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RANGE AND VELOCITY RESOLUTION OF LINEAR- FREQUENCY-MODULATED SIGNALS ON SUBARRAY-MIMO RADAR

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ABSTRACT

The most important radar system performance is determining the range-velocity of the detected target. This performance is obtained from processing an ambiguity-function (AF) between signals from target reflections and radar radiation signals. Selection of the appropriate waveform transmitted by the radar is a key factor in supporting high resolution radar performance in the AF. There are many waveforms that have been studied in radar systems, especially for multi-antenna radars, i.e., subarray-MIMO (SMIMO) radar which can form phased array (PA) and MIMO radars simultaneously, in the form of linear-frequency-modulated (LFM) signals. In this paper, we examine the use of LFM waveforms combined with SMIMO radar to produce plots of three-dimensional AF as a function of time delay and Doppler shift. The results of the comparison with the Hadamard signal determine the effectiveness of the observed AF performance on parameters such as magnitude, range-velocity resolution, peak sidelobe level ratio, and integrated sidelobe ratio by taking into account the factors of the number of Tx antennas on the PA radar and the number of Tx subarrays on the MIMO radar. The evaluation results of the SMIMO radar configuration (M = 6) with the number of Tx-Rx antenna elements the being 8 provide the best mainlobe magnitude, sidelobe magnitude, range resolution, velocity resolution, PSLR, and ISLR of AF LFM signals compared to conventional radars are 235.2dB, 7.54dB, 37.5m, 75km/s, 29.89dB, and 29.8dB, respectively. Meanwhile, the LFM signal is far superior to the Hadamard signal which has PSLR and ISLR 1.16dB and -3.36dB, respectively.

Keywords: *ambiguity-function, linear-frequency-modulated (LFM), MIMO radar, peak sidelobe level ratio, range and velocity resolution.*

I. INTRODUCTION

IN recent decades, the development of multi-antenna radars such as phased array (PA) radar [1] and MIMO radar [2] continues to be a research topic that continues to be investigated in the field of remote and remote sensing to date. A recent combination that combines high directional gain, which is characteristic of PA radar, as well as multiple radiation capabilities to detect multiple targets, which is characteristic of MIMO radar, is implemented in a multi-antenna radar system called subarray-MIMO (SMIMO) radar [3]. In this radar, the presence of overlapping subarrays at the transmitter (Tx) and/or receiver (Rx) results in high directional gain and forms mutually orthogonal radiation elements to detect multiple targets, a concept that has been investigated by [4]. The use of subarrays in radar arrays provides high target detection resolution [5], while minimizing the appearance of grating lobes [6] and suppressing sidelobe levels so that they are strong against interference and jamming [7]. The SMIMO radar has performance advantages such as high angle detection resolution and high signal to interference plus noise ratio (SINR) so it is resistant to interference effects. The subarray method in the SMIMO radar can play an important role in supporting range and speed detection performance, especially increasing range and speed resolution. The use of subarrays makes this radar beamforming have a low sidelobe level so as to maximize the mainlobe for target detection, which supports the range and speed resolution of the radar. The range-velocity resolution is also strongly determined by the use of the transmission waveform of the radar.

There are many studies that examine the use of waveforms from radar, especially the MIMO radar such as linear frequency modulated (LFM) [8]-[13]. According to [8], the use of LFM in the Synthetic Aperture Radar (SAR) application can properly identify two adjacent targets at a very long distance. In automotive radar applications, the LFM signal is widely used because it has a low sidelobe of around -13.25dB [9]-[10]. For airborne applications, by combining the MIMO radar with the advantages of its virtual array and LFM signals, the resulting radar performance has a high signal to clutter plus noise ratio (SCNR) so that it is able to detect targets with weak RCS [11]. The use of LFM signals apparently has an impact on signal spectrum classification which can be overcome by providing filters equipped with peak detection and thresholds [12]. However, transmitting the LFM signal combined with the space time method on the antenna subarray can reduce the sidelobe level [13]. Based on several LFM references, an opportunity is given to apply LFM signals to the SMIMO radar by applying the subarray method.

To determine the range-velocity resolution of the radar from the application of a transmitted waveform, it is applied by evaluating and analyzing its ambiguity function (AF). It is well known that AF is a tool for determining the performance of a radar system such as time delay (range), Doppler frequency (velocity), parameter estimation, maximum number of targets detected, probability of false alarm detection, etc. [14]-[19]. Various kinds of highly orthogonal codes were applied by [14] to the MIMO radar to determine AF in 4-dimensional plots (range, azimuth, elevation, and Doppler frequency) such as Golay code, Direct Spread Spectrum (DSS), Space-Time Block Coded, and Costas code to overcome interference against weak targets in the presence of strong targets and backgrounded by clutter. The increase in AF performance with a millimeter wave photonic-based radar system at 100 GHz to increase the peak sidelobe level ratio (PSLR) towards the target has been reported by [15] at 38.35 dB compared to a conventional system with PSLR of 14.5dB. Study [16] has presented an AF method with frequency and time domains to overcome conventional AF which has weaknesses, such as having low resolution and remaining in the presence of multiple adjacent targets. AF as a function of SNR has been reported by [17] on distributed MIMO radar. Meanwhile, in [18], AF is a passive radar which is expressed by parameters such as amplitude, range-Doppler resolution, and sidelobe ratio. Furthermore, [19] presents the ability of the transmitted waveform to follow its environment to form adaptive AF as measured by the volume-invariant property and integrated sidelobe ratio (ISLR) parameters.

This paper discusses several aspects that have not previously been covered in research on AF using LFM signals for MIMO radars with subarray or SMIMO elements. It is found that AF with LFM signals has low sidelobes, tends to increase the Peak-to-Sidelobe Ratio (PSLR), and with the addition of a subarray on a MIMO radar, it can increase the processing gain which impacts the high mainlobe level and reduces the sidelobe level thus increasing the PSLR and reducing the ISLR. In addition to the AF plot on the SMIMO radar, taking into account the range-velocity resolution, this paper contributes to showing the influence of AF on the magnitude, PSLR, and ISLR parameters which are formed by the number of antenna elements in one Tx subarray of the PA radar and variations in the number of Tx-Rx subarrays in the SMIMO radar. The AF plot is expressed as: (a) as a function of time delay and Doppler frequency, (b) as a function of time delay = 0, (c) as a function of Doppler frequency = 0, (d) as a function of the number of antenna elements in Tx on the PA radar, and e) as a function of the number of subarray elements in the Tx-Rx SMIMO radar.

II. RESEARCH METHOD

The following is an explanation and review of the methods applied in this paper. It starts with the formulation of AF on LFM signals. This is followed by a special AF expression for SMIMO radar implemented on the transmission signal in the form of LFM signal. Next, the stages of evaluating the AF performance of SMIMO radars with LFM signals are presented. Finally, to evaluate the AF performance, the values of several parameters used in this study are given.

A. Ambiguity Function of LFM Signal

It is known that AF is a tool commonly used to investigate signals emitted by radar [20]. AF is a function of the variables time delay (t_d) and Doppler frequency (f_D), which are described as the output of the corresponding filter. According to [20], the AF of the LFM signal is given as (1).

$$|AF(t_d, f_D)|^2 = \left|\rho \frac{sin(\pi t'_d(\mu t_d - f_D)\rho)}{\pi t'_d(\mu t_d - f_D)\rho}\right|^2 \qquad |t_d| \leq t'_d \tag{1}$$

where $\rho = 1 - (|t_d|/t'_d)$ and μ is ± 1 where +1 and −1 mean up-chirp and down-chirp, respectively.

B. Ambiguity Function of SMIMO Radar for LFM Signal

The mathematical derivation of the AF expression from SMIMO radar is made following the derivation that has been done by [21] for MIMO radar and by [22] for Phased-MIMO radar. After the AF performance formulation of the proposed radar is obtained, the evaluation of the effectiveness of the radar's performance is compared with the PA and the MIMO radars by taking into account various parameters of time delay, Doppler shift, target angle, and number of Tx-Rx subarrays. The AF SMIMO radar is in (2).

$$|AF(t_d, f_D, \theta)|^2 = \left|\sqrt{\frac{K}{M}}\mathbf{b}^T(\theta)\mathbf{C}(t_d, f_D)[\mathbf{c}(\theta)\odot\mathbf{d}(\theta)]\right|^2 \tag{2}$$

where θ denotes the target direction to antennas Rx, K and M as the number of antennas in Tx and the number of subarrays in Tx, respectively. $\mathbf{C}(t_d, f_D)$ is the AF matrix of the LFM transmission signal of size $K \times M$, $\odot$ is the Hadamard multiplication operator on vectors, $\mathbf{c}(\theta)$ and $\mathbf{d}(\theta)$ according to [3] notation of vector coherent processing and waveform diversity, respectively, formed by subarrays in Tx.

It can be seen from (2) that the AF amplitude of the SMIMO radar is determined by the combinations of the number of subarrays in the Tx array, i.e., M, which is represented by $\mathbf{c}(\theta)\odot\mathbf{d}(\theta)$. Thus, what determines range and Doppler resolution is not the number of subarrays in Tx but is practically determined by the type of waveform used in the radar system, which in this case is the LFM signal.

C. Evaluation Steps of the AF Radar SMIMO with LFM Signal

Before entering Section III, the stages for the AF evaluation process on the SMIMO radar with LFM signals are given.

Determination of AF for LFM signals using (1) for up-chirp and down-chirp types includes AF as a function of time delay and Doppler frequency, AF as a function of time delay = 0, and AF as a function of Doppler frequency = 0. Next, determine the range resolution (ΔR) and velocity (Δv) of AF for the assumption that the working frequency (f_c) of a multi-antenna radar is 1 GHz, respectively, i.e., (3) and (4).

$$\Delta R = \frac{ct_d}{2} \tag{3}$$

$$\Delta v = \frac{cf_D}{2f_c} \tag{4}$$

where t_d is strongly determined by the signal bandwidth (B) and c is the velocity of light in a vacuum of about 3×10^8 m/s^2. Next, it is compared with AF from Hadamard signals as reported by [23] to find its effectiveness in terms of PSLR and ISLR. Determination of PSLR and ISLR is determined by (5) and (6) [18].

$$PSLR = \frac{1}{M_{MLL}^2} max\{M_{SLL,n}^2\} \tag{5}$$

$$ISLR = \frac{1}{M_{MLL}^2}\sum_{n=1}^{N}\{M_{SLL,n}^2\} \tag{6}$$

where M_{MLL} and M_{SLL} are the magnitudes of the mainlobe and sidelobe, respectively.

TABLE 1
PARAMETERS FOR AF PERFORMANCE EVALUATION OF THE SMIMO RADAR WITH LFM SIGNAL

Description	Symbol	Value
Interval of time delay	t_d	[-2, +2] μs
Interval of Doppler frequency	f_D	[-10, +10] MHz
Number of Tx antenna elements	K	8
Number of Rx antenna elements	L	8
Number of Tx subarrays	M	$1 \leq M \leq 8$
Frequency operation of Radar	f_c	1 GHz
Wavelength	λ	0.3 m
Spacing of element antenna Tx-Rx	d_{Tx}, d_{Rx}	0.5λ
Direction of Arrival form target	θ	[-90, 90] deg

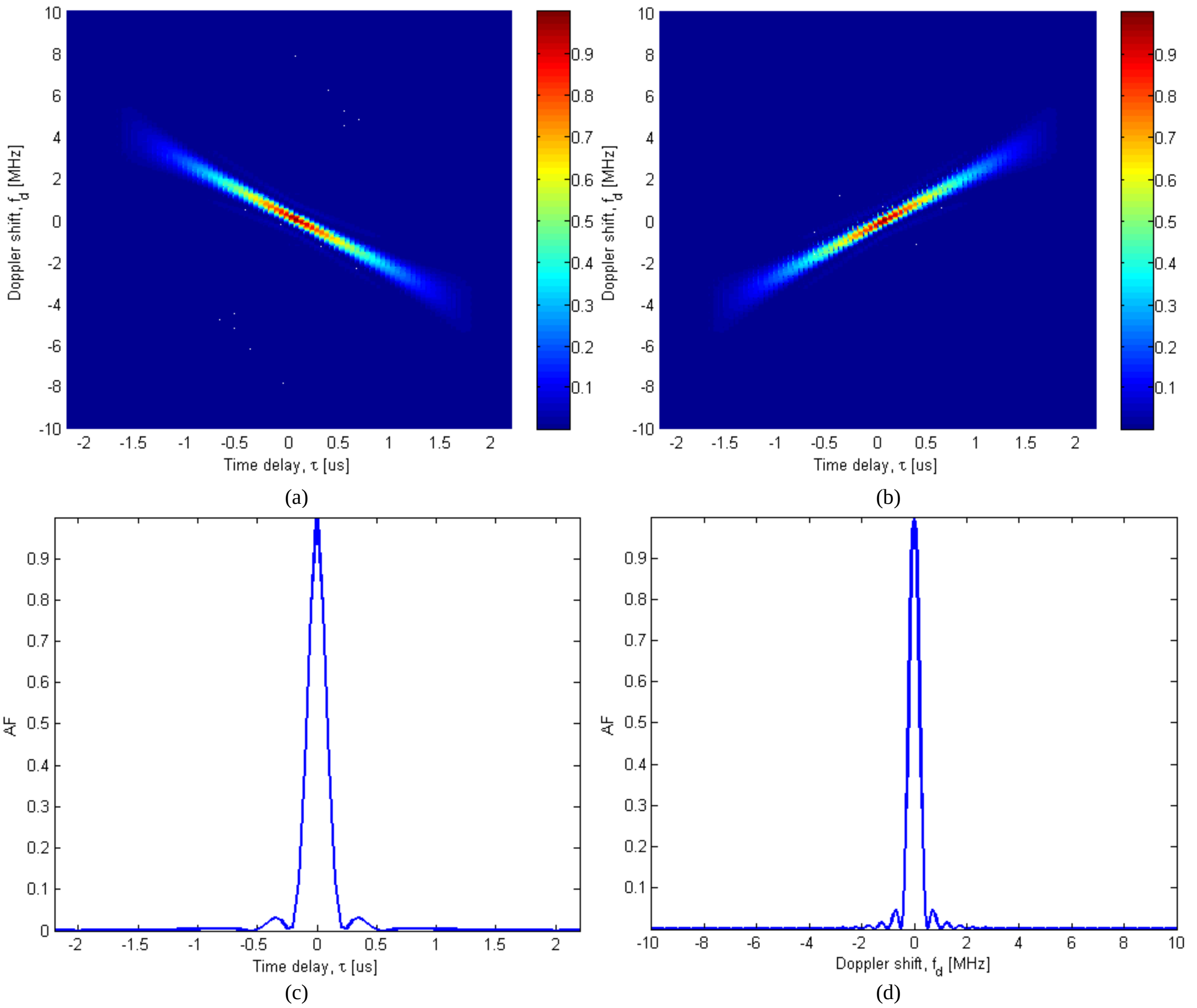
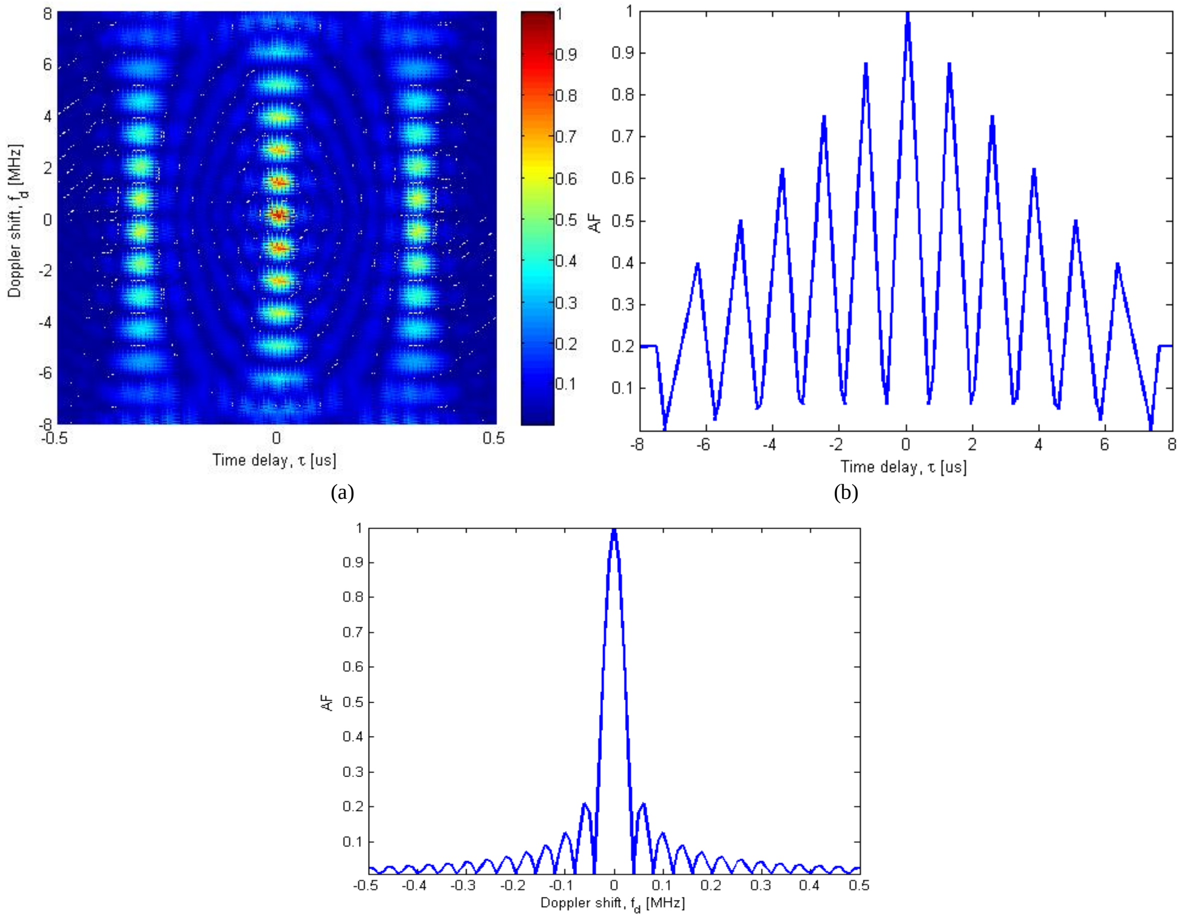


Figure 1. AF of the LFM signal for: (a) type down-chirp function (t_d,f_D), (b) type up-chirp function (t_d,f_D), (c) function $f_D = 0$, and (d) function $t_d = 0$.

Determining the AF of the SMIMO radar for LFM signals using (2) with the conditions $M = 1$ for the PA radar, $M = K$ for the MIMO radar, and $M = 4$ for other SMIMO radars and up-chirp types. Calculation of the AF PA radar for LFM signals using (2) with conditions $M = 1$ and up-chirp for varying the number of antenna elements in Tx starting from 1, 2, ..., and K. AF is expressed in decibels (dB) from linear AF. Determination of the AF SMIMO radar for LFM signals using (2) with M conditions varying from $M = 1, 2, ..., K$ for the up-chirp type.

D. Parameter Assumptions for AF Performance Evaluation of the SMIMO Radar with LFM Signals

Several values of parameters for evaluating the AF of SMIMO radar with LFM signals as summarized in Table 1.



(a) (b)

(c)

Figure 2. AF for Hadamard signals with: (a) as a function of (t_d,f_D), (b) as a function of t_d = 0, and (c) as a function of f_D = 0.

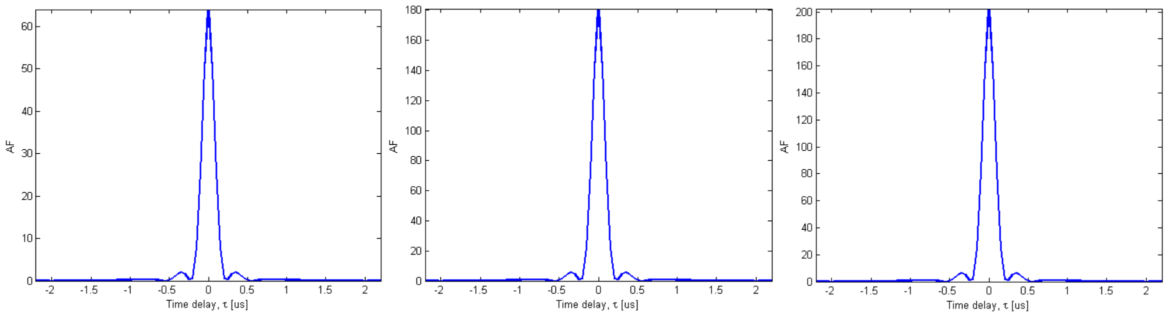
III. Results and Discussion

Below are the results of the AF performance evaluation for the SMIMO radar based on the evaluation steps described in Section II.C, followed by discussion.

A. AF from LFM Signal

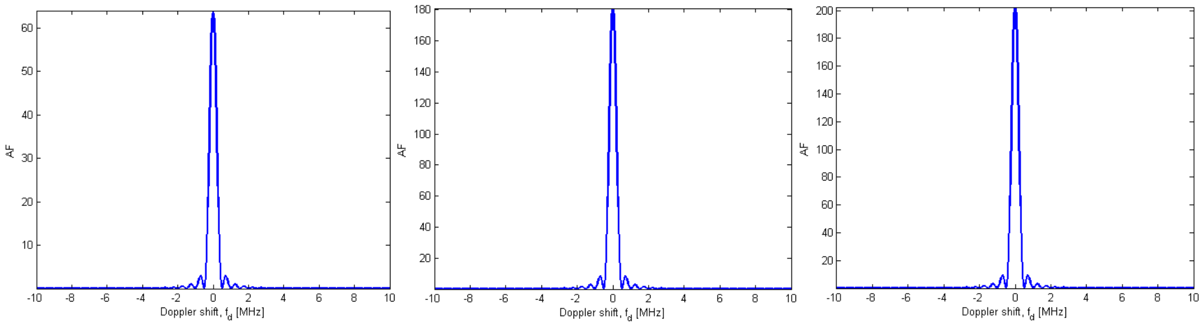
After carrying out the 1st stage according to Section II.C with all the parameters presented in Table 1, the results obtained are as in Figure 1(a)-(d). Figures 1(a) and 1(b) show the types of LFM signals, down-chirp and up-chirp, respectively. Figure 1(a) is of the down-chirp type because it can be seen that with the t_d range from -2μs to +2μs, the f_D trend decreases in frequency, which means from the original high f_D to low f_D as seen from 4MHz to -4MHz. Meanwhile, Figure 1(b) shows the up-chirp type because it can be seen that with the t_d range from -2μs to +2μs, the f_D trend is increasing in frequency, which means from the original low f_D to high f_D which can be seen from -4MHz to +4MHz. For the next experiment, an up-chirp type LFM signal will be used. Both down-chirp and up-chirp LFM signals have the same magnitude and level of mainlobe and sidelobe peaks as shown in Figure 1(c)-(d).

Based on Figure 1(c), which is AF as a function of f_D = 0, the resolution range, PSLR and ISLR are obtained. In Figure 1(c), it is found that the mainlobe first touches the time-delay axis at around t_d = ± 0.25μs, thus obtaining a resolution range using (3) of ΔR = 37.5m. This indicates that two adjacent targets will be able to be detected accurately by radar if the distance between them is at least 37.5m. The results of Figure 1(c) show that the mainlobe level (M_{MLL}) is 1 and the maximum peak sidelobe level ($M_{SLL,1}$) is 0.032 so that PSLR using (5) is obtained at 976.56 or around 29.89dB. To calculate ISLR using (6), if the total sum of SLL squares is 0.0011, the ISLR is 955.94 or 29.8dB. Based on the results in Figure 1(d), which is AF as a function of t_d = 0, a velocity resolution will be obtained where it is obtained that the mainlobe touches the Doppler frequency axis for the first time at around f_D = ± 0.5MHz,



(a) (b) (c)

Figure 3. AF as a function of $t_d = 0$ for up-chirp LFM signals and $\theta = 0^o$ for: (a) the PA radar (M = 1), (b) the MIMO radar (M = 8), and (c) the SMIMO radar (M = 4).



(a) (b) (c)

Figure 4. AF as a function of $f_D = 0$ for up-chirp LFM signals and $\theta = 0^o$ for: (a) the PA radar (M = 1), (b) the MIMO radar (M = 8), and (c) the SMIMO radar (M = 4).

thus obtaining a velocity resolution using (4) with the radar working frequency f_c = 1GHz is Δv = 75km/s. Based on this speed resolution, two adjacent targets can be detected and differentiated correctly by radar if the speed between them is at least 75km/s.

Figure 2(a)-(c) is the AF of the Hadamard signal. Based on Figure 2(b), which is AF as a function of $f_D = 0$, the Hadamard signal is obtained ΔR, PSLR, dan ISLR. In Figure 2(b) it is found that the mainlobe forms the first null on the t_d axis at around $t_d = \pm\ 0.062\mu$s, thus obtaining a resolution range using (3) of ΔR = 9.3m. This indicates that two adjacent targets will be able to be detected correctly by radar if the minimum distance between them is around 9.3m. The results of Figure 2(b) show that M_{MLL} is 1 and $M_{SLL,1}$ is 0.875 so that the PSLR is 1.31 or the equivalent of 1.16dB. Meanwhile, ISLR was obtained at 0.46 or -3.36dB. According to Figure 2(c), which is AF as a function of $t_d = 0$, we obtain Δv where the mainlobe forms the first null on the Doppler frequency axis around $f_D = \pm\ 0.04$MHz so that Δv for f_c = 1GHz is Δv = 6km/s. Based on Δv, two adjacent targets can be uniquely detected by radar if the minimum velocity between them is 6km/s.

B. AF of the PA, the MIMO, and the SMIMO Radar (M = 4) for LFM Signals.

After carrying out the 2nd research stage in Section II.C, results were obtained as in Figure 3(a)-(c). It can be seen that the AF of the three types of radar, namely the PA (M = 1), the MIMO (M = 8), and the SMIMO (M = 4) for the up-chirp LFM signal where the AF obtained is similar to the AF in Figure 1(c) but different in magnitude. The AF magnitudes on the three types of radar are 64, 181, and 202.4, respectively. It appears that the SMIMO (M = 4) configuration has a higher AF than the two types of conventional radar because this radar takes advantage of the AF properties of both the PA (M = 1) and MIMO (M = 8) radar types, i.e., directional coherent gain as well as waveform diversity gain. Meanwhile, the values of ΔR, Δv, PSLR, and ISLR for the LFM signal are the same as the previous experiment, namely 37.5m, 75km/s, 29.89dB and 29.8dB, respectively. For the results in Figure 4(a)-(c) which are AF with the same amplitude according to the type of radar as a function of $t_d = 0$, the obtained Δv from the three types of radar are similar to the previous LFM signal experiment. In this AF, the mainlobe touches the Doppler frequency axis first at around $f_D = \pm\ 0.5$MHz so that Δv for f_c = 1GHz is Δv = 75km/s.

TABLE 2
AF OF LFM SIGNAL FOR THE PA RADAR WITH VARYING NUMBER OF TX ANTENNA ELEMENTS

N_{Tx}	AF magnitude (dB)	SLL (dB)
1	13.55	-1.39
2	15.05	0.11
3	15.93	0.99
4	16.56	1.62
5	17.04	2.1
6	17.44	2.5
7	17.77	2.83
8	18.06	3.12

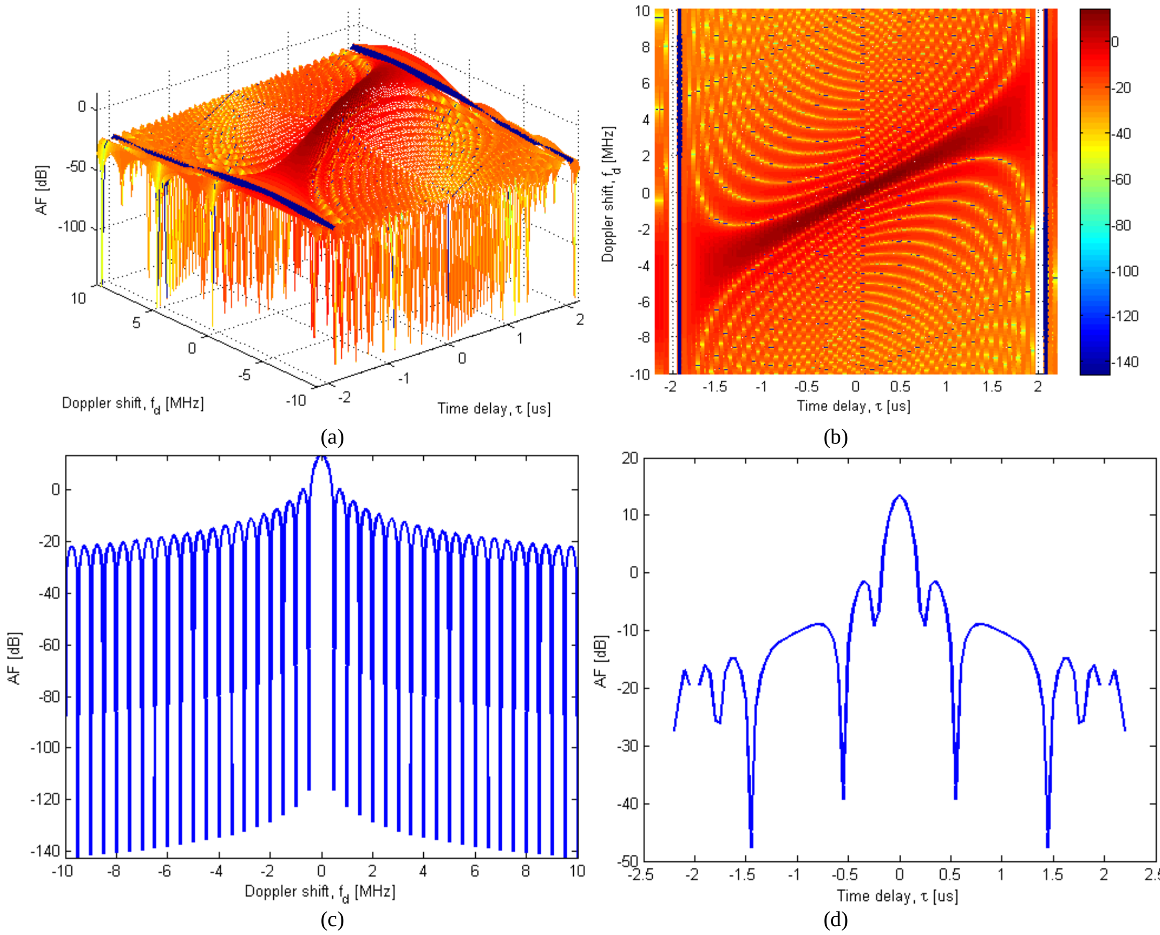


Figure 5. AF (in dB) of the LFM signal for the PA radar with N_{Tx} = 2 as: (a) function (t_d,f_D), (b) function (t_d,f_D) top view, (c) function t_d = 0, and (d) function f_D = 0.

C. AF of LFM signal for the PA Radar with Varying Number of Tx Antenna Elements

This experiment was carried out by carrying out the 3rd research stage in Section II.C. Therefore, so the results in Figure 5(a)-(d) were obtained where the AF of the LFM signal for the PA radar was conditional on the number of antennas in Tx, namely N_{Tx} = 2. In this experiment, the magnitude obtained was mainlobe and sidelobe are 15.05dB and 0.11dB respectively. This experiment was carried out to see the effect of varying the number of antennas on the Tx array of the PA radar, namely N_{Tx} = 1, 2, ..., 8. As with the previous LFM signal AF experiment, the resulting AF has the same ΔR, Δv, PSLR, and ISLR, only different on the magnitude of both the mainlobe and sidelobe because it is determined by the number of Tx antennas. The complete AF results for this experiment are presented in Table 2. It can be seen in Table 2 that with the increase in the number of antennas in Tx, the AF magnitude increases. Likewise with the amount of Sidelobe Level (SLL) in each configuration, as the number of transmit antennas (Tx) increases on the Phased Array (PA) radar, SLL also increases.

TABLE 3
AF OF LFM SIGNALS FOR THE SMIMO RADAR WITH VARYING NUMBER OF TX SUBARRAYS

M	AF magnitude (dB)	SLL (dB)
1	18.06	3.12
2	20.78	5.84
3	22.21	7.27
4	23.06	8.12
5	23.55	8.61
6	23.71	8.77
7	23.5	8.56
8	22.58	7.64

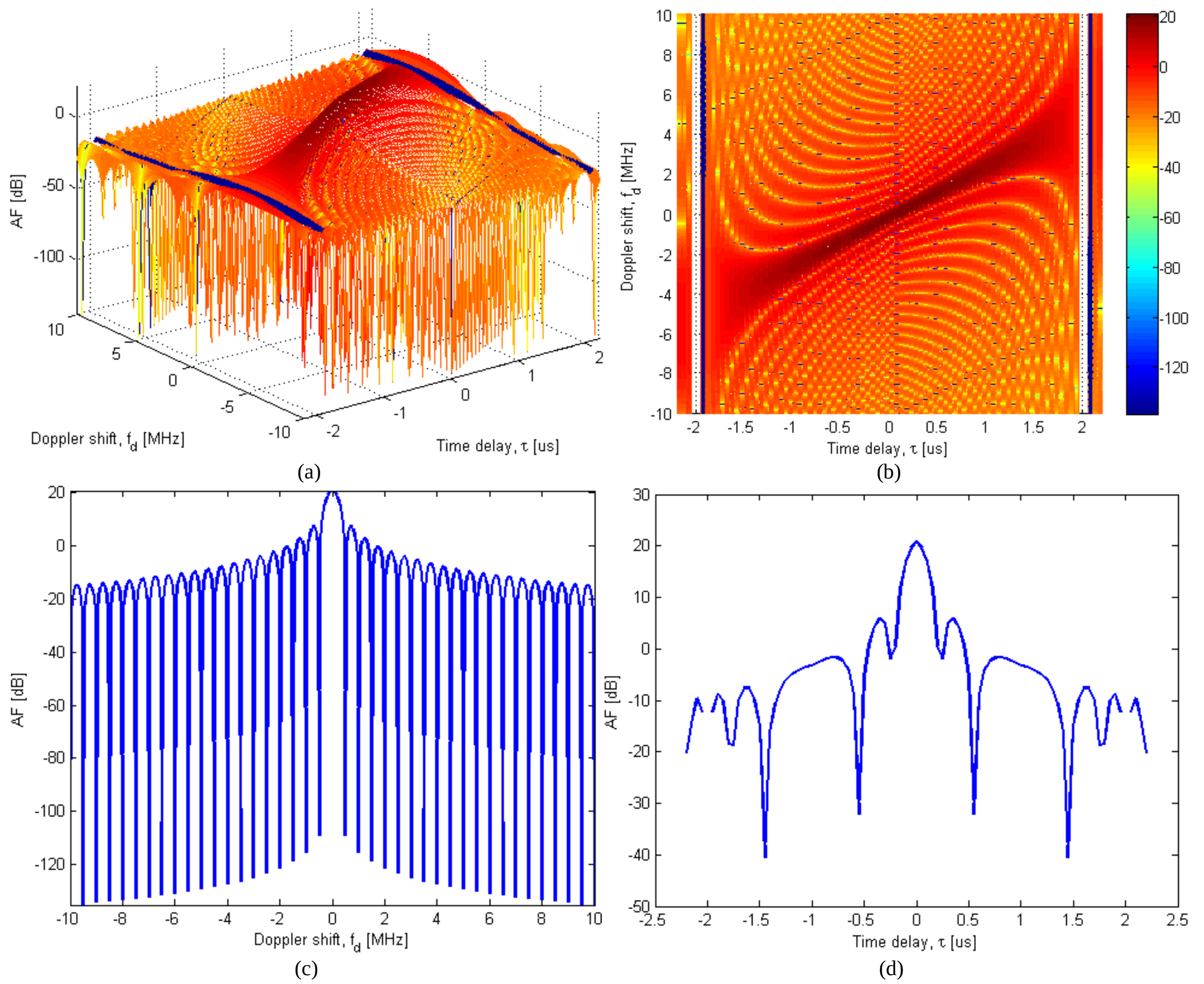
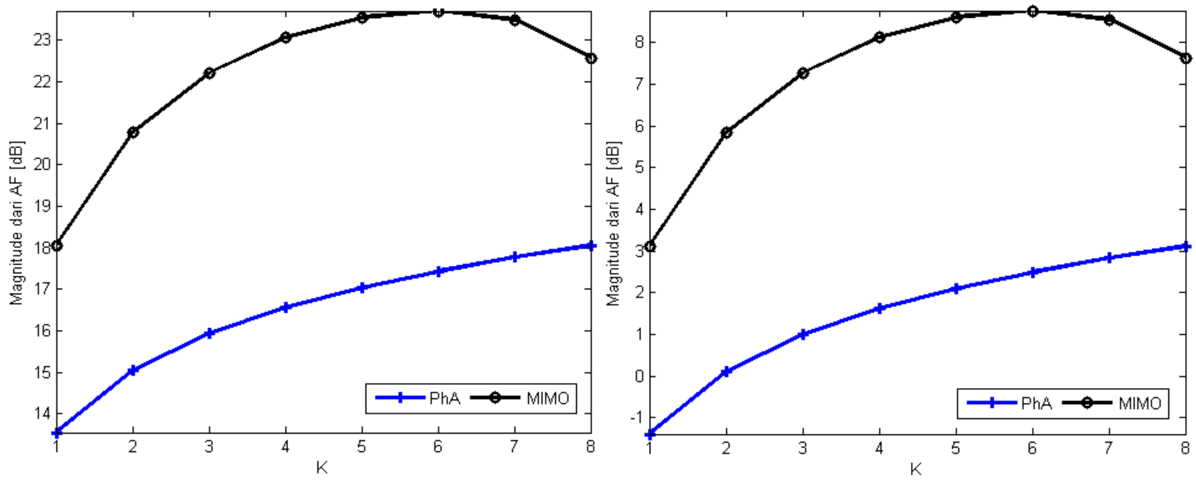


Figure 6. AF (in dB) of the LFM signal for the SMIMO radar with variations of M as: (a) function (t_d,f_D), (b) function (t_d,f_D) top view, (c) function $t_d = 0$, and (d) function $f_D = 0$.

D. AF of LFM Signal for the SMIMO Radar with Varying Number of Tx Subarrays

Based on the 4th research stage in Section II.C, the results in Figure 6(a)-(d) were obtained. This experiment was carried out to see the effect of varying the number of subarrays (M) on the Tx array of the SMIMO radar, namely M = 1, 2, ..., 8. Due to the LFM signal type, the resulting AF has the same ΔR, Δv, PSLR, and ISLR as the previous experiment but the magnitude in both the mainlobe and sidelobe varies according to the number of subarrays in Tx. For example, the case in Figure 6 is given for M = 2 so that the magnitudes obtained in the mainlobe and sidelobe are 20.78dB and 5.84dB, respectively. The other M results on the SMIMO radar are presented in Table 3. It can be seen in Table 3 that with the increase in the number of subarrays in Tx, the AF magnitude increases until M = 6 and then decreases for the next M which occurs for both the mainlobe and sidelobe.

Figure 7(a)-(b) shows the trend of the magnitude level of the mainlobe and sidelobe of the PA and the MIMO radars for varying the number of elements in the Tx array. It can be seen in Figure 7(a) that with



(a) (b)

Figure 7. Comparison of the AF magnitude of the LFM signal for the PA and the MIMO radars for levels: (a) mainlobe and (b) sidelobe.

the increase in the number of antenna elements in Tx, there is an increase in mainlobe magnitude in both types of the PA and the MIMO radars. However, especially for MIMO radar, for 8 elements from the total number of antennas, $M = 6$ produces the maximum magnitude value. If the mainlobe level is higher than the SLL, it will give a better PSLR effect. This is more significant if supported by the high working frequency of the radar system, as reported in [15], or other machine-to-machine communication systems [24].

For Figure 7(b), with an increase in the number of Tx antenna elements, there is an increase in sidelobe magnitude in both types of the PA and the MIMO radars. Similar to Figure 7(a), especially the MIMO radar at $M = 6$ produces the maximum magnitude value. It should be emphasized that increasing the sidelobe level greatly influences the radar detection capability of targets which will be minimal due to increasing interference levels. For automotive radar applications, the SMIMO radar can have a sidelobe level below -1.39dB by setting a smaller M number. This supports studies [9]-[10] for AF with low sidelobes. This experiment can also show the ability of the SMIMO radar to adjust the number of antennas and the number of subarrays in Tx to obtain AF performance that has the desired ΔR, Δv, PSLR, and ISLR so that targets can be detected well.

IV. CONCLUSION

This paper has presented the performance of AF on a SMIMO radar for LFM signals including the expression of its AF. AF in this paper is performed on LFM signals, radar types (PA, MIMO, and SMIMO), the effect of varying the number of Tx antenna elements, and the effect of varying the number of Tx subarrays with respect to parameters such as range resolution, velocity resolution, mainlobe-sidelobe magnitude, PSLR, and ISLR. The AF of the SMIMO radar with an LFM signal for a radar working frequency of 1 GHz has ΔR, Δv, PSLR, and ISLR, respectively, namely 37.5m, 75km/s, 29.89dB, and 29.8dB. For the condition that the number of antennas on the Tx-Rx is 8 elements, the AF magnitudes for the three types of radar are 64, 181, and 202.4, respectively. Increasing the number of Tx antenna elements results in an increase in the mainlobe magnitude of the AF in both PA and MIMO radar types. However, in particular, the SMIMO radar for $M = 6$ produces maximum mainlobe-sidelobe magnitude values. This experiment shows the ability of the flexible SMIMO radar to adjust the number of antennas and the number of Tx subarrays to obtain AF performance that has the desired ΔR, Δv, PSLR, and ISLR so that targets can be detected well. It is expected that in the future, modified transmission signals from LFM, such as nonlinear FM, will be formed to improve AF performance, especially in the aspects of PSLR and ISLR. This is expected to provide assistance and recommendations to radar designers in detecting targets that are close to each other.

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