MULTIMEDIA TRANSMISSION USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASED ON COGNITIVE RADIO

HILMI MUJAHID `ADLI BIN HUSIN

UNIVERSITI TEKNOLOGI MALAYSIA

MULTIMEDIA TRANSMISSION USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASED ON COGNITIVE RADIO

HILMI MUJAHID `ADLI BIN HUSIN

A thesis submitted in fulfilment of the
requirement for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2016

Specially dedicated to my family

ACKNOWLEDGEMENT

All praise be to Allah, the Almighty, the Benevolent for His blessing and guidance for giving me inspiration and spirit to embrace on this journey and inculcating patience in my heart complete my Master Research project successfully.

I would like to acknowledge my supervisor, Dr. Sharifah Kamilah Syed Yusof for advice, giving the idea and knowledge in my Master Research project. I would like to thank also to Arief Marwanto, Mohd Adib Sarjari and Mohd Khairul Rashid for giving guidance and cooperation to complete my final project.

I am particularly indebted to my family for their supports and guidance. Last but not least, I would like to thank others who I may left out for their help and encouragement.

ABSTRACT

With the rapid growth of multimedia applications over the wireless Internet, the demand for radio spectral resources has increased significantly. Referring to frequency spectrum allocations in Malaysia, major parts of spectrum have been assigned for government and commercial use. Despite the spectrum scarcity in meeting the demands for multimedia services, it was found from previous studies that most of the spectrum is actually not being utilised efficiently. Henceforth, lots of researches have been conducted to exploit this underutilised spectrum opportunistically without affecting the incumbents operations. Through the enabling Software Defined Radio (SDR) technology, Cognitive Radio (CR) has been proposed to solve the inefficient spectrum utilisation problems. CR is an adaptive, intelligent radio and network technology that has the ability to detect available vacant channels in radio frequency spectrum and change its particular transmission or reception parameters for efficient communication link achieved. In this thesis, SDR platform which consists of GNU Radio and Universal Software Radio Peripheral (USRP) is used for CR multimedia transmission development. In this system, adaptive Orthogonal Frequency Division Multiplexing (OFDM) is implemented to support robust multimedia transmission effectively. Next, Pseudorandom Multiband Frequency Switching is proposed for seamless frequency agility provision. For proof of concept, the proposed system is evaluated on several multimedia signals transmission. The results showed that the minimal time duration for each frequency switching of the system is approximately 1 second which resulted 20 dB for peak signal-to-noise ratio (PSNR) achievement. However, with higher rate of intermittent presence of incumbent or primary user (PU), faster switching rate is needed. Hence, the system developed needs further enhancement for a reliable and seamless multimedia transmission system to be realised.

ABSTRAK

Dengan pertumbuhan pesat aplikasi multimedia melalui Internet tanpa wayar, permintaan terhadap sumber spektrum radio telah meningkat dengan ketara. Merujuk kepada peruntukan spektrum di Malaysia, bahagian-bahagian utama spektrum tersebut telah ditugaskan untuk kegunaan kerajaan dan komersial. Walaupun kekurangan spektrum dalam memenuhi permintaan perkhidmatan multimedia, didapati daripada kajian sebelum ini, bahawa kebanyakan spektrum yang diperuntukkan sebenarnya tidak digunakan dengan cekap. Oleh itu, banyak kajian telah dijalankan untuk mengeksploitasi peluang menggunakan spektrum yang tidak digunakan sepenuhnya ini tanpa menjejaskan operasi penyandang spektrum. Melalui teknologi Radio Terikat Perisian (SDR), Radio Kognitif (CR) telah dicadangkan untuk menyelesaikan masalah ketidakcekapan penggunaan spektrum. CR adalah teknologi rangkaian radio penyesuaian pintar yang mempunyai keupayaan untuk menukar dan mengesan saluran kosong tersedia dalam spektrum frekuensi radio serta menukar parameter tertentu sistem pemancar atau penerima agar pautan komunikasi cekap tercapai. Di dalam tesis ini, platform SDR yang terdiri daripada Radio GNU dan Persisian Radio Perisian Universal (USRP) digunakan untuk pembangunan sistem penghantaran multimedia berdasarkan CR. Dalam sistem ini, Pemultipleksan Pembahagian Frekuensi Ortogon (OFDM) mudah suai dilaksanakan untuk menyokong penghantaran multimedia yang kukuh dan berkesan. Seterusnya, Pensuisan Frekuensi Pseudorawak Berbilang-jalur dicadangkan untuk peruntukan kelancaran frekuensi. Untuk pembuktian konsep, sistem yang dicadangkan ini dinilai dengan menggunakan penghantaran beberapa isyarat multimedia. Hasil kajian menunjukkan bahawa tempoh minimum bagi setiap penukaran frekuensi ialah 1 saat yang boleh menghasilkan pencapaian 20dB nisbah isyarat-kepada-hingar puncak (PSNR). Walau bagaimanapun, dengan kadar tinggi kehadiran sekali-sekala penyandang atau pengguna utama (PU), kadar peralihan frekuensi yang lebih cepat diperlukan. Oleh yang demikian, sistem yang dibangunkan ini perlu dipertingkatkan supaya sistem penghantaran multimedia yang lancar serta boleh dipercayai boleh dicapai.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	-	Analog-Digital-Converter
ADSL	-	Asymmetric Digital Subscriber Line
BPSK	-	Binary Phase Shift Keying
CP	-	Cyclic Prefix
CR	-	Cognitive Radio
DAB	-	Digital Audio Broadcasting
DAC	-	Digital Analog Converter
DDC	-	Digital Down Converting
DSA	-	Dynamic Spectrum Access
DSP	-	Digital Signal Processing
DVB-H	-	Digital Video Broadcasting - Handheld
DVB-T	-	Digital Video Broadcasting - Terrestrial
FFT	-	Fast-Fourier Transform
FPGA	-	Field Programmable Gate Array
GRC	-	GNU Radio Companion
ICI	-	Inter-Carrier Interference
ISI	-	Inter Symbol Interference
IF	-	Intermediate Frequency
IFFT	-	Inverse Fast Fourier Transform
IPTV	-	Internet Protocol Television
ISM	-	Industrial, Scientific and Medical
JPEG	-	Joint Photographic Experts Group
MAC	-	Medium Access Control Layer
MP3	-	MPEG Layer 3
MSE	-	Mean Squared Error
OFDM	-	Orthogonal Frequency Division Multiplex
OSS	-	Open Source Software

PAQM	-	Perceptual Audio Quality Measure
PEAQ	-	Perceptual Evaluation of Audio Quality
PHY	-	Physical Layer
PoC	-	Proof of concept
PGA	-	Programmable Gain Amplifier
PSK	-	Phase-Shift Keying
PSNR	-	Peak Signal to Noise Ratio
PU	-	Primary User
QoS	-	Quality of Service
QAM	-	Quadrature Amplitude Modulation
QPSK	-	Quadrature Phase Shift Keying
RF	-	Radio Frequency
RX	-	Receiver
SDR	-	Software Defined Radio
USB	-	Universal Serial Bus
SNR	-	Signal to Noise Ratio
SU	-	Secondary User
SWIG	-	Simplified Wrapper and Interface Generator
TX	-	Transmitter
TV	-	Television
UHF	-	Ultra High Frequency
USRP	-	Universal Software Radio Peripheral
VHF	-	Very High Frequency
WAV	-	Waveform Audio File Format
WLAN	-	Wireless Local Area Network

LIST OF SYMBOLS

MHz	-	Megahertz
Hz	-	Hertz
MB	-	Megabits
bps	-	Bit per Second
kHz	-	Kilohertz
s	-	Second
dB	-	Decibel

CHAPTER 1

INTRODUCTION

1.1 Overview

Wireless multimedia has grown at an exponential pace where lots of digital multimedia content are delivered over the wireless Internet in recent years. Nevertheless, the increasing demand has taken its toll on the quality of service of wireless multimedia content and the bandwidth required to deliver the payload. In order to meet quality of service, various techniques such as channel coding, distribute streaming, multicast and many more have been considered. The limited bandwidth available has become major bottlenecks for high-quality multimedia wireless service. A reason behind this is the fact that a major portion of the spectrum has already been allocated. Figure 1.1 depicts the channel allocation in Malaysia spectrum, which is almost fully allocated for the governments and commercial use. In addition, there are still small quota for free frequency channel but it is already jammed up by the various wireless devices. However, actual measurements taken on the spectrum occupancy on licensed bands, such as TV bands, show significant underutilisation of the spectrum. For instance, actual measurement taken on the Ultra High Frequency (UHF, 470 – 790 MHz) band in Taman Universiti, Johor [1], shows a significant underutilisation of the spectrum. Figure 2 shows the spectrum occupancy of the UHF TV band. As seen from the graph, the occupancy is high at the lower region of the band and becomes lesser as the band progress towards higher frequencies. However, it could be observed that channel 25 (500 MHz) and channel 30 (545 MHz), turn off their transmission during midnight. Thus, it is proven that not all channels are always utilised.

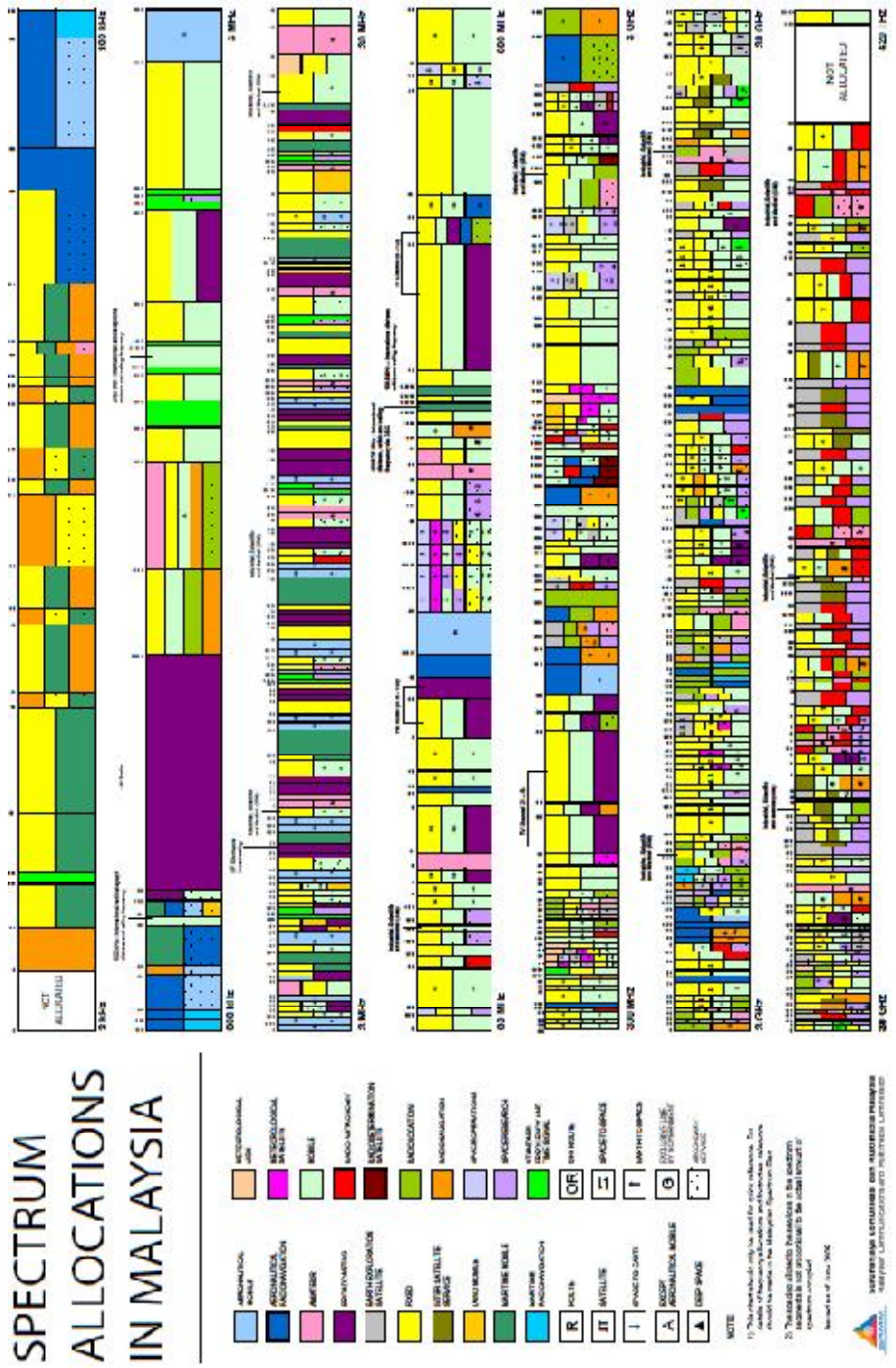

Figure 1.1 Channel Allocations in Malaysia [2]

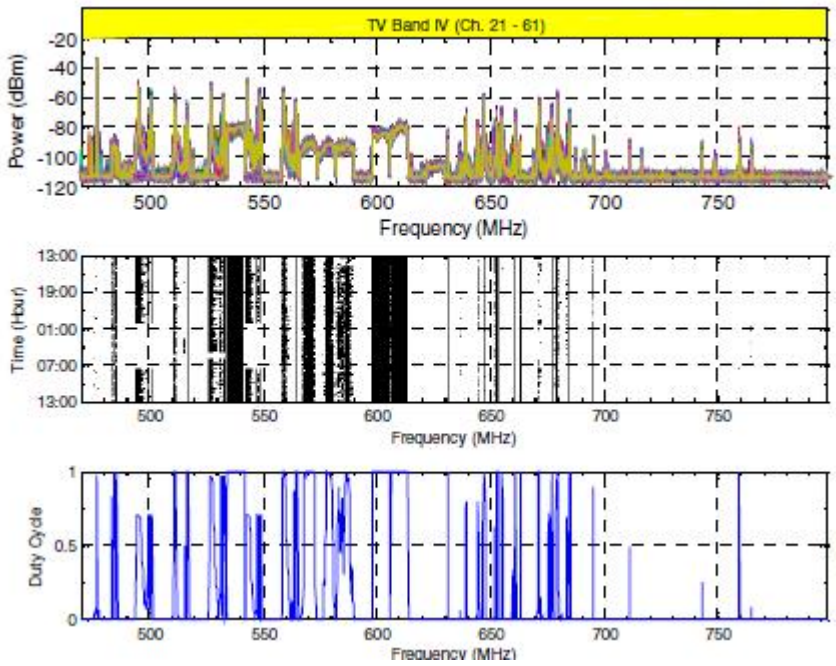

Figure 1.2 Spectrum Occupancy of UHF TV Band in Taman Universiti [1]

One of the brilliant ideas about how to tackle spectrum scarcity and underutilisation is to use the unused part of the spectrum owned by the primary licensed holder. In other word, to study the idea of sharing a spectrum between licensed and unlicensed user. There are researches conducted in this area known as Dynamic Spectrum Access with the purpose to tackle spectrum scarcity. Dynamic Spectrum Access which also known as DSA is a spectrum sharing model that allows secondary users to access the abundant spectrum holes or white spaces in the licensed spectrum bands [3]. Moreover, this mechanism is facilitated by the use of cognitive radio (CR), which is one of the promising technologies that can solve spectrum scarcity problem, potentially without major changes to incumbents.

Cognitive radio is a wireless communication paradigm in which either the network or the wireless node itself changes particular transmission or reception parameters to execute its tasks efficiently based on interaction with the environment in which it operates [4]. This parameter adaptation is based on several factors, such as the operating radio frequency (RF) spectrum, user behavior, and network state. A cognitive radio may depend on a flexible radio platform to implement the functionality to support reconfiguration. Fortunately, with the help of software

defined radio (SDR), the development of such agile radio system becomes feasible [4].

The demand of current multimedia application such as multimedia streaming and live application are high. Hence, more research on providing such services within limited medium are encouraging [5]. In this work, an association of CR and multimedia transmission concept are applied to provide a platform for multimedia transmission. Such work is introduced to study the effect of proposed CR components on multimedia data. There are lots of work including simulation and experimental done to build a new wireless protocol or spectrum access scheme involving CR. However, the number of research involving multimedia data over CR platform is relatively small.

1.2 Problem Statement

Lack of available frequency spectrum resources has failed to meet the demands of new multimedia application. Nonetheless, lots of licensed spectrums are not fully utilised by the license holder as depicted in Figure 1.1. In order to realise a new method to relieve the spectrum scarcity issue, CR offers a scheme whereas unlicensed user or also known as secondary user (SU) could borrow a spectrum opportunistically without affecting the rightful owner activity as mentioned in the previous section.

CR system could be applied in any conventional transmit mechanism for multimedia transmission. As CR technique used in multimedia transmission, there are some limitations needed to be addressed for the system to acquire good quality of service. Most of the multimedia services are better known for its bandwidth demanding application and delay-sensitive data. This type of data application requires efficient communication and DSA capabilities. In exacerbation to this matter, CR users have to halt their transmission and dynamically change their frequency to avoid PU. Therefore, to achieve efficient multimedia transmission, a stable connection is preferred. These challenges need to be addressed in achieving

an efficient multimedia application in CR network. Solution such as agile physical layer sensing technique is recommended in this thesis.

In order to exploit temporal frequency channel while maintaining a stable connection, this work incorporates CR system with Orthogonal Frequency Division Multiplex (OFDM). Orthogonal Frequency Division Multiplex (OFDM) has developed into a popular scheme for multimedia transmission, whether wireless or wire. Such method is usually used in digital television and audio broadcasting. However, OFDM are mainly evolved around conventional radio transmission which is a great loss because there are many OFDM attributes that can be exploited through CR. As a proof-of-concept, an OFDM based CR is developed to convey multimedia data in CR environment. OFDM is chose over other simpler modulations due to its spectral efficiency and higher throughput. In addition, OFDM has many attributes that can be exploited such are the type of modulation, FFT length and others. Through CR, these attributes can be altered during the data transmission to adapt to the spectrum environment, maintaining robustness and many more. Additionally, to support the throughput-intensive multimedia application, multi-carrier modulation technique is needed.

1.3 Research Objectives

The key aspect for this research work is to provide an alternative platform for multimedia data to be delivered via underutilised frequency spectrum. With the help of CR ability, it is hoped that the proposed platform could fulfill these objectives:

- To develop a frequency agility technique for CR multimedia transmission system
- To design an adaptive OFDM-based CR system for multimedia transmission
- To evaluate the performance of the proposed CR system using multimedia data

1.4 Scope of Work

The scope of this research is to design the CR system for multimedia application, which consists of spectrum sensing, spectrum analysis, spectrum decision module on SDR platform. SDR platform used consisted of GNU Radio software and Universal Software Radio Peripheral (USRP) hardware. This project incorporates CR ability with adaptive OFDM method, which focuses more on encoding digital data on multiple carrier frequencies. The term adaptive OFDM refers to the parameters of OFDM, which are reconfigurable based on the interaction with the channel condition.

In this work, several key technology offered by CR are implemented in this research such as spectrum sensing and frequency switching. For the spectrum sensing, due to its low complexity, energy detection is chose as a sensing component. Moreover, spectrum sensing is essential because in this work, frequency switching and adaptive OFDM components rely on the information gathered from it. For proof-of-concept, the adaptive OFDM component uses two types of modulations which are Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK). A double thresholding technique is devised to help adaptive OFDM component in deciding the modulation.

The payload will be in the form of multimedia content which is stored images and audio. The image is in the form of JPEG compression and for the audio file is in form of MP3 format compression. Furthermore, this experimental work focuses on data transmission scenario between two SUs in pre-fixed spectrum band with the effect of multipath fading being ignored. The received payload is evaluated through several performance metrics such are PSNR for image and the number of glitches for the audio file.

1.5 Significant Contribution

This thesis describes the development of experimental work of CR system for multimedia transmission on SDR platform. In general, the contributions of this research work are listed below:

- Development and implementation of parallel sensing and transmit mechanism for a stable multimedia transmission application. The sensing and transmission processes run concurrently hence reducing time taken for transmission.
- Development of reconfigurable SDR testbed for CR OFDM multimedia transmission and CR system using GNU Radio and USRP. A double thresholding technique is used in the adaptive OFDM modulation decision to improve the efficiency of the system.

1.6 Research Framework

The development of this project can be illustrated in the flowchart in Figure 1.3. This project initiated by distinguishing the research problem statements and provides solutions using SDR approach. As the scope of work, the combination of GNU Radio software and USRP hardware are adopted due to its flexibility which could help the development of a reconfigurable testbed. However, in order to achieve the desired objectives, the most essential step is to understand CR and SDR system using GNU Radio platform. The supports from literature review and related documentation are updated regularly in conjunction with the research progress.

Initially, the basic OFDM transmission is developed using GNU companion (GRC). Later, the development of more complex component such as parallel process of sensing and data transmission, multimedia transmission using OFDM, double threshold for adaptive OFDM modulation and its overall system algorithm. The CR ability of this system can be reflected at the parallel process of frequency

sensing and data transmission. Another component with CR ability embedded in this project is the double thresholding in identifying the type of OFDM modulation needed during transmission.

Finally, all components for the proposed system are translated into GNU Radio software. After the system is ready, the payload in the form of image and audio data is transmitted through the system. The performance of the received payload is measured.

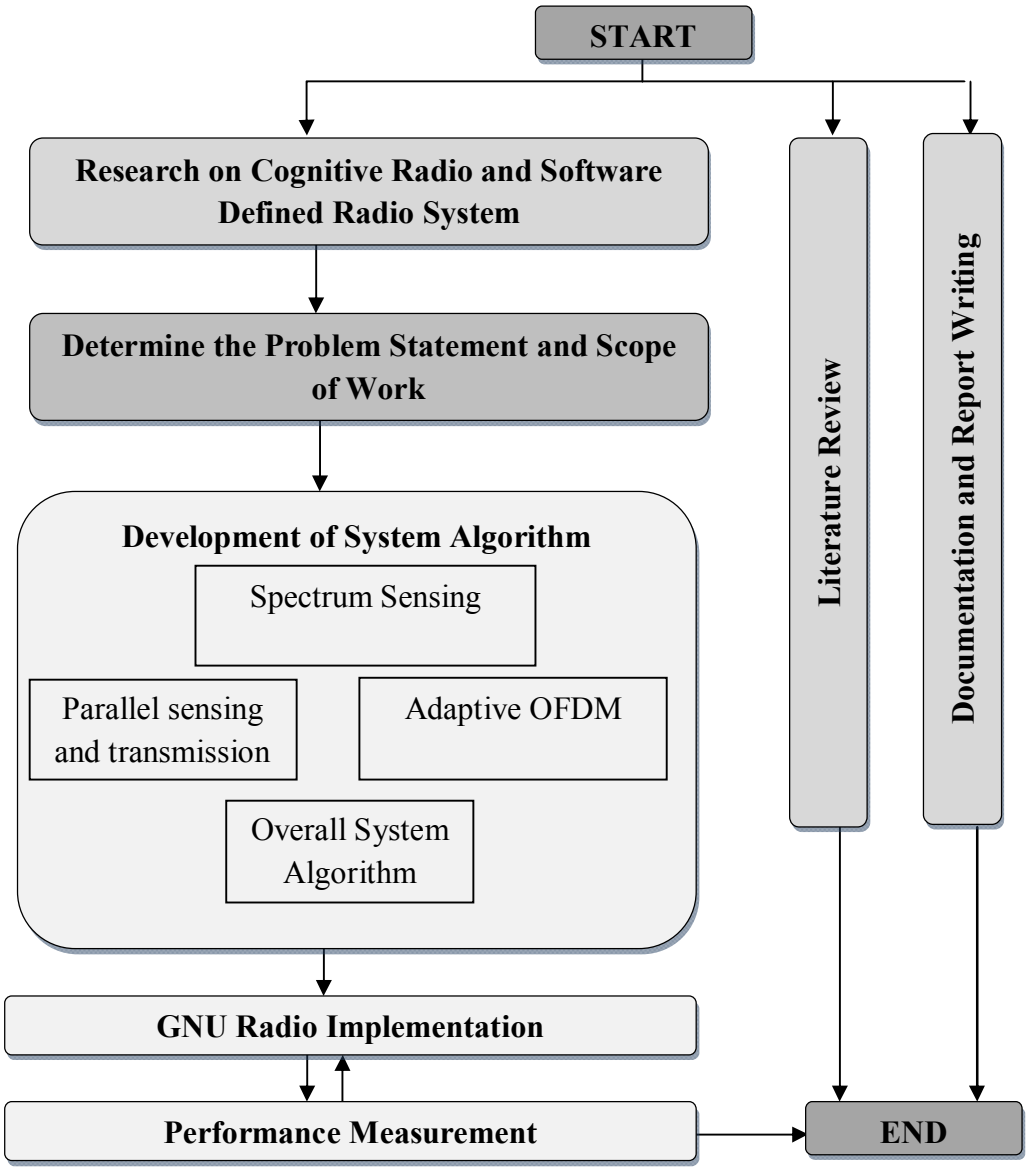

Figure 1.3 Flow Chart of Research Framework

1.7 Organization of the Thesis

This thesis consists of six chapters. Chapter 1 covers background of the research work, research objective, methodology, research contributions and organization of the thesis.

Chapter 2 provides the relevant background for understanding the challenges of multimedia transmission, CR system, OFDM transmission and also the SDR platform. The final part of chapter 2 discusses on the existing works related to the multimedia application using CR technology.

Chapter 3 explains the details on the applied concept of the proposed system. The explanation includes the design concept for this work which includes multimedia transmission with CR system, algorithm for parallel sensing and adaptive OFDM method.

Chapter 4 describes the set up and the experimental works. It includes the architecture and connection of the system, spectrum allocation, user characterization, the implementation of the spectrum sensing and frequency mobility.

Chapter 5 will shows the results and discussions for each finding. Last chapter concludes the outcomes and proposes the new ideas for future works.

REFERENCES

1. M. R. Dzulkifli, M. R. Kamarudin, T. A. Rahman "Spectrum Occupancy of Malaysia Radio Environment Radio Application," in *IET International Conference on Wireless Communication and Application*, 2012, 22-28
2. SKMM. (MCMC), "Spectrum Allocation in Malaysia." Available: http://www.skmm.gov.my/Spectrum/Spectrum-Allocation-List/Spectrum-Allocation.aspx. [Accessed: 04-Nov-2011]
3. S. Hykin, Cognitive Radio: Brain: Empowered Wireless Communication, *IEEE Journal on Selected Areas in Communication.* vol. 23, no. 2, February 2005, 201 – 220
4. I. F. Akydiz, W-Yeol Lee, M. C. Vuran, "NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Network: A Survey," *The International Journal of Computer and Telecommunication Networking,* 2006. vol. 50, 2127 -2159
5. A. Kumar, K. G. Shin, J. Wang, "A Case Study of QoS Provisioning in TV-Band Cognitive Radio Networks," Proceedings of 18th International Conference on Computer Communications and Networks, 2009.
6. M. S. Lu, Optimizing Transmission Wireless Video Streaming, Doctor of Philosophy, Carnegie Mellon University, 2009
7. D. E. Smith, "IP TV Bandwidth Demand: Multicast and Channel Surfing," in *Proceeding IEEE Conference on Computer Communication (INFOCOM)*, May 2007
8. R. Flickenger, *Wireless Networking in the Developing World: A Practical Guide to Planning and Building Low-cost Telecommunications Infrastructure. 2nd edition*, Hacker Friendly LLC., 2007, http://wndw.net/pdf/wndw2-en/wndw2-ebook.pdf
9. K. Witrisal, OFDM Air-Interface Design for Multimedia Communications, Doctor of Philosophy, Technische Universität Graz, 2002

10. P. Rahagude, M. Demde, "BER Analysis of BPSK based MIMO & MIMO-OFDM System," in *International Journal Of Pure And Applied Research In Engineering And Technology IJPRET*, 2012, vol. 1, 401-409

11. Marcos Majo, "Design and Implementation of an OFDM-based Communication System for the GNU Radio Platform," Master Thesis, University of Stuttgart, 2009

12. D. T. Nguyen, "Implementation of OFDM Systems Using GNU Radio and USRP," University of Wollongong, 2013

13. Mattias Kjellson, USRP Implementation Strategies, KTH Electrical Engineering, 2010

14. J. Mitola, Maguire, G.Q., Jr., "Cognitive radio: making software radios more personal," *Personal Communications, IEEE*, vol.6, no.4, 13 - 18, 1999

15. J. Mitola, The Software Radio Architecture. *IEEE Communication Magazine*, August 2002, vol.33 issue 5, 26 – 38

16. J. Mitola, "Software Radios Survey, Critical Evaluation and Future Direction," in *National Telesystem Conference (NTC),* 13 – 23, 1992

17. S. Hykin, "Cognitive Dynamic System," *Proceeding of the IEEE*, November 2006, vol. 94, no. 11, 1910 – 1911

18. Y. Xing, "Cognitive radio networks: Learning, games and optimization," 2006

19. G.P. Joshi, S.Y. Nam, S.W. Kim. "Cognitive Radio Wireless Sensor Networks: Applications, Challenges and Research Trends," Sensors Journal, 2013

20. S. Zengyou, W. Qianchun, and C. Chenghua, "Study of Cognitive Radio Spectrum Detection in OFDM System," in Asia-Pacific Conference on Wearable Computing Systems (APWCS), 2010, 2010, 235–238.

21. R. M. Johannes Schmitz, Milan Zivkovic, "Extended Cyclostationary Signatures for OFDM-Based Cognitive Radio."

22. M. A. Sarijari, A. Marwanto, N. Fisal, S. K. S. Yusof, R. A. Rashid, and M. H. Satria, "Energy detection sensing based on GNU radio and USRP: An analysis study," in IEEE 9th Malaysia International Conference Communications (MICC),2009, 2009, pp. 338–342.

23. G. Yu, C. Long, M. Xiang, and W. Xi, "A Novel energy detection scheme based on dynamic threshold in cognitive radio systems," J. Comput. Inf. Syst., vol. 8, no. 6, pp. 2245–2252, 2012.

24. H. Wang, G. Noh, D. Kim, S. Kim, and D. Hong, "Advanced sensing techniques of energy detection in cognitive radios," J. Commun. Networks, vol. 12, no. 1, pp. 19–29, 2010.

25. F. F. Digham, M.-S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," IEEE Trans. Commun., vol. 55, no. 1, pp. 21–24, 2007.

26. L. Haiyuan, L. Yongjiao, and H. Yue, "Cyclic stepping spectrum sensing based on energy detection," in International Conference on Mechatronic Science, Electric Engineering and Computer (MEC), 2011, 2011, pp. 486–489.

27. Mohd Adib Sarijari. *Dynamic Spectrum Access Using Cognitive Radio Utilizing GNU Radio and USRP*. Master Thesis, Universiti Teknologi Malaysia, 2010

28. Mohd Khairul Rashid Khairuddin. *Time Division Multiple Access Based Cooperative Dynamic Spectrum Access Mechanism*. Master Thesis, Universiti Teknologi Malaysia, 2013

29. GNU Radio Manual and C++ API Reference, available: http://gnuradio.org/doc/doxygen/page_ofdm.html

30. Universal Software Radio Peripheral – USRP Architecture Overview and FAQ. http://gnuradio.org/redmine/

31. P. Yadav, R. Mahajan, "Energy Detection for Spectrum Sensing In Cognitive Radio Using Simulink," in International Journal of Advanced Research in Electrical Electronic and Instrument Engineering, vol. 3(5), May 2014

32. A. O. Bicen, V. C. Gungor, O. B. Akan, "Delay-sensitive and Multimedia Communication in Cognitive Radio Sensor Networks," *Journal Ad Hoc Networks*, 816 – 830, 2012

33. F. Mulot, and V. Calmettes, "A Comparison of Digital Transmission Techniques under Multichannel Conditions at 2.4 GHz in the ISM BAND," *In Journées Micro-Drones*, Sept 2004

34. J. Su, A. M. Wyglinski, "Multihop Routing and Resource Allocation for Multimedia Application," on 2011 IEEE Pacific Rim Conference Communications Computers and Signal Processing (PacRim), 752 – 767

35. H. Kushwaha, Y. Xing, R. Chandramouli, H. Heffes, "Reliable Multimedia Transmission Over Cognitive Radio Networks Using Fountain Codes," *Proceeding of the IEEE,* January 2008, vol. 96, 155 – 165

36. H. Mahmoud, T. Yucek, , H. Arslan, "OFDM for Cognitive Radio: Merits and Challenges," IEEE Wireless Communications, vol. 6(2), May 2009

37. S. Hirve, S. Gumudavally, "Transmitting a JPEG file in GNU Radio and USRP," Cleveland State University

38. N. Manicka, "GNU Radio Testbed," Master Thesis, March 2008

39. Eric Qin Cheng, *Wireless H.264 Video Testbed Using GNU Radio*, available: http://www.wu.ece.ufl.edu/projects/wirelessVideo/project/realTimeCoding/

40. J. Zhu, Z. Xu, F. Wang, B. Huang, B. Zhang, "Double Threshold Energy Detection of Cooperative Spectrum Sensing in Cognitive Radio," *Cognitive Radio Oriented Wireless Networks and Communication (CrownCom 2008)*, May 2008, 1 - 5

41. A. Ghasemi, E. S. Sousa, Collaborative Spectrum Sensing for Opportunistic Access in Fading Environment, in *Proceeding IEEE DySPAN 2005*, November 2005, 131 – 136

42. T. F. L. Porta, T. F. Sabnani, R. D. Gitlin, "Challenges for Nomadic Computing: Mobility Management and Wireless Communications," in *ACM Journal of Nomadic Computing*, no. 1, 1996

43. T. O'Shea, T. Clancy, H. Ebeid, "Practical Signal Detection and Classification in GNU Radio," *SDR Forum Technical Conference*, November 2007

44. S. S. Kalamkar, A. Banerjee, "Improved Double Threshold Energy Detection for Cooperative Spectrum Sensing in Cognitive Radio," *Defence Science Journal (DESIDOC 2013)*, vol. 63, no. 1, 34 – 40

45. C. Sun, W. Zhang, K.B. Lethaif, "Cooperative Spectrum Sensing for Cognitive Radio Under Bandwidth Constraints," in *Proceeding IEEE WCNC 2007*, 1 – 5, 2007

46. H. A. Mahmoud, "*Advanced Transceiver Algorithm for OFDM System*," University of South Florida, 2009

47. W. Hashim, A. F. Ismail, S. K. Syed Yusof, H. Mujahid, "DSA Impacts on Data Transmission: An experimental Study," *Wireless Advance (WiAd 2012)*, June 2012, 121 – 126

48. D. Ziou, "Image Quality Metrics: PSNR vs. SSIM," *20th International Conference on Pattern Recognition (IPCR)*, August 2010, 2366 – 2369

49. L. Boney, A. H. Tewfik, K. N. Hamdy, "Digital Watermarks for Audio Signals," *Proceeding of the Third IEEE International Conference on Multimedia Computing and Systems,"* June 1996, 473 – 480

50. J. F. Tilki, A. A. Beex, "Encoding a Hidden Digital Signature onto an Audio Signal Using Psychoacoustic Masking," *7th International Conference on Signal Processing, Applications and Technology*, 476 – 480

51. A. Sahai, N. Hoven, R. Tandra, "Some Fundamental Limits in Cognitive Radio," *Allerton Conference on Communication, Control and Computing*, October 2004

52. T. S. Rappaport, *Wireless Communications: Principle and Practice*, Second Edition, Prentice Hall, 2002

53. M. A. Sarijari, R. A. Rashid, N. Fisal, S. K. S. Yusof, "Dynamic Spectrum Access Using Cognitive Radio Utilizing GNU Radio and USRP," in *IEEE Symposium Wireless Technology and Application (ISWTA)*, 2011

54. M. A. Sarijari, A. Marwanto, N. Fisal, S. K. S. Yusof, R. A. Rashid, and M. H. Satria, "Energy detection sensing based on GNU Radio and USRP: An Analysis Study," in *IEEE 9th Malaysia International Conference Communications (MICC)*, 2009, 338–342

55. R. Prasad, *OFDM for Wireless Communication System*, Artech House Inc., 2004

56. K. M. Khairul Rashid, M. A. Sarijari, N. Dahlia, R. A. Rashid, S. K. S. Yusof, "Parallel Spectrum Sensing and Data Transmission for Opportunistic Access," unpublished, 2012

57. Cameron Nicklaus Christon, Optimal Dither and Noise Shaping in Image Processing, University of Waterloo, 2008

58. A. Khalifeh, H. Yousefi'zadeh, "Optimal Audio Transmission over Wireless Tandem Channels," *Conference on Data Compression*, 2008, 525 - 535

59. M. Zivkovic, R. Mathar, D. Auras, "OFDM-based Dynamic Spectrum Access," *IEEE Symposium on New Frontiers in Dynamic Spectrum*, 1 – 2, 2010

60. M. Zivkovic, R. Mathar, D. Auras, "Reconfigurable Framework for Adaptive OFDM Transmission," *Proceedings of the 4th ACM International Workshop on Experimental Evaluation and Characterization WINTECH 2009*, 91 – 92, 2009

61. M. Zivkovic, R. Mathar, "Design Issues and Performance Evaluation of a SDR-based Reconfigurable Framework for Adaptive OFDM Transmission," *Proceedings of the 6th ACM International Workshop on Wireless Network Testbed, Experimental Evaluation and Characterization WINTECH 2011*, 75 – 82, 2011

62. Mikhail Tadjikov, *Real-Time Detection and Characterization of Frequency Hopping Devices Using USRP*, available: http://www.tadjikov.com/node/2

63. C. Y. Chen, F. H. Tseng, K. D. Chang, H. C. Chao, J. L. Chen, "Reconfigurable Software Defined Radio and Its Applications," *Tamkang Journal of Science and Engineering*, vol. 13, no. 1, 29 – 38, 2010

64. P. Popovski, H. Yomo, R. Prasad, "Strategies for Adaptive Frequency Hopping in the Unlicensed Bands," *IEEE Wireless Communication*, December 2006, vol. 13, 60 – 68

65. B. Le, T. W. Rondeau, D. Maldonado, D. Scaperoth, and C. W. Bostian, "Signal Recognition for Cognitive Radios," in *Proceeding SDR Forum 06 Technical Conference*, 2006

66. N. Manicka, "GNU Radio Installation Notes," November 2006

67. Simple DVB with Gstreamer and GNU Radio, available: http://wiki.oz9aec.net/index.php/Simple_DVB_with_Gstreamer_and_GNU_Radio

68. G. Zacheo, D. Djukic, A. Dorni, F. Babich, F. Ricciato, "A Software-Defined Radio Implementation of an 802.11 OFDM Physical Layer Transceiver," *IEEE 17th Conference on Emerging Technologies & Factory Automation ETFA 2012*, September 2012, vol. 1, no. 4, 17-21

69. E. P. Lawrey, *Adaptive Techniques for Multiuser OFDM*. Doctor of Philosophy Thesis, James Cook University, 2001

70. L. Toni, *Adaptive Wireless Multimedia Communication Systems*. Doctor of Philosophy Thesis, University of Bologna, 2009