IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Analysis On Drone Detection and Classification in LTE-Based Passive Forward Scattering Radar System

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DOI: https://doi.org/10.30880/ijie.2023.15.03.011
Received 6 November 2022; Accepted 29 May 2023; Available online 15 August 2023

Abstract: Long-Term Evolution (LTE) is most commonly used in connection with 4G networks with high spectral efficiency, high peak data rates, flexible in frequency and bandwidth. By utilizing LTE signal in passive forward scattering radar as transmitter, this system is able to create a microwave domain at the radar's receiver part which generated a moving object's Doppler signature. The emergence of guided missiles, humans, airplanes, and drones that travel through between the forward scatter radar systems can really be spotted with this passive radar system. This study's primary goal is to employ passive forward scattering radar and an LTE signal to detect drones, which are commonly used by individuals to violate or invade private and secure places. In detail, a drone was detected at two distinct heights of two meters (lower) and three meters (higher) from the ground by utilizing passive forward scattering radar to generate Doppler signature of the flying drone. This experimental work is conducted at two locations which are Taman Suria (UiTM, Shah Alam) and Teluk Kemang (Port Dickson), due to the telecommunication transmitter antenna transmits Long-Term Evolution (LTE) signal with frequency of 1.8 GHz and 2.6 GHz. The results of drone detection at various heights were evaluated using Principal Component Analysis (PCA) on all the experimental data obtained. According to the evaluation, the lower height of the drone performed better in classification and confusion matrices analysis than the upper height due to a larger cross-sectional area for the lower height of the drone that travelled through the forward scatter zone. In summary, the overall study clearly demonstrates the effective categorization of flying drone detection at upper and lower positions in Principle Component Analysis (PCA). For future contribution of this research, 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: Passive radar, drone, detection, LTE, classification

1. Introduction

Radar is a target detecting device that utilizes radio waves to identify the angle, velocity, or range of objects. Radar also capable of detecting airplanes, ships, satellites, guided missiles, automobiles, climate patterns, and topography [1]. In this investigation, a Forward Scattering Radar (FSR) system was employed to identify drones. FSR is one type of bistatic radar that are used to identify and classify targets [2], [3].

Radar sends out radio waves or microwaves, which are reflected by any object in their path. The reflected waves are received and processed by a receiver radar. A passive radar system is one that just contains a receiving antenna.

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Thus, the passive radar lacks a transmitter. Hence, this system will emit radio waves using an existing commercial telecommunication antenna and receive them using its own reception antenna.

For the meantime, investigations regarding passive forward scatter radar (FSR) had been conducted by several researchers. Research using Global System for Mobile Communications (GSM) as an input signal that implemented the forward scatter geometry for object tracking is described in [4], [5], [6]. Subsequently, Global Positioning System (GPS) signals are also recognized to be among the signals for passive radar systems for air target identification, as validated in [7], [8]. Another research that used the real LTE signal transmitted the telco tower station also investigated on the detection and classification of ground moving target [9].

A passive FSR system had been employed in this study to identify the moving target such as an aerial drone, at various heights. A few incidents involving drone burglary have happened recently in several states which are Selangor, Kuala Lumpur, Perak, Johor, and Negeri Sembilan [10]. These are a concerning scenario because it is occurring in Malaysia. Drones have been used in burglaries to watch the owner of the property before invading it. This research can assist to strengthen security and protection against drone intrusions, especially near Malaysian borders or key events. This passive radar technology can assist police in eliminating this behavior by employing radar autonomously without operator supervision. The Doppler signature can be used to capture the signature of a moving drone. When an item in motion enters a radar system, the signal amplitude and frequency of the captured signiture will change. The variations in the signal are generated by signal scattering, which occurs when the signal collides with an object. The speed and size of the item, as well as the length of gap between the targeted object and the receiver, all have an impact on the signal. The passive radar detects movement in a given region, monitors those targets, and raises a notice if the targets cross into banned zones, which is known as the Doppler Effect [11]. Moreover, passive FSR provides several enticing features, including generally simple hardware, an enhanced target radar cross section, a long coherence interval of the receiving signal, stealth technology security, and the capacity to work with a non-cooperative transmitter [9], [12]. The Malaysian Communications and Multimedia Commission (MCMC) provide 4G Long Term Evolution (LTE) signals of 1.8 GHz and 2.6 GHz frequency to send signal from the telecommunications industry, as indicated in Fig. 1. Furthermore, the LTE frequency of 2.6 GHz is excellent for covering highly populated regions and managing huge volumes, but 1.8 GHz might give two times the coverage and superior indoor signal strength than 2.6 GHz. MATLAB software was used throughout the data collecting phase, as well as data processing and analysis. The principal component analysis (PCA) is implemented to establish drone detection in the region. PCA's real goal is to lower the size of the dataset with a significant number of related factors [13].

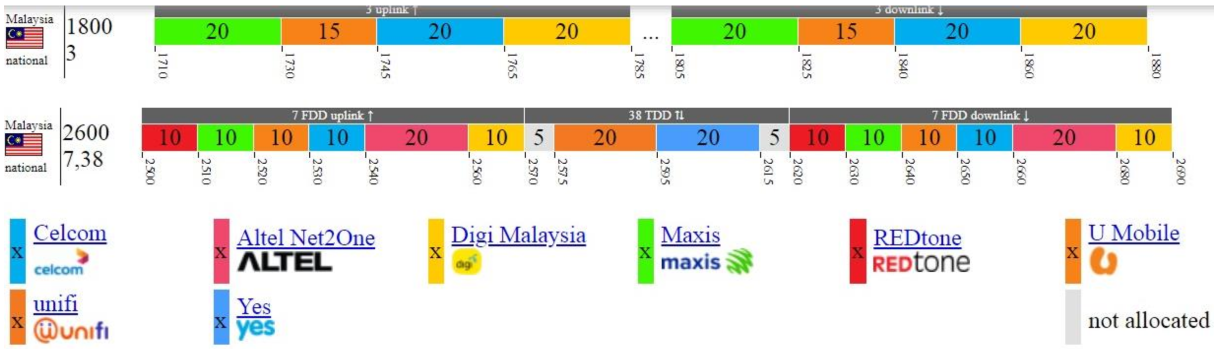


Fig. 1 - Malaysia's frequency bands [14]

2. Methodology

2.1 Signal Processing

To evaluate the process, all the data obtained throughout the study was evaluated and processed using the MATLAB computer software. This application demonstrates a high level of technical proficiency through evaluating and providing raw data in order to provide a structured visual output. When using the MATLAB program, there are a few actions that must be taken. There are several methods for obtaining distinct results that will appear in the graph display. Furthermore, using the MATLAB programme, the outcomes of every wave configuration and signal of a flying drone can be categorized.

As depicted in Fig. 2, these are all of the techniques to analyze data with MATLAB software. The Doppler signature duration is set to 20 seconds to capture the data. It will record and evaluate the target signature of the moving drone at various heights throughout that period. The Doppler was developed in data segmentation to record and evaluate the flying drone signature in 3 seconds. The raw data will next be subjected to the denoise procedure. At this point, all undesired signals is denoised by using MATLAB coding, leaving only the drone's virtually flawless signature. Following that, all of the denoise signal process's denoised data will be translated into the Power Spectral Density (PSD) frequency domain. Finally, the frequency domain in PCA will be used to signify several of the characteristics in the set of data. Afterward, during the classification operation, the signatures of drones flying at varying heights will be organized into their own cluster.

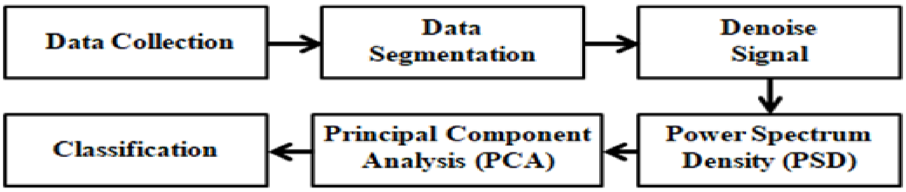


Fig. 2 - The steps of data analysis procedure

2.2 Drone as a Flying Target with Two Level of Heights and Experiment Sites

A moving drone has been employed as the moving object in this experiment, and its specifications have been listed in Table 1. For this project, two distinct heights were chosen as the modified parameter. The higher position had a height of 2 metres from the ground, while the lower position had a height of 3 metres from the ground. The 1.8 GHz and 2.6 GHz spectrum bands for 4G LTE transmissions are chosen for carrying signals from the telecommunications industry. Furthermore, the LTE frequency of 2.6 GHz is excellent for covering highly populated regions and managing huge volumes, but 1.8 GHz might give two times the coverage and superior indoor signal strength than 2.6 GHz.

Table 2 summarizes the quantity of samples obtained in each location and the frequencies with which they were collected. In Table 2, the total number of samples for 1.8 GHz at Taman Suria and Teluk Kemang, the upper position was 46 and the lower position was 45. While the total number of samples for 2.6 GHz at both locations were 25 and 23, for upper and lower positions, respectively. Only 1.8 GHz frequency present at Teluk Kemang because the transmitter tower does not transmit 2.6 GHz frequency of signal. The total number of samples taken at Teluk Kemang was 45. To test the accuracy classification of drone detection with different heights, the number of samples was divided into training and testing data. For testing purpose, there are only 4 data was taken into the upper position and lower position of drone in motion in Taman Suria and Teluk Kemang. The method is crucial in determining the precision during the classification of the data evaluation.

The variations in the sample size obtained at every location and frequency spectrum band attributed to the changing situations and conditions as it can be bright, foggy, raining, wet, or thundery, which is the usual weather in Malaysia, has an influence on data collecting.

Table 1 - The drone physical descriptions

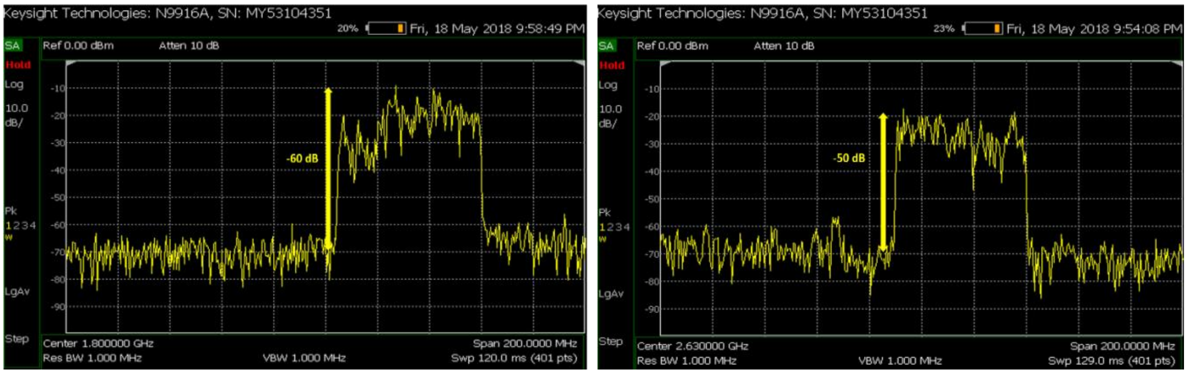
Silhouette	Height (m)	Length (m)	Dimension (m^2)	Material	Weight (g)	Battery power (mAh)
	0.193	0.35	0.06755	ABS (Acrylonitrile butadiene styrene)	645	2000

Table 2 - Details concerning number of samples

Location	Number of Samples							
	1.8 GHz				2.6 GHz			
	Upper		Lower		Upper		Lower	
	Training	Testing	Training	Testing	Training	Testing	Training	Testing
Taman Suria	20	4	18	4	21	4	19	4
Teluk Kemang	18	4	19	4	-	-	-	-
Total	38	8	37	8	21	4	19	4
	46		45		25		23	

Two distinct places must be suitable and appropriate to carry out this study. Several criteria and features required to be highlighted. For example, signal strength, gap length between transmitter and receiver, signal obstruction, and environmental well-being. The first experiment was carried out in Taman Suria, UiTM Shah Alam, Malaysia. The telecommunication transmitter antenna emits an LTE signal by using the 1.8 GHz and 2.6 GHz signal frequencies. The distance between the transmitter and the location of the receiver is at 187.5 metres. This location was chosen since it is close to a telecom transmitter antenna and has a good LTE signal. A spectrum analyzer is used to determine the power of the spectrum of known and unknown signals. The spectrum analyzer measurement for the frequency 1.8 GHz was -60 dB for signal power, as illustrated in Fig. 3 (a). While Fig. 3 (b) displays the signal power reading for 2.6 GHz, which is -50 dB. The location of the experiment in Taman Suria is seen in Fig. 4.

The second experiment location was chosen near the beach of Teluk Kemang, Port Dickson, Negeri Sembilan as indicated in Fig. 5 (a). The communications transmitter antenna was approximately 580 metres away from the radar receiving equipment. This area was chosen because it acts as a border with a seaside region where invaders generally cross the border. Depending upon the output of the spectrum analyzer, only 1.8 GHz signal was identified for this location. Before receiving the most excellent signal from the transmitter tower, the angle and location of the receiver needs to be adjusted. The best signal from the transmitter will arise from a precise location and angle. Figure 5 (b) depicts the 1.8 GHz signal strength. The signal frequency in Fig. 5 (b) is 1.8 GHz, with a power of -35 dB. Figure 6 depicts the benchmark test for drone identification, which started flying in between transmitter and receiver.



(a) **(b)**

Fig. 3 - LTE signal strength in Taman Suria at the frequency of (a) 1.8 GHz; (b) 2.6 GHz

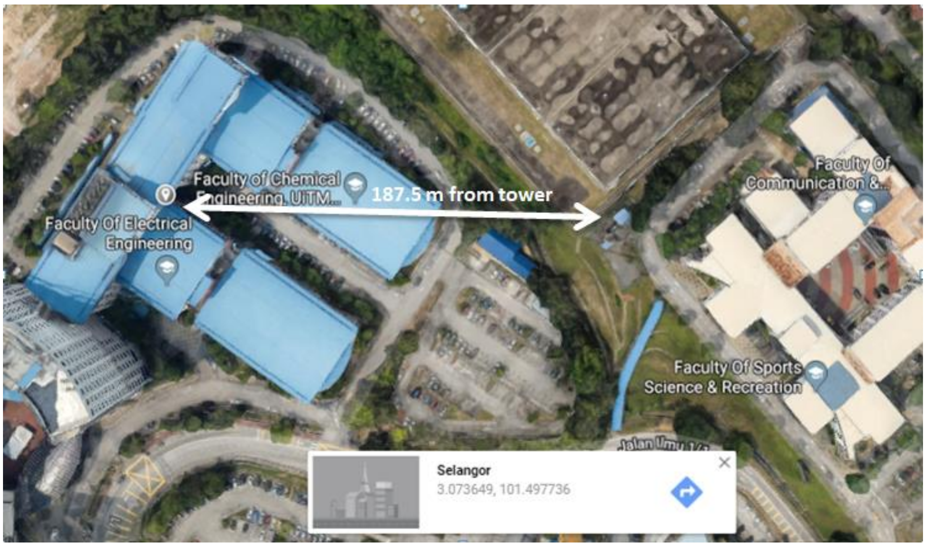
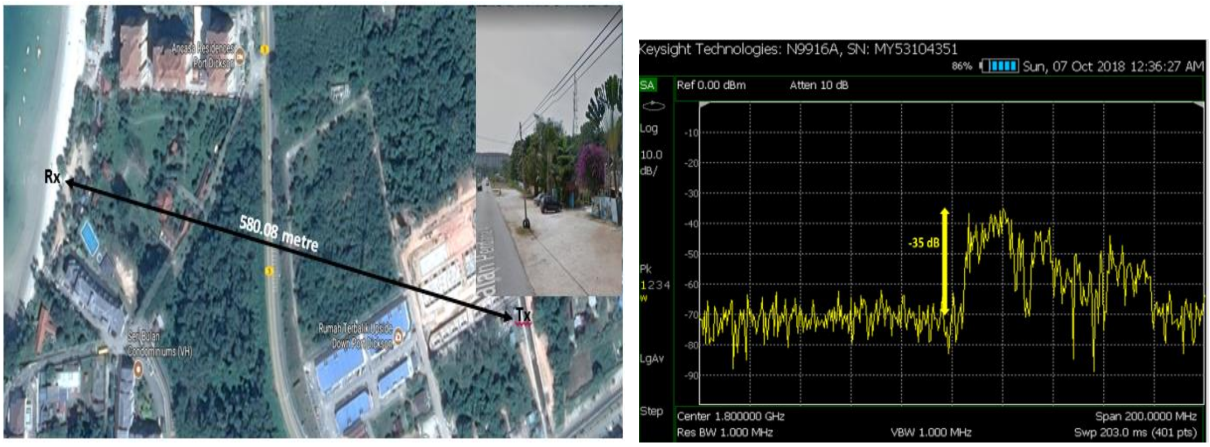


Fig. 4 - Experiment site at Taman Suria



(a) (b)

Fig. 5 - Teluk Kemang (a) experiment site; (b) LTE signal strength at frequency of 1.8 GHz

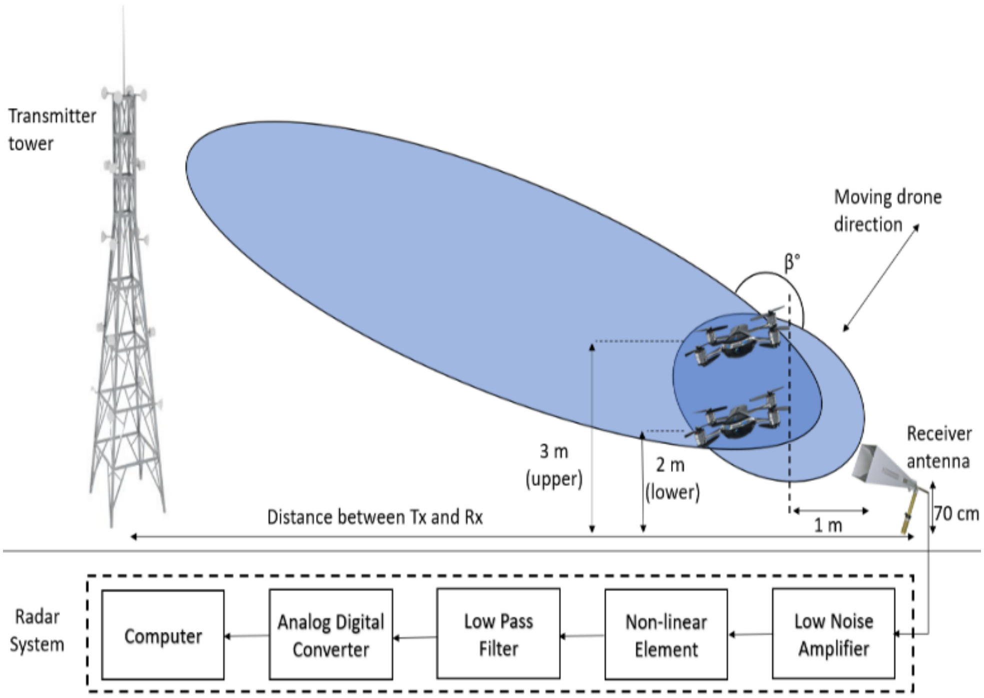


Fig. 6 - LTE-based PFSR layout to identify and categorize the data

3. Result and Discussion

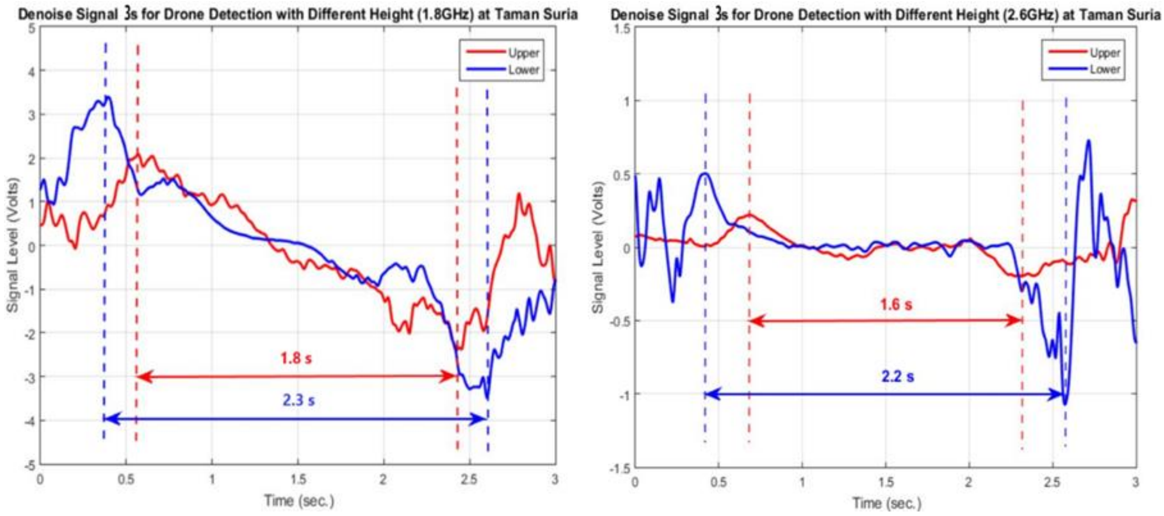
3.1 Time Domain After Denoise Process

After denoising undesired signal, the results showed that a time domain signal is required in order to depict the Doppler signature of the targeted drone in motion at various heights. Doppler signatures varied in in these two different locations due to the difference in frequencies. Even so, since MATLAB software could not recognize the Doppler signature on its own, the denoise process did not eliminate all of the undesirable signal in the resulting signal.

Fig. 7 and Fig. 8 demonstrate the denoised signature of the drone in motion at various heights. Despite the fact that the same drone was used in these studies, the signatures were different due to the different frequencies and areas. The red line represents the flying drone's upper position, while the blue line signifies its lower position.

Fig. 7 (a) depicts the time domain of a flying drone at various heights using a frequency of 1.8 GHz at Taman Suria. The upper position took about 1.8 seconds to pass between the transmitter and receiver, while the lower position took 2.3 seconds. There was only a 0.1 second difference in the time it took the drone to fly. Due to the same drone's structure, the signatures of the flying drone for these two different heights were quite identical. Figure 7 (b) depicts the time domain signal for the flying drone at different heights on the 2.6 Ghz frequency band in Taman Suria. In Taman Suria, the signal strength of 2.6 GHz frequency is quite weaker than 1.8 Ghz frequency. The drone flew in the upper position for 1.6 seconds between the receiver and transmitter, as illustrated in Fig. 7 (b). This was considerably different from the 2.2 seconds required for the similar drone's dimension to fly in the lower position.

Meanwhile, Fig. 8 depicts the detection of time domain at Teluk Kemang at 1.8G Hz signal frequency. The time it took the drone to travel at various heights diverged considerably. The drone required 1.9 seconds in the upper position, but just 2.5 seconds in the lower ones. However, the signal frequency measured from the Teluk Kemang transmitter was only 1.8 GHz. Despite having a significantly lower signal level than Taman Suria, Teluk Kemang could still be employed for a flying drone detection investigation. This is because the transmitter and receiver are so far apart. The time required for the drone to fly in the upper position was less than in the lower position, as illustrated in Fig. 7 and Fig. 8. This is because the bottom position of the FSR has a bigger cross-sectional area than the top location.



(a) **(b)**

Fig. 7 - Time domain graph in Taman Suria at signal frequencies of (a) 1.8 GHz and; (b) 2.6 GHz

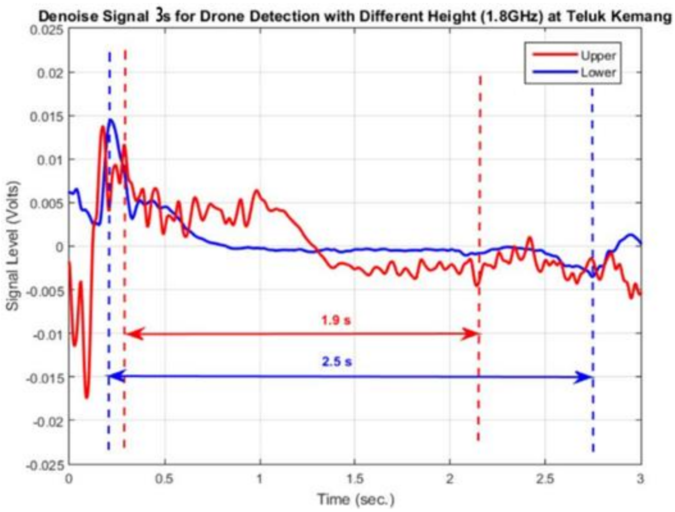
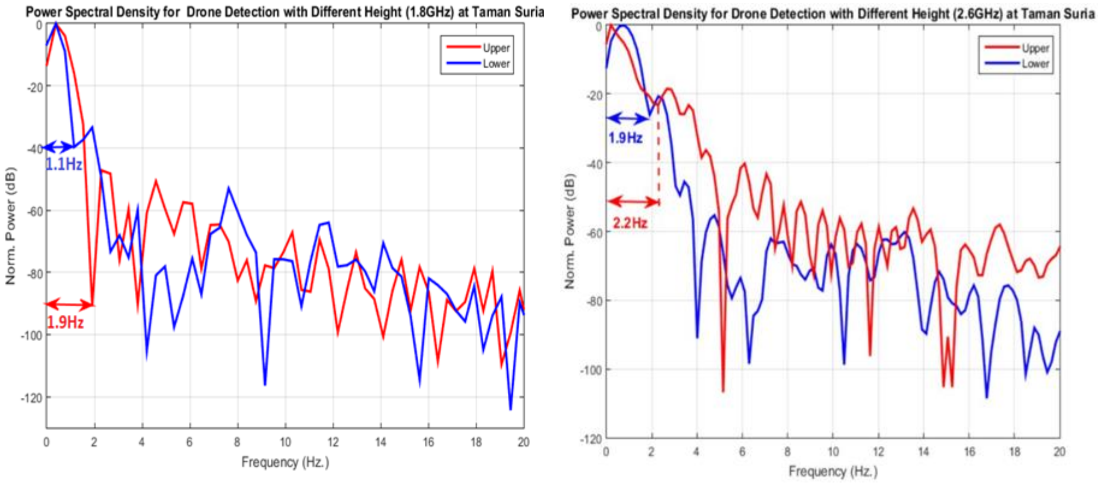


Fig. 8 - Time domain graph in Teluk Kemang at signal frequency of 1.8 GHz

3.2 Power Spectral Density and Spectrogram of Drone Detection

Power Spectral Density (PSD) had been applied to transform the graph with the signal in order to analyse and measure the different frequencies for the signal. PSD can be defined as the amount of signal power content versus frequency [15]. PSD was focused on this research is to identify the drone signature signal. The spectral resolution used to digitalize the signal which normalizes the PSD amplitude. This analysis depicts the relationship between Frequency (Hz) and Normalized Power (dB) of a flying drone at various heights. The PSD outcomes are shown in Fig. 9 and Fig. 12. The results affect the frequency dropped of the signature although the similar drone was utilized for the upper and lower position of flying drone identification. The normalized power for the flying drone at the upper position was -40 dB in Fig. 9 (a), and the frequency acquired was 1.1 Hz at Taman Suria with the signal transmitted at 1.8 GHz. The lower position had a normalized power of -90 dB and a frequency of 1.9 Hz. Fig. 9 (b) depicts the PSD of a 2.6 GHz signal used for drone identification in Taman Suria. The upper position had a normalized power of -50 dB and a frequency of 2.2 Hz. The lower position produced a normalized power of -28 dB and a frequency of 1.9 Hz.

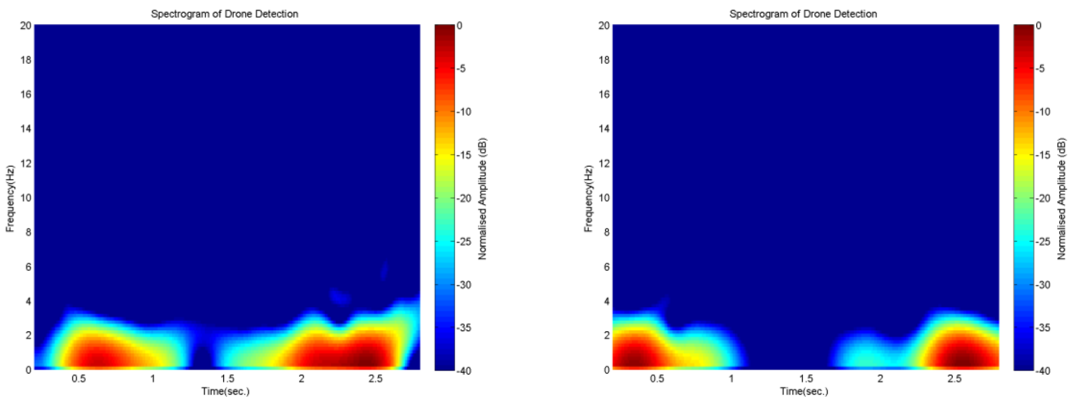


(a) **(b)**

Fig. 9 - Power spectral density of (a) 1.8 GHz; (b) 2.6 GHz signal frequency in Taman Suria

Spectrogram is a same idea of PSD which interprets a three-dimensional plot of energy for the frequency content in a signal as it changes over time. As shown in Fig. 10, Fig. 11 and Fig. 13, These were spectrogram results for every experiment site and frequencies. The spectrogram result was dependent on the signal strength and frequency level, as demonstrated by the Power Spectral Density (PSD) results. Fig. 10 (a) shows the frequency value for spectrogram of upper position which approximately same amplitude of frequency in Fig. 9 (a) which is 1.9 Hz. The bright color of orange curve is the sine wave moving up in pitch indicates the frequency of this spectrogram of upper position for drone detection around 1.95 Hz. This shows a similarity with time domain outcome in Fig. 7 (a), where the amplitude of sine wave is identical for both in spectrogram and time domain. Refer to Fig. 10 (a), the time range from 0.5 seconds to 1.2 seconds shows the normalized amplitude of the upper position of moving drone was high. For 1.2 seconds until 1.5 seconds, the amplitude was becoming silent (minimum power) and it was synchronized with outcome in Fig. 7 (a). The factor where in this figure showcases too many appearance of bright color is due to the signal transmitting power in Taman Suria for 1.8 GHz is very high and good enough for drone identification.

Fig. 10 (b) shows the spectrogram of lower position of drone flying in Taman Suria at 1.8 GHz of LTE signal frequency. The bright orange color is larger at timeframe around 0 seconds until 0.5 seconds. For timespan around 1 second to 1.7 seconds, it shows the minimum value of the power spectrum. In term of power spectrum density (PSD) as shown in Fig. 9 (a), it shows the position around 1.1 Hz and synchronized with the spectrogram result in Fig. 10 (b).



(a) **(b)**

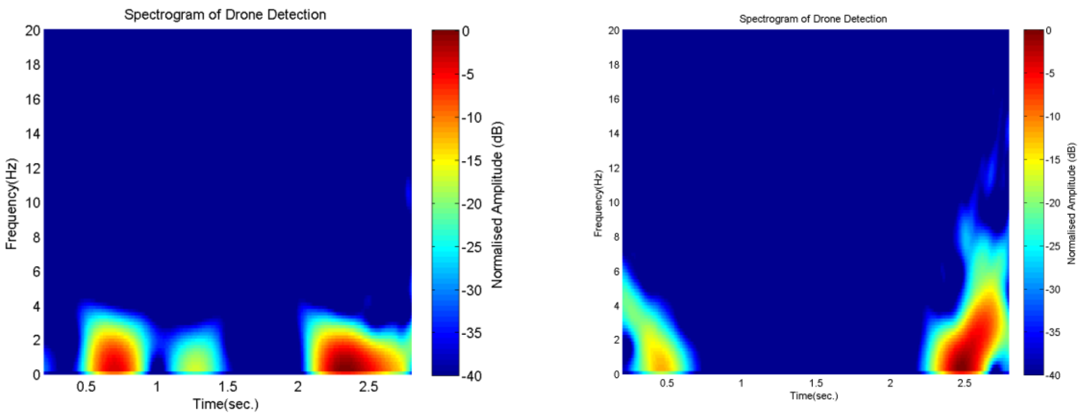
Fig. 10 - Spectrogram of drone identification in Taman Suria using frequency of 1.8 GHz (a) upper; (b) lower

Fig. 11 (a) shows the spectrogram outcome of drone identification for upper position in Taman Suria with the LTE signal frequency of 2.6 GHz. The accumulation of power of amplitude for the bright color shows the lowest intensity among the other sites. This is due to the transmitting power from the telecommunication base station of LTE signal with the frequency of 2.6 GHz was the lowest as compared to 1.8 GHz. In Fig. 7 (b) for time domain result, the highest level of power amplitude is 0.5 volts. Contrast with the spectrogram in Fig. 11 (a), the bright color of amplitude occurs within 0.5 seconds until 1 second which is synchronized with the time domain outcome. The power amplitude is silent in interval between 1.5 seconds until 2 seconds synchronized with result in time domain which the amplitude signal is 0 volts and it starts increase again in the period of 2.1 seconds until 3 seconds.

Fig. 11 (b) shows the spectrogram at Taman Suria for 2.6 GHz at lower position of drone detection. This result is synchronized with the outcome in Fig. 7 (b) of time domain. The time between 0.2 seconds until 0.6 seconds shows the appearance of bright color indicates the sine wave of movement. The power amplitude remains 0 volt until it reaches 2.2 seconds in time domain result; and next it increased to 1 volt, same goes with the bright colors in the spectrogram which indicates the power amplitude is deteriorate for drone detection at upper position.

The power spectrum density in Fig 9 (b) shows the highest value of 2.2 Hz and comparable with the frequency amplitude obtained in Fig. 11 (b), also shows the bright red color indicating the highest amplitude. For 2.6 GHz signal at Taman Suria, the transmitting power by the telecommunication tower is lesser than 1.8 GHz of LTE signal.

In Fig. 9 (b) of PSD, the frequency obtained for lower position of drone detection was 1.9 Hz and connected with the frequency obtained in spectrogram is 2.2 Hz. Fig. 11 (b) shows the bright red color is separating until the frequency of 2.2 Hz. It is demonstrated that the outcome in Power Spectral Density (PSD) is synchronized with the frequency obtained in spectrogram view.



(a) **(b)**

Fig. 11 - Spectrogram of drone identification in Taman Suria using frequency of 2.6 GHz (a) upper; (b) lower

The Power Spectral Density (PSD) outcome for the final study in Teluk Kemang with frequency signal of 1.8 GHz is depicted in Fig. 12. The normalized power obtained at the upper detection position was -38 dB, and the frequency drop was 2.5 Hz. The normalized power produced for the lower position was -60 dB, and the frequency was 2 Hz. As shown in Fig. and Fig. 12, frequency in the frequency domain graph was inversely associated with time in the time domain graph. This is due to the frequency-time relationship between frequency and time. The time decreases as the frequency increases.

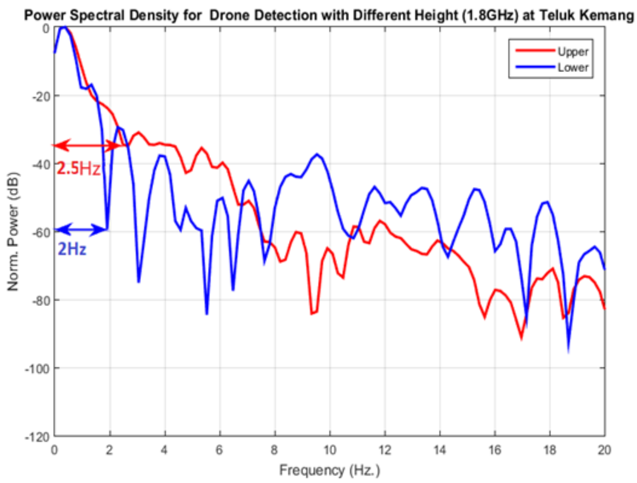
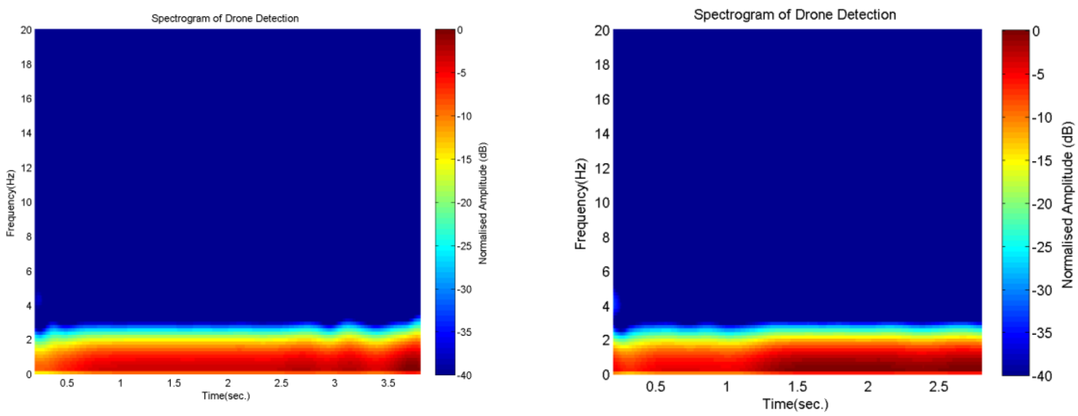


Fig. 12 - Power spectral density in Teluk Kemang using 1.8 GHz of frequency signal

In Fig. 13, there are the spectrogram results of drone identification regarding upper and lower positions in Teluk Kemang using frequency signal of 1.8 GHz. The power amplitude is higher in times between 0 seconds until 4 seconds. The amplified power of this drone detection is unchanging from 0 seconds until 4 seconds because the signal level in Teluk Kemang at frequency 1.8 GHz was good enough. For PSD the frequency is 2 Hz and by comparing with spectrogram view in Fig. 13 (a), the red color is distributed around the area between 0 seconds and 4 seconds and the level of frequency around 2.5 Hz.

Fig. 13 (b) shows the spectrogram of drone detection at lower position with 1.8 GHz. The power amplitude is high from 0 seconds until 3 seconds. The bright color was referring to the strong sine wave moving up in pitch of the drone detection signal. The result is confirmed by referring to the spectrogram result in Fig. 13 (b). The power amplitude level in lower position is little bit lower than upper position, however it still higher than spectrogram of Taman Suria for 1.8 GHz and 2.6 GHz frequency. For frequency analysis, the spectrogram shows the equal amplitude of frequency with PSD which is 2 Hz. This indicates the radiating signal from the drone's sine wave movement.



(a) **(b)**

Fig. 13 - Spectrogram of drone detection at Teluk Kemang with 1.8 GHz (a) upper; (b) lower

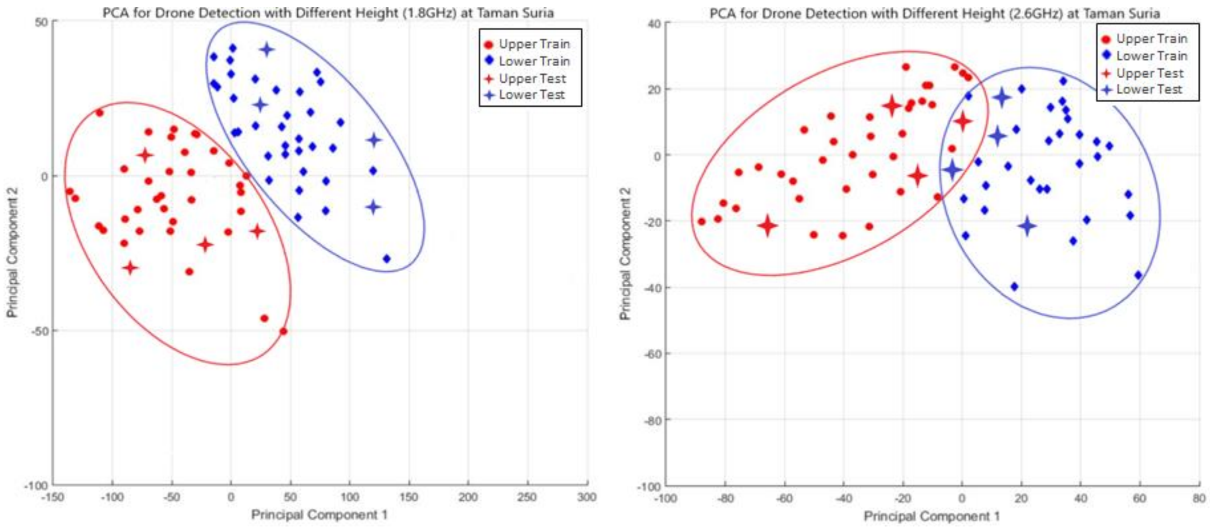
3.3 Principal Component Analysis

PCA has been employed to transform several of the data input into linearly uncorrelated variables known as principle components. The PCA outcome can distinguish the trend of drone identification at different heights in a particular location. The PCA output at Taman Suria for 1.8 GHz and 2.6 GHz are displayed in Fig. 14 (a) and Fig.14 (b). The blue dots represent the lower position, while the red dots represent the upper position. These dots refer to the training data where the next step is classification. The result of classification is present as star (*) with their own color according to their cluster called testing data.

According to Fig. 14 (a), the cluster properly categorised the data, and Fig. 14 (b), the PCA results demonstrated which the grouping for 2 distinct heights clash. When compared to 2.6 GHz, the signal strength and quality at 1.8 GHz were stronger and better quality with low noise. The high-quality signal in Taman Suria also is attributable to the transmitter's proximity to the radar receiver, located only 187.5 metres away. Besides, the good blockage by the buildings nearby managed to prevent the signal from becoming disrupted by another signal from other transmitter towers, resulting in a high-quality signal received.

Following that, the PCA result at Teluk Kemang is depicted in Fig. 15 for the signal of 1.8 GHz only because no signal of 2.6 GHz seemed to be nearby the experiment site. The analysis can be classed, but not as well as at Taman Suria. The clusters almost overlapped due to the nearly identical dimension, but the signal quality at Teluk Kemang was insufficient to achieve a better result. One of the factors was that the gap between the transmitter and receiver, at 580 metres, was too far. Furthermore, the experiment site was an open space with no obstructions from surrounding buildings, which could cause the signal to be disrupted by other transmitting tower signals, resulting in interference during the experiment.

The heights of drone detection are successfully classified because there is slightest overlapping cluster with each other. From the observation, the classification of 1.8 GHz at Taman Suria is much better compared with 2.6 GHz at Taman Suria and 2.6 GHz at Teluk Kemang due to the LTE band frequency band. In addition, the LTE frequency of 1.8 GHz contributes two times wider coverage compared to 2.6 GHz and has better indoor signal which give impact to the drone detection and classification in this experimental work.



(a) (b)

Fig. 14 - Principal component analysis in Taman Suria at the frequency of (a) 1.8 GHz; (b) 2.6 GHz

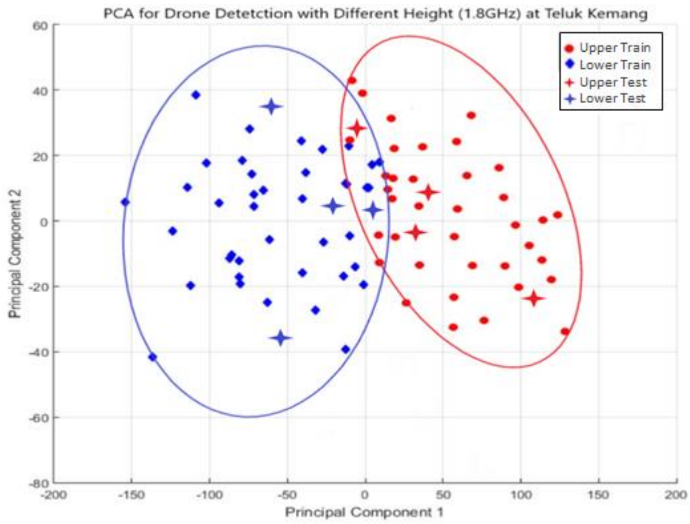


Fig. 15 - PCA in Teluk Kemang using frequency signal of 1.8 GHz.

3.4 Confusion Matrix

In this investigation, the confusion analysis was used to obtain its classifier's quality and accuracy. The entire analysis was tallied and expressed as a percentage. Table 3, Table 4, and Table 5 show the findings of the confusion matrix for drone detection at various heights, frequencies, and locations. Table 3 summarises the results of the confusion matrix at Taman Suria with a frequency of 1.8 GHz. According to the PCA results, all of the testing data remained in its cluster. It yielded 100% success testing data. Table 4 shows the confusion matrix outcome for the frequency of 2.6 GHz at Taman Suria. 75% of the upper and lower detection data stayed in their respective clusters. The PCA results have demonstrated this. Only 25% of the tested data did not remain in its cluster. Taman Suria data collection was quite good and adequate for both frequencies. This was caused by the higher signal transmission from the transmitter tower and minimal impediments.

Table 5 summarizes the Teluk Kemang confusion matrix findings. There were four data points evaluated for each upper and lower drone detection. The result demonstrates that just one data did not remain in its group, while the other three data did. In percentage terms, 75% of the tested data remained in their clusters, whereas the remaining 25% did not.

Table 3 - Confusion matrix in Taman Suria using 1.8 GHz frequency

Level of height	Number of samples		Automatically classified (100%)	
	Training	Testing	Upper	Lower
Upper	20	4	**100**	0
Lower	18	4	0	**100**

Table 4 - Confusion matrix in Taman Suria using 2.6 GHz frequency

Level of height	Number of samples		Automatically classified (100%)	
	Training	Testing	Upper	Lower
Upper	21	4	**75**	25
Lower	19	4	25	**75**

Table 5 - Confusion matrix in Teluk Kemang using 1.8 GHz frequency

Level of height	Number of samples		Automatically classified (100%)	
	Training	Testing	Upper	Lower
Upper	18	4	**75**	25
Lower	19	4	25	**75**

4. Conclusion

In this PFSR system which utilized LTE signal as illuminator of opportunity is successfully accomplished and is proved by the experimental works based on detection and classification of two difference heights of flying drone at two different places. The drone's Doppler signature characteristic affected by the radar cross sectional area and the level of flying drone. If the drone's radar cross sectional is larger, the Doppler signature become wider as appear in the time domain and Doppler frequency is increased in PSD.

Furthermore, it clearly displays the good outcomes of data classifying in PCA between the identification of a moving drone at the upper and lower places. The identification of a drone in Taman Suria at 1.8 GHz using an LTE signal and a passive forward scatter radar hardware system was the most successful. This was demonstrated by the confusion matrix of testing data, in which all of the testing data remained in its group. In addition, the LTE frequency of 1.8 GHz contributes two times larger coverage compared to 2.6 GHz which give impact to the drone detection and classification in this experimental work. Moreover, the gap between the transmitter and receiver antennas influenced the data analysis outcomes. The greater the distance between transmitter and receiver, the lesser the signal quality received. This can be seen in the analysis of signal quality at Teluk Kemang which the gap length between the transmitter and receiver was a bit far away compared to Taman Suria and consequently gives impact to the quality of signal received and lesser classification.

This PFSR device's high potential opens up a new study field in passive radar which can be implemented in a variety of remote monitoring applications, such as national defense, microwave barriers, facility surveillance, vehicle tracking, and so on. Future LTE-based passive forward scattering radar research may include air targets like helicopters as well as sea targets like combat ships, humans, and animals.

For future recommendations, the passive forward scattering radar system could use the signal from the transmitter with a 5 Generation Wireless System (5G) network, which provides a stronger, higher-quality, and wider network coverage signal capable of detecting drones precisely and clearly displaying the Doppler signature.

Acknowledgements

An appreciation goes to Antenna Research Centre (ARC), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA for supporting the research work.

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