in the introduction of the article. Table 2 shows the parameters adopted for the simulations. Table 3 shows a comparison of DoA measurements for different algorithms. Figs. 11–12 showing a comparison of the performance of various algorithms are intended to show how a given algorithm unambiguously (highest signal power at a given angle) indicates DoA. That is, the higher the value of the received signal at a given angle, the greater the confidence that the signal is indeed coming from that direction.

Table 2. Parameters assumed for the simulations.

Parameter	**Simulation Figs. 11–12**	**Simulation Fig. 13**	**Simulation Fig. 14**	**Simulation Fig. 15**
Transmitting antennas	3	2 3 4	3	3
Receiving antennas	4	3 4 8	4	4
Carrier frequency of the radar system	10 GHz			
Wavelength	0.03 m			
Interelement distances d_t	0.015 m	0.015 m	0.015 m	0.015 m
Interelement distances d_r	0.045 m	0.030 m 0.045 m 0.120 m	0.045 m	0.045 m
SNR	5 dB	5 dB	–5 dB 5 dB 15 dB	5 dB
Snapshots	200	200	200	20 60 100
Simulated DoA of the signal	0°	0°	0°	0°

Table 3 indicates specific DoA measurement values with errors for different configurations. It should be noted that the algorithm proposed in the article has the smallest errors with respect to the specific value. The proposed algorithm gains from the small size of the antenna array and the small amount of data contained in the radar data cube.

Table 3. Comparison of DoA measurements for different algorithms

Parameter		**ESPRIT**		**MUSIC**		**CAPON**		**Modified CAPON**	
		–5°	**25°**	**–5°**	**25°**	**–5°**	**25°**	**–5°**	**25°**
Antennas	2Tx 3Rx	–5.25°	25.1°	–5.15°	25.11°	–5.15°	25.10°	–5.02°	25.01°
	3Tx 4Rx	–5.16°	24.91°	–5.12°	24.94°	–5.08°	24.97°	–5.00°	24.98°
	4Tx 8Rx	–5.06°	24.95°	–5.02°	24.97°	–5.01°	24.97°	–5.00°	24.99°
SNR	–5 dB	–5.25°	25.1°	–5.15°	25.11°	–5.15°	25.10°	–5.02°	25.01°
	5 dB	–5.16°	24.91°	–5.12°	24.94°	–5.08°	24.97°	–5.00°	24.98°
	15 dB	–5.06°	24.95°	–5.02°	24.97°	–5.01°	24.97°	–5.00°	24.99°
Snapshots	20	–5.55°	25.80°	–5.35°	25.34°	–5.15°	24.90°	–5.08°	25.08°
	60	–5.21°	24.91°	–5.10°	24.94°	–5.05°	24.97°	–4.98°	24.99°
	1000	–5.07°	24.95°	–5.02°	24.97°	–5.01°	24.99°	–5.00°	25.00°

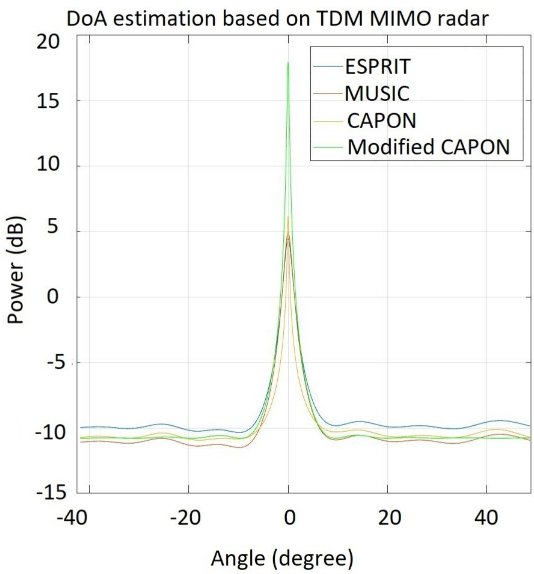

Fig. 11. Performance comparison of different DoA measurement algorithms.

The accuracy of the DoA measurement is affected by essential elements of the entire system, namely the number of transmitting and receiving antennas, the number of snapshots taken from the radar data cube for further processing, and external factors that are interference, and those which were simulated by the SNR in the radar's receiving path. This allowed practical conclusions to be drawn.

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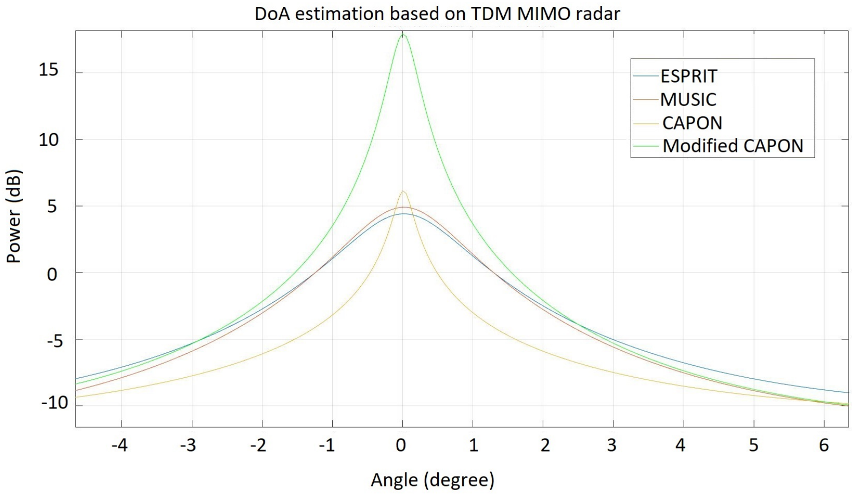

Fig. 12. Performance comparison of different DoA measurement algorithms – zoom.

Figure 13 shows the results of simulated angle-of-arrival measurements for a TDM MIMO radar system for different antenna system configurations only for the modified Capon algorithm. Figure 14 shows simulation results of signal arrival angle measurements for the TDM MIMO radar system for different SNR values. Figure 15 shows simulation results of signal arrival angle measurements for TDM MIMO radar system for different snapshot values.

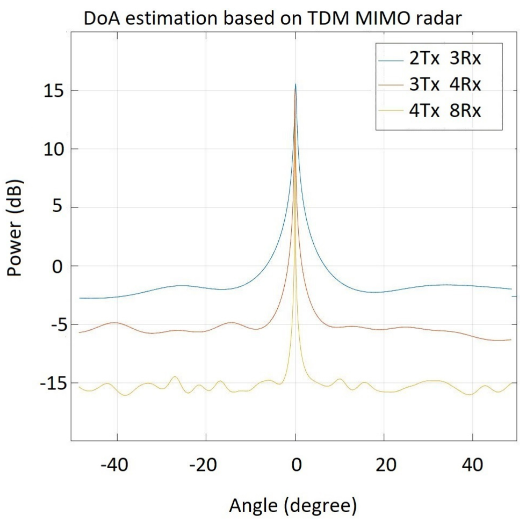

Fig. 13. Performance comparison of different DoA measurement algorithms – different antenna system configurations.

As can be seen, the more extensive the antenna system, the more accurate the DoA measurement. Of course, this results in a larger size of the radar data cube and longer processing time for all the data, as confirmed by the simulation in Fig. 15. On the other hand, if the level of current interference during signal transmission and reception becomes more and more intense, it results

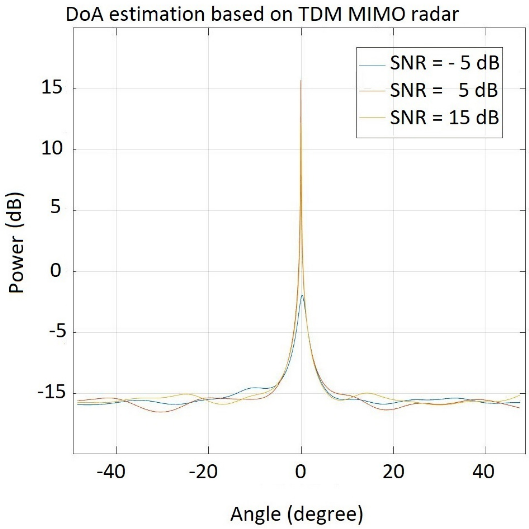

Fig. 14. Performance comparison of different DoA measurement algorithms – different SNR values.

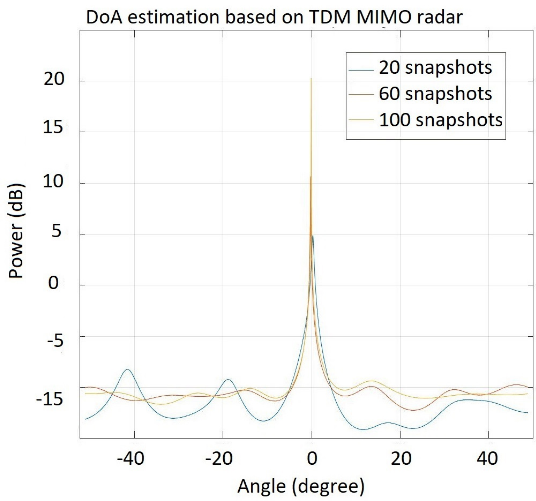

Fig. 15. Performance comparison of different DoA measurement algorithms – different snapshots values.

in a deterioration of the accuracy of DoA measurement, which naturally becomes a further stage of research work for the authors of the article on this topic.

5. Conclusions

The main purpose of the article was to present a novel method for measuring direction of arrival in a TDM-MIMO radar operating at 10 GHz, transmitting a string of pulses by using orthogonality with time-division multiplexing and to present the most important technical aspects.

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This article focuses on TDM-MIMO radars because they are easier to implement compared to more complicated coding schemes.

The article includes a mathematical model of signal processing in TDM MIMO radar and a block diagram of angle-of-arrival measurement starting from signal generation and transmission through the transmitting antennas of the TDM MIMO radar system, through the creation of the radar data cube ending with a direct DoA measurement.

With the MIMO technique and the modified Capon algorithm, it is possible to obtain much more accurate DoA measurements compared to other algorithms. Besides, using the MIMO technique, it is possible to reduce the cost of building an antenna system. The accuracy of DoA measurement is influenced by important elements of the whole system, namely the number of transmitting and receiving antennas, the number of snapshots taken from the radar data cube for further processing, and external factors such as interference, which was simulated by SNR of the radar's receiving path. The radar system and DoA measurement method presented in the article is a proposal for a radar system that an enemy radio reconnaissance unit can be equipped with.

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