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Drone Detection and Classification using Passive Forward Scattering Radar

Muhammad Azharudin Che Mamat[1], Noor Hafizah Abdul Aziz[1*]

[1]School of Electrical Engineering, Faculty of Electrical Engineering,
Universiti Teknologi MARA, Shah Alam, 40450, Selangor, MALAYSIA

*Corresponding Author

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Abstract: Radar is a system that can analyze object detection that uses radio waves to determine the range, angle or velocity of the object. The passive radar system consists of both transmitters, to generate microwaves domain and produce the electromagnetic waves for radio system, and the receiver, to receive and process the data obtain from the transmitter signal to determine the Doppler signature of the objects that can be used to detect any presence of drone, aircraft and guided missiles that pass through the system between the transmitter and receiver. The objective of this study was mainly to detect drones, which can be liken to a situation where an unmanned aerial vehicle (UAV) is used, and the drone is mainly used by humans to enter or trespass private and secured zone. Besides that, this study can help improve the security at Malaysian borders or at important events, such as during the latest Malaysian 14th General Election, where man flew a drone during the nomination process. The detection can be done by differentiating the size of the drone and prototype, with a focus on the dimension. In this study, we used passive forward scattering radar for drone detection to get the Doppler signature. The Doppler signature is produced when the antenna detects the presence of the drone passing between the transmitter and receiver. The transmitter produces a power signal that transmits a frequency of Long-Term Evolution (LTE), and in this study, the frequencies used were 1.8 GHz and 2.6 GHz. The 1.8 GHz signal provided better quality compared to 2.6 GHz because it has wider and better network coverage known as 4G LTE as introduced by Maxis provider. Furthermore, all of the data collected was processed and analyzed using MATLAB software to classify drone and prototype signatures through Principal Component Analysis (PCA) results. For future contribution of this project, it can be used at the airport to detect any unwanted drones trespassing the flight departure area, and important areas such as the Federal Administrative Centre of Malaysia, Putrajaya for spying purposes.

Keywords: Doppler signature, drone, forward scattering, passive radar.

1. Introduction

Radar is commonly used in detection of objects and it locates the object or person by the reflection of electromagnetic waves. Radar operation is through radiating the electromagnetic waves into free space and the echo signal is reflected back to the receiver. The reflected signal indicates where the object or person is located. By comparing the transmitted and received signal, the location and distance of the object or person can be determined [1]. However, a radar system that only consists of a receiver and can receive the entire signal from any transmitter tower is called the passive radar [2].

Passive radar can be defined as a system where the receiver antenna receives radio waves that is transmitted by existing telecommunication transmitter antenna in the area. In this project, the passive forward scattering (FSR) radar was used to detect a drone. The FSR can be used to detect a moving target and can reach up to 180 degrees of range for

*Corresponding author: noor4083@uitm.edu.my

detection [3], [4]. The moving target between the transmitter and receiver will diffract the signal around the target to give the silhouette area, which can be analyzed. Furthermore, to detect the moving target in FSR, the transmitter and receiver must be in a straight line to get the line of sight while the moving target is moving between the systems [5]. FSR provides a lot of interesting features such as the generally simple hardware, an improved target radar cross section, a long coherent interval of the receiving signal, protection from stealth technology and possible operation using non-cooperative transmitter [6],[7].

Meanwhile, studies on passive radar with forward scatter radar mode have been carried out by several researchers. GPS signals is considered to be one of the signal for passive radar system, as demonstrated in [8], [9] for air target detection, and in [10] for ground target detection. A research using GSM as a signal source that utilized the forward scatter geometry for target detection is explained in [11]. Recent publications on passive forward scatter radar by exploiting the actual LTE signal transmitted through the air from the base station had classified three different vehicles into three different categories [7].

All of the process for the data gathered, from processing and analyzing, was done using MATLAB software. The principal component was analyzed to prove the drone detection in the area. The purpose of a principle component analysis is to decrease the dimensionality of data collection that comprises of a substantial number of interrelated variables [12].

2. Methodology

2.1 Drone and Prototype of Drone as a Moving Target

In this project, a drone and a prototype were used as the moving targets. The results were collected at two different locations, which are at Taman Suria, Science and Technology (S&T) Tower UiTM Shah Alam and Teratai Homestay 2 at Kuala Terengganu, Terengganu. Additionally, this project differentiated the Doppler signature of the drone and the prototype with different frequencies. The frequencies used in this project were 1.8 GHz and 2.6 GHz. Table 1 shows the information of the moving target silhouette, which were the drone and the prototype. Nowadays, due to variety of shape and size of drone, we chose the prototype size as reference to compare to the real size of a drone that has four propellers. In the future, the size of drone might be smaller and harder to detect. Thus, for the first detection of drone using Passive Forward Scattering Radar system, the prototype was designed with a measurement of 0.2 m (height), 0.4 m (length) and 0.08 m2 (dimension), which was slightly larger than the real drone in this experiment.

Table 1 - Information of the drone and prototype

Silhouette	Height (m)	Length (m)	Dimension (m^2)
 **Drone**	0.193	0.35	0.06755
 **Prototype**	0.2	0.4	0.08

2.2 Experimental Site

The first experiment was done at Taman Suria, Science and Technology (S&T) Tower UiTM Shah Alam, Malaysia at the latitude and longitude of 3.07°, 101.49°. The telecommunication transmitter antenna there transmits a signal power strength of 1.8 GHz and 2.6 GHz, which was located 187.5 meter away from the radar receiver. The passive radar system was used as a receiver to receive the signal. Figure 1 shows the location of the experiment as mentioned above. Besides that, the spectrum analyzer was used to measure the power of spectrum of known and unknown signal from which provider. Figure 2 and Figure 3 indicate the signal strength for 1.8 GHz and 2.6 GHz frequency at the experiment site, respectively. The power for signal of 1.8 GHz was -21 dB and for 2.6 GHz was -30 dB.

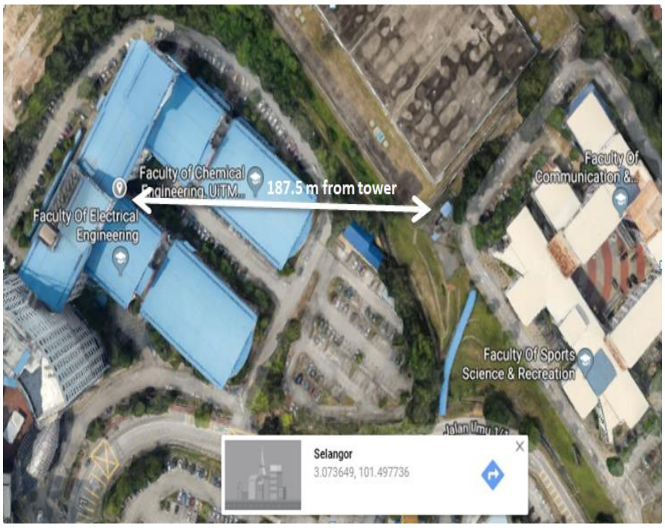

Fig. 1 – Experiment site at Taman Suria, UiTM Shah Alam

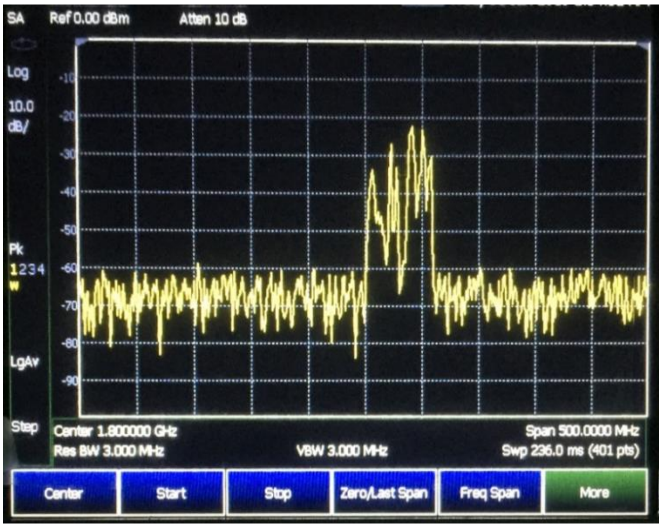

Fig. 2 – Spectrum analyzer for 1.8 GHz at Taman Suria

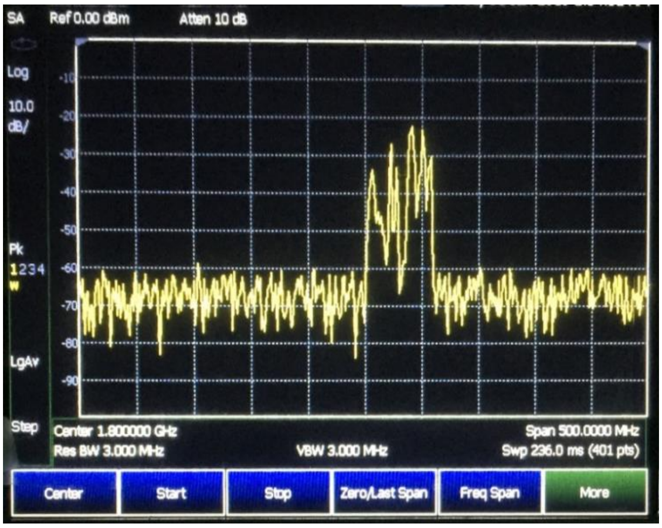

Fig. 3 – Spectrum analyzer for 1.8 GHz at Taman Suria

The second location was at Teratai Homestay 2, Kuala Terengganu, Malaysia. The latitude and longitude of the destination is 5.29°, 103.15°, and was chosen because the location was near to a telecommunication transmitter antenna. The LTE base station was strong enough to do the experiment. Before setting up the experiment, the perfect angle was determined to get the strongest signal from the target transmitter antenna due to the presence of other transmitter antennas near the location of the experiment. Then, the receiver antenna was set up with a range of 609 meter away from the commercial transmitter antenna, as shown in Figure 4. The transmitter signal frequency used in this experiment was only 1.8 GHz due to no other provider with a signal of 2.6 GHz was around. Furthermore, the signal strength for this experiment site is shown in Figure 5, where the signal was 1.8 GHz with power for signal at -25 dB.

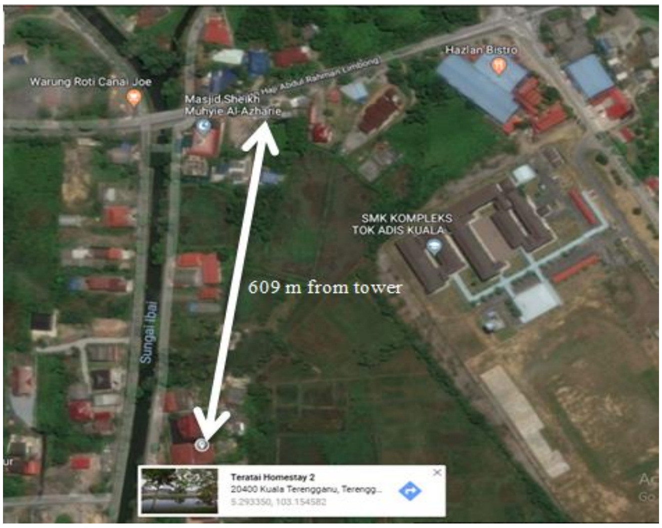

Fig. 4 – Experiment site at Kuala Terengganu, Terengganu

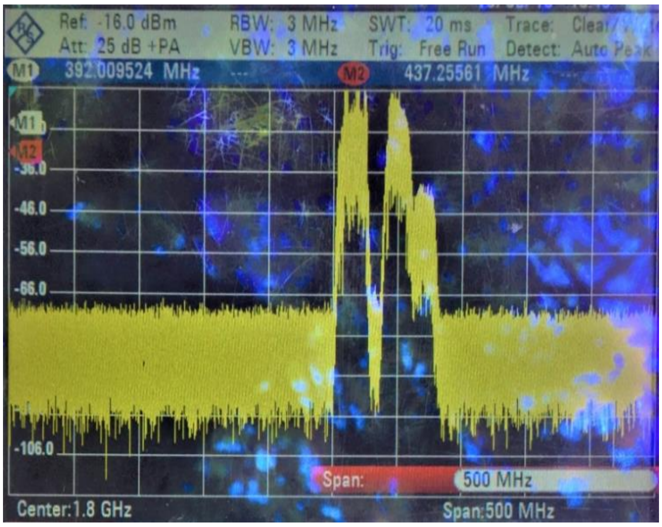

Fig. 5 – Spectrum analyzer for 1.8 GHz at Kuala Terengganu

The arrangement of the baseline experiment is illustrated in Figure 6. The radar system shows the drone as the moving target that flies through between the transmitter and receiver.

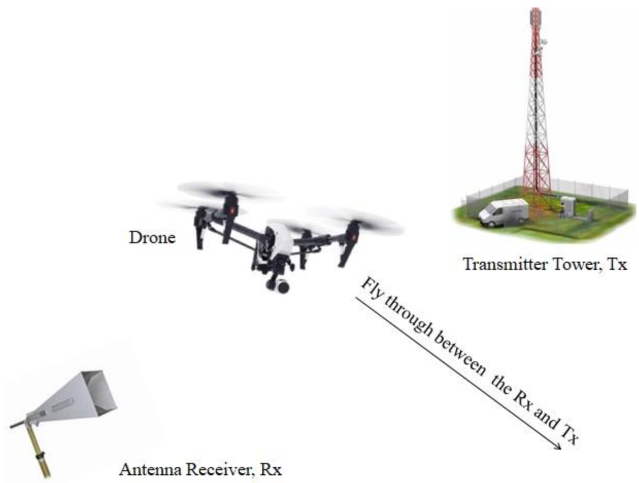

Fig. 6 – Spectrum analyzer for 1.8 GHz at Kuala Terengganu

2.3 Experimental Site

All of the data collected during the experiment were processed and analyzed by using the MATLAB software. This software is a high-level technical computing language for data visualization, data analysis and data processing to optimize the process for solving the problem. The steps for processing the data using MATLAB software is different to obtain different kinds of results shown in the graphs. Furthermore, perfect and complete signal wave patterns can be obtained by MATLAB software and the moving target can be classified.

Figure 7 shows specifically all the steps for the data analyzing process using MATLAB software. The Doppler data was set to 20 seconds to collect the data, and then it will analyze to get the drone and prototype Doppler signatures. Besides that, the data was segmented to 2 seconds only to get the drone and prototype Doppler signatures. After the data segmentation, noise from the raw data was denoised, where the unwanted noise was removed via the denoising process that was already coded in MATLAB. Next, in the Power Spectral Density (PSD) graph, the denoised data is plotted. Lastly, some of the values are represented in the scatter plot through Principal Component Analysis (PCA) process before the classification of the drone and prototype data.

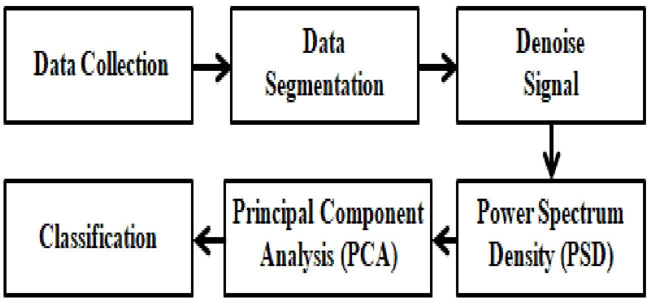

Fig. 7 – The flowchart of data analysis process

3. Results and Discussion

3.1 Time Domain After Denoising Process

Based on the results, the time domain signal acquired after denoising the unwanted signal will show the Doppler signature of the drone and prototype. The Doppler signature of the target was different at Taman Suria and Kuala Terengganu with respect to frequency. But, the denoising process did not remove all the unwanted noise in the signal obtain because the MATLAB software did not just detect the Doppler signature.

Throughout the experiment, the time taken for the data in the denoising process was set to 2 seconds. Figure 8, Figure 9 and Figure 10 show the denoised signal for the drone and prototype based on different places and different frequency. Figure 8 shows the denoised signal for the drone and prototype for 1.8 GHz at Taman Suria. The blue line indicates the Doppler signature signal for the drone and red line indicates the prototype.

For the drone, the Doppler signature was quite similar to that of the prototype but it had a small signal level compared to the prototype. In addition, the time taken for the drone was faster than the prototype due to the dimension of the drone being smaller. For the drone, the time taken was 0.41 seconds, while the prototype took 0.76 seconds.

Figure 9 explains the time domain for the drone and prototype at Taman Suria for 2.6 GHz. For the drone, the time taken was 0.42 seconds and the prototype, 1.09 seconds. Lastly, the time taken at Kuala Terengganu for 1.8 GHz was 0.37 seconds for the drone and 0.89 seconds for the prototype, as shown in Figure 10.

At Kuala Terengganu, the signal frequency presence in the area was only 1.8 GHz. Signal with a frequency of 2.6 GHz was not available in the area. But, the signal was strong enough to do the experiment to get the Doppler signature of the drone and prototype. As we can see, the Doppler signature can be clearly seen at both ends of the signal when the horn antenna, which is the receiver, receives the signal from the transmitter with the moving target between them. Both the drone and prototype produces different Doppler signature with different times, which depend on the drone and prototype's dimension. The dimension of the moving target increases with the time domain for each drone and prototype in the experiment.

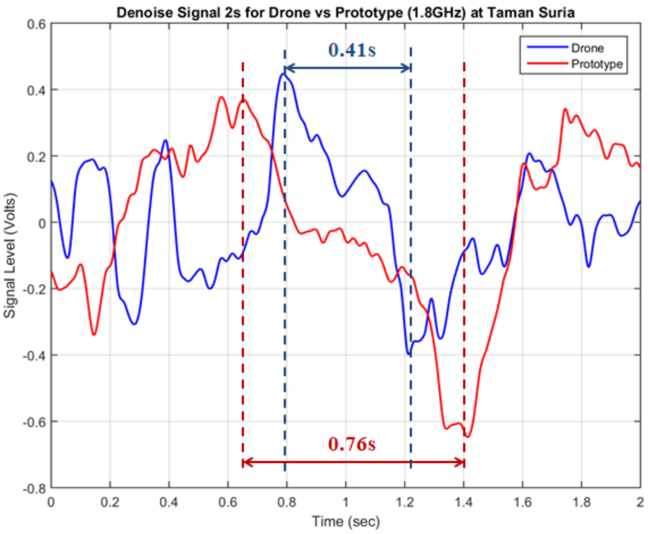

Fig. 8 – Time domain for drone versus prototype with a frequency of 1.8 GHz at Taman Suria, UiTM

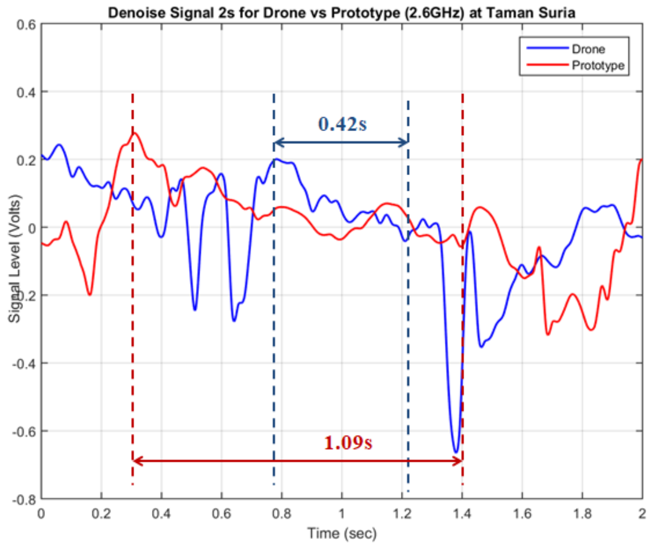

Fig. 9 – Time domain for drone versus prototype with a frequency of 2.6 GHz at Taman Suria, UiTM

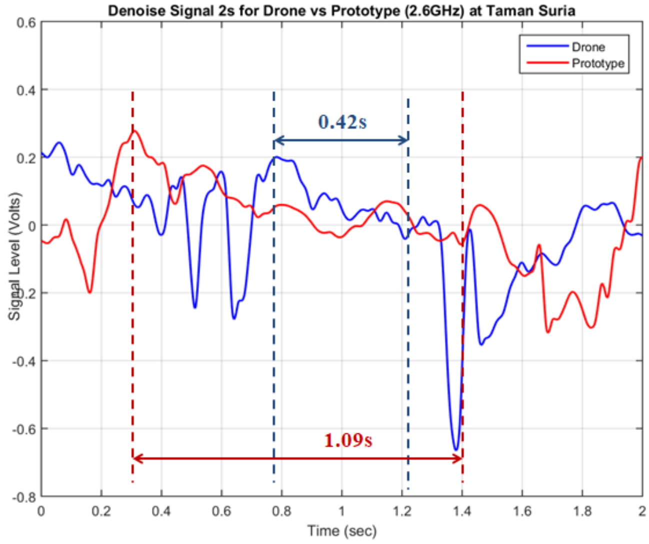

Fig. 10 – Time domain for drone versus prototype with a frequency of 1.8 GHz at Kuala Terengganu

3.2 Power Spectral Density of Drone and Prototype Detection

Power Spectral Density (PSD) with normalization was used to evaluate all signal data in the form of power frequency. The denoised signal from previous time domain results was converted to the frequency domain by using a Fast Fourier Transform (FFT). Figure 11, Figure 12 and Figure 13 show the PSD result of the drone and prototype at Taman Suria and Kuala Terengganu by a graph with normalized power (dB) against frequency (Hz).

The frequency drop can be explained by the dimension of the drone and prototype that can be attributed to the size being almost the same, which were 0.06755m2 and 0.08m2 according to Table 1. Figure 11 shows the PSD at Taman Suria with a frequency signal of 1.8 GHz. The normalized power for the drone was -30 dB and the frequency was 1.9 Hz. For the prototype, the normalized power and frequency were -40 dB and 3.2 Hz. Figure 12 shows the PSD for the drone and prototype at Taman Suria with 2.6 GHz frequency signal. From the PSD result obtained, the normalized power and frequency for drone were -30 dB and 2.5 Hz, while for the prototype were -24 dB and 3.4 Hz. Lastly, the PSD result at Kuala Terengganu, which used frequency signal of 1.8 GHz, is as shown in Figure 13. The normalized power and frequency obtained for drone were -31 dB and 2.3 Hz. While for the prototype, the normalized power and frequency were -40 dB and 2.8 Hz.

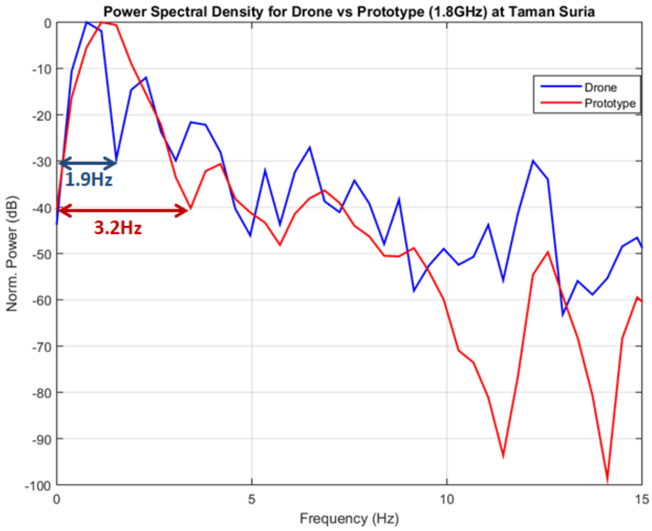

Fig. 11 – Power Spectral Density for drone versus prototype with a frequency of 1.8 GHz at Taman Suria, UiTM

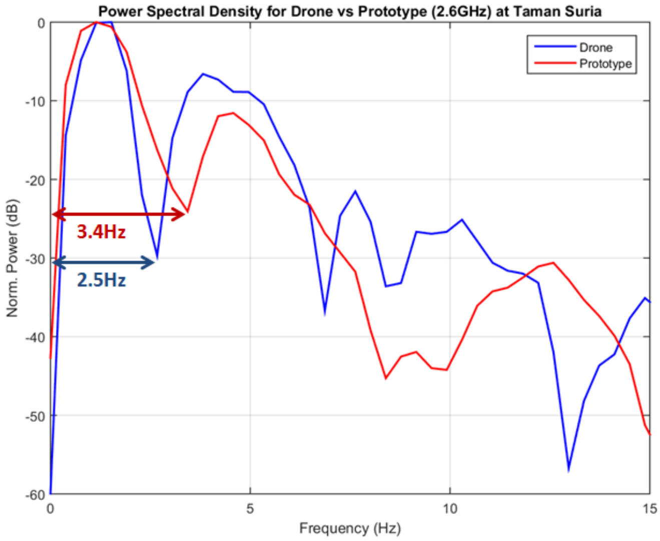

Fig. 12 – Power Spectral Density for drone versus prototype with a frequency of 2.6 G Hz at Taman Suria, UiTM

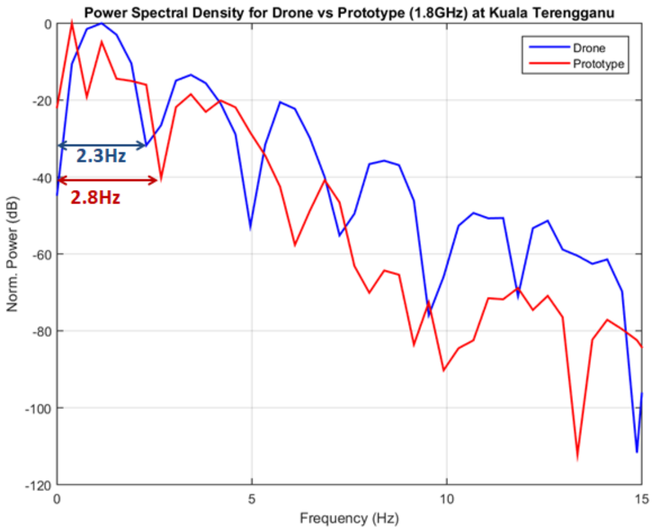

Fig. 13 – Power Spectral Density for drone versus prototype with a frequency of 1.8 GHz at Kuala Terengganu

3.3 Principal Component Analysis

Principle Component Analysis (PCA) is used to convert processed data into linearly uncorrelated variables that is principle components [12]. The feature extraction of spectral signature is identified as Principal Component (PC), where the PC1 indicates the maximum amount of variance in the data, while the PC2 indicates the subsequent maximum and so forth. The PCs are organized where the variance amount of data explained by each PC has decreased. Generally, the first few principal components are essential to exemplify the information contained within the data extraction. Subsequently, PCA could carry out a linear transformation from the spectral feature vector, v into the principal component space that produces the unique feature vector, V as in equation (1) [13]:

$$V = W.(\mathrm{v} - \bar{x})^T \tag{1}$$

where $\bar{x}$ is a mean feature vector of training data, *W* is transformation matrix. Through the PCA result, it can differentiate the pattern of the drone and prototype at the specific area. A significant study used another approached on feature extraction by using K-Mean techniques with Euclidean distance as dissimilarity and cosine similarity [14].

The result of PCA at Taman Suria for 1.8 GHz and 2.6 GHz are shown in Figure 14 and Figure 15. The blue dots indicate the drone, and the red dots represent the prototype. Based on Figure 14 and Figure 15, the result of the PCA shows that the clusters for the drone and prototype overlap each other due to their dimensions being almost the same. In Figure 14, the drone and prototype clusters overlap more compared to those in Figure 15 because the signal strength and quality for frequency signal of 1.8 GHz was stronger and better quality with low noise compared to 2.6 GHz. Moreover, the good quality signal at Taman Suria is attributed to the transmitter being located near the radar receiver at 187.5 meter away. In addition, the good blockage by the surrounding buildings helped the signal from being interrupted with other signals from different transmitter towers, which lead to good quality signal received. The small overlapping in PCA is interesting as it depends on the capability of the analysis system, and this project is shown to have proficiently classified the drone and prototype that had only a small difference in size.

Next, the result of PCA at Kuala Terengganu is shown in Figure 16 for the signal of 1.8 GHz only because there was no signal with 2.6 GHz present near the experiment site. The clusters did not overlap due to the LTE signal being strong enough to get the Doppler signature of the drone and prototype even though the distance between the LTE transmitter and passive radar receiver was 609 meter. Moreover, the area of the experiment site was an open space without any blockage that can make the signal interrupted by other signals that can lead to interference during the experiment.

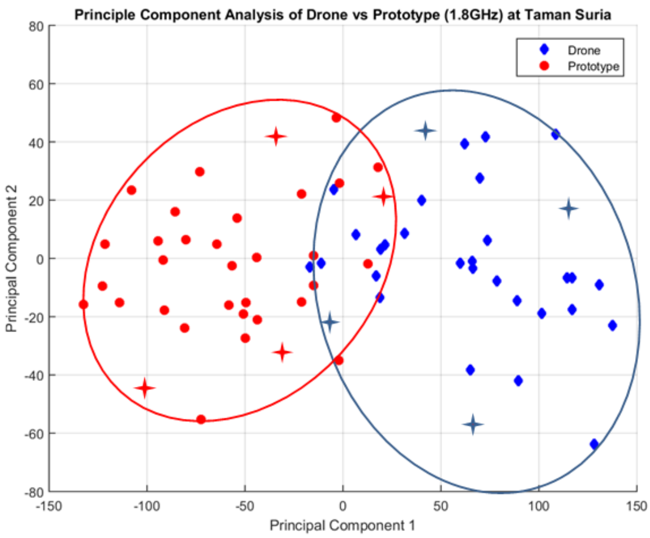

Fig. 14 – Principal Component Analysis for drone versus prototype with a frequency of 1.8 GHz at Taman Suria, UiTM

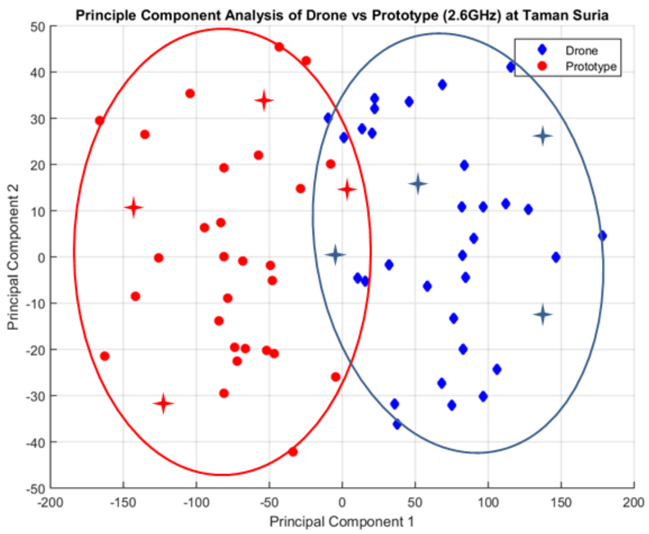

Fig. 15 – Principal Component Analysis for drone versus prototype with a frequency of 2.6 GHz at Taman Suria, UiTM

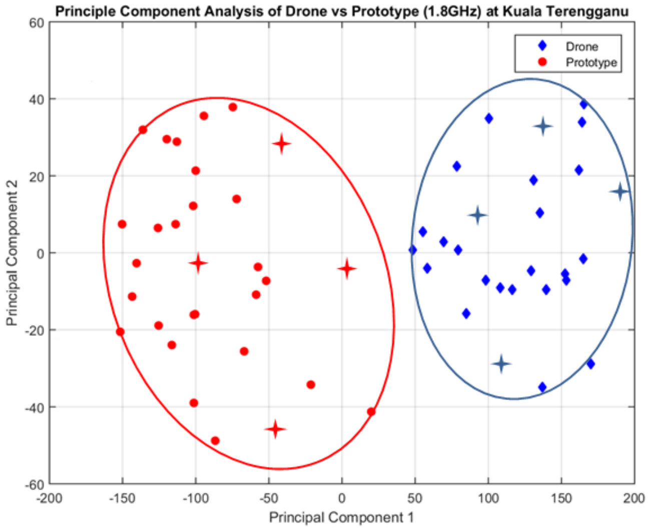

Fig. 16 – Principal Component Analysis for drone versus prototype with a frequency of 1.8 GHz at Kuala Terengganu

3.4 Confusion Matrix

Confusion matrix is a method used to determine the precision and performance of the classifier. The evaluation is tabulated in the form of percentages. Table 2, Table 3 and Table 4 indicate the confusion matrix of the drone and prototype at different locations and with different frequency used.

In Table 2, the confusion matrix done was for the drone and prototype at Taman Suria with 1.8 GHz frequency signal. For the drone and prototype, training samples were 29 and 31, respectively, while the number of testing samples were 4 and 4, respectively. The percentage of classification was calculated based on how many testing data at each target silhouette was in their region of PCA cluster, else it is considered as misclassifications that interfered other speed of cluster. As shown in Table 2, the testing result shows 75% data for both targets successfully stayed in their drone cluster and prototype cluster. The testing was easily automatically classified because the signal strength for 1.8 GHz is much better compared to 2.6 GHz. This result is validated by the power received at the passive radar using a frequency of 1.8 GHz, as shown in Figure 2, being -21 dB, which is larger than 2.6 GHz as shown in Figure 3 with only -30 dB. For signal frequency of 2.6 GHz, the result of confusion matrix is shown in Table 3. It shows the same results, where 75% of data successfully stayed in their clusters. Overall testing of the confusion matrix at Taman Suria was very good due to better signal quality and the transmitter being close to the receiver.

The number of training samples was decided to be above 20 samples due to the durability of the drone's battery to fly the drone. The total data taken for training varied due to uncontrolled environment that may differ from day to day as it can be sunny, cloudy, windy, rainy or stormy, which is the typical climate in tropical Malaysia that have an impact in data collection. However, this project is focused on target detection and classification, and it was still able to compare the drone and prototype even though their sizes were almost the same in height and width.

For Table 4, the result in PCA for the drone and prototype taken in Kuala Terengganu shows the confusion matrix, where 100% of the data successfully stayed in the clusters. The clusters are not overlapped due to the signal strength at Kuala Terengganu being strong enough to get the Doppler signature of the drone and prototype. Therefore, the drone and prototype obtained 100% success because of the the silhouette can be easily seen in the results of time domain. Thus, the Doppler signature can be differentiated and classified easily.

The confusion matrix for 1.8 GHz at Taman Suria, Shah Alam and Kuala Terengganu are not the same, even though the frequency used is the same, because of the LTE signal power level received by the passive radar system is dissimilar. Other factors that influenced the results are multiple LTE frequencies from different LTE providers and different angles of tower location. In Taman Suria, Shah Alam, there were three LTE signal frequencies from three angles of tower location, which interfered the received signal at the passive radar system. Compared to Kuala Terengganu, even though there were two LTE frequencies, both signals were from the same angle of direction, which amplified the power received at the passive radar receiver.

Table 2 – Confusion matrix for 1.8 GHz at Taman Suria

Target Silhouette	**No. of samples**		**Automatically classified (100%)**	
	Training	Testing	Drone	Prototype
Drone	29	4	**75**	25
Prototype	31	4	25	**75**

Table 3 – Confusion matrix for 2.6 GHz at Taman Suria

Target Silhouette	**No. of samples**		**Automatically classified (100%)**	
	Training	Testing	Drone	Prototype
Drone	31	4	**75**	25
Prototype	28	4	25	**75**

Table 4 – Confusion matrix for 1.8 GHz at Kuala Terengganu

Target Silhouette	**No. of samples**		**Automatically classified (100%)**	
	Training	Testing	Drone	Prototype
Drone	23	4	**100**	0
Prototype	25	4	0	**100**

4. Conlusion

In conclusion, the overall results clearly show that the PCA can be classified easily based on the drone and prototype dimensions, which are different from each other. Besides that, the difference of the experiment site also produced different data analysis due to the distance of the transmitter and receiver. The farther the distance between the receiver of the baseline experiment and commercial transmitter tower, the weaker the signal quality received. This will lead to difficulty in classifying the signal due to additional noise that interrupts the signal. In addition, blockage from the buildings is another matter that could be considered to block the signal from different transmitter tower to prevent the signal interference.

Furthermore, the strength of the signal with frequency of 1.8 GHz and 2.6 GHz is important to get better result. At the end of the study, it can be concluded that the signal with 1.8 GHz provided better quality of signal and stronger signal compared to 2.6 GHz to detect the drone and prototype. This is because 1.8 GHz is a 4G LTE network, which provided bigger coverage area and stronger signal strength. From that, a good result of data was received and it was proven by the Principle Component Analysis results with the average of successfulness in percentage of the confusion matrix. It can be concluded that the drone and prototype detection and classification using Passive Forward Scattering Radar system was successful by using real data obtained from the experiment work.

The great potential of this Passive Forward Scatter Radar system provides a new research area in passive radar that can be used for diverse remote monitoring, including border protection, microwave fences, building monitoring, traffic surveillance, and so forth. Henceforward, future LTE based passive forward scattering radar investigations may consider air targets such as helicopters, and sea targets such as battle ships, humans and animals.

For the future recommendation, the Passive Forward Scattering Radar system could use the signal from transmitter with 5 Generation Wireless System (5G) network that provide stronger, better quality and wider network coverage signal which can detect drone precisely and give the result of Doppler signature more clearly.

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