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LTE-BASED PASSIVE RADAR FOR GROUND TARGET DETECTION AND TRACKING

ASEM AHMAD MOHAMAD SALAH

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By

ASEM AHMAD MOHAMAD SALAH

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

May 2015

قال تعالى:

((وَوَصَّيْنَا الإِنسَانَ بِوَالِدَيْهِ حَمَلَتْهُ أُمُّهُ وَهْناً عَلَى وَهْنٍ وَفِصَالُهُ فِي عَامَيْنِ أَنْ اشْكُرْ لِي وَلِوَالِدَيْكَ إِلَيَّ الْمَصِيرُ))

لقمان 14

This thesis is dedicated to:

my beloved parents, (Ahmed and Ilham),

my lovely wife (Nour) ,

my brothers and sisters,

my parents, brothers and sisters in-law,

all of my friends,

and to my beloved home land Palestine.

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

LTE-BASED PASSIVE RADAR FOR GROUND TARGET DETECTION AND TRACKING

By

ASEM A. M. SALAH

May 2015

Chairman: Assoc. Prof. Raja Syamsul Azmir b. Raja Abdullah, PhD

Faculty: Engineering

Passive radar system constitute of a receiver without the co-located transmitter. It uses non-cooperated illumination sources for target detection and tracking. Thus, it has numerous advantages over the conventional radar system such as: (1) it is practically invisible to surveillance receivers using conventional radio direction finding techniques; (2) it is easily transported, due to its smaller size; (3) it is cheaper as it does not send out a signal and (4) it requires no spectrum allocation. Consequently, it has no environmental impact. Of late, the use of illuminators of opportunity by passive radar systems has gained the interest of radar engineers and researchers. In this thesis, LTE signal was used as illumination source for passive radar application.

Detail studies on the feasible analysis, system design, implementation and applications in ground moving target detection were conducted in this thesis. Firstly, the LTE signal waveform was analyzed in terms of range and Doppler resolutions which are important for radar system. The LTE signal range and Doppler ambiguities were evaluated by applying the ambiguity function to both simulated and real LTE signals transmitted from LTE eNB (base station). The results of these analyses and calculations showed that LTE signal ambiguities do not affect the detection and tracking of a ground moving target. In addition, the LTE signal outperforms other illumination sources in range and Doppler resolutions.

Secondly, the proposed LTE-based passive radar system performance was evaluated by conducting an outdoor field experiment using a real LTE eNB transmitter as an illumination source, to detect ground moving targets and display it in 2-D Doppler/range plane. Nine scenarios were carried out to investigate the system capability of detecting diverse ground moving targets which move in different speeds and different directions. The systems capability to detect multi-targets moving on the ground in the same scene was also examined. The experimental results showed that the LTE-based passive radar system has the capability of detecting cars, motor bikes and human bodies

moving with varies speeds such as 10, 20, 30 and 40 km/h, and they are detected with different ranges from 0-160 m.

Finally, the LTE-based passive radar was developed for tracking ground moving targets in x-y plane. An effective tracking algorithm was proposed based on CFAR and Kalman filter to track the moving target in x-y plane precisely. The proposed LTE-based passive radar system for tracking performance was evaluated by conducting an outdoor field experiment using a real LTE eNB transmitter. In the experiment, two scenarios were carried out to investigate the system capability for tracking a ground moving target moving in different trajectories. The experimental results demonstrated that the LTE-based passive radar system has the capability of tracking a car moving along a straight line as well as an oval shape path. From the experimental results, it is shown that the predicted target positions obtained after the application of a standard Kalman tracking algorithm was almost following the ground truth of the moving car.

The obtained experimental results manifested that the LTE passive radar system can detect and track ground moving target accurately. This demonstrates the efficiency of the designed system and the proposed algorithm. The current study exhibits the feasibility of LTE signal as passive radar illumination source from both theoretic and practical aspects. It also shows the superiority of LTE signal as the passive radar illumination source. All the results revealed the effectiveness of the LTE-based passive radar, which can be developed and implemented in many practical applications including border protection, traffic surveillance and building monitoring.

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

PENYELIDIKAN ISYARAT LTE SEBAGAI PELUANG PEMANCAR BARU UNTUK APLIKASI RADAR DWISTATIK PASIF

Oleh

ASEM AHMAD MOHAMAD SALAH

Mei 2015

Pengerusi: Prof. Madya. Raja Syamsul Azmir b. Raja Abdullah, PhD

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Sistem radar pasif terdiri daripada penerima tanpa pemancar yang ditempatkan bersama. Sebaliknya ia menggunakan sumber pemancar lain untuk mengesan dan menjejak sasaran, dengan itu ia mempunyai lebih banyak kelebihan berbanding sistem radar konvensional dalam pelbagai cara. Sebagai contoh, ianya boleh dikatakan tidak kelihatan kepada penerima pengawasan menggunakan teknik carian arah radio konvensional, ianya mudah dibawa kerana saiznya lebih kecil, lebih murah kerana tidak perlu menghantar isyarat dan tidak memerlukan peruntukan spektrum serta tidak memberi kesan kepada alam sekitar. Sejak kebelakangan ini, penggunaan peluang pemancar oleh sistem radar pasif telah mendapat kepentingan jurutera dan penyelidik radar. Dalam tesis ini, isyarat LTE buat pertama kali digunakan sebagai sumber pemancar untuk aplikasi radar pasif.

Kajian ini akan menjalankan pelaksanaan analisis secara terperinci, reka bentuk dan pelaksanaan sistem, aplikasi dalam mengesan pergerakan sasaran. Pertama, isyarat gelombang LTE dianalisis dari segi julat dan resolusi Doppler yang mana ianya penting untuk sistem radar. Julat isyarat LTE dan kesamaran Doppler dinilai dengan menggunakan fungsi kekaburan bagi kedua-duanya; isyarat LTE yang disimulasi dan yang asal dihantar dari LTE ENB (stesen pangkalan). Pengubahsuaian parameter isyarat LTE lapisan fizikal yang memberi kesan terhadap tingkah laku fungsi kekaburan adalah diramal. Keputusan analisis dan pengiraan ini menunjukkan bahawa kekaburan isyarat LTE tidak mempunyai kesan ke atas pencarian dan penjejakan pergerakan sasaran darat dan isyarat LTE yang mengatasi sumber pemancar lain dalam julat dan resolusi Doppler. Kedua, dicadangkan sistem seni bina radar pasif LTE dipermudahkan untuk pengesanan, dan disedari bahawa sistem radar pasif berasaskan LTE adalah antara yang terawal. LTE mudah alih berdasarkan ujikaji luar dalam pengesanan sasaran bergerak berjaya dijalankan dan jenis pergerakan sasaran darat dapat dikesan dalam bentuk satah julat Doppler 2-D untuk pelbagai senario. Akhir sekali, radar pasif

berasaskan LTE dibangunkan untuk kebolehan mengesan sasaran bergerak dalam satah x-y. Algoritma pengesanan yang efektif dicadangkan berdasarkan penapis Kalman untuk mengesan sasaran bergerak dalam satah x-y secara terperinci.

Keputusan eksperimen menunjukkan bahawa sistem radar pasif LTE boleh mengesan, menjejaki dan menempatkan sasaran darat bergerak secara tepat, yang menunjukkan bahawa sistem yang direka dan algoritma yang dicadangkan dapat beroperasi secara efektif. Oleh yang demikian, tesis ini telah menunjukkan kebolehlaksanaan LTE sebagai isyarat sumber pemancar radar pasif dari kedua-dua aspek teori dan praktikal. Ia juga menunjukkan bahawa keunggulan isyarat LTE sebagai sumber pemancar radar pasif. Semua hasil keputusan dapat membantu radar pasif LTE yang akan dibangunkan untuk kegunaan praktikal atau komersial.

my worm gratitude to Assoc. Prof. Dr. Nasser Hamad for the kind support I have been enjoining from him since my undergraduate to date.

In the final note, I would like to extend my sincere thanks to all and sundry, who helped me in one way or other, but whose names I have not been able to mention one by one.

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I certify that a Thesis Examination Committee has met on (29-5-2015) to conduct the final examination of (Asem Ahmad Muhamad Salah) on his thesis entitled " LTE-BASED PASSIVE RADAR FOR GROUND TARGET DETECTION AND TRACKING" 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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LIST OF ABBREVIATIONS

Radar	radio detection and ranging
LTE	long term evolution
DVB	digital video broadcasting
DAB	digital audio broadcasting
WiFi	wireless fidelity
GSM	global systems for mobile communications
WiMAX	worldwide interoperability for microwave access
OFDMA	orthogonal frequency division multiple access
FDD	frequency division duplex
TDD	time division duplex
CFAR	constant false alarm rate
DBSTV	direct broadcast satellite television signal
DOA	direction of arrival
GPS	global position system
DTV-T	digital television–terrestrial
AF	ambiguity function
MIMO	multiple-input-multiple-output
CSRS	cell specific reference signals
SS	synchronization signals
SAR	synthetic aperture radar
eNB	evolved node B
3GPP	3rd generation partnership project
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
SC-FDMA	single carrier frequency division multiple access
RBs	resource blocks
CP	cyclic prefix
DwPTS	downlink pilot time slot
GP	guard period
UpPTS	uplink pilot time slot
RE	resource element
ISI	inter symbol interference

PBCH	physical broadcast channel
PDSCH	physical downlink shared channel
PMCH	physical multicast channel
PCFICH	physical control format indicator channel
PDCCH	physical downlink control channel
PHICH	physical hybrid arq indicator channel
RS	reference signal
SS	synchronization signal
P-SS	Primary Synchronization Signal
S-SS	secondary synchronization signal
SNR	signal to noise ratio
LOS	line-of-sight
AF	ambiguity function
CIT	coherent integration time
LNA	low noise amplifier
BPF	band pass filter
CAF	cross ambiguity function
BC	bistatic couples
CUT	cell under test
FSR	forward scattering radar
UAV	unmanned aerial vehicle

LIST OF SYMBOLS

P_t	transmitted power
G_t	antenna gain for the transmitter
G_r	antenna gain for the receiver
λ	wavelength
Γ	reflection coefficient
R_{los}	LOS distance between the transmitter and receiver antennas
P_{refl}	ground reflected signal power
R_{refl}	total distance for the ground reflected signal
Δd	difference between two paths distances
$\Delta\phi$	phase difference between two signals
εr	different dielectric
μr	permability
σ	conductivity
Γ_v	reflection coefficient for the vertical polarized signal
Γ_h	reflection coefficient for the horizontal polarized signal
P_{Tot_Rec}	total received power including ground reflected signal
f_c	carrier frequency
h_t	transmitter height
h_r	receiver height
P_t	transmission power
ΔR	range resolution
B	signal bandwidth
c	speed of light
β	bistatic angle
Δf_d	Doppler resolution
T	CIT
$f_{d_{T1}}$	received echoes Doppler from first target
$f_{d_{T2}}$	received echoes Doppler from second target
v_{T1}	velocity of target 1
v_{T2}	velocity of target 2

α_1	velocity radial angel for target 1
α_2	velocity radial angel for target 2
Δv	velocity resolution
$\chi(\tau, f)$	ambiguity response
$s(t)$	transmitted signal
τ	time delay
f_d	Doppler shift
T_u	data symbol duration
$\mathrm{T_{sym}}$	symbol width
R_1	range between the LTE eNB and Ch1 antenna
R_2	range between the LTE eNB and the moving car
R_3	range between the moving car and Ch2 antenna
v	velocity
$m(t)$	original modulated LTE signal
$x_{d\_1}(t)$	received signals from Ch1 antenna
$x_{r\_1}(t)$	received signals from Ch2 antenna
$s_d(t)$	LTE signals received from Ch1 antenna
$s_r(t)$	LTE signals received from Ch2 antenna
τ_d	delay time of the received signals for Ch1
τ_r	delay time of the received signals for Ch2
R_1	range between the LTE eNB and the receiver's antenna of Ch1
R_2	range between the LTE eNB and the target
R_3	range between the target and Ch2 antenna
R_4	range between the target and Ch3 antenna
α	angle between the target velocity direction and the relative velocity
v_R	relative velocity
$w_{LO}(t)$	local oscillator signal
f_{LO}	frequency oscillator
$s_r(t)$	reflected signal
$s_d(t)$	directed signal
N	number of samples in CIT
f_s	sampling frequency

$A(\tau, f_d)$	cross ambiguity function output matrix
Th	threshold
s	scaling factor (threshold factor)
P_n	estimated noise power
x_m	the sample in each training cell
N	number of training cells
τ_1	time delay for the received signals for Ch2
τ_2	time delay for the received signals for Ch3
D_1	distance between Ch1 and Ch2
D_2	distance between Ch1 and Ch3
a_1	semi-major axis of ellipse
b_1	semi-minor axis of ellipse

CHAPTER 1

INTRODUCTION

1.1 Background

Radar (Radio detection and ranging) is an object-detection system, which was invented in the late 19th century. Several nations successfully developed the radar system since before World War II up to date. Besides the military applications for the radar systems like air-defense and guided missile target locating applications, it has many modern civilian uses, some of which are air traffic control, radar astronomy, marine radars to locate landmarks and other ships.

Generally, the radar transmitters in radar systems transmit electromagnetic waves in the space which hits the object present in the radar coverage area. Subsequently, the waves scatter back to the receiving antenna for detection, and all information about the object can then be determined. If the transmitter and receiver are located in close proximity to one another, then the radar is called 'monostatic radar'. Otherwise, if the transmitter and receiver have a distance comparable to the maximum range of a target then it is called 'bistatic radar'.

In view of the fact that the monostatic and bistatic transmitters emit electromagnetic waves, it is possible for the enemy to discover the radar transmitters' location and jamming them. Hence, the passive radar system was proposed to overcome the aforementioned problem.. The passive radar is essentially bistatic radar that uses non-cooperative transmitters. Meaning that, it exploits other external radiation source (illuminator of opportunity) for detecting and tracking the targets. Passive radar has more advantages as compared to the conventional radar, for the former does not emit electromagnetic waves. Other specific advantages of passive radar are attributed to the fact that it can be easily hidden, consumes less power, low cost, resistant to low-altitude and anti-radiation missiles, anti-stealth capability. Furthermore, it can use multiple networks as ubiquitous network and does not need spectrum allocation, thus, no environmental electromagnetic pollution. These characteristics allow passive radar to occupy an important place in the modern electronic warfare technologies, which made the passive radar technology one of the interesting research areas for the recent years.

Many illuminators have been employed for passive radar applications from number of sources such as: television broadcasting [1], FM radio [2], digital video broadcasting (DVB) [3], digital audio broadcasting (DAB) [3], satellites [4], wireless fidelity (WiFi) [5-7], global systems for mobile communications (GSM) [8, 9], and worldwide interoperability for microwave access (WiMAX) [10-12]. However, the use of Long Term Evolution (LTE) as an illuminator of opportunity for passive radar is recently a new research area.

LTE is one of the latest wireless communication technologies, which provides last-mile broadband wireless access with anticipated widespread accessibility. The LTE signal has some parameters and characteristics which made it attractive for passive radar application. These parameters and characteristics consist of:

i. A broad bandwidth within the range of 1.4 – 20 MHz which allows it to have high range resolution.
ii. The use of a special downlink frame structure for LTE with orthogonal frequency division multiple access (OFDMA), which guarantees low side-lobes of the ambiguity function.
iii. A large frequency band ranging from 800-3500MHz as well as its ability to support both frequency division duplex (FDD) and time division duplex (TDD) [13, 14], which enhances the opportunity of LTE to be deployed worldwide.
iv. The number of commercial LTE networks is in a massive increase year by year. Therefore, increasing the LTE signal availability will enhance the LTE-based passive radars deployment opportunity.

Passive radar could be utilized but not limited to the following potential applications: Firstly, for border protection, since passive radar transmits no signals, it will be invisible to surveillance which rendered it suitable for border monitoring and protection. Secondly, passive radar can be used for low altitude flying targets detection. The low altitude flying targets could be detected as the illuminator of opportunity emits its signals in the space. Thirdly, passive radar can be also used for building monitoring against any moving intruders as the passive radar can detect the human bodies. Fourthly, passive radar can be used for traffic surveillance. Figure 1.1 illustrates some of the LTE–based passive radar potential applications.

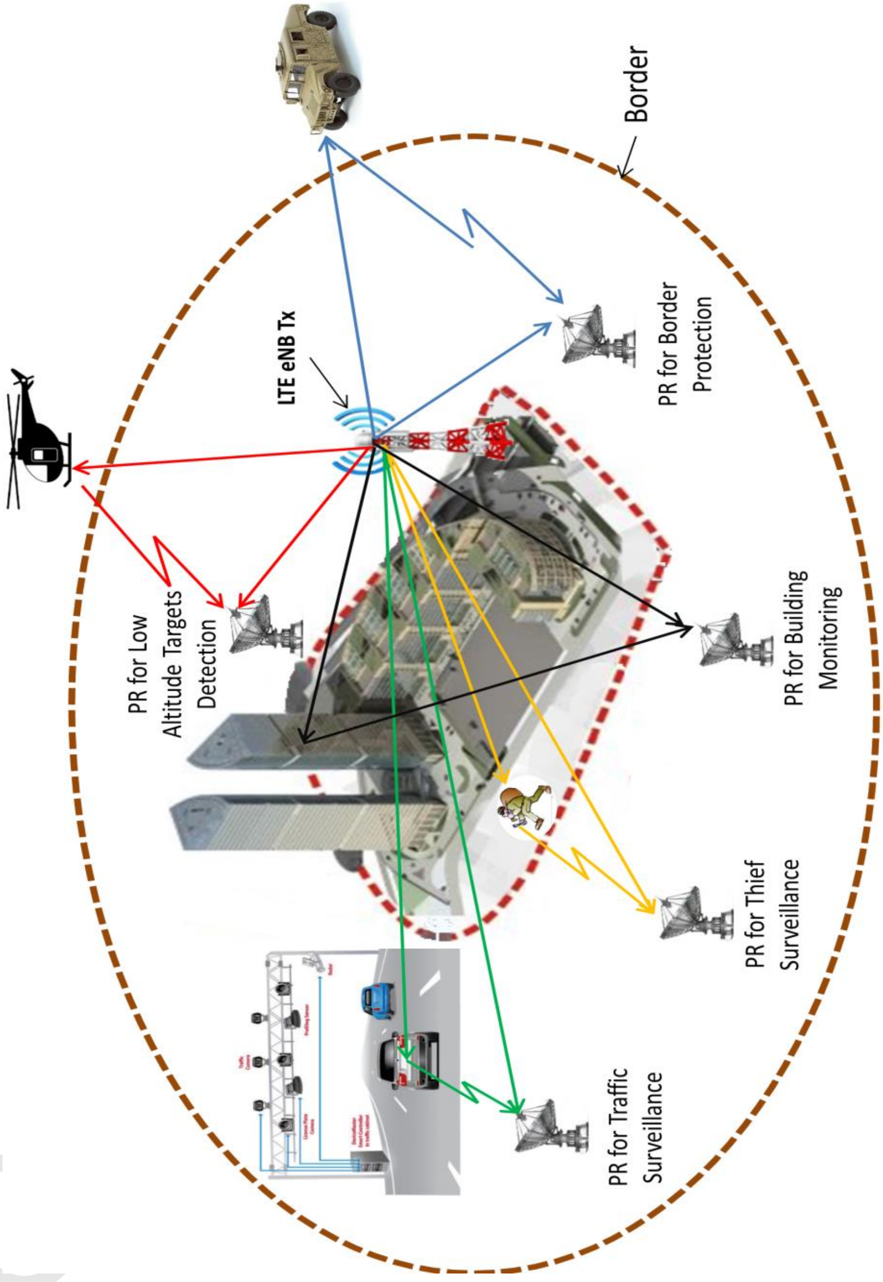

Figure 1.1: LTE-based passive radar potential applications

This thesis investigates the potential of LTE-based passive radar to detect and track ground moving targets using two approaches: Firstly, theoretical calculations and analysis were applied on both simulated and real LTE signal. Secondly, two field experiments were conducted to examine the LTE-based passive radars capability for detecting and tracking ground moving targets.

1.2 Problem Statement

The main goal of proposing the passive radar system is to ease number of challenges facing the conventional radar, these challenges includes:

i) Unhidden to the enemy detectors: The conventional radar transmits its own electromagnetic waves which permits the enemy receivers detect these waves and discover its source location. Thus, the radar system becomes easily destroyed by the enemy. Hence, it is vital to keep the radar system hidden from the enemy threats.

ii) Unsuitable for low altitude coverage: The conventional radar has a long range feature that makes it more suitable for high altitude target applications. Therefore, the defense system becomes penetrative from the ground moving threats or even from the low altitude objects.

iii) Spectrum congestion: The conventional radar system needs to occupy spectrum bands which are costly.

iv) Its high cost, complexity and power consumptions.

Therefore, many researches have attempted to find a suitable illuminator of opportunity to be used with passive radar applications. A number of illumination sources like FM, DVB, GSM, WiFi, and WiMAX were previously investigated in many researches. Though, some of these illuminators partially succeeded as illuminator of opportunity for passive radar applications, none of the used passive radar systems can suit all applications. Some of the passive radar systems lack resolution while others have limited coverage range. Moreover, some of the existing systems might dissipate in the near future. Thus, with the advantages of LTE signal (i.e. high resolution, wide coverage and future signals availability), the LTE-based passive radar can complement the drawbacks of the existing passive radar systems.

To the best of our knowledge, no experimental work has been published regarding the investigation of LTE-based passive radar capability for detecting and tracking moving targets, except the ones published by the UPM research group. The results from the thesis can be a reference for the future development of LTE passive radar.

1.3 Aim and Objectives

The aim of this thesis was to develop LTE-based passive radar for moving target detection and tracking. To achieve this aim, the following objectives are to be accomplished:

i. To show the feasibility of using LTE signal as new illuminator of opportunity for passive radar application.

ii. To investigate the capability of LTE-based passive radar system for ground moving targets detection.
iii. To investigate the capability of LTE-based passive radar system for ground moving targets tracking.
iv. To develop experimental LTE-based passive radar system and conduct an experiment work for ground targets detection and tracking.

1.4 Thesis Scope

On the basis of system configuration, radar systems can be classified into monostatic and bistatic radar. If the radar's receiver and transmitter are co-located to each other, then the radar is called monostatic radar. Whereas, if they are separated with a proportional distance, then the radar is called bistatic radar as shown in Figure 1.2 (a) and (b). The bistatic radar can be further classified into two categories depending on the radiation source used; the cooperation radiation source and, the non-cooperative radiation source.
The first category is bistatic radar that uses external allied or friendly cooperative transmitters separated with proportional distance from the receivers. The antenna receives the reflected or scattered waves from the targets and after doing some analysis on the received signals the detection and tracking purpose can be achieved. This kind of systems improve the radar survivability because once the transmitters had been destroyed, the system cannot work anymore.

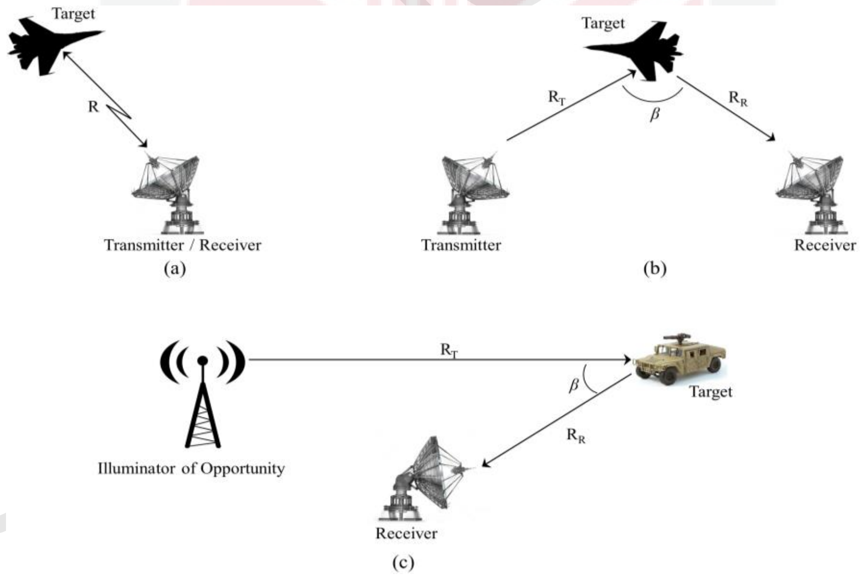

Figure 1.2: Radar systems (a) Monostatic radar (b) Bistatic radar and (c) Passive bistatic radar.

The second category is the passive radar that uses the external hostile or neutral non-cooperative illuminators of opportunity. These opportunities could be illuminators with long range transmission like TV, FM radio, DVB, DAB and satellites, and some other illuminators are with short range transmission like wireless fidelity WiFi. Additionally, there are other illuminators with a medium range like GSM, WiMAX and LTE. The scope of this thesis focused on passive bistatic radar using the medium range illuminator of opportunity exactly the LTE as illustrated by the study module in Figure 1.3.These are discussed in detail in the subsequent chapters.

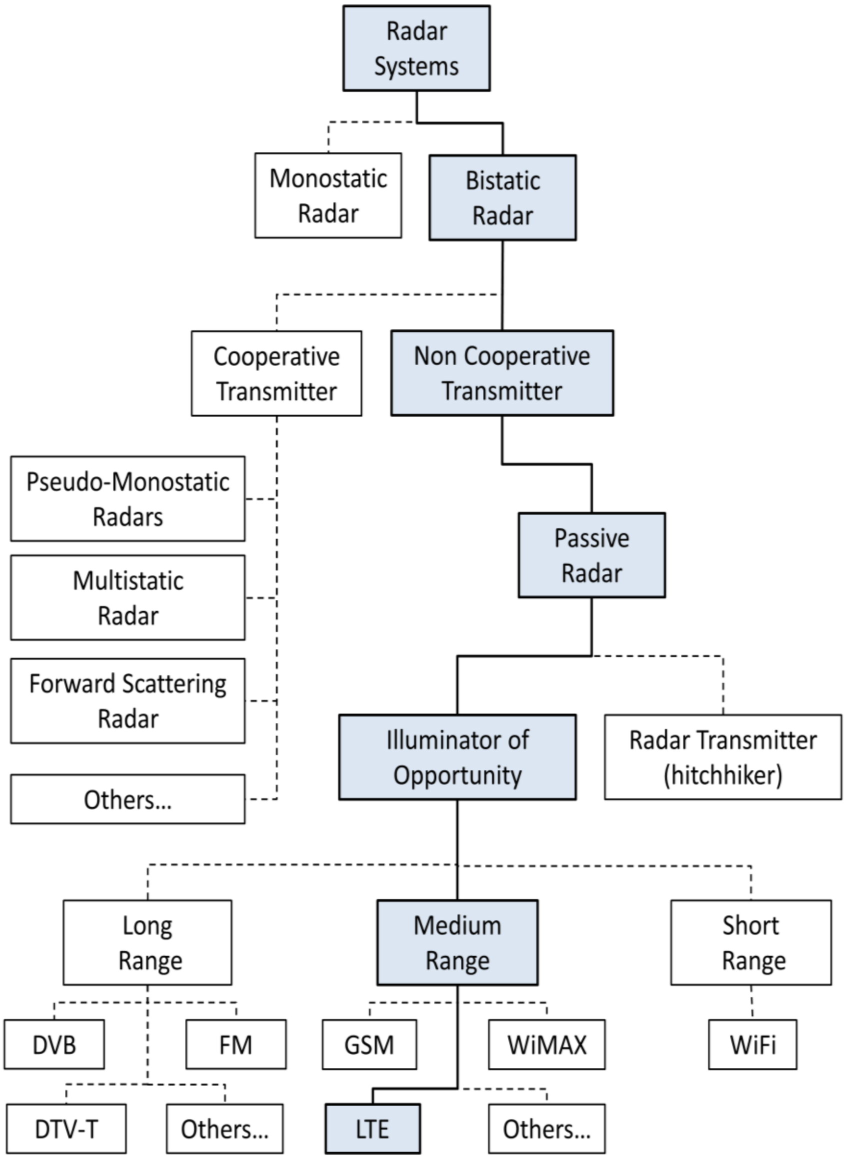

Figure 1.3: LTE-based passive radar study module

1.5 Contribution

In this thesis, the focus is on developing LTE-based Passive radar for moving target detection and tracking. The main contributions of this thesis are:

i. Analyzing and Adopting the LTE signal for passive radar applications.

ii. Developing LTE-based passive radar with signal processing scheme for different ground targets (car, motor bike and human) detection.

iii. Developing LTE-based passive radar with signal processing scheme for tracking ground targets moving with different trajectories.

1.6 Thesis Organization

The remaining chapters of this thesis are organized as follows:

Chapter 2 commenced with a brief discussion on the bistatic radar developments, which was followed by detail discussion on passive radar. Three categories of passive radar were discussed; the first and second categories are with long range and short range transmitters, respectively. While the third category has a medium range transmitters which include the GSM, WiMAX and LTE. The details of LTE technology were also presented; where the LTE channel and frame structures were discussed in detail, followed by a summary of the LTE downlink channels and signals. The LTE current and future deployments which can affect the passive radar future were finally discussed at the end of the chapter.

Chapter 3, entails analyzes of the LTE signal waveform from radar perspective. Where, practical measurements and analyses of the transmitted LTE signal are used for illustrating its effects on the resulting system and design performance. In particular, the range and Doppler resolutions are computed for all LTE waveforms modes that could be transmitted by the LTE eNB. Subsequently, the AF was computed for both simulated and experimental LTE signals to enable the limits on range and Doppler resolution to be determined. The chapter ends by comparing different passive radar illumination sources.

Chapter 4 describes the investigation of the LTE-based passive radar capability for detection ground moving targets. In this chapter, the experimental setup for the proposed LTE-based passive radar for detection was demonstrated. The data formatting and signal processing algorithms were also depicted in the current chapter. And then the conducted experimental scenarios results, for examining the proposed LTE-based passive radar system capability for detection, are presented and discussed.

Chapter 5 consists of the investigation of the LTE-based passive radar capability for tracking a ground moving targets. The experimental setup for the proposed LTE-based passive radar for tracking was depicted in the beginning of this chapter. Then the tracking signal processing algorithms including Kalman filter and the constant false alarm rate (CFAR) algorithms were demonstrated. Finally, the tracking experimental results for the conducted scenarios were illustrated and discussed.

Chapter 6 summarizes and concludes the research based on the results presented in this thesis. This is followed by some suggestions for further investigations in the future.

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