International Journal of Advanced Technology and Engineering Exploration, Vol 10(98)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2022.1010015

Research Article

Joint beat-spectrum averaging in a multi-frequency MIMO radar approach on a slow-fluctuating object range detection

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Received: 16-September-2022; Revised: 10-January-2023; Accepted: 12-January-2023

Abstract
Radar is widely applied in detecting such as aircrafts, ships and motor vehicles, mainly for security and safety purposes. However, a small object is hard to be detected moreover if it is fluctuating. Meanwhile, utilisation of a multiple-input multiple-output (MIMO) in the radar configuration has been acknowledged in many recent works, benefiting from its waveform diversity. In this study, various processing schemes for a MIMO frequency modulated continuous waveform (FMCW) radar were evaluated in detecting a slow-fluctuating object due to water ripples. Employing small and lightweight commercial-off-the-shelf (COTS) modules, a 2×2 co-located MIMO radar configuration was constructed. Beat signals received were post-processed in MATLAB, applying a spectrum averaging (SA), beat averaging (BA) and finally, merging the BA together with SA (BA-SA) schemes. The performance was compared against various averaging methods for MIMO processing, and a single-input single-output (SISO) configuration. Performance was analysed in terms of probability of range error, range error means, root mean square error (RMSE) and scattering index (SI). It was observed that MIMO was performing against SISO, and the combination of BA-SA in MIMO signal processing yielded the best result in all performance indicators compared to other evaluated schemes.

Keywords
Slow-fluctuating object, Signal averaging, Signal processing, Radar, Accuracy.

1.Introduction
Object detection is crucial in the surveillance system, either for a ground target or a non-ground target monitoring. Commonly, the application is meant for security and safety of the observing area from intrusion, land, sea or air. Various types of detecting methods such as camera [1], ultrasonic signal [2], acoustic signal [3], laser and radar [4, 5] have been utilised. There was also a recent research that had been carried out implementing an internet-based monitoring system [6]. Zheng et al. [1] presented a detection, localization and tracking of micro aerial vehicles (MAV) by deploying a panoramic stereo type camera networks. The effectiveness of the proposed approach was verified through experimental test.

However, utilization of camera has its limitation when privacy is a concern to users such as when monitoring across the private land or area. The laser technology is also favoured as it provides high resolution and high accuracy for target detection. Nevertheless, when it involves air traffics such as airplane and airport application, it may cause accidents due to temporary blindness to the pilots and others, resulted from its high intensity laser beam [7].

Tang et al. [3] in their work had observed the potential of the chirp acoustic signal in detecting static obstacles. A stable-window-based method was suggested to distinguish the static obstacle out of mobile objects, and the work presented a high detection accuracy up to 97%. Yet, the ultrasonic signal is known to have a poor angular resolution [7].

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Radar technology is an alternative for target detection as it has the ability to perform target distance measurements under various environmental conditions, day and night. Tavanti et al. [4] proposed a microwave based radar by utilising a frequency modulated continuous waveform (FMCW) to detect multi-target over a short-range distance. It resulted in a low-cost with limited resolution and computational capabilities, but having the ability to recognize targets effectively. Meanwhile, Kocur et al. in year 2021 had explored on the ultrawide band (UWB) radar for static person localization through their novel signal processing scheme [5]. Driven by the expansion of radar technology in detection and localization, thus, this paper introduced a new processing scheme by combining averaging methods for a multiple-input multiple-output (MIMO) FMCW radar.

Commonly, a radar-based detection system involves a single-input single-output (SISO) configuration which has limitation of coverage and reliability in terms of system redundancy. This type of setup normally is dedicated for a large target that has more visibility to the radar. Placement of SISO radar is crucial to ensure the angle and location of radar provides the best signal quality for signal processing [8]. However, a fluctuating behaviour of an object increases the difficulty of detection due to reflected energy dependencies to target radar cross section (RCS) [9–11]. In a real scenario, a target visual angle constantly changes from a radar’s point of view, which resulting in the fluctuation of received signal amplitude, that causing a reduction in the detection probability [12]. The effect worsens if the size of the target is small and a stealth target. Furthermore, echo signals received were also influenced by the location of radar; for example, a maritime shore-based radar is exposed to ground and water clutter depends on the signal propagation environment [13]. Thus, the detection of a fluctuating target is still an open issue to ensure better detection probability.

Related literature is briefly discussed in the section 2. Next, the section 3 explained the methodology which comprising experimental setup and configuration, data acquisition and processing schemes. This section focused on the averaging schemes involved in range estimation. Section 4 and section 5 presented results and discussion, respectively. Finally, section 6 concluded the study together with future work.

2.Literature review

Swerling models categorized the characteristic of the fluctuating target. There are four models representing the object's fluctuation scenario based on the RCS slow-changing and fast-changing [14, 15]. Several analyses have been conducted by researchers in detecting a fluctuating target based on various applications, such as airborne radar [11, 16] and spaceborne radar [17]. Finkelman et al. [11] simulated the probability of detection of an aerial target with the consideration of noise and clutter, to produce a more reliable simulation. This work resulted in the more realistic detection performance of an aircraft in motion along a specific track and provided better detection estimation in a simulated environment. Besides, a work by Zuk [16] also described the radar detection’s problem of correlated gamma-fluctuating targets in the presence of clutter with the focus on airborne maritime radar systems. It is crucial to include the effect of noise and clutter to mimic the real scenario of target detection. Meanwhile, in the year of 2021 De et al. [17] also observed on the detection of a spaceborne radar. It studied the effect of plasma turbulence on detection performance for space situational awareness (SSA). In 2021, Enma et al. [18] proposed a novel approach to divide the transmitted long pulse into short pulses while adopting the convolutional error control coding technique in detecting Swerling I and III targets. The study demonstrated the improvement of detection probability through simulation, but yet to be proven through practical implementation. Addabbo et al. [19] addressed the issue of detecting a signal of interest in Gaussian noise with the performance was also assessed over a Swerling I and III targets, but with a focus on the Rician target.

With the presence of clutter and behaviour of fluctuating target, the selection of radar transmit waveform and placement of radar are important to increase the radar detection performance. The recent evolution of radar configuration presents a MIMO setup with various benefits to offer. A MIMO radar has been a research interest due to its diversity [20]. Bergin and Guerci [20], in their book presents an unbiased analysis on both advantages and disadvantages bring by MIMO. They stated that through MIMO clutter estimation in radar provides effective rapid detection and mitigation of strong clutter discrete. Besides, an optimum MIMO technique through multiple signals increase the signal quality and enhance target detection performance [20, 21].

In the year 2022, Reza et al. studied the multi-static multi-band synthetic aperture radar, a coherent MIMO approach known to increase the system resolution through fusion multi-band orthogonal signal [22]. They introduced photonic processing by allowing flexible band generation.

The FMCW in radar is favoured, especially over short-range applications such as target detection and classification, for its high resolution, cost-effective and small size [23]. Li et al. [24] presented a high-resolution FMCW ranging system utilising multi-source stitching of light detection and ranging (LiDAR) system. The implementation of FMCW LiDAR increases the sensitivity and anti-interference of the system. Several FMCW sweep modulation techniques can be applied such as ramps, sawtooth and triangular. A triangular FMCW modulation such as studied by Ge at al. [25] and Xu et al. [26] consists of upper and lower chirps which is useful for a Doppler target detection. This type of modulation is able to determine the range and Doppler through transmitting a single triangle signal. Meanwhile, a sawtooth signal comprises a ramp of signal and return back to the initial frequency after completed one sweep [27–29]. This sweep method only able to produce range and requires multiple ramps for a Doppler estimation. Meanwhile, a ramp is similar to the sawtooth modulation technique. However, it remains at the end of the frequency after completed a ramp.

In this paper, the FMCW was adopted for its robustness in over a fluctuating target [30, 31] employing a triangular waveform. Aside of the modulation technique, FMCW waveform approach is crucial when involving MIMO. Various FMCW approaches are available to produce orthogonality between signals in MIMO implementation [32]. Each approach has advantages and disadvantages, which requires a trade-off between on the capability of the system and its performance. Noor et al. [33] and Zainuddin et al. [13] investigated on the performance of the multi-frequency approach, where the FMCW MIMO signals were swept with similar bandwidth (BW) in multiple frequency ranges at the same period. This method provides the capability to separate signal by the frequency offset, however, may require additional license to operate in more frequency bands and need synchronization of signals. A next approach that's available is a time staggered FMCW. This method provides the ability to distinguish the MIMO signals through the time offset, but the time offset elements must be larger than maximum round-trip time. Endo et al. [34] utilised a linear array antenna to separate the signal with time offset. The FMCW MIMO signal also can be distinguished by having an opposite slope of signal within the same frequency and BW. This method has the limitation in the number of signals can be utilised. Next, there is a work by Kumbul et al. [35] explored the potential of phase-coded FMCW MIMO to reduce the sidelobe level while maintaining the quality of FMCW signal. Another approach available is FMCW signals with different BW. This approach allows occupancy of same frequency band and time, without additional license required. However, this method may encounter degradation of resolution on the waveform with lower BW. Suryana and Ridha [36] introduced the polarization diversity, yet it offered a limited degree of freedom. By having MIMO, a fusion method needs to be established to obtain the information out of multiple received signals.

Numerous techniques have been explored for MIMO signal and data fusion in previous studies. Wang et al. [37] has proposed a multi-station signal association and fusion method based on a sequential Bayesian algorithm for a distributed MIMO radar configuration. The proposed approach was to mitigate the issue of target matching from multi-station and the output indicated the improvement of radar power capability and detection of weak targets. Meanwhile, Lu et al. [38] proposed an intuitive weighting method over a fusion-based detection. Overall, the fusion method proposed are based on the configuration of transmitters-receivers of the MIMO radar system. Implementation of a MIMO radar has pros and cons, also not suitable to certain radar applications. The multiple signals introduced need to be utilised optimally to ensure improvement of the performance, instead of additionally introducing additional processing time and cost. Adopting MIMO requires tradeoffs between advantages and disadvantages it has to offer based on the system specification and application requirement. Thus, this paper will discuss on a signal fusion method based on averaging. Three signal averaging schemes for multi-frequency MIMO processing of a co-located MIMO configuration were studied. A new joint averaging method between time and frequency domain is explored in this paper, and compared against signal averaging method in time domain by the Noor et al. [33] and frequency domain by Zainuddin et al. [13].

A signal averaging or a signal recovery is a technique known to obtain the desired signal out of the noise signal. It requires repetitive synchronous signals in order to extract the coherent pattern. The literature shows that averaging multiple signal sweeps of a signal improves system sensitivity, dynamic range, resolution, and accuracy [39, 40]. Hence, the averaging method will be observed in detecting a slow-fluctuating object with regards to a multi-frequency MIMO FMCW radar. Noor et al. [33] had observed the potential of beat averaging (BA) while Zainuddin et al. [13] studied alternative processing utilising a spectrum averaging (SA). Both schemes had proven a significant improvement in range estimation accuracy. However, both references never compared the performance between those two averaging methods. Thus, this paper will analyse the detection performance by both methods and the proposed of joint method between BA and SA. The proposed joint approach was meant to exploit the potential of both averaging schemes while lessens the number of fast Fourier transform (FFT) processing compared to the SA. This paper assessed the slow-fluctuating target over a water surface by employing a co-located MIMO radar configuration.

An FMCW radar employs a backscatter signal reflected by targets to obtain the target's information. *Figure 1* illustrates the triangular FMCW principle and the concept of multi-frequency for a 2×2 MIMO FMCW. A triangular FMCW comprises of an up-chirp and down-chirp for a cycle, which offers a range and Doppler estimation in a single cycle [41].

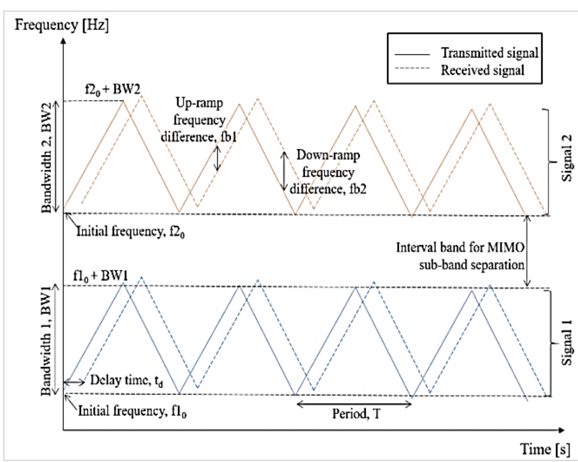


Figure 1 A multi-frequency 2×2 MIMO FMCW transmitted and received signals

An FMCW signal sweep frequency is defined as BW which is reciprocal to the range resolution that can be offered by the radar. A beat signal indicates the frequency difference between transmit and receive signals. The FFT was utilised to produce the frequency spectrum of the beat signal, and a peak detection algorithm was applied to obtain beat frequency for estimation given in Equation 1.

$$R = \frac{cT}{4BW} fb \quad (1)$$

In which R is the estimated range, c is the speed of light, T is the period of FMCW signal, BW is the bandwidth and fb is the beat frequency. The beat frequency for calculation is given by Equation 2 with fb1 is the up-ramp frequency difference and fb2 is the down-ramp frequency difference.

$$fb = \frac{fb1 + fb2}{2} \quad (2)$$

The utilisation of the multi-frequency MIMO FMCW results in multiple beat signals at the receiver's end. These beat signals are exploited to increase the range estimation accuracy through post-processing. Commonly, signal averaging is implemented over multiple sweeps of a signal. However, in this paper, the averaging was done over beat signals from different sweep bandwidths with four signal's cycles. In order to analyse the averaging scheme, a commercial-off-the-shelf (COTS) based radar offers a simple and expedite solution to construct a multiple node analysis. Many COTS-based radars are available in the current market, such as Distance2go (D2G) [42] and innovation in manufacturing system and technology (IMST) module. Most of the COTS available operate at 24 GHz and 77 to 81 GHz within the industrial, scientific and medical (ISM) band. In the analysis, we applied a D2G by Infineon for data acquisition.

Various analysis methods have been explored on signal processing to observe the signal's quality. One of the criteria reviewed by Zawawi et al. [43] was on the time domain features analysis which can be acquired directly from raw signal in time representation. Analysis in time domain usually involves a fast features extraction of the signal and easy to be adopted due to implementation of simple mathematical properties, such as root mean square (RMS). On the other hand, analysis in frequency domain provides another angle of evaluating a signal. To observe the signal in the frequency representation requires a raw signal to be transformed from time to frequency, which Fourier analysis is one of the tools that widely been used [44]. Power spectral density (PSD) and spectrogram are some of the major analyses in observing the frequency domain [45]. Periodogram also provides the analysis view through the distribution of the power signal over the frequency and capability to determine harmonic components in power signal. Besides, the time-frequency analysis technique such as short time Fourier Transform (STFT) and S-Transform is also a very useful technique to represent the signal in both domains, time and frequency [43, 46]. In this paper, the final MIMO signal was transformed into frequency domain through FFT and the peak magnitude was obtained from the spectrum. Performance was analysed in terms of mathematical analysis which is the number of successful range estimation, probability of error percentage, error mean, root mean square error (RMSE) and scattering index (SI).

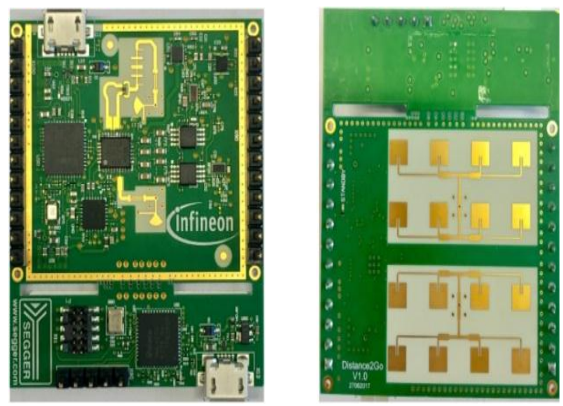
Overall, the works of literature present the necessity of improvement in target detection, moreover with the existence of fluctuating scattered and stealth targets. Various studies have been conducted through simulations and experiments on multiple radar types, configurations and environments. Previous works also displayed the advantages of MIMO configuration compared to conventional setup and the robustness of FMCW as the transmit signal. In addition, various analysis methods have been discussed by other researchers to examine the signal's quality, either in the time or frequency domain, and the performance was commonly presented through mathematical analysis. Hence, this paper observed an FMCW MIMO radar signal processing by applying averaging schemes over the received signals, an extension of previous research on BA and SA approaches.

3.Methodology

3.1Experimental setup and configuration

The COTS module employed in this experiment was a D2G by Infineon. The module operates at 24 GHz, a typical band in the radar industrial market. *Figure 2* presents the top and bottom views of the COTS. A 1-meter height plastic bin was used for the experiment as a static object. The bin was covered with aluminium foil to increase its visibility. The object was placed on a float over a lake surface. During the experiment, the water surface condition was calm with approximately 1 cm ripples which caused a slow-fluctuating to the target of interest. The D2G is a SISO FMCW radar chipset. Hence, four D2G modules were mounted over a 2-meters pole to mimic a 2×2 co-located MIMO. The arrangement of the modules is illustrated in *Figure 3*. Each D2G module was separated by 3 cm to accommodate the required minimum distance for a 24 GHz signal. Each D2G was connected directly to a laptop for data acquisition. Meanwhile, *Figure 4* presents the 2×2 MIMO radar configuration and its equivalent blocks utilised in the experiment. A multi-frequency transmitting waveform is introduced by having two different frequency ranges emitted by different antennas to produce orthogonality of MIMO signal, and a 2 MHz offset was configured to avoid signals overlapping.

Table 1 tabulated the configuration of COTS for the experimental evaluation to measure a target that located 10 m from the transceivers. Configuration of COT was done through radar graphic user interface (GUI) tool in the Infineon toolbox provided by Infineon. The Infineon toolbox needs to be installed prior for COTS configuration and data acquisition. *Figure 5* depicts the layout for the experiment setup.



(a) (b)

Figure 2 A D2G module (a) top and (b) bottom view

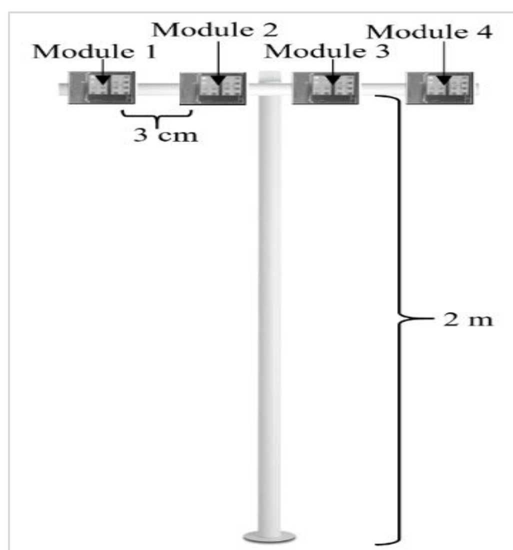


Figure 3 D2Gs mounted on a 2-m pole with 3-cm separation between modules

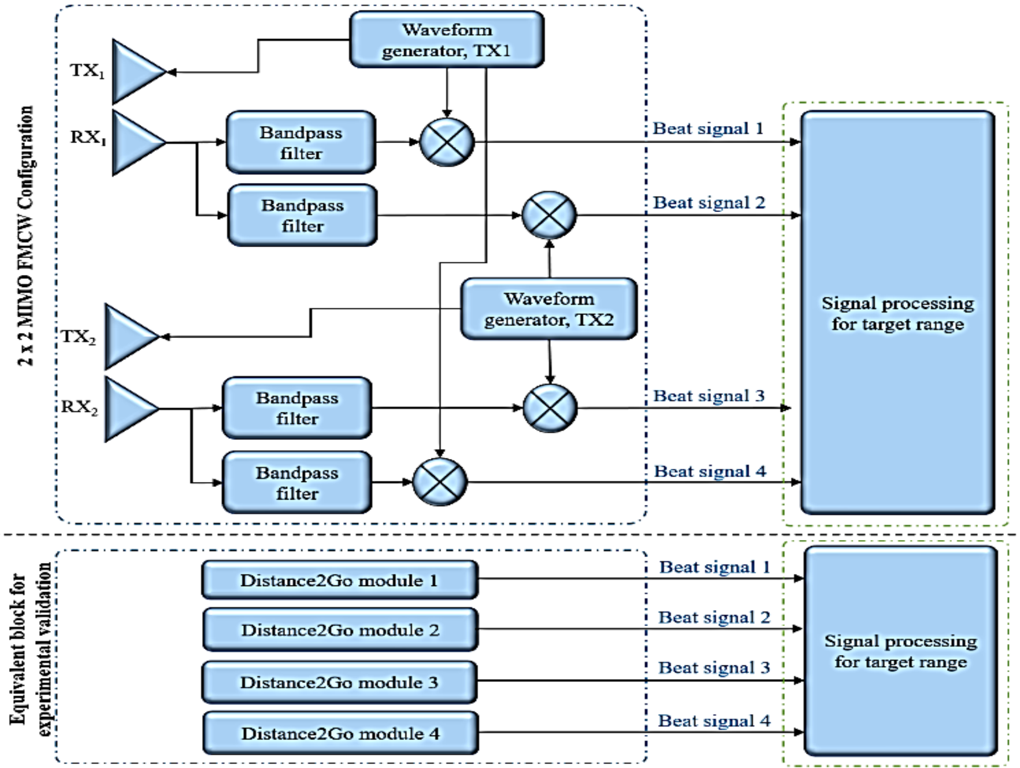


Figure 4 2×2 MIMO FMCW configuration and its equivalent block for experimental validation

Table 1 Configuration for experimental evaluation

Parameter	Value
Type of waveform, Chirp method	FMCW, Triangular chirp
Sweep bandwidth, BW	20 MHz
Sweep time, T	400 us
Target range from transceivers, R	10 m
Sampling frequency, fs	640,000
Number of samples, Ns	256
Transceiver height, h_A	2 m
Target height, h_T	1 m
Sweep frequency:	
Module 1	24.025 GHz to 24.045 GHz
Module 2	24.047 GHz to 24067 GHz
Module 3	24.025 GHz to 24.045 GHz
Module 4	24.047 GHz to 24067 GHz
Iteration	1,500

After the beat signal dataset was gathered by a D2G module, all data were collated and post-processed at the main laptop. Data was taken for 1,500 sets per modules. Next, these four MIMO beat signals were applied with various processing schemes and compared. By utilising Equation 3, the maximum range error, ΔR, was 7.5 m, equal to the range resolution. In the equation, c indicates the speed of light, T is the cycle period, fs if the sampling frequency, BW is the bandwidth, and Ns is the number of samples. The performance was also compared against a SISO setup. Each averaging scheme is explained in the following subsection.

$$\Delta R = \frac{cTfs}{2BW.Ns} \tag{3}$$

A beat signal received from each COTS was added with additive white Gaussian noise (AWGN) at the required noise level before entering the processing blocks. It was to examine the performance trend across signal-to-noise ratio (SNR) levels.

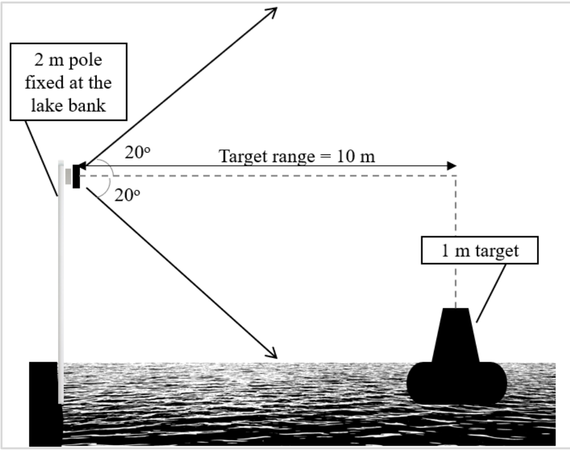


Figure 5 D2Gs mounted on a 2-m pole with 3-cm separation between modules

A dataset of 1,500 readings per module was acquired to detect a static slow-fluctuating target at a 10 m distance from transceivers. The module was configured with two different sweep bandwidths, as in *Table 1*. Dataset gathered were post-processed with various averaging schemes, which were the BA, the SA and the proposed scheme of joint BA-SA. Results were compared between the various averaging methods also with SISO configuration. The system's performance was analysed in terms of distribution of estimation, probability of range error, mean of the estimated range, RMSE and SI. Signals were also observed over the FFT spectrum to understand each of the scheme effect over the processed signal. *Figure 6* depicts the distribution of received signals represents the Swerling 1 behaviour with a skew to the left of a fluctuating target [9].

3.2Data acquisition

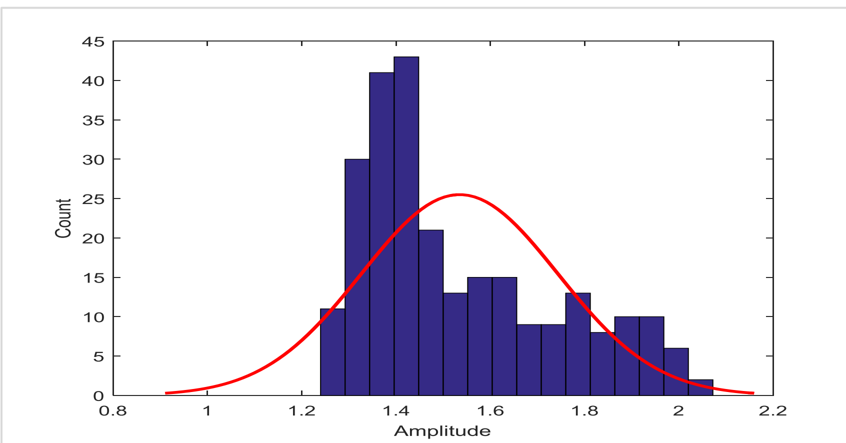


Figure 6 Histogram of signal acquired represented the distribution of Swerling 1

3.3Data processing

The beat signal obtained by each COTS can be presented by $S_{B(1)}(t)$ for module 1, $S_{B(2)}(t)$ for module 2, $S_{B(3)}(t)$ for module 3 and $S_{B(4)}(t)$ for module 4, which was in a time domain. These beat signals at the MIMO receivers can be written as per Equation 4.

$$S_{B\_RX}(t) = \begin{bmatrix} S_{B(1)}(t) \\ \cdots \\ S_{B(4)}(t) \end{bmatrix} \quad (4)$$

The multiple beat signals received were post-processed with MATLAB to produce the target range from the transceiver. This paper evaluated three signal averaging schemes for MIMO signal processing which are BA, SA and finally, the proposed joint BA-SA scheme.

The BA scheme

The BA scheme was studied by the Noor et al. [33], in which it combined MIMO beat signals in the time domain by the mean of averaging. In this scheme, the beat signal from each receiving MIMO node is added and averaged in time domain for each of the sample point. This process can be presented as in Equation 5.

$$S_{B\_MIMO}(t) = \sum_{n=1}^{4} S_{B(n)}(t)/N \quad (5)$$

N is the total number of beat signal, which in this setup is 4. The result from the BA block was converted to a frequency domain with a FFT before being applied with a peak detection algorithm. The FFT of the averaged beat signal is given by Equation 6.

$$FFT(S_{B\_MIMO}(t)) = S_{B\_MIMO}(f) \quad (6)$$

Local maxima peaks detected in the positive and negative FFT spectrum region were used to calculate and estimate the target range. The maximum peak detected in positive region is defined as fb1.

Meanwhile, the maximum peak detected in negative region is defined as f_{b2}. The process can be written as follows in Equation 7.

$$P(f_b) = \begin{cases} f_{b1} = \max[P(S_{B_{MIMO}}(f); f \text{ is in positive spectrum region} \\ f_{b2} = \max[P(S_{B_{MIMO}}(f); f \text{ is in negative spectrum region} \end{cases} \quad (7)$$

The f_{b1} and f_{b2} obtained were applied to Equation 2 and 1 for range estimation. *Figure 7* illustrates the post-processing of the BA scheme after signals received from COTS. This method applied a simple averaging calculation at each sampling point in the time domain and only involved one FFT process.

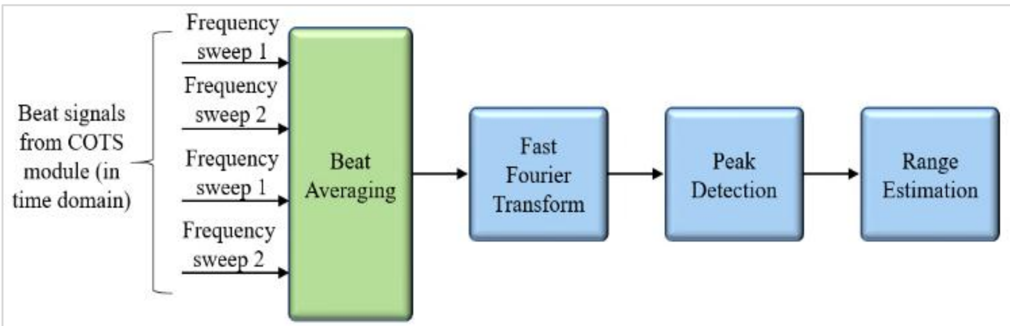


Figure 7 Beat averaging signal processing scheme

The SA scheme

Meanwhile, the SA processing scheme had been explored in the Zainuddin et al. [13] for an FMCW MIMO radar in detecting a slow-fluctuating object of interest. This processing method requires each beat signal received to be converted into FFT spectrums, and those multiple spectrums were averaged before undergoing a peak detection process. Similarly, beat signals received were as per Equation 4. However, each of the beat signal was applied with FFT algorithm to transform into a frequency domain, which can be presented as in Equation 8.

$$FFT(S_{B\_RX}(t)) = \begin{bmatrix} S_{B(1)}(f) \\ \cdots \\ S_{B(4)}(f) \end{bmatrix} \quad (8)$$

Four beat signals in frequency domain were average at each sample point of the spectrum as per Equation 9.

$$S_{B\_MIMO}(f) = \sum_{n=1}^{4} S_{B(n)}(f)/N \quad (9)$$

Peak detection algorithm selects the highest magnitude frequency similar as per Equation 7, and utilises it for range estimation. However, this method increases the processing time cost with every new MIMO node introduced as the FFT process increases. *Figure 8* illustrates the processing blocks of the scheme. This approach involved four FFT concurrent processes for four beat signals, and next, signals in the frequency domain were averaged at each sampling points. The difference between SA schemes compared to BA scheme is, the averaging of signals was done in the frequency domain for SA while the signal averaging were done in the time domain for BA.

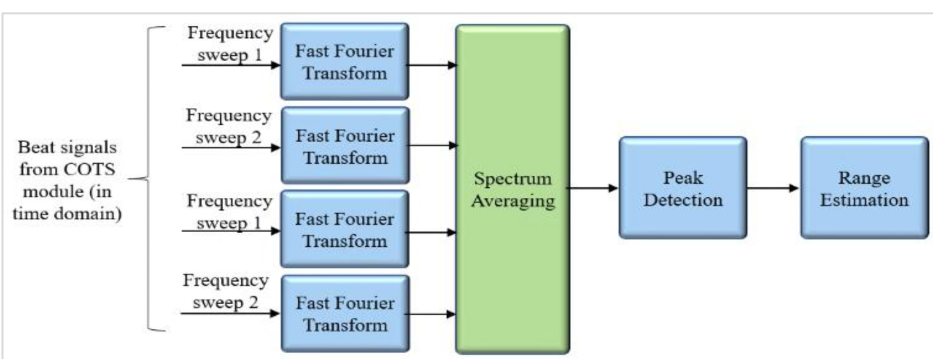


Figure 8 Spectrum averaging signal processing scheme

The proposed BA-SA scheme

By observing the improvement brought by BA and SA methods, thus, this paper proposed the joint BA-SA approach, in which the scheme introduces two stages of averaging for a similar number of beat signals. Firstly, beat signals at each receiver from different sweep frequencies were averaged in the time domain. The process can be written as shown in Equation 10 and 11.

$$S_{B\_MIMO1}(t) = \sum_{n=1}^{2} \frac{S_{B(n)}(t)}{N}, for\ receiver\ 1 \quad (10)$$

$$S_{B\_MIMO2}(t) = \sum_{n=3}^{4} \frac{S_{B(n)}(t)}{N}, for\ receiver\ 2 \quad (11)$$

In this case N for each receiver is 2. By averaging beat signals at each receiver, the MIMO received signal in the time domain can be presented as in Equation 12.

$$S_{B\_MIMO}(t) = S_{B\_MIMO(1)}(t) + S_{B\_MIMO(2)}(t) \quad (12)$$

The output from each BA block was translated into the frequency domain by applying FFT before feeding into the SA block as given in Equation 13.

$$FFT(S_{B\_MIMO}(t)) = \begin{bmatrix} S_{B_{MIMO(1)}}(f) \\ S_{B_{MIMO(2)}}(f) \end{bmatrix} \quad (13)$$

In SA block, magnitude at each FFT point was averaged, resulting in a single FFT spectrum output as follows in Equation 14.

$$S_{B\_MIMO}(f) = \sum_{n=1}^{2} S_{B_{MIMO(n)}}(f)/N \quad (14)$$

The spectrum frequency was applied with peak detection as per Equation 7 and calculated for range estimation. By having the same number of MIMO node configuration, this scheme increases the processing by having a two-BA blocks but with lesser FFT processing than the SA scheme. *Figure 9* simplifies the beat signal processing flow.

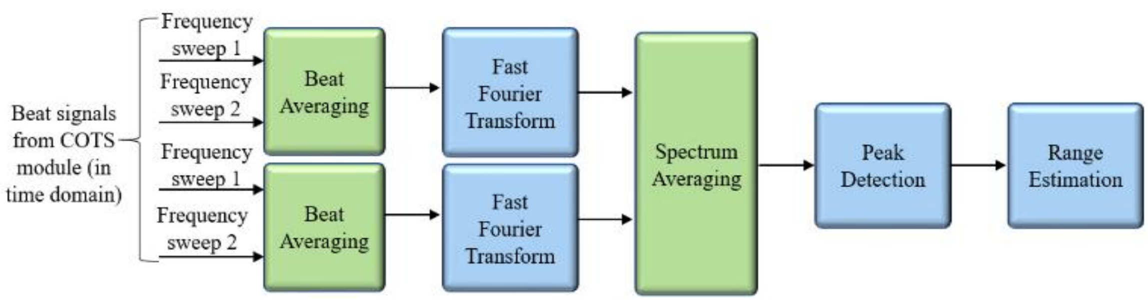


Figure 9 The joint beat-spectrum averaging signal processing scheme

4.Results

Firstly, observation was done on the capability of the system to estimate range within the acceptable error margin. The error margin was assigned based on the maximum range error, ΔR, as per Equation 3. For the experiment, ΔR obtained was 7.5 m with velocity of light, c = 3×108 m/s, signal period, T= 0.4 ms, sampling frequency, fs= 640 kHz, bandwidth, B= 20 MHz, and the number of samples, Ns = 256. In this context, this parameter provides a view of the system's decision-making. It indicates the frequency of error in estimation for each configuration.

The observation was conducted over three different SNR levels, starting with 0 dB to 20 dB, with 10 dB steps incremental. *Figure 10* presents frequency spectrums of the beat signal at 0 dB, 10 dB and 20 dB. From the figure, we can observe that the peak of beat frequency for range estimation is unable to be distinguished due to other peaks are more remarkable. This led to the estimation error and degraded the accuracy of estimation. However, the peak of the beat frequency is clearer when the SNR level increases. At 20 dB SNR, the peak is easily distinct from unwanted peaks.

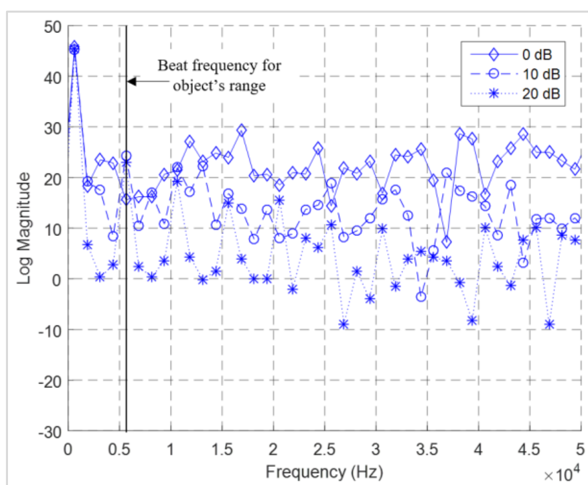


Figure 10 Spectrum of beat signal at 0 dB, 10 dB and 20 dB

Table 2 tabulates the distribution of range estimation by various processing schemes over a MIMO FMCW radar and SISO FMCW radar configuration. All three MIMO configurations surpassed the SISO setup at 0 dB, 10 dB and 20 dB. At 20 dB, all configurations reached 100% range estimation indicate the FMCW signal robustness against noise. At 0 dB, the proposed scheme of joint BA-SA displays the best result compared to others by producing 229 decisions within margin, which was 15.27% out of the total iteration. It was followed by a MIMO with BA processing at 14.07%, MIMO with SA at 8.87% and SISO at 3.53%.

At 10 dB SNR, again, a MIMO with joint BA-SA yielded the best result by producing 1,476 estimations within the margin, which is 98.4% from total data. Next, a MIMO with SA with 98.07% and a MIMO with BA with 97.07% acceptable estimation. Finally, a SISO with 75.67%, which is equal to 1,135 estimations within the threshold.

Table 2 Distribution of range estimation by various processing schemes and FMCW radar configuration

SNR	Range estimation	Configuration & processing scheme			
		SISO	**MIMO + SA**	**MIMO + BA**	**MIMO + Joint BA-SA**
0 dB	Within margin	53	133	211	229
	Out of margin	1, 447	1,367	1,289	1,271
	Percentage within margin	3.53%	8.87%	14.07%	15.27%
10 dB	Within margin	1,135	1,471	1,456	1,476
	Out of margin	365	29	44	24
	Percentage within margin	75.67%	98.07%	97.07%	98.40%
20 dB	Within margin	1,500	1,500	1,500	1,500
	Out of margin	0	0	0	0
	Percentage within margin	100%	100%	100%	100%

Figure 11 presents the successful number of range estimation using various processing schemes at SNR between 0 dB to 20 dB, with 10 dB incremental. Meanwhile, a range error measured with four processing schemes and at different SNR levels illustrates in *Figure 12*. The probability of error defines the ability of the setup to produce a right decision within the maximum error threshold of 7.5 m. All setups were producing a high percentage of error at low SNR level and improved with incremental of SNR level. The setup with proposed joint BA-SA displayed the best performance by producing 20% of error at 5.9 dB, leading other setups. It was followed by MIMO+BA setup, MIMO+SA setup and finally, SISO.

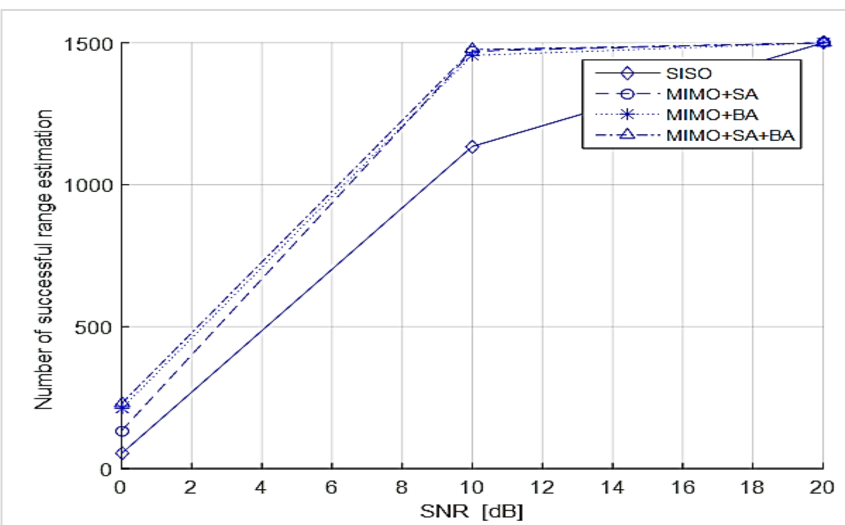


Figure 11 Number of successful range estimation using various processing schemes at 0 dB, 10 dB and 20 dB SNR

Next, error parameter was observed in terms of error mean. Error mean reflects the accuracy of the estimation produced by the system. At low SNR, all configurations present a high error mean caused by signal was submerged by noise at the receiver, and it drops rapidly between 0 dB to 10 dB. The joint configuration produced mean error below 7.5 m at 6.3 dB. Setup MIMO+BA, MIMO+SA and SISO, each produced the same performance at 6.9 dB, 7.2 dB and 11.1 dB respectively. The proposed joint BA-SA approach was observed to have better performance at lower SNR quality.

To investigate the performance of the proposed method, RMSE and SI were also employed. The RMSE is proportional to the observed mean value, thus, SI provides a non-dimensional error measurement, which make both parameters as a good measure for evaluating the error performance. From graph (c) and (d) in *Figure 12*, we can observe that the joint BA-SA method is producing better RMSE at a lower quality of SNR. However, it has a slightly higher SI compared to other averaging methods. Overall, performance for all MIMO with various signal averaging techniques provides a huge improvement in terms of the observed error parameters over SNR. *Table 3* tabulates the range error parameter values between 0 dB to 30 dB with 10 dB incremental.

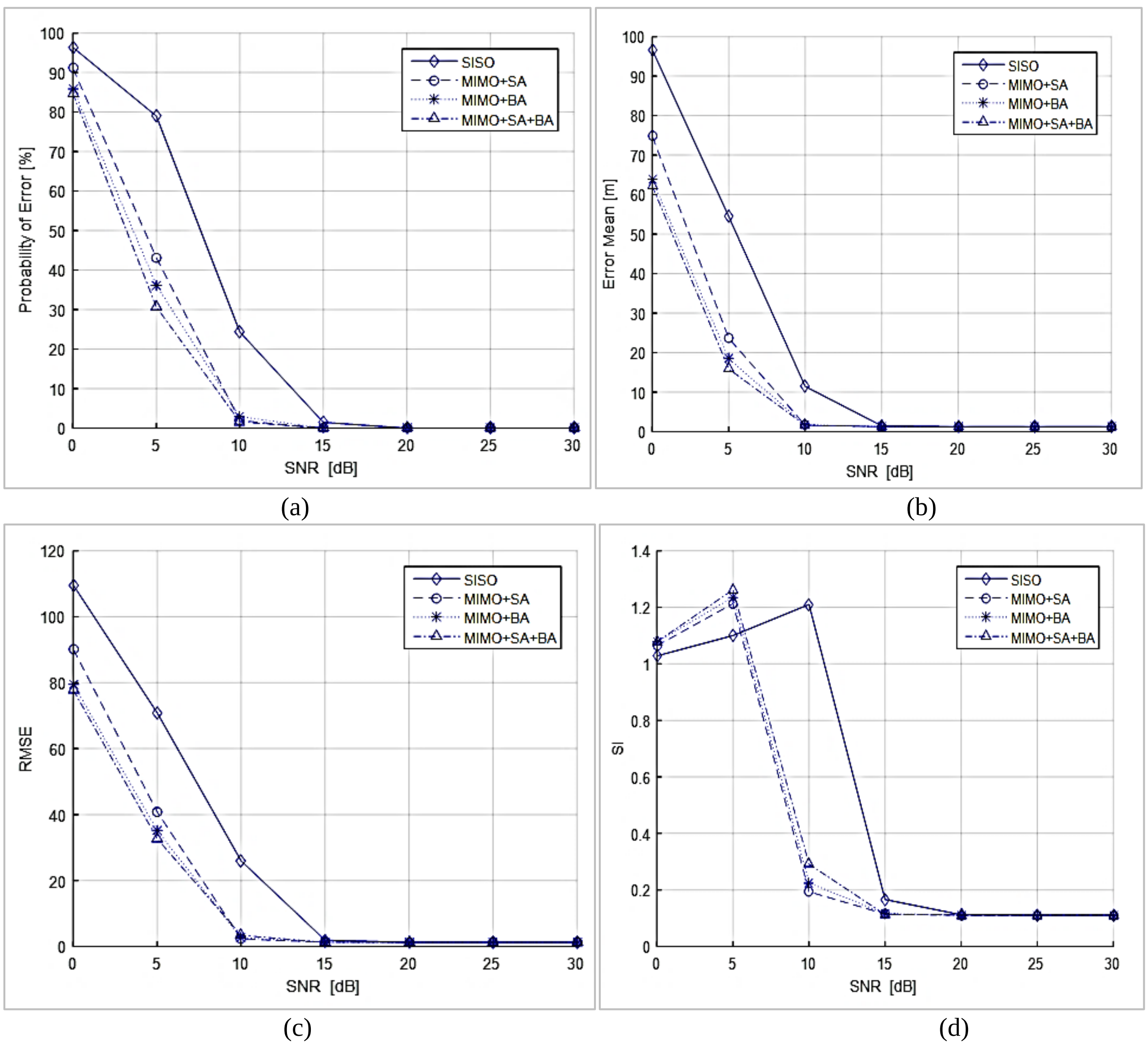


Figure 12 Range error measurement using various radar configuration and processing schemes at different SNR level: (a) probability of error, (b) error mean, (c) RMSE and (d) SI.

Table 3 Range error readings by various processing schemes and FMCW radar configurations

SNR	Range Error	Configuration & Processing Scheme			
		SISO	MIMO + SA	MIMO + BA	MIMO + Joint BA-SA
0 dB	Probability	96.4%	91.13%	85.93%	84.73%
	Mean	96.65	74.8	63.89	62.19
	RMSE	109.6	90.17	79.56	77.78
	SI	1.028	1.064	1.077	1.078
10 dB	Probability	24.33%	1.933%	2.93%	1.6%
	Mean	11.45	1.653	1.743	1.652
	RMSE	25.95	2.256	2.637	3.393
	SI	1.21	0.1936	0.2246	0.2912
20 dB	Probability	0%	0%	0%	0%
	Mean	1.255	1.25	1.25	1.25
	RMSE	1.255	1.25	1.25	1.25
	SI	0.1122	0.1111	0.1111	0.1111
30 dB	Probability	0%	0%	0%	0%
	Mean	1.25	1.25	1.25	1.25
	RMSE	1.25	1.25	1.25	1.25
	SI	0.1111	0.1111	0.1111	0.1111

Next, frequency spectrums from various averaging schemes and radar configuration were analysed in *Figure 13.* Spectrums for MIMO+SA produced slightly higher peak magnitudes, while spectrum for MIMO+BA produced slightly lower peak magnitudes due to its averaging mechanism. Thus, the joint BA+SA method inherits the quality of high magnitude of the peak. On the other hand, the MIMO+BA yielded a low flooring magnitude of the spectrum at an average of -20 dB. The MIMO+SA yielded a higher flooring magnitude of the spectrum at an average of -12 dB. It made the joint BA-SA method carry the quality of low flooring magnitude. These characteristics of high peak and low flooring magnitudes brought into the proposed joint scheme increased the signal peaks to be easily distinguished and contributed to range estimation improvement.

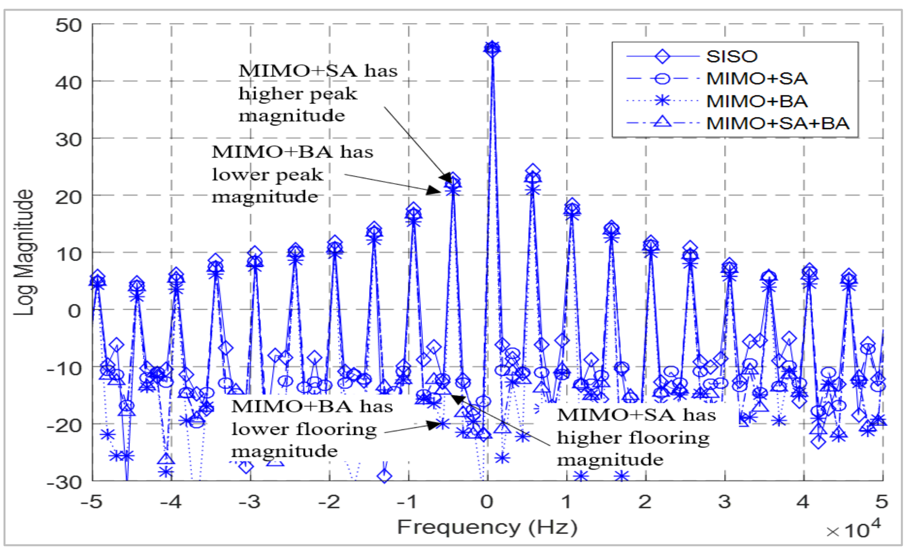


Figure 13 Frequency spectrum of various signal averaging schemes and radar configurations

5.Discussion

From the result, we observed that implementation of MIMO increased the accuracy through better range estimation compared to a single node setup. Furthermore, the application of the processing scheme contributed to the better signal enhancement, providing better signal quality. By utilising the real capture data, signals were processed for BA [33] and SA [13]. Both detection performance resembles the behaviour presented in literature with MIMO was performing better than SISO configuration, over SNR. However, there was no work done on comparison between these two averaging approaches.

From observation from both literatures, BA shall perform slightly better compared to SA which satisfied with the performance obtained in this research work. Next, the proposed approach of BA-SA joint two averaging approaches was introduced an alternative to reduce the number of FFT processing in the SA scheme while improving the target detection capability for a fluctuating object. Analysis from spectrum presented the characteristic of the BA spectrum to have lower flooring magnitude and SA spectrum to have higher peak magnitude. Hence, the combination of these averaging schemes yields a higher peak magnitude with lower flooring magnitude in frequency spectrum. It resulted in more distinguish and significant peaks to be applied for peak detection. The improvement brings by this proposed method is proven through the range error analysis.

Limitation

An experiment was conducted using COTS with a limited number of samples allowed. Besides, other parameters also based on the specification of the module.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

In this paper, the error performance of MIMO radar with various signal averaging schemes for detection a slow-fluctuating object has been demonstrated and compared to a SISO configuration. A COTS FMCW module namely D2G by Infineon Technologies were utilised for data acquisition in field experiments. Results indicate the improvement contributed by signal averaging of multi-frequency MIMO. The MIMO radar configuration which applying the joint BA-SA averaging scheme yields the best result compared to other signal averaging schemes. From observation, this scheme inherits the quality of high peak magnitude from SA scheme and low flooring magnitude from the BA scheme which produces a better spike in the frequency spectrum for peak detection. However, the proposed solution comes with a trade-off between complexity of processing and accuracy which was not examined further in this research work.

Acknowledgment

This work was supported by the Collaborative Research in Engineering, Science and Technology (CREST) Malaysia under CREST R&D Grant, project T05C1-67. The authors would like to thank the Faculty of Electrical and Electronic Engineering Technology (FTKEE), Universiti Teknikal Malaysia Melaka, Research and Innovation Management Center (CRIM) and Universiti Teknologi MARA for all the supports.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Suraya Zainuddin: Conceptualization, investigation, data collection, interpretation of result, writing – original draft and funding. **Nur Emileen Abd Rashid**: Conceptualization, writing-review and supervision. **Idnin Pasya Ibrahim:** Conceptualization, writing-review and supervision. **Khairul Khaizi Mohd Sharifff:** Writing review and editing. **Zahariah Manap**: Analysis result and editing.

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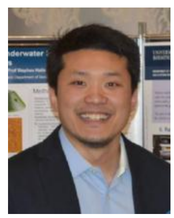

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Appendix I

S. No.	Abbreviation	Description
1	AWGN	Additive White Gaussian Noise
2	BA	Beat Averaging
3	BA-SA	Beat-Spectrum Averaging
4	BW	Bandwidth
5	COTS	Commercial-Off-The-Shelf
6	D2G	Distance2Go
7	FFT	Fast Fourier Transform
8	FMCW	Frequency Modulated Continuous Waveform

9	GUI	Graphic User Interface
10	IMST	Innovation in Manufacturing System and Technology
11	ISM	Industrial, Scientific and Medical
12	LiDAR	Light Detection and Ranging
13	MAV	Micro Aerial Vehicles
14	MIMO	Multiple-Input Multiple-Output
15	PSD	Power Spectral Density
16	RCS	Radar Cross Section
17	RMS	Root Mean Square
18	RMSE	Root Mean Square Error
19	SA	Spectrum Averaging
20	SI	Scattering Index
21	STFT	Short Time Fourier Transform
22	SISO	Single-Input Single-Output
23	SNR	Signal-to-Noise Ratio
24	SSA	Space Situational Awareness
25	UWB	Ultrawide Band