UNIVERSITI PUTRA MALAYSIA

PASSIVE FORWARD SCATTER RADAR BASED ON LTE SIGNAL FOR VEHICLE DETECTION AND CLASSIFICATION

NOOR HAFIZAH BINTI ABDUL AZIZ

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By

NOOR HAFIZAH BINTI ABDUL AZIZ

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

June 2018

DEDICATION

This thesis is dedicated to:

My late father,

Allahyarham Hj. Abdul Aziz B Abdul Ghani

Alfatihah

My beloved mother,

Hjh. Kamariyah Binti Mohd Salleh

My brothers and sisters,

and to all of my friends.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

PASSIVE FORWARD SCATTER RADAR BASED ON LTE SIGNAL FOR VEHICLE DETECTION AND CLASSIFICATION

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June 2018

Chairman : Professor Raja Syamsul Azmir b. Raja Abdullah, PhD
Faculty : Engineering

Passive bistatic radar (PBR) system can utilise suitable signal from illuminator of opportunity to improve radar proficiency. In conventional PBR, a heterodyne receiver and concept is employed. This is due to the PBR requiring reference signal from a direct transmission for synchronization, and then the signal is down converted to the base band where target detection is evaluated by analyzing the ambiguity function of the received signal. On the other hand, by using the forward scattering phenomena and technique in specific mode of PBR, the operation can be further enhanced and improved especially in target detection and classification. This specific system is identified as the passive forward scattering radar (FSR). One of the main condition of passive FSR is the operational mode limited to within the radar baseline. In this scenario, the desired received signal is formed through the shadowing of a direct signal by the target shape rather than back scattering signal from the target such as in conventional radar system. Passive forward scattering radar system offers a number of advantages including enhanced target cross section, long coherent intervals of the receiving signal, absence of signal fluctuations, reasonably simple hardware, economical as it does not need a transmitter system and a spectrum allocation, practically unseen to surveillance receivers, portable due to its smaller size, no synchronization needed for reference signal from direct signal of illuminator, straightforward signal pre-processing for target detection and enhanced classification capability.

Thus, the aim of this thesis is to develop and prove the concept of passive forward scattering radar especially for ground detection and classification. The objective is to implement the experimental analysis and results for vehicle detection and classification by exploiting the latest 4G LTE technology signal. This thesis clarifies in details the LTE based passive forward scatter radar receiver circuit, the detection scheme and the classification algorithm. In addition, the proposed passive forward

scatter radar circuit employed the self-mixing technique at the receiver, hence it did not require a synchronization signal from the LTE base station. The classification capability in passive forward scattering radar increases the effectiveness of the system.

Three vehicle categories with different sizes and shapes were tested, namely Compact, Saloon and Small Sport Utility Vehicle (SUV). The passive FSR experiment results show that the vehicles were successfully detected, even by raw received signals without any complicated signal processing techniques and the proposed classification system provided outcomes of satisfactory classification performance. The Doppler spectrum scattered by the vehicle is used as the features for input to the classification system. The classification algorithm was developed based on Principal Component Analysis (PCA) and k-Nearest Neighbours (k-NN). In addition, the baseline crossing range distance from the radar receiver, as well as vehicle's speed, was successfully predicted.

In general this thesis presents the first classification analysis and performance for the passive forward scatter radar system. The great potential of the passive forward scatter radar system provides a new research area in passive radar that can be used for diverse applications. The thesis also proved that if the FSR mode can be integrated or hybrid with the conventional passive radar system and still have similar performance competency, the system can achieve tremendous improvement. Hence, it opens up a new frontier in passive radar that can be used for many applications including border protection, microwave fences, building monitoring, traffic surveillance, and so forth.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

RADAR PENYERAKAN KE HADAPAN PASIF BERDASARKAN SIGNAL LTE BAGI PENGESANAN DAN KLASIFIKASI KENDERAAN

Oleh

NOOR HAFIZAH BINTI ABDUL AZIZ

Jun 2018

Pengerusi : Profesor Raja Syamsul Azmir b. Raja Abdullah, PhD
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Sistem radar bistatik pasif (PBR) boleh menggunakan isyarat yang sesuai dari pemancar yang berpeluang untuk meningkatkan penguasaan radar. Di dalam PBR konvensional, penerima dan konsep heterodin digunakan. Ini adalah disebabkan oleh PBR memerlukan isyarat rujukan daripada penghantaran langsung untuk penyegerakan, dan isyarat itu kemudian ditukar kepada jalur asas di mana pengesanan sasaran dinilai dengan menganalisis fungsi kekaburan daripada isyarat penerimaan. Sebaliknya, dengan menggunakan fenomena dan teknik penyerakan ke hadapan dalam mod tertentu PBR, operasi dapat dipertingkatkan dan diperbaiki terutama di dalam pengesanan dan klasifikasi sasaran. Sistem ini dikenal pasti sebagai radar penyerakan ke hadapan (FSR) pasif. Salah satu syarat utama bagi FSR pasif adalah mod operasi terhad kepada tempoh asas radar. Di dalam senario ini, isyarat penerimaan yang dikehendaki terbentuk melalui bayangan isyarat langsung oleh bentuk sasaran dan bukannya daripada isyarat penyerakan yang terbias daripada sasaran seperti dalam sistem radar konvensional. Sistem radar penyerakan ke hadapan pasif menawarkan beberapa kepentingan, termasuk bahagian silang sasaran dipertingkatkan, keteguhan kepada sasaran tersembunyi, isyarat penerimaan mempunyai sela koheren yang panjang, tiada turun naik isyarat, perkakasan yang mudah dan munasabah, menjimatkan kerana ia tidak memerlukan sistem pemancar dan peruntukan spektrum, boleh dikatakan ghaib kepada penerima pengawasan, mudah alih kerana saiz yang lebih kecil, tidak ada penyelarasan yang diperlukan bagi isyarat rujukan dari isyarat langsung sistem pemancar, isyarat mudah diproses untuk mengesan sasaran dan kemampuan pengklasifikasian dapat dipertingkatkan.

Oleh itu, tujuan laporan ini dilaksanakan adalah untuk membangunkan dan membuktikan konsep radar penyerakan ke hadapan pasif terutamanya bagi pengesanan dan pengelasan sasaran di atas darat. Objektif adalah untuk melaksanakan penganalisaan secara eksperimen dan keputusannya untuk pengesanan

dan klasifikasi kenderaan dengan mengeksploitasi isyarat teknologi 4G LTE yang terkini. Tesis ini menjelaskan secara terperinci mengenai litar radar penyerakan ke hadapan pasif berasaskan penerima LTE, skim pengesanan dan algoritma pengelasan. Di samping itu, litar radar penyerakan ke hadapan pasif yang dicadangkan menggunakan teknik pencampuran diri di dalam alat penerima, oleh itu ia tidak memerlukan isyarat penyegerakan dari stesen pangkalan LTE. Keupayaan pengelasan di dalam radar penyerakan ke hadapan pasif dapat meningkatkan keberkesanan sistem.

Tiga kenderaan yang bersaiz dan berkelajuan berbeza telah diuji, iaitu Compact, Saloon dan Small Utility Vehicle (SUV). Keputusan eksperimen daripada FSR pasif menunjukkan bahawa kenderaan telah berjaya dikesan, walaupun dengan isyarat kasar yang diterima tanpa sebarang teknik pemprosesan isyarat yang rumit dan sistem klasifikasi yang dicadangkan memberikan hasil prestasi klasifikasi yang memuaskan. Penyerakan spektrum Doppler daripada kenderaan digunakan sebagai ciri-ciri untuk input kepada sistem klasifikasi. Algoritma pengelasan telah dibangunkan berdasarkan ketumpatan kuasa spektrum (PSD), Analisis Komponen Prinsipal (PCA) dan k-kejiranan yang terdekat (k-NN). Di samping itu, jarak garis dasar pelbagai lintasan daripada penerima radar, serta kelajuan kenderaan telah berjaya diramalkan.

Secara umum tesis ini membentangkan analisis klasifikasi dan prestasi yang pertama untuk sistem radar penyerakan ke hadapan pasif. Sistem radar penyerakan ke hadapan pasif berpotensi besar di dalam menyediakan ruang penyelidikan baru di dalam radar pasif yang boleh digunakan untuk pelbagai aplikasi. Tesis ini juga membuktikan bahawa jika mod FSR yang boleh disepadukan atau hibrid dengan sistem radar pasif konvensional dan masih mempunyai kecekapan prestasi yang sama, sistem boleh mencapai peningkatan yang amat besar. Oleh itu, ia membuka satu era baru dalam radar pasif yang boleh digunakan untuk pelbagai aplikasi termasuk perlindungan sempadan, pagar mikro, pemantauan bangunan, pengawasan lalu lintas, dan sebagainya.

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I certify that a Thesis Examination Committee has met on 11 June 2018 to conduct the final examination of Noor Hafizah binti Abdul Aziz on her thesis entitled "Passive Forward Scatter Radar Based on LTE Signal for Vehicle Detection and Classification" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

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This is to confirm that:

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LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
ADC	Analog to Digital Converter
AF	Ambiguity Function
ANN	Artificial Neural Network
ARQ	Automatic Repeat Query
ASR	Aircraft Security Radar
BFSC	Bistatic Forward Scattering Radar
BPF	Band Pass Filter
BTS	Base Transceiver Station
CDMA	Code Division Multiple Access
CFI	Control Format Indicator
CP	Cyclic Prefix
CPF	Complex Profile Function
CRC	Cyclic Redundancy Check
CSRS	Cell Specific Reference Signals
CST	Computer Simulation Technology
DAB	Digital Audio Broadcasting
DC	Direct Current
DCI	Downlink Control Information
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting-Terrestrial
EDGE	Enhanced Data rates for GSM Evolution
EM	Electromagnetic

eNB	evolved NodeB
FDD	Frequency Division Duplex
FFT	Fast Fourier transform
FM	Frequency Modulation
FR4	Flame Retardant 4
FS	Forward Scatter
FSCS	Forward Scatter Cross Section
FSML	Forward Scatter Main Lobe
FSR	Forward Scattering Radar
GMTI	Ground Moving Target Indication
GNSS	Global Navigation Satellites Systems
GP	Guard Period
GPS	Global Positioning System
GSM	Global Systems for Mobile communications
HPF	High Pass Filter
HSPA	High Speed Packet Access
IEEE	Institute of Electrical Electronics Engineers
ISAR	Inverse Synthetic Aperture Radar
J-FET	Junction – Field Effect Transistor
k-NN	k-Nearest Neighbours
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LOS	Line of Sight
LPF	Low Pass Filter
LTE	Long-Term Evolution

MAEPS	Malaysia Agro Exposition Park Serdang
MCMC	Malaysian Communications and Multimedia Commission
MDV	Minimum Detectable Velocity
MIB	Master Information Block
MIMO	Multiple Input and Multiple Output
MIMO-OFDM	Multiple Input and Multiple Output–Orthogonal Frequency Division Multiplexing
MRCS	Monostatic Radar Cross Section
NACK	Non-Acknowledgement
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PBCH	Physical Broadcast Channel
PBR	Passive Bistatic Radar
PC	Principal Component
PCA	Principal Component Analysis
PCB	Printed Circuit Board
PRB	Physical Resource Block
PSD	Power Spectrum Density
PSS	Primary Synchronization Signal
QPSK	Quadrature Phase Shift Keying
RADAR	Radio Detection and Ranging
RB	Resource Block
RCS	Radar Cross Section
RHS	Radio Holographic Signal
SAR	Synthetic Aperture Radar

SISAR	Shadow Inverse Synthetic Aperture Radar
SLR	Signal to Leakage Ratio
SMS	Short Messaging Services
SNR	Signal to Noise Ratio
SSS	Secondary Synchronization Signal
SUV	Sport Utility Vehicle
TDD	Time Division Duplex
TRP	Two-Ray Path
UAV	Unmanned Aerial Vehicle
UeSRS	User equipment Specific Reference Signals
UMTS	Universal Mobile Telecommunications System
UPM	Universiti Putra Malaysia
UpPTS	Uplink Pilot Time Slot
UWB	Ultra Wideband
VHF	Very High Frequency
VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 Background

Passive bistatic radar (PBR) system can utilize the illuminator of opportunity to improve radar proficiency. By exploiting the forward scattering technique and procedure into the specific mode of passive bistatic radar, the target detection and classification in passive radar can be enhanced. This system is identified as the passive bistatic Forward Scattering Radar (FSR). The operational mode of the FSR related to the bistatic angle is near 180°, where the desired radar signal is formed through the shadowing of a direct signal by the target rather than back scattering signal from the target such as in conventional radar system [1]. Among the uniqueness of FSR features are enhanced target radar cross section, long coherent intervals of the receiving signal, absence of signal oscillations and essentially simple equipment and implementation [2], [3].

A passive bistatic radar system uses non-cooperative transmitter, which means it exploits other external radiation source for target detection. Therefore, this advantage makes passive radar remarkably cost effective due to the low expenses to be paid for a transmitter system. The basis of non-emitting radio energy leads to the system being practically camouflaged to surveillance. Until now, illuminators of opportunity have been employed namely in Television Broadcasting [4], FM radio [5], Digital Video Broadcasting (DVB) [6], Digital Audio Broadcasting (DAB) [6], satellites [7], [8], Global Systems for Mobile communications (GSM) [9] and Long Term Evolution (LTE) [10].

In conventional passive bistatic radar, the receiver circuit uses the heterodyne concept that involves a reference signal from direct transmission for synchronization. The received signal is then down converted to the base band and then the target detection is evaluated by analyzing the ambiguity function of the received signal. Alternatively, this thesis presents the FSR mode being integrated into a passive radar system, which is valuable due to the passive FSR not requiring a reference signal from the base station, and target detection scheme based on signal envelope is straight forward without the complicated signal preprocessing step. In addition it also enjoys the simple forward scatter receiver circuit and significant improvement in radar cross section (RCS) at the forward scatter main lobe (FSML). The motivating feature in passive forward scatter radar configuration is the sharp rise of the forward scatter radar cross section (RCS), which increases the sensitivity of the radar system.

Current investigations organized by other researchers using the passive radar with FSR mode are such as Global Positioning System (GPS) satellites signals and have been demonstrated in [11]–[14] for air target detection and in [15] for ground target detection. An investigation using GSM as a signal source and exploiting the forward scatter geometry for target detection is explained in [16], by using two antennas for reference and target's receive signals. Latest publications on passive forward scatter radar using Digital Video Broadcasting-Terrestrial (DVB-T) signals have presented a new algorithm for signal detection, which is for air target detection, whereby it could detect an airplane [17].

Despite the research done so far, the literature is lacking in results for ground target detection and no result was found for ground target classification in passive FSR system. Therefore, the aim of this thesis is to show the feasibility of passive FSR for ground moving target detection and classification. In addition, the target's distance from the radar sensor can also be determined. The evaluation was carried out on a real Long Term Evolution (LTE) signal transmitted through air. Three vehicles of different sizes and speeds were tested. The three categories of cars that were used and tested were namely Compact, Saloon and Sport Utility Vehicle (SUV). The passive FSR experiment results show that the vehicles were successfully detected, even by unprocessed received signals without any complicated signal processing techniques, and the proposed classification system provided results on classification. The results from this thesis can enhance the passive radar system's capability by integrating FSR mode in the conventional PBR system.

The LTE has special characteristics that makes it attractive to be used as an illuminator of opportunity for passive radar applications. Among the characteristics of the LTE signal are it has a broad bandwidth range, from 1.4 MHz to 20 MHz, which provides a high range resolution in comparison to other illuminators of opportunity, and the variety of allocated frequency bands in the range of 800 MHz until 3.5 GHz allowing the LTE to be deployed in many countries, is significant for the future broad coverage of LTE worldwide [18]. Additionally, the number of commercial LTE networks is seeing a massive increase year by year. For that reason, the growth of LTE signal availability will increase LTE based passive radars' deployment opportunities. Moreover, analysis on the LTE signal Ambiguity Function, (AF) which employs the orthogonal frequency division multiple access (OFDMA), shows that low side lobes and high range resolution can be achieved [19]. Thus, the LTE signal characteristics, among others, inspired this research to use the LTE signal as an illuminator of opportunity for passive FSR system, especially for ground moving target detection and classification.

Moreover, FSR performance does not depend on the LTE signal modulation and consequently does not interrupt the detection and classification of ground moving target in LTE based passive forward scattering radar system. This emphasizes the capability of FSR to detect ground moving target through monitoring perturbations in the direct path of LTE signal.

Furthermore, this thesis shows the first classification result on ground moving target in passive forward scatter radar system. The power spectral density of the vehicle signal is used as the target signature and input of the classification system. The frequency spectrum is extracted for feature selection, which has useful information of different targets. The difference in spectrum is referred to the frequency domain signature that is unique for each ground moving target's silhouette and target forward scatter radar cross section that is useful for target classification. The feature selection have high dimensions where PCA is employed to reduce the dimensionality of the spectral feature vectors inherently clustering and classifying the data by exploiting the correlation between the features. The great potential in the 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. Figure 1.1 illustrates several possible application of the LTE based passive FSR.

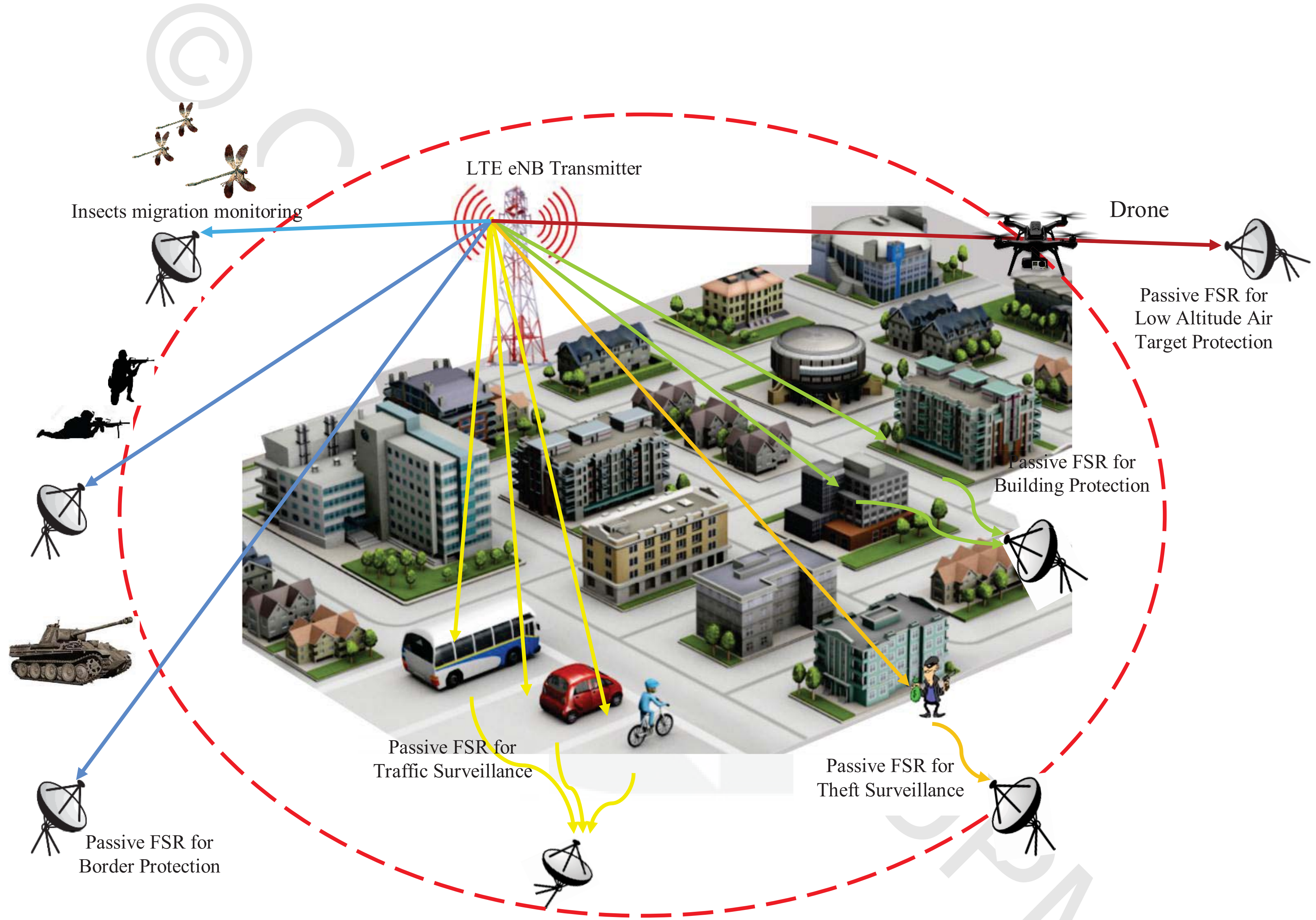

Figure 1.1 : Possible application of LTE based passive FSR

1.2 Problem Statement and Research Opportunity

The main challenges faced by conventional passive radar are:

i. Conventional passive radar system uses two channels for synchronisation between direct signal and reflected signal. It then uses the difference between the two channels for target detection and target range. Having two channels at the receiver will give implication to extra cost. In addition, the requirement for signal synchronisation complicates the signal processing.
ii. The received signal from illuminator of opportunity have varies signal modulation characteristic that introduce more ambiguities in conventional passive radar processing which affects target detection. Furthermore, modulation in the signal affects classification complexity due to the requirement of many databases for each signal modulation type.
iii. Radar system for air target is designed for high altitude targets and long range, making low altitude targets undetectable in the shadow region of that radar system. So, low altitude coverage is required to detect targets moving near to the ground closed to the radar system such as the ground moving threats or any low altitude targets through the shadowing of a direct signal by the target shape.

1.3 Aim and Objectives

The aim of this thesis is to develop an LTE based passive forward scatter radar system for ground moving target detection and classification. The following objectives have been set in order to fulfil this aim:

i. To investigate the feasibility of forward scatter configuration mode using LTE signal as an innovative illuminator of opportunity in passive radar system for ground moving targets detection.
ii. To develop experimental LTE based passive forward scatter radar system receiver and organize site experiments for ground moving target detection and classification.
iii. To find the unique features of Doppler frequency for ground moving targets from the LTE based passive forward scatter radar system for classifier.

1.4 Thesis Contributions

The specific contributions of this thesis that focuses on developing LTE based passive forward scatter radar system for ground moving target detection and classification are listed in the respective chapters throughout the thesis. The main contributions of this thesis are presented:

i. Proof of concept by real experiment data of a passive forward scatter radar based on LTE signal for vehicle (ground target) detection and classification.
ii. The selection of good features of the received signal that represent vehicle signature to be used for vehicle classification.
iii. Vehicle classification system and algorithm in passive forward scatter radar based on LTE signal.
iv. Prediction system of vehicle's speed and baseline crossing point in passive forward scatter radar based on LTE signal.

In this research work, there is several limitation, which are:

i. One transmitter is used from the LTE base station in passive forward scatter radar system. This is a limitation to the system since LTE signal is the first to be investigated in forward scatter configuration to detect the ground moving target.
ii. Three ground moving targets which are Compact, Saloon and SUV, are used for detection and classification, and are common vehicles in Malaysia with different size and shape.
iii. The distance between the LTE transmitter and passive radar receiver is limited to 450 meters because the experiment work is carried out in a parking space, where it has a suitable geometrical area, good coverage of LTE signal and the point of receiver to transmitter is in direct line-of-sight.

1.5 Thesis Outline

The layout of this thesis is organized as follows:

Chapter 2 briefly discusses the radar configuration that indicates passive forward scatter radar system. This chapter emphases on the target detection technique in passive FSR by exploiting the enhancement of the target's RCS. The fundamental received signal equation is derived and the proposed passive FSR system is also explained. The passive forward scatter radar development are discussed on illuminator sources for passive radar, which includes WiMAX, GSM, GPS and LTE. The specifics of LTE are also presented, which contains channel, frame structure, downlink channel and signal of LTE, current and future development of LTE and LTE propagation characteristics. At the end of this chapter, pattern classification for the target detection using LTE based passive forward scatter radar that emphasize on Principal Component Analysis (PCA) and k-Nearest Neighbours (k-NN) algorithm is discussed.

Chapter 3 elaborates on the LTE based passive forward scattering radar architecture at the experiment site. The experiment data collection is briefly discussed on the experiment setup, hardware description, circuit of Doppler frequency filter and amplifier, recording data format, data collection method and target description. Subsequently, the chapter goes into detail on the experimental data description, which comprises simulation target and measured signal.

Chapter 4 explains the experiment results obtained from an LTE based passive forward scattering radar at MAEPS to perform the vehicle feature extraction and classification. The feature extraction involves data selection, segmentation, denoise and transformation into power spectral density (PSD). The explanation of the raw data signal processing for vehicle classification in passive forward scattering radar is deliberated in details in this chapter. Next, discusses the classification system commencing on training and testing data, and overview of the classification system for target classification by using PCA. This chapter also concentrates on classification performance for various target baseline crossing range and classification performance for various target speed for each type of vehicle. Next, it describes classification performance for various vehicle with fixed target speed and fixed target baseline crossing range. The ultimate classification performance is from the accumulation of various target speed and from the accumulation of various target baseline crossing range, which positively resulted in distinguishing the vehicles in the three categories (Compact, Saloon and SUV).

Chapter 5 summarizes and concludes the research based on the results presented in this thesis. The conclusion and direction for future work are outlined in the last section.

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