OPTIMISED TIME-FREQUENCY ANALYSIS FOR DRONE DETECTION IN A MULTI-SIGNAL ENVIRONMENT

CHIA CHUN CHOON

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

This thesis is dedicated to my parents for their endless support and encouragement.

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ABSTRACT

The abuse of recreational drones has caused security issues, crimes, and privacy problems. Thus, drone detection is needed as evidence for law enforcement or support countermeasures such as radio jamming, and remote control override. One way to detect drones is by monitoring the radio frequency (RF) link between the remote control and drone. The challenge is that recreational drones operate at the 2.4 GHz and 5.8 GHz industrial, scientific and medical (ISM) bands, which have wide bandwidth of 100 MHz and 150 MHz respectively make the analysis costly. Furthermore, the drone signals like frequency-hopping spread spectrum (FHSS) and hybrid spread spectrum (HSS) are time-varying and require a time-frequency analysis (TFA). Also, the choice of window size is crucial for a TFA due to the uncertainty principle in time-frequency representation (TFR). Moreover, other wireless technologies in the environment, such as direct sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM), which is Wi-Fi operates in the same ISM band could interfere with the drone signal detection activity. In this thesis, an adaptive stepped frequency scan spectrogram (Adaptive-SFSS) was developed to analyse a large bandwidth at a lower sampling rate, including an adaptive window size estimation. In the Adaptive-SFSS, the received signal is divided into multiple sub-bands and scan through the large analysis bandwidth, the window size is estimated by balancing time and frequency resolution, the channel frequency and hop duration are estimated from TFR and used to derive the instantaneous frequency (IF). Three types of drone signals, the fast FHSS, slow FHSS, and HSS, together with two types of background signal, the DSSS and Wi-Fi were simulated. Then, the simulated received signal was analysed by the Adaptive-SFSS and compared with the adaptive wideband spectrogram (Adaptive-WS), the non-adaptive SFSS and WS. The performance of the Adaptive-SFSS was verified by Monte-Carlo simulation with 20 realizations at a signal-to-noise ratio (SNR) range from −16 dB to 12 dB. In the presence of additive white Gaussian noise (AWGN), the Adaptive-SFSS obtained a detection cut-off point of −12 dB for fast and slow FHSS and −5 dB for HSS. Additional background signals such as DSSS and Wi-Fi increased the cut-off point to 5 dB for fast-FHSS, 7 dB for slow-FHSS, and 8 dB for HSS. The Adaptive-SFSS is better because it has a similar cut-off point as the WS even the sampling rate is 4 times lower and capable of choosing the right window size automatically, rather than trial-and-error which is the conventional way.

ABSTRAK

Penyalahgunaan dron rekreasi telah menyebabkan berlakunya kes-kes jenayah, keselamatan dan ancaman privasi. Oleh itu, pengesanan dron diperlukan sebagai bukti untuk penguatkuasaan undang-undang atau menyokong langkah pencegahan dron, seperti gangguan radio, dan ambil alih kawalan radio. Satu cara untuk mengesan dron ialah memantau isyarat frekuensi radio (RF) antara alat kawalan jauh dengan dron. Cabarannya ialah dron rekreasi ini berfungsi dalam jalur industri, saintifik dan perubatan (ISM) 2.4 GHz dan 5.8 GHz, merupakan jalur yang lebar iaitu 100 MHz dan 150 MHz masing-masing meningkatkan kos analisis. Selain itu, isyarat dron seperti spektrum tersebar lompatan frekuensi (FHSS) dan spektrum tersebar hibrid (HSS) adalah bersifat isyarat masa selanjar dan memerlukan analisis masa-frekuensi (TFA). Pilihan saiz jendela adalah penting untuk TFA disebabkan prinsip ketidakpastian dalam perwakilan masa-frekuensi (TFR). Selanjutnya, kewujudan teknologi tanpa wayar lain di persekitaran, seperti spektrum tersebar langsung (DSSS) dan pemultipleksan pembahagian frekuensi ortogonal (OFDM) iaitu Wi-Fi juga berfungsi dalam jalur ISM yang sama mengganggu aktiviti pengesanan isyarat dron. Dalam tesis ini, spektrogram imbasan frekuensi berlangkah adaptif (Adaptif-SFSS) diperkenalkan untuk menganalisis jalur yang lebar pada kadar persampelan yang lebih rendah berserta dengan anggaran saiz jendela adaptif. Dengan Adaptif-SFSS ini, isyarat diterima itu dibahagikan kepada beberapa jalur separa dan imbas setiap jalur separa, saiz jendela dianggar dengan mengimbangkan resolusi masa dan frekuensi, saluran frekuensi dan jangka masa lompatan dianggarkan dari TFR dan digunakan untuk menghasilkan frekuensi seketika (IF). Tiga jenis isyarat dron iaitu FHSS pantas, FHSS perlahan, dan HSS, bersama dua jenis isyarat latar iaitu DSSS dan Wi-Fi telah disimulasikan. Selepas itu, isyarat simulasi itu dianalisis oleh Adaptif-SFSS dan berbanding dengan spektrogram jalur lebar adaptif (Adaptif-WS), serta WS dan SFSS yang bukan adaptif. Prestasi Adaptif-SFSS telah dinilai oleh simulasi Monte-Carlo dengan 20 realisasi pada nisbah isyarat-hingar (SNR) antara −16 dB hingga 12 dB. Dengan kewujudan tambahan hingar putih Gaussian (AWGN), Adaptif-SFSS memperoleh titik pemotong pengesanan adalah −12 dB untuk FHSS pantas dan perlahan, dan −5 dB untuk HSS. Selain itu, kewujudan isyarat latar seperti DSSS dan Wi-Fi meningkatkan titik pemotong kepada 5 dB untuk FHSS pantas, 7 dB untuk FHSS perlahan, dan 8 dB untuk HSS. Adaptif-SFSS adalah lebih baik kerana mempunyai titik pemotong yang sama dengan WS walaupun kadar persampelan itu 4 kali lebih rendah, dan dapat memilih saiz jendela yang betul secara automatik, bukannya dengan percubaan dan kesilapan yang merupakan cara konvensional.

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LIST OF ABBREVIATIONS

RF - Radio Frequency
ISM - Industrial, Scientific, and Medical
FHSS - Frequency-Hopping Spread Spectrum
DSSS - Direct Sequence Spread Spectrum
HSS - Hybrid Spread Spectrum
OFDM - Orthogonal Frequency-Division Multiplexing
CC - Computational Complexity
TFR - Time-Frequency Representation
TFA - Time-Frequency Analysis
WS - Wideband Spectrogram
FAA - Federal Aviation Administration
SFSS - Stepped Frequency Scan Spectrogram
IF - Instantaneous Frequency
SNR - Signal-to-Noise Ratio
RCS - Radar Cross Section
LOS - Line Of Sight
RC - Radio Control
IEEE - Institute of Electrical and Electronics Engineers
MAC - Medium Access Control
ADC - Analogue-to-Digital Converter
FFT - Fast-Fourier Transform
LO - Local Oscillator
IQ - In-phase and Quadrature
LFP - Low-Pass Filter
STFT - Short-Time Fourier Transform

IIR	-	Infinite Impulse Response
WVD	-	Wigner-Ville Distribution
CM	-	Concentration Measure
DLBS	-	Doppler-Lag Block Searching
BFSK	-	Binary Frequency Shift Keying
BPSK	-	Binary Phase Shift Keying
QPSK	-	Quadrature Phase Shift Keying
CCTV	-	Wireless Closed-Circuit Television
AWGN	-	Additive White Gaussian Noise
WLAN	-	Wireless Local Area Network
GPS	-	Global Positioning System
APE	-	Absolute Percentage Error
AAPE	-	Average Absolute Percentage Error
SD	-	Symbol Duration
MLW	-	Main Lobe Width
TFD	-	Time-Frequency Distribution
FM	-	Frequency Modulation
SP	-	Simple Pulse
CC4	-	4-Costas Coded
MSE	-	Mean-Squared-Error

LIST OF SYMBOLS

t_{eff}	-	Effective time interval where signal is concentrated
f_{eff}	-	Effective frequency bandwidth of signal
$p(t)$	-	Pseudorandom sequence code waveform
N_w	-	Window size
f_s	-	Sampling frequency
$\bar{E}$	-	Mean energy
N	-	Signal length in samples
$y(t)$	-	Received signal function
T_{hop}	-	Hop duration
f_c	-	Channel frequency
k_c	-	Channel index
f_{BW}	-	Bandwidth
f_{Δ}	-	Frequency difference
R_s	-	Symbol rate
R_c	-	Chirp rate
T	-	Signal length in time
$a(t)$	-	Information bearing signal
$s_n(t)$	-	Drone signal function
$v_n(t)$	-	Background signal function
f_k	-	Subcarrier frequency
A	-	Signal gain
Δf_k	-	Subcarrier spacing
$n(t)$	-	Additive white Gaussian noise signal
${\sigma_n}^2$	-	Variance of Additive white Gaussian noise

f_{LO} - Frequency of local oscillator

$x_d(t)$ - Down-converted signal

$x_r(t)$ - Received radio frequency signal

$x_I(t)$ - Demodulated in-phase signal

$x_Q(t)$ - Demodulated quadrature signal

$x_i(t)$ - Intermediate frequency signal

$\emptyset_{LO}$ - Phase angle of local oscillator

ω_{LO} - Angular velocity of local oscillator

$x_f(t)$ - Filtered signal

$x(m)$ - Discrete signal from analogue-to-digital converter

$h(t)$ - Filter kernel

$w(n)$ - Window function

$S_x(n,k)$ - Time-frequency representation

$g_a(t)$ - Variable prefilter kernel

f_a - Frequency of variable local oscillator

ω_a - Angular velocity of variable local oscillator

$X(n,k)$ - Signal spectrum matrix

$X_s(n,k_s)$ - Signal sub-spectrum matrix

N_T - Number of time bins

N_F - Number of frequency bins

T_r - Time resolution

F_r - Frequency resolution

$P_x(k)$ - Power spectrum

P_{ave} - Average threshold

$P_T(k)$ - Threshold power across spectrum

$P_B(k)$ - Maximum power of background signal

f_p - Frequency peak

f_{low} - Lower frequency

f_{upp} - Upper frequency

$P_i(n)$ - Instantaneous power

t_e - Start time for rise of instantaneous power

t_s - End time for fall of instantaneous power

f_i - Instantaneous frequency

APE_T - Absolute percentage error of hop duration

APE_F - Absolute percentage error of signal bandwidth

T_{bit} - Signal bit-duration

N_{w_min} - Minimum window size

N_{w_max} - Maximum window size

d - Down-sampling ratio

n_f - Total number of estimated channel frequency

n_{hop} - Total number of estimated hop duration

C_{specg} - Computational complexity of spectrogram method

C_{f_est} - Computational complexity of channel frequency estimation

C_{T_est} - Computational complexity of hop duration estimation

C_{param_est} - Computational complexity of signal parameter estimation

C_{win} - Computational complexity of window size estimation

C_{thres} - Computational complexity of threshold estimation

C_{IF} - Computational complexity of Instantaneous frequency estimation

C_{adp_sfss} - Computational complexity of the Adaptive-SFSS

C_{adp_ws} - Computational complexity of the Adaptive-WS

C_{sfss} - Computational complexity of the SFSS

C_{ws} - Computational complexity of the WS

CHAPTER 1

INTRODUCTION

1.1 Background

Drone applications for civilian and commercial have grown for the past decade. Drones are referred to as radio-controlled unmanned aircraft systems that provide beneficial visual service in the sky. Examples of the legal use of drones are industrial and building safety inspection, geographic mapping, aerial monitoring, photography and videography, delivery, and agriculture research [1]. Nevertheless, this emerging technology and mass penetration to the market had been classified as one of the issues in electromagnetic spectrum monitoring [2].

In addition, the widespread use of recreational drones, such as miniature, multi or single rotor drones has caused security issues, crime, terrorism, and privacy problem. For example:

a) On 20th Jun 2020, 4 Singaporeans have been arrested after the authorities seized a drone carrying drugs at Kranji Reservoir Park, Singapore. They were suspected to have operated the drone to import drugs from Johor Bahru, Johor, Malaysia [3].

b) On 9th Jun 2020, a man is accused of flying a drone over a protected Ministry of Defence base in Singapore seven times and taking pictures [4].

c) On 14th Jan 2019, 8 reports of illegal drones flying near Changi Airport over the past 3 years [5].

d) On 21st Dec 2018, 120,000 passengers had their flights delayed and cancelled at Gatwick Airport in London because a drone was detected near the airfield [6].

e) On 12th Aug 2017, UK Navy carrier security was under review after an amateur landed a drone on deck undetected [7].

Thus, drone detection is needed as evidence for law enforcement or support countermeasures such as radio jamming, and remote control override.

In drone signal detections, it includes monitoring the radio frequency (RF) link between the remote control and drone and estimating drone signal parameters. Besides, the recreational drone uses the same 2.4 GHz and 5.8 GHz industrial, scientific and medical (ISM) band as other wireless technologies, such as Wi-Fi and Bluetooth could interfere with the drone signal detection in this multi-signal environment.

1.2 Problem Statement

Usually, drones are flying in public and noisy environments. To protect against interference, drones adopt spread spectrum technologies such as frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), hybrid spread spectrum (HSS), and orthogonal frequency division multiplexing (OFDM) which is Wi-Fi operate in 2.4 GHz ISM band [8]. These are time-varying signals with parameters such as hop duration, hop rate, and channel frequency are useful to detect the presence of drones. Thus, representing the signal information in the time and frequency domain is important in drone signal analysis.

Besides, the 2.4 GHz ISM band is reserved internationally for unlicensed RF application and have a large bandwidth of 100 MHz. The Shannon-Nyquist theorem stated that to perfectly represent an analogue signal, the sampling frequency must higher than twice the signal’s bandwidth [9]. Since a recreational drone that uses the FHSS signal can hop across the 100 MHz frequency band, monitoring the entire bandwidth requires a very high sampling rate [10]. In addition, the higher the sampling rate, the larger the signal samples and eventually contributes to higher computational complexity (CC). As the drone signal is hopping across the large frequency band makes it difficult to detect while maintaining a low sampling rate at the same time.

In time-frequency representation (TFR), there is a trade-off between the resolution of time and frequency due to the uncertainty principle [11]. It is impossible to get a high resolution TFR in both time and frequency simultaneously. However, this is crucial if precision is required to estimate the time and frequency parameters of a signal. This is best illustrated by a modulated Gaussian pulse [12]. It is shown that this is the only signal where the product of effective time, t_{eff} and effective frequency, f_{eff} is constant at 1/4π, and other signals should conform to this equality $t_{eff}f_{eff} \geq 1/4\pi$. The result of this inequality is also known as the uncertainty principle similar to the Heisenberg uncertainty principle in quantum physics. Since the product is a constant, a short duration pulse will have a broad bandwidth and vice versa. Similarly, an increase in time resolution will cause a decrease in frequency resolution and vice versa. Since each drone has different signal bandwidth and hop duration needs an analysis window size adapting to signal characteristics by balancing between time and frequency resolution.

Additionally, the 2.4 GHz and 5.8 GHz ISM bands used by the recreational drone are also used by other wireless technologies such as Wi-Fi, and Bluetooth. In this multi-signal environment, the other wireless technology signals are mixed with drone signals, and difficult to distinguish them [13]. Unlike the white noise, background signals like Wi-Fi have a dedicated transmission channel and only affect drone signals at certain frequency range. Hence, the threshold for drone signal detection could be adapted to the change of frequency spectrum.

1.3 Objectives of the Study

This thesis embarks on the following objectives:

a) To develop a time-frequency analysis (TFA) method that minimises sampling rate by splitting a large frequency band into sub-bands and perform scanning.

b) To develop an adaptive window size algorithm that automatically chooses an analysis window size by balancing the time and frequency resolution according to the drone signal characteristic.

c) To separate drone signal from background signal with a threshold derived from baseline spectrum and detect drone signal based on the estimated signal parameters such as hop duration, channel frequency, and hop sequence.

1.4 Scope of Study

The scopes of work in this study are:

a) Target only on frequency-agile drone signals like FHSS and HSS signals and operate in 2.4 GHz to 2.5 GHz (2.4 GHz ISM band).

b) Non-frequency-agile drone signal like DSSS is excluded because the channel frequency is static and not occupy the entire frequency band.

c) Bluetooth wireless technology is excluded from environment signal because it is for short-range communication, low data rate transmission, and usually use in an enclosed space.

d) In signal analysis, the RF signal would be down-converted to an intermediate frequency signal as the received signal to the drone signal detection system.

e) The Sampling frequency is set at the Nyquist rate, which is 200 MHz for the wideband spectrogram (WS), and 50 MHz for the proposed method.

f) For the non-adaptive spectrogram method that chooses a window size manually, the choice of window size is a power progression from 64 to 4096 samples, equivalent to 64, 128, 256, 512, 1024, 2048, 4096 samples [14].

g) For sub-bands scanning for the proposed method, the settling time of switching from one sub-band to the next sub-band considered is zero.

h) In a typical multi-signal environment, the background signals contain white noise, Wi-Fi, DSSS, and free from any drone signals. This is a baseline signal that being sample ahead of time before separating the drone signal from the background signal.

i) Multipath fading effect is not considered in this study because the recreational drones normally fly in an open area and above the ground with the maximum allowable altitude of 400 feet stated in the Federal Aviation Administration (FAA) fact sheet [15].

j) During the development, testing, and benchmarking of the algorithm, MATLAB software will be used as the simulation tool.

1.5 Contribution of Work

This study proposed an adaptive stepped frequency scan spectrogram (Adaptive-SFSS) method to represent a signal in TFR and estimate signal parameters. The Adaptive-SFSS can analyse large bandwidth at a lower sampling rate compared to the WS. This is done by dividing the large analysis bandwidth into multiple small sub-bands and scan through. Even though the Adaptive-SFSS might miss some of the signals that appear in certain sub-band that are not actively in the scan, it is not an issue when the scanning speed is faster than the signal hopping speed. Furthermore, the Adaptive-SFSS has a lower sampling rate and a smaller number of samples for signal representation that eventually lower down the computational cost.

Secondly, this study proposed an adaptive window size algorithm based on the balance between time and frequency resolution. The algorithm can optimize the analysis window size by adapting the time and frequency resolution to the signal characteristic. Plus, this algorithm enables automatic window size selection, provides an accurate TFR, and improves the signal parameter estimation. Since the algorithm is adaptable, it allows easy-to-deploy in measurement setup which is one of the suggested strategies for next generation spectrum monitoring [2].

Additionally, the drone signal parameters such as hop duration, channel frequency, and instantaneous frequency (IF) are estimated by analysing the instantaneous power and power spectrum derived from the TFR. In signal classification, these signal parameters and IF are useful in identifying a wireless technology and hopping sequence used by drones, and eventually trace back to the drone manufacturer and buyer.

1.6 Thesis Organization

There are five chapters in this thesis, it begins with Chapter 1 as an introduction. Chapter 2 is a literature review that consists of the discussion of drone signals and detection technologies, signal representation, and analysis. Chapter 3 would focus on the methodology of the WS and SFSS spectrogram, threshold setting, adaptive window size algorithm, and signal parameters estimation. After that, Chapter 4 would present the result and discussion about the adaptive window size algorithm, signal representation, and analysis. A Monte Carlo simulation is carried out to verify the spectrogram performance in different multi-signal environments at a various signal-to-noise ratio (SNR). Conclusion and future work are described in Chapter 5.

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