https://doi.org/10.24191/jeesr.v22i1.007

Numerical Analysis of MIMO FM-CW Radar Performance using Beat Signal Averaging

Asiah Maryam Md Noor, Idnin Pasya, Nur Emileen Abd Rashid, Suraya Zainuddin, and Abdul Rahman Abdullah

Abstract— **Radar for years has been used as the typical instrument in maritime surveillance especially in border security. However, there is yet a big challenge in maritime radars to be resilient against the large clutter of the seawaves, which produces a low signal-to-noise ratio (SNR) environment. This paper proposes the approach of beat signal averaging method to imply multiple-input multiple-output (MIMO) configuration on frequency modulated continuous wave (FM-CW) radar system in maritime environment. The system works by the basis of transmitting multiple FMCW signal with different frequencies and bandwidth, and formulating multiple beat signals from each of the transmitted signals at the receiver. Then, beat signals averaging was conducted prior to peak detection and range estimation. This method is proposed to improve the ranging accuracy, especially when working SNR is low. A numerical simulation was performed to study the performance of the proposed method in terms of target ranging error probability against low SNR. It was found that higher order MIMO scheme of the radar system shows better accuracy for range estimation. The performance of the proposed radar was further explored by comparing with existing method such as spectrum averaging, and their computational complexity was also analyzed.**

Index Terms—**MIMO radar, FM-CW, maritime radar**

I. Introduction

DETECTING small moving targets in the occurrence of high disturbance during signal transmission due to the natural sea spikes has been an ongoing challenge in the maritime monitoring activity. The conventional radar systems for the said purpose needs improvement in the aspects of performance stability against clutter, signal propagation range, and detection resolution.

Multiple-input-multiple-output (MIMO) alternative in signal transmissions has been a popular study for radar application due to its superiority to the conventional single-input-single-output system notably in terms of improved accuracy and detection probability against noise [1][2]. MIMO configuration can be implemented in radars through various methods such as time division multiplexing (TDM) method, frequency division multiplexing (FDM) method, or code division multiplexing (CDM) method [3]. FDM is found to be superior in terms of better signal-to-noise ratio (SNR) compared to other methods [4].Meanwhile, one of the most prevalent type of radar used for maritime application is the frequency modulated continuous wave (FM-CW) radar, in which the transmitted signal in the form of continuous sinusoidal wave radio energy is modulated in frequency[5][6]. The signal waveform for this type of radar can be designed in various patterns in accordance to the measurement purposes, such as the triangle/ sawtooth form in which high range of distance can be measured, or in sinusoidal form where micromotion of objects can be obtained [7].

Conventional FM-CW radar applies the Doppler effect of the backscatterd signal to obtain information of target's range and velocity during radar detection. A singularly transmitted signal of an FM-CW radar, s_T can be expressed as per following equation [8] [9];

$$s_T(t)=A_T\cos(2\pi f_c t+2\pi\int_0^t f_T(\tau)d\tau) \quad (1)$$

where A_T is the signal amplitude, T is the duration of time, f_c is the carrier frequency, and $f_T(\tau)$ is the transmit frequency as a linear function of time. For a linearly swept FM-CW signal, the transmit frequency, f_T can also be expressed as $\frac{B}{T}\tau$ as a function of time τ in which it is the change of frequency, or bandwidth, B, over the duration of time.

In the case of linearly transmitted FMCW signal with the initial frequency f_0, change of frequency B and sweep time T, the backscatterd receiving signal of the radar, $s_R(t)$ with signal amplitude A_R can be denoted as per follows;

This manuscript is submitted on 20rd November 2021 and accepted on 14th December 2022. This work was supported in part by the Collaborative Research in Engineering, Science and Technology (CREST) Research and Development Grant, Project T05C1-67". Asiah Maryam Md Noor, Idnin Pasya and Nur Emileen Abd. Rashid are from Microwave Research Institute, Universiti Teknologi MARA, Shah Alam, Malaysia.Suraya Zainuddin is with Faculty of Electrical and Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka, Malaysia. Abdul Rahman Abdullah is with Araken Sdn. Bhd., Kuala Lumpur, Malaysia.(email: rahman@araken.biz)

*Corresponding author
Email address: 2017718365@student.uitm.edu.my

$$s_R(t)=A_R\cos\left(2\pi f_c(t-t_d)+2\pi\left[\frac{B}{T}(t-t_d)+f_o\right]_0^t\right) \quad (2)$$

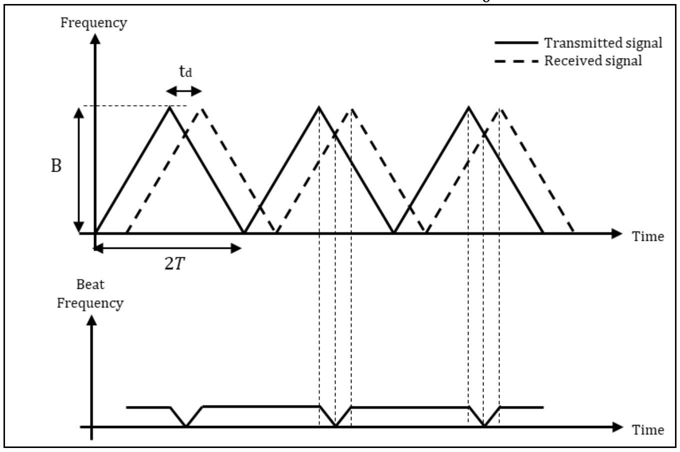


Fig 1. Conventional FM-CW signal basic mechanism

Referring to the Fig 1 above, assuming that the transmitted triangular FM-CW radar signal was backscattered by a target in range R with time delay t_d, the Doppler effect can be measured at the receiving frequency, $f_R(t)$ that can be denoted as;

$$f_R(t)=\frac{B}{T}(t+t_d)+f_D \quad (3)$$

From equation (3), the receiving frequency is shifted from the transmitted frequency by the Doppler shift, f_D where it can also be expressed in relationship to the signal propagation speed, $c = 3\times10^8\ ms^{-1}$, and v as the relative velocity of target to the radar, as

$$f_D=-2\frac{f_c v}{c} \quad (4)$$

The doppler shift can be measured to obtain the time delay t_d caused by the target with the frequency-time domain conversion using Inverse Fast Fourier Transform (IFFT). Meanwhile, t_d can then be used to obtain the range of the object, R, from the following relationship;

$$t_d=2\frac{R+vt}{c} \quad (5)$$

In the case of a non-moving target or target that is relatively much slower than the signal propagation speed, the range of target R can be simply denoted as

$$R = \frac{c}{2}t_d \quad (6)$$

This paper proposes a MIMO FM-CW radar which extends the conventional FM-CW to transmit multiple bandwidth B, and apply multiple FM-CW processing at the receiver side, to obtain beat frequencies corresponding to each of the transmitting signal. Then, the average beat frequency is formulated prior to implementing the range detection. It will be shown in this paper that the proposed method indicated a performance improvement compared to the conventional FM-CW, and performed better than existing spectrum averaging method, while having less computational complexity.

II. MIMO Approach: Beat Signal Averaging Method

The proposed MIMO FM-CW radar was studied using numerical simulation model of a single-input-single-output (SISO) FM-CW radar before increasing the number of radar signals by varying the frequency bands of each signal for MIMO configuration. The simulated SISO FM-CW radar model is shown in Fig. 2 below where the transmitted and backscattered signal, studied in baseband, are mixed to obtain beat frequency and post-processed afterwards by Fast Fourier Transform (FFT) for range estimation. The parameters for the designed SISO FM-CW radar system are described in Table 1.

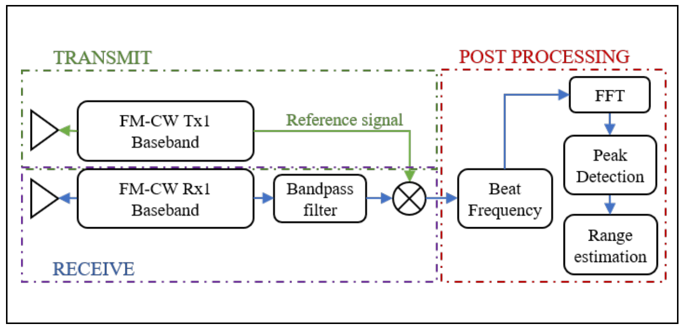


Fig. 2. FM-CW SISO simulation flow

TABLE I
PARAMETERS FOR SIMULATED SISO FM-CW RADAR

Parameter	Value
Bandwidth	10 MHz
Sweep Waveform	Triangular
Sweep Period (Half Cycle)	0.01 ms
Sampling frequency	40 MHz
Target range	50 m
Sweep Frequency	0-10 MHz
Iteration	1000

In this simulation, the MIMO FM-CW radar extends the SISO FM-CW to a M x N system, where M and N is the number of transmitting and receiving antennas, respectively. The illustration of the MIMO FM-CW waveform is illustrated in Fig 3. Each transmitting antenna radiates a unique FM-CW signal with different bandwidth, and each antennas receives and implement a band pass filter, which its bandwidth corresponds to the transmitted signals. This way, each receiving antenna is able to extract a unique FM-CW signal. Therefore, at the receiver, the system will obtain a total of $M\times N$ beat signal, as shown in Fig. 4(b). Beat signal averaging (BA) is applied before computing the peak and range detection. The beat signal averaging process can be expressed through the equation as per follows.

$$s_{B_{ave}}(t) = \frac{1}{M \times N} \sum_{m=1}^{M} \sum_{n=1}^{N} s_{B_{(m,n)}}(t) \quad (7)$$

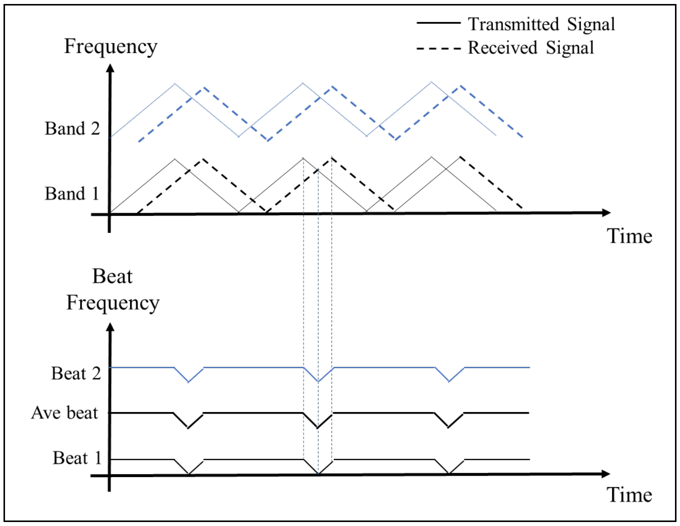
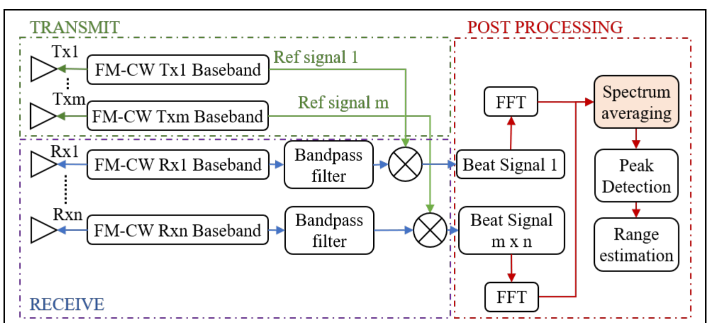
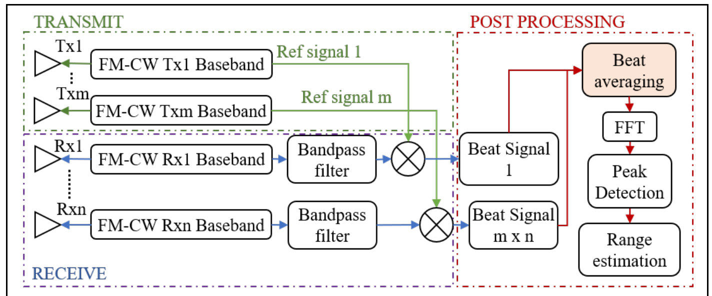


Fig 3. Example of proposed MIMO-FM-CW mechanism (2x2 configuration)

Another existing method of MIMO FM-CW processing uses Spectrum Averaging (SA) approach as proposed in [10][11], where the beat signals for each frequency bands undergo FFT before they are averaged and computed for range estimation. Meanwhile, the currently proposed beat averaging (BA) approach, the obtained beat signals are averaged as per described in equation (7) before FFT for a smaller computational complexity of the post-processing. This is due to the fact that the FFT operation is only required once when using the latter approach, while than the former approach requires M number of FFT, corresponding to the number of transmitted signals. The difference between both methods is illustrated in Fig. 4.



(a)



(b)

Fig. 4. MIMO FM-CW radar using (a) SA approach; and (b) BA approach.

Fig. 5(a) shows the simulation result of BA approach for SISO, MIMO 2x2 and MIMO 3x3 in terms of range estimation limit when SNR = 10dB while Fig. 5(b) shows the result when SNR = 5dB. It is depicted in both SNRs that better results are obtained by increasing the number of radar signals for MIMO.

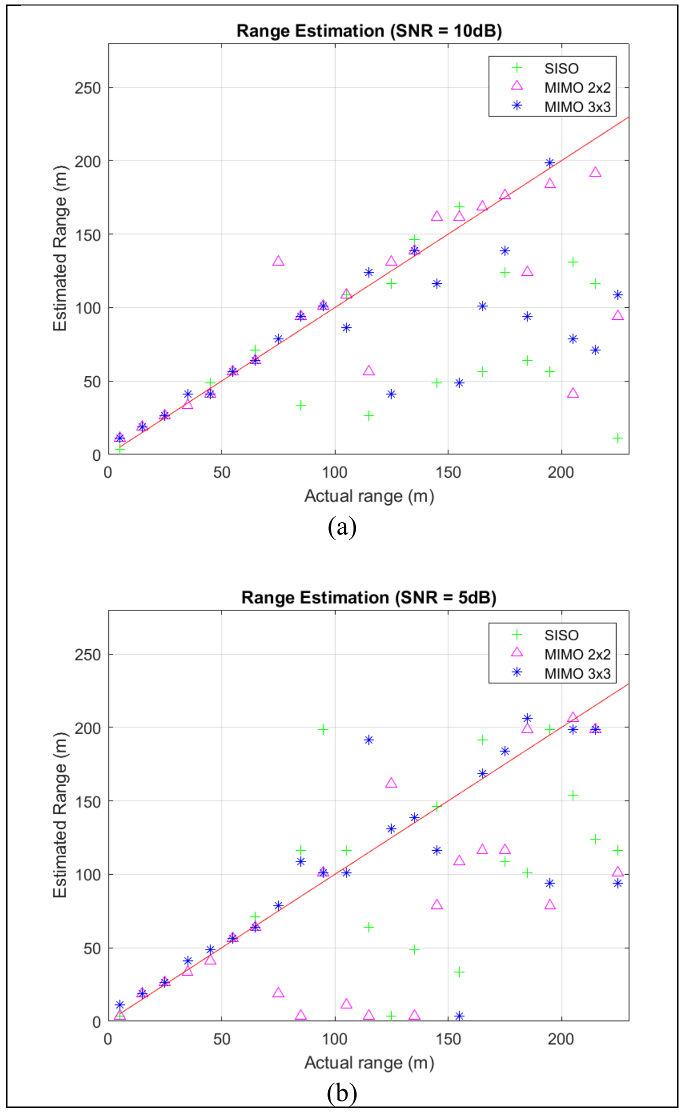


Fig. 5. Range estimation results of simulated MIMO FM-CW radar using BA approach for when SNR is (a) 5dB; and (b) 10dB.

III. Probability of Range Error

A numerical simulation was conducted to study the performance of the proposed radar. The target was positioned at 50 m range from the radar whereas the reflection coefficient used was Swerling's Target Model 1 with Additive White Gaussian Noise (AWGN) added to the receiving signals. The parameters for the designed MIMO FM-CW radar system are described in Table 2 below.

TABLE II
Parameters for Simulated MIMO FM-CW Radar

Parameter	Value
Bandwidth	10 MHz
Sweep Waveform	Triangular
Sweep Period (Half Cycle)	0.01 ms
Sampling frequency	40 MHz
Target range	50 m
MIMO approach	Frequency Division Multiplexing
Sweep Frequency Bands	i) 0-10 MHz
	ii) 12-24 MHz
	iii) 26-36 MHz
Noise	AWGN
Reflection Coefficient	Swerling's Model 1
SNR	-6 to 20dB, 2dB intervals
Iteration	1000

In the simulation, the radar is evaluated in terms of probability of range error against varying SNR values. Random noise of Additive White Gaussian Noise (AWGN) is added to the backscattered signal for each iteration and the target's reflection coefficient is modeled to be Swerling's Type 1 Model. The simulation is conducted by 1000 iteration for each SNR values between -6dB to 20dB with 2dB intervals.

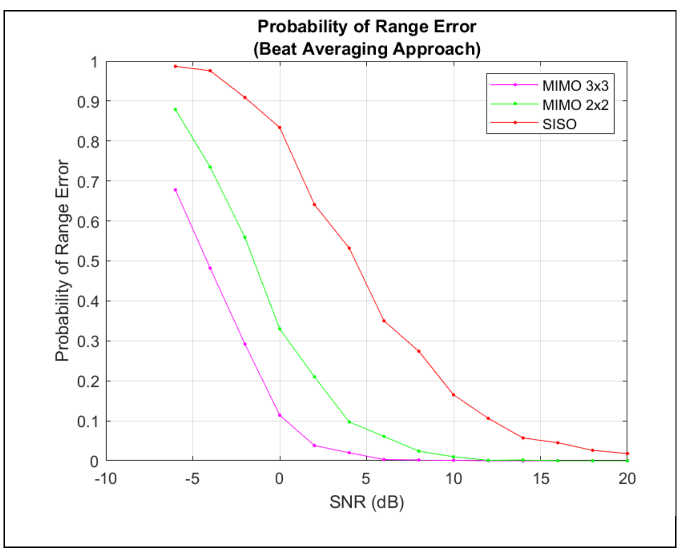


Fig. 6. Comparison of the probability of range error against SNR between SISO radar and MIMO radar using BA approach..

The result demonstrated a quite significant improvement by the MIMO approach where the SNR values required for 20% probability of range error to occur is observed to be approximately -1 dB and 2dB for MIMO 3x3 and MIMO 2x2 respectively as compared to SISO with approximately 9dB.

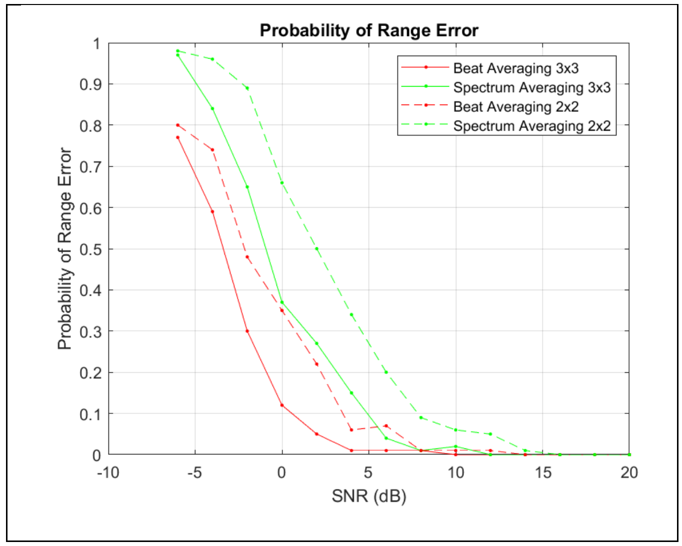


Fig. 7. Comparison of the probability of range error against SNR between BA approach and SA approach (iteration = 100).

IV. Comparison with Exisitng Method

The simulation results are further compared with another existing method, which employes the SA approach. As per shown in Fig. 7, it is found that the BA approach has better results than SA approach, with approximately 2-4 dB difference for both 2x2 and 3x3 MIMO simulation at 20% probability of range error.

In addition, the two methods are compared in terms of computational complexity, focusing on the averaging method processing. As mentioned in Section II, the proposed method only required FFT operation once, due to the averaging of multiple beat signal is done prior to the FFT. Assuming $\tilde{N}$ is the total number of sample in one frame of processing, and M is the total number of transmitted signal, the computational complexity for the beat averaging is $O(M\tilde{N}) + O(\tilde{N})$, and $O(\tilde{N}/2 \log_2 \tilde{N})$. Meanwhile, the existing method employing the SA method implement spectrum averaging after the FFT, where it requires M number of FFT, hence its total complexity is $O(M\tilde{N}/2 \log_2 \tilde{N}) + O(M\tilde{N}) + O(\tilde{N})$. The computational complexity is therefore is significantly lower by using the proposed BA method. The proposed MIMO FM-CW using the BA method uses lesser computation while showing better performance (as mentioned in Section III).

V. Conclusion

The study demonstrated the feasibility of MIMO approach in FM-CW radars by beat averaging method and the improvement of radar's performance in terms of robustness against low SNR in maritime environment . Further study is required to evaluate the maximum range detection to produce better radar for maritime application.

REFERENCES

[1] H. Yang, Y. Wang, W. Xie, and Y. Di, "Persymmetric adaptive target detection without training data in collocated MIMO radar," *2016 CIE Int. Conf. Radar, RADAR 2016*, pp. 6–9, 2017, doi: 10.1109/RADAR.2016.8059463.

[2] M. Alshaya, M. Yaghoobi, and B. Mulgrew, "Frequency domain system identification for wide swath high resolution IRCI-Free MIMO SAR," *2019 IEEE Radar Conf. RadarConf 2019*, pp. 134–137, 2019, doi: 10.1109/RADAR.2019.8835622.

[3] H. Sun, F. Brigui, and M. Lesturgie, "Analysis and comparison of MIMO radar waveforms," 2014, doi: 10.1109/RADAR.2014.7060251.

[4] M. Q. Nguyen, R. Feger, J. Bechter, M. Pichler-Scheder, M. H. Hahn, and A. Stelzer, "Fast-Chirp FDMA MIMO Radar System Using Range-Division Multiple-Access and Doppler-Division Multiple-Access," *IEEE Trans. Microw. Theory Tech.*, vol. 69, no. 1, pp. 1136–1148, 2021, doi: 10.1109/TMTT.2020.3039795.

[5] D. O. D. Handayani, W. Sediono, and A. Shah, "Design and development of the FMCW Radar Scene Generator," *ISIEA 2012 - 2012 IEEE Symp. Ind. Electron. Appl.*, pp. 39–44, 2012, doi: 10.1109/ISIEA.2012.6496667.

[6] W. Butler, P. Poitevin, and J. Bjomholt, "Benefits of wide area intrusion detection systems using FMCW radar," 2007, doi: 10.1109/CCST.2007.4373486.

[7] B. Peng, X. Wei, B. Deng, H. Chen, Z. Liu, and X. Li, "A Sinusoidal Frequency Modulation Fourier Transform Transform for Radar-Based Vehicle Vibration Estimation," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 9, pp. 2188–2199, 2014.

[8] J. J. Lin, Y. P. Li, W. C. Hsu, and T. S. Lee, "Design of an FMCW radar baseband signal processing system for automotive application," *Springerplus*, vol. 5, no. 1, pp. 1–16, 2016, doi: 10.1186/s40064-015-1583-5.

[9] A. G. Stove, "Linear FMCW radar techniques," *IEE Proceedings, Part F Radar Signal Process.*, 1992, doi: 10.1049/ip-f-2.1992.0048.

[10] S. Zainuddin *et al.*, "Performance of MIMO FMCW Radar in Detecting Small Vessels," 2018, pp. 2–5.

[11] S. Zainuddin, N. E. Abd Rashid, I. Pasya, and R. S. A. Raja Abdullah, "Simulation of Multi-band MIMO FMCW Radar Performance in Detecting Maritime Vessels," in *2019 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET)*, 2019, pp. 1–5, doi: 10.1109/ICRAMET47453.2019.8980384.