Probability of Detection of Ultra Wideband (UWB) Multi-Input Multi-Output (MIMO) Radar Considering Radar Cross Section (RCS) Characteristics of Vehicular Target.

Fadilla 'Atyka bt Nor Rashid
Faculty of Electrical Engineering
Universiti Teknologi Mara
40450, Shah Alam, Selangor, Malaysia
fadilla.atyka@gmail.com

***Abstract*—Nowadays, ultra wideband (UWB) signals has become a solution to the most important problems in observing radar target due to various advantages brought by its frequency diversity. UWB permits better data to be acquired due to frequency dependence and the high time resolution of the scattering centers over the extremely wide bandwidth. On the other hand, multi-input multi-output (MIMO) antenna systems have been developed in recent years to improve target detection and localization. MIMO capitalizes on the independence between signals from different transmitters and on the diversity of target scattering to improve the information received from the response. Motivated by the benefits of MIMO and advantages of using UWB signals, this paper presents the probability of detection by using UWB MIMO radar while considering radar cross section (RCS) characteristics of vehicular target. A new RCS model will be developed for wideband signal based on actual measurement data. Then, distribution fitting will be carried out to select the best fit to the wideband RCS data. Next, this study will study the detection performance of UWB MIMO radar integrated with the measurement-based RCS model; through numerical simulation of the radar performance. Simulation results indicated that the detection performance was better in terms of signal-to-noise ratio (SNR) when using full band UWB signal in MIMO radars.**

***Keywords*—Ultra Wideband, UWB, Multi-input Multi-output, MIMO, Radar Cross Section, RCS.**

I. INTRODUCTION

Radar, (RAdio Detection And Ranging) is a system of electromagnetic to detect and locate reflecting objects such as ships, aircraft, vehicles, people and the natural environment [1]. Radar meets expectations by transmitting the vitality into the space and distinguishing the reverberation sign reflecting from an item, or target. Thither are many cases of radar and each case of the radar depends on the diligence itself.

The most basic radar systems basically use a pair radar at transmitter and receiver, defined as a single-input single-output SISO either a monostatic radar or a bi-static radar system. SISO Radar is adequately a standard radio channel that the transmitter runs with one antenna and then does the recipient. At that point, no diversity and no additional processing needed. SISO does not have to process in terms of the diverse kinds of diversity that may be utilized. Though, interference and fading will severely impact the performance of a SISO radar system.

On the other hand, MIMO Radar can be delineated as an array radar system that affects the transmission and reception of different signals from each antenna in the array. This radar has been described by using multiple transmitting antennas to simultaneously transmit multiple waveforms and using multiple receiving antennas to receive reflected signals. MIMO Radar has many benefits from its multiple transmitter and receiver as it can be implemented in the agriculture application based on bistatic SAR Configuration. The MIMO radar system seems to be the best solution to be applied in many areas of applications especially in the agriculture sector. Furthermore, the second example clarifies the application of MIMO radar to acquire a diversity gain to control fades in target RCS. Diversity gains are usually used for target detection and direction finding. In both cases, the target is motionless and it is pragmatic along with a background of white Gaussian noise.

SISO radar uses narrowband transmission. Narrowband MIMO radar, as well as all narrowband radars are sensitive to RCS fluctuations. RCS fluctuations severely degrade the probability of detection while in localization applications the SNR significantly reduced. Hence, degrading the accuracy of target localization. On the other hand, it is difficult to operate with high-speed data communication as the receiver use a narrow bandwidth. The usage of wideband signal can reduce the effect of fluctuating RCS.

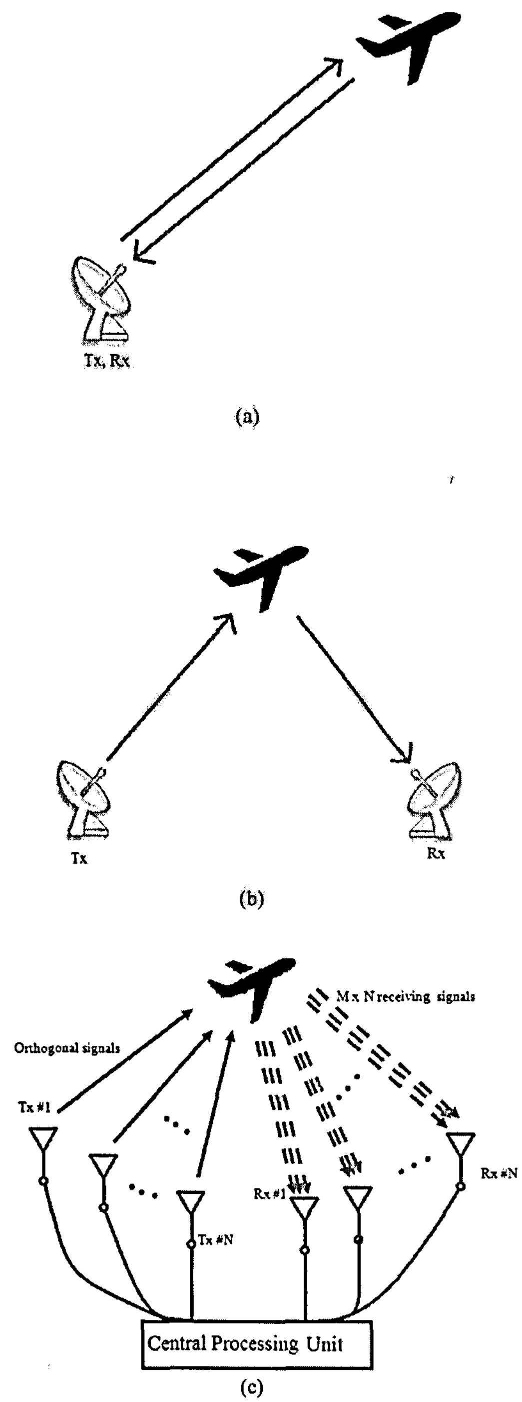

Fig 1: Comparison of basic radar geometry; (a) monostatic, (b) bistatic, (c) MIMO.

However, conventional RCS models such as the Swerling Models, are incompatible with wideband signal. Integrating conventional models to predict the performance of wideband MIMO radar can lead to errors and inaccurate results. Thus, this research will evaluate the performance of MIMO radar systems in terms of probability of detection, while considering RCS observed using UWB signal. The RCS will be statistically modeled based on actual measurements of an automobile illuminated using UWB signal [2]. Although several works have reported some results in RCS of vehicles, they have never been rigorously analyzed in the case of UWB signal, and have not been studies for the case of MIMO radars [3, 4]. Numerical simulations of detection probability of MIMO radars will be presented while integrating the modeled RCS characteristics.

II. SIMULATION MODEL

Initially, a simulation model was constructed to numerically investigate the detection performance of the *m*-sequence-based MIMO radar system in ideal cases, assuming perfect synchronizing between each of the respective transmitter and receiver pairs. Fig. 2 depicted the block diagram of the simulation model. Major parameters of the simulation model are summarized in Table 1. Each transmitter emits a unique *m*-sequence which was generated by a 7-step shift registers. In order to guarantee the orthogonality between these signals, utilization of codes with low cross-correlation properties is essential.

In this study, we chose a set of preferred pair *m*-sequence as listed in Table 1. The signal are sampled at 2.5GS/s and filtered to occupy 500MHz of bandwidth. At every receiver, a matched filter corresponding to each transmitting sequence was implemented. Hence, a total of $M \times N$ signals will available to be process at the centralized processing unit as all the arriving signal will be matched filtering at the receiver. Independent Gaussian noise is added to each of the receiving signals to model the overall system noise, which we assumed to be mainly contributed by thermal noise [5].

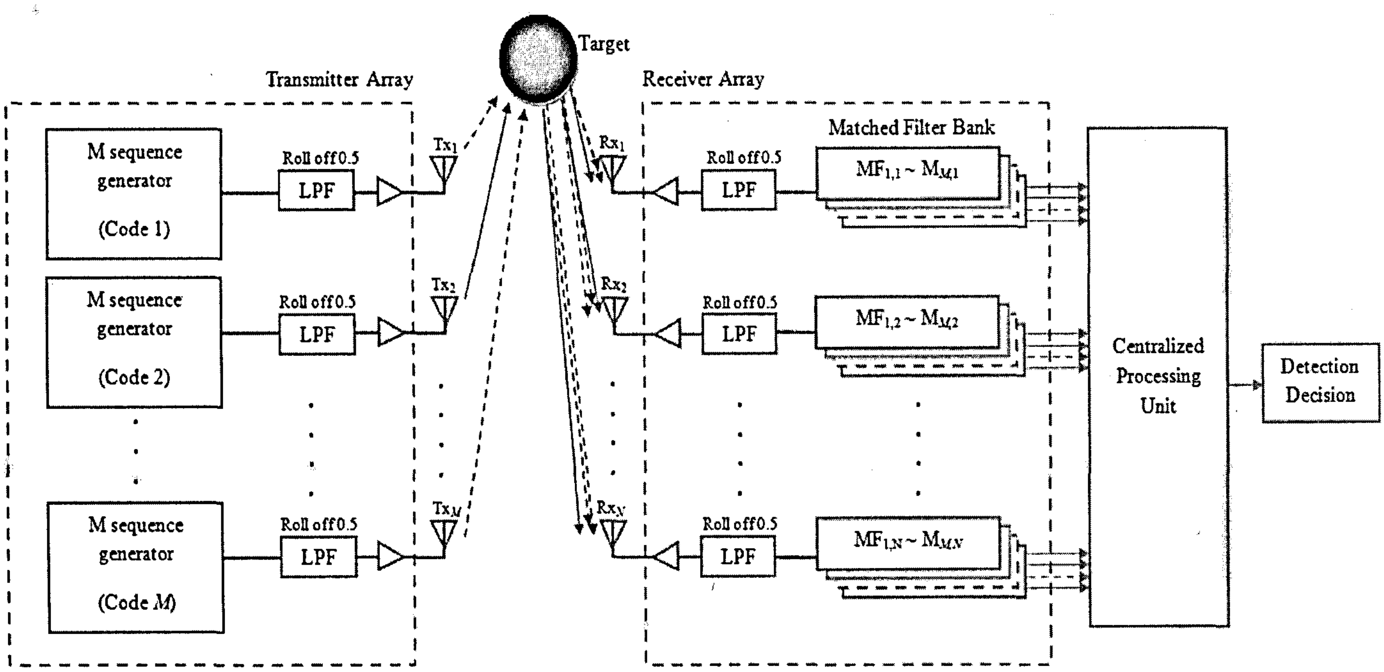

Fig 2: Block Diagram of Simulation MIMO Radar System

Table 1: Simulation parameters

Parameters	Description
Sampling rate	2.5GS/s
Filter roll-off factor	0.5
Oversampling	5
Bandwidth	500 MHz
MIMO configuration	2×2, 3×3, 4×4
M-sequence (code length)	Order of 7 (127)
M-sequence code set	(7,1) (7,3,2,1) (7,5,3,1) (7,6,5,3,2,1)
Number of simulated data points in each iteration	100 000

The example of simulated MIMO radar waveforms and their cross-correlation properties are depicted in Fig. 3, illustrating the importance of the MIMO radar system was evaluated against varying SNR, for the sake of simplicity; we simulated the detection performance using $M = N$, varying the configuration from 2 x 2 until 4 x 4. The SNR is defined as the ratio of the average of the total signal power, to the total noise power at the receiver. In the simulations, the P_{fa} was fixed at 10^{-5} for all cases.

Hence, we plotted P_{fa} curve of each *m*-sequences as a function of threshold value where only white Gaussian noise with zero mean and normalized variances is input to the receiver. Figure 4 shows the simulated P_{fa} of the MIMO radar for each the *m*-sequence used to compare to the theoretical curve of SISO. The detection performance versus SNR was plotted in Figure 5. It is shown that the *m*-sequences yielded improvements in detection probability compared to the SISO case.

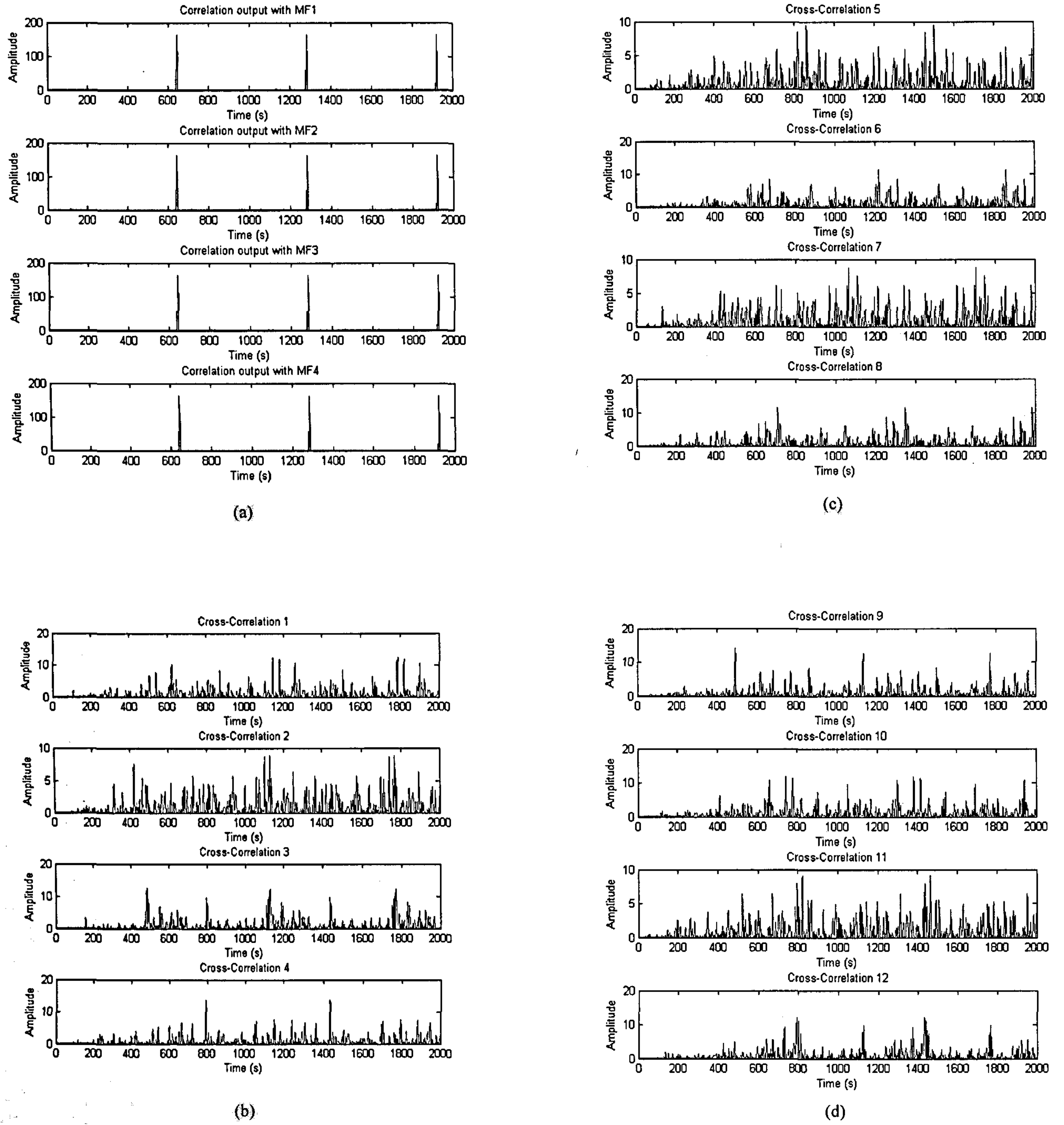

Fig 3: Example of MIMO Cross Correlation (4 x 4)

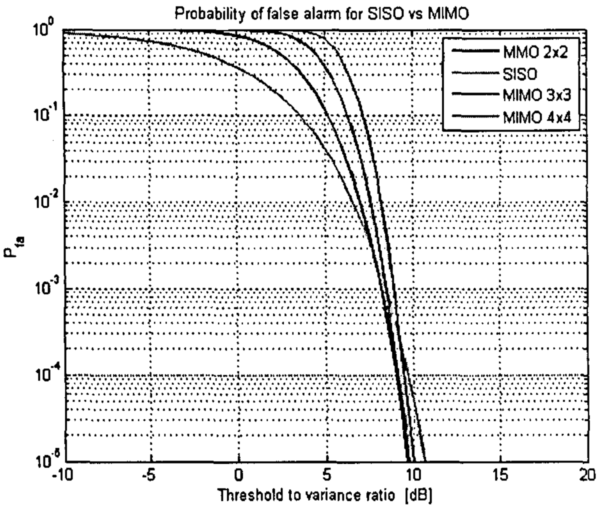

Fig 4: Probability of False Alarm for SISO versus MIMO ($P_{fa} = 10^{-5}$)

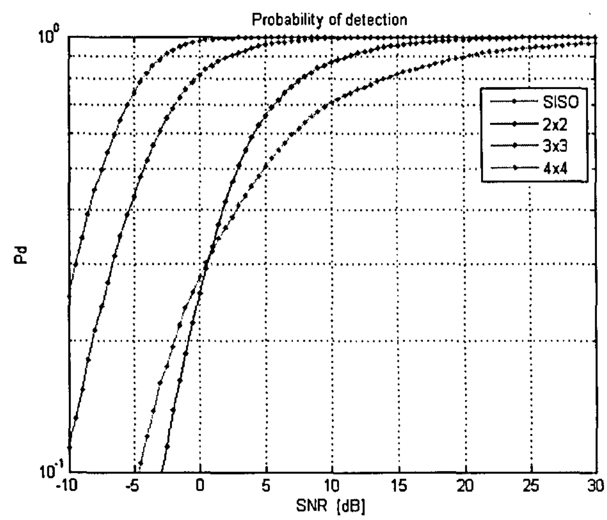

Fig 5: Probability of Detection for MIMO radars and SISO (Constant RCS)

III. STATISTICAL ANALYSIS OF RCS DATA

In the case of UWB MIMO radar, a model that considers the RCS throughout the UWB signal bandwidth is required. An experiment has been conducted in detecting a vehicular target. The experiment was done from the previous researcher [7]. The measurement data was taken to include observation angle from 0° to 360°, illuminated with UWB signal with frequency 22 -29 GHz (using 1 GHz, 3 GHz, 5GHz and 7 GHz bandwidth). For each case of bandwidth, the RCS were evaluated after calculating the power integration over the UWB bandwidth.

$$P_w = 10 \log \left\{ k \int_{f_L}^{f_H} 10^{(P(\text{linear})*f/10)} \right\} \qquad \text{(i)}$$

where k is the inverse of fractional bandwidth, $f_H - f_L$. Here f_H is the highest frequency and f_L is the lowest frequency. Measurement in a radio anechoic chamber will be done for pedestrian RCS to scrutinize the simulated results. The measurements will be done using a vector network analyzer as the transceiver and wideband antennas, on several subjects with different form-factors. The result of the calculated wideband RCS from the data collected in the experiment above was analyzed using a Chi-Squared Goodness of Fit test.

Goodness of Fit (GOF) tests computes the similarity of a random sample with a theoretical probability distribution function. In other words, these tests show how well the distribution selected fits to the data. In this study, a GOF test that has been chosen to be use as distribution test is a Chi Squared test. The test statistic is a chi-square random variable (x^2) defined by the following equation:

$$x^2 = \sum \left(\frac{(O_i - E_i)^2}{E_i} \right) \qquad \text{(ii)}$$

the results from the Chi-Squared test of the most fitting distribution has been tabulate and ranked as below:

Table 3: Distribution Rank

	1GHz	3GHz	5GHz	7GHz
1	Lognormal	Lognormal	Lognormal	Weibull
2	Weibull	Weibull	Weibull	Lognormal
3	Gamma	Exponential	Exponential	Exponential
4	exponential	Gen. Pareto	Gamma	Gen. Pareto

Hence, from the results above we can conclude that the partially band (BW : 1GHz, 3GHz, 5GHz) are best fitted by lognormal distribution which cumulative distribution function is given by

$$f(x) = \Phi \left(\frac{\ln x - \mu}{\sigma} \right) \qquad \text{(iii)}$$

where μ, σ, and Φ are the shape, scale parameters and laplace integral resepectively. While for the full band (BW: 7 GHz), the data is best fitted by Weibull Distribution. Therefore, the targets considered in the simulation were modeled to have Lognormal distributed RCS for bandwidth of 1, 3 and 5 GHz, and Weibull distributed RCS for 7 GHz bandwidth (fullband UWB signal), which cumulative distribution function is given by

$$f(x) = 1 - \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \qquad \text{(iv)}$$

where α and β are the shape and scale parameters, respectively. The values of α and β were selected so as to equal the RCS median of the vehicular targets.

IV. RESULTS AND DISCUSSION

UWB radars mostly use single transmit-receive systems or multi-static single transmit-multiple receive systems. Some systems use multiple pulses at the transmitter and pulse integration at the receiver to enhance SNR. This section compares different approaches with the proposed UWB MIMO radar.

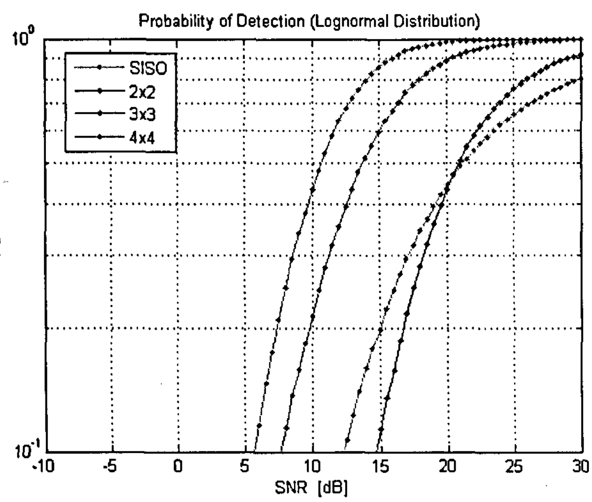

Fig 5: Simulated Lognormal Distribution for MIMO and SISO (BW: 1GHz, 3GHz, 5GHz)

Fig. 5 shows the simulation of probability detection in Lognormal Distribution. This distribution is best fitted by the partially band (1 GHz, 3 GHz, 5 GHz).The graph below, prove that *m*-sequences MIMO radars were better than SISO. While between the *m*-sequences, 4x4 is leading for a better SNR. However, Fig. 6 illustrates the probability of detection for full band (7 GHz) using Weibull Distribution which is the best fitted for the bandwidth. This graph also proves that MIMO radar enhanced SNR much better than SISO. And once again, 4x4 sequences are better at detecting vehicular target.

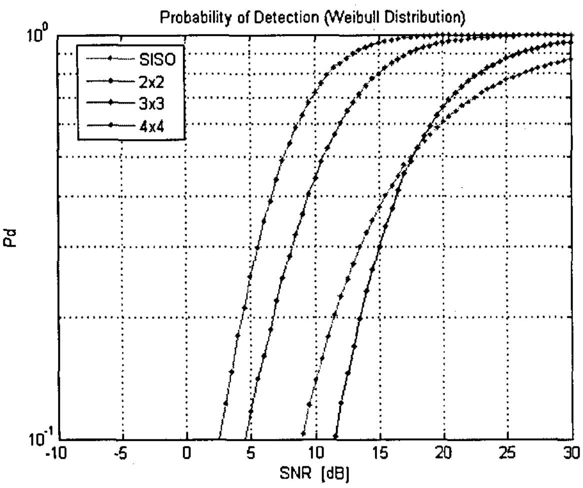

Fig 6: Simulated Weibull Distribution for MIMO and SISO (BW: 7GHz)

Next, from the illustrated Lognormal and Weibull distribution, we can clearly state that Weibull Distribution does better than Lognormal. It can be defined at P_d = 0.8 (80%), Weibull Distribution enhanced SNR by 3 dB than Lognormal Distribution. This result indicated that a fullband UWB signal requires 3 dB lower radiation power compared to partial band UWB signal, to achieve similar Pd. This is attributable to maximum frequency diversity effects that can be achieved by fully exploiting the full bandwidth of UWB signal. The simulation results presented in this paper also showed that it is important to consider accurate RCS characteristics of targets in deriving the detection probability of MIMO radar systems.

V. CONCLUSION

This paper has presented simulation results of the probability of detection on UWB MIMO radar systems considering RCS characteristics of vehicular target. The RCS of the targets were analyzed based on existing data of experimental measurements of the RCS of an automobile using UWB signal. The results showed that the detection probability of MIMO radars were better when using full band UWB signal compared to partial usage of the bandwidth, approximately 3 dB in SNR. In addition, MIMO radars contribute higher P_d compared to SISO systems, as they use larger number of antennas as the transmitters and receivers.

REFERENCES

[1] M. I. Skolnik, "Introduction to radar," *Radar Handbook*, vol. 2, 1962.

[2] T. Kobayashi, N. Takahashi, M. Yoshikawa, K. Tsunoda, and N. Tenno, "Measurement of Automobile UWB Radar Cross Sections at Ka Band," in *Ultra-Wideband, Short-Pulse Electromagnetics 7*, F. Sabath,

E. Mokole, U. Schenk, and D. Nitsch, Eds., ed: Springer New York, 2007, pp. 586-592.

[3] C. Pengfei, S. Meric, R. El-Makhour, O. Lafond, and M. Himdi, "Investigating the influence of rotating steel platform in the RCS measurement of vehicles at 22–26 GHz for automotive radar application," in *Antennas and Propagation (EuCAP), 2013 7th European Conference on*, 2013, pp. 3606-3610.

[4] I. Matsunami, R. Nakamura, and A. Kajiwara, "RCS measurements for vehicles and pedestrian at 26 and 79GHz," in *Signal Processing and Communication Systems (ICSPCS), 2012 6th International Conference on*, 2012, pp. 1-4.

[5] I. Pasya and T. Kobayashi, "Simulation of time jitter effects on the detection performance of M-sequence-based MIMO radar systems," in *Radio and Wireless Symposium (RWS), 2013 IEEE*, 2013, pp. 208-210.

[6] A. Lee and M. Mason, "MATLAB simulation for computing probability of detection," in *Radar Conference, 2002. Proceedings of the IEEE*, 2002, pp. 478-483.

[7] I. Pasya, N. Iwakiri, and T. Kobayashi, "Performance of joint direction-of-departure and direction-of-arrival estimation in UWB MIMO radars detecting targets with fluctuating radar cross sections," in *European Radar Conference (EuRAD), 2014 11th*, 2014, pp. 277-280.

[8] M. Akcakaya and A. Nehorai, "MIMO radar sensitivity analysis for target detection," in *Radar Conference (RADAR), 2011 IEEE*, 2011, pp. 633-638.

[9] S. Bin, W. Xuezhi, B. Moran, and L. Xiang, "Target tracking using range and RCS measurements in a MIMO radar network," in *Radar Conference 2013, IET International*, 2013, pp. 1-6.

[10] P. F. Sammartino, C. J. Baker, and H. D. Griffiths, "Target Model Effects on MIMO Radar Performance," in *Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on*, 2006, pp. V-V.

[11] F. C. Commission, "In the matter of revision of part 15 of the commission's rules regarding ultra-wideband transmission systems, First Report and Order," ed: Apr, 2002.

[12] M. T. Frankford, K. B. Stewart, N. Majurec, and J. T. Johnson, "Numerical and experimental studies of target detection with MIMO radar," *Aerospace and Electronic Systems, IEEE Transactions on*, vol. 50, pp. 1569-1577, 2014.

[13] H. A. Khan, W. Q. Malik, D. J. Edwards, and C. J. Stevens, "Ultra wideband multiple-input multiple-output radar," in *Radar Conference, 2005 IEEE International*, 2005, pp. 900-904.

[14] F. Yuanzhang, Y. Zhiliang, B. Xiangyuan, and A. Jianping, "Radar waveform design and multi-target detection in vehicular applications," in *Estimation, Detection and Information Fusion (ICEDIF), 2015 International Conference on*, 2015, pp. 286-289.

[15] I. Matsunami, N. Ryohei, and A. Kajiwara, "Target state estimation using RCS characteristics for 26GHz short-range vehicular radar," in *Radar (Radar), 2013 International Conference on*, 2013, pp. 304-308.