SPECTRUM SENSING USING ENERGY DETECTION FOR RECONFIGURABLE ANTENNA

KHAIRUL HILMI BIN YUSOF

UNIVERSITI TEKNOLOGI MALAYSIA

SPECTRUM SENSING USING ENERGY DETECTION FOR RECONFIGURABLE ANTENNA

KHAIRUL HILMI BIN YUSOF

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

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2016

Dedicated to my beloved mother and father

ACKNOWLEDGEMENT

In the name of Allah, The Most Gracious and The Most Merciful

I would like to express my sincere appreciation to my supervisor Prof. Dr. Mohamad Kamal A Rahim and co-supervisor Dr. Kamaludin Mohamad Yusof for the guidance, ideas and encouragement, without their supports this research would not have completed.

I also kite to thank Dr. Huda, Dr. Osman, Dr. Asniza, Dr. Asmawati, Dr. Fairus, Dr. Rijal, and Dr. Farid for your knowledge given, that lead to this research completion. Not forgetting Mr. Azfar, Mr. Raimi, Mr. Ezwan, Mr. Syazwan, Mr. Hazmi, Mr. Ameerul, Ms. Afifah, and Ms. Syahirah thank you for your ideas.

Especially, I would like to express my gratitude to my beloved father and mother for all your continuous support and sacrifices that they have done for me. Lastly, to all my friends thank you all.

ABSTRACT

Rigorous development in Software Defined Radio (SDR) helps to realize the dream of Cognitive Radio. The SDR can be used with a reconfigurable antenna to achieve full Cognitive Radio system. Reconfigurable antenna is an antenna designed that is capable of changing its operating frequency. However, the SDR such as Universal Software Radio Peripheral (USRP) B200 does not come with a software algorithm that can change the operating frequency of the reconfigurable antenna. To overcome this problem, an energy detection algorithm that can work with wideband to narrowband reconfigurable antenna switching algorithm and narrowband to narrowband reconfigurable antenna switching algorithm are proposed. By using the algorithms, the switching of operating frequency of the reconfigurable antenna can be done via software. All algorithms were developed using GNU Radio and Arduino micro-controller to reconfigure antenna switching to replace manual switching. USRP B200 was the selected SDR for all measurements. Probability of detection was the parameter that had been measured and simulated. Statistical test was conducted to verify the result between measurement and simulation, which revealed that there was no significant difference between them. Results for wideband antenna, wideband to narrowband reconfigurable antenna, and narrowband to narrowband reconfigurable antenna show 3.2% to 18% difference between measurement and simulation. Hence, it can be concluded that there is a good agreement between the measurement and simulation.

ABSTRAK

Pembangunan yang meluas dalam Perisian Penakrifan Radio (SDR) membantu merealisasikan Radio Kognitif yang diimpikan. SDR boleh digunakan dengan antena konfigurasi boleh ubah untuk mencapai sistem Radio Kognitif penuh. Antena konfigurasi boleh ubah ialah antena yang direka supaya mampu menukar frekuensi operasi. Walau bagaimanapun, SDR seperti Perisian Radio Universal (USRP) B200 tidak datang dengan algoritma yang mampu menukar frekuensi operasi antena konfigurasi boleh ubah. Jadi untuk mengatasi masalah ini, satu algoritma pengesanan tenaga yang boleh digunakan dengan algoritma antena konfigurasi boleh ubah jalur lebar ke jalur sempit dan algoritma antena konfigurasi boleh ubah jalur sempit ke jalur sempit adalah dicadangkan. Dengan menggunakan algoritma-algoritma ini, penukaran frekuensi operasi antena konfigurasi boleh ubah boleh dilakukan melalui perisian. Semua algoritma telah dibangunkan menggunakan GNU Radio dan mikro-pengawal Arduino untuk menukar frekuensi operasi antena konfigurasi boleh ubah menggantikan pensuisan manual. USRP B200 adalah SDR yang telah pilih untuk semua pengukuran. Parameter yang diukur dan disimulasi adalah kebarangkalian pengesanan. Ujian statistik telah dilakukan untuk mengesahkan keputusan di antara pengukuran dan simulasi, yang mendedahkan bahawa tiada perbezaan yang signifikan di antara keduanya. Hasil pengukuran antena jalur lebar, antena konfigurasi boleh ubah jalur lebar ke jalur sempit, dan antena konfigurasi boleh ubah jalur sempit ke jalur sempit menunjukkan 3.2% ke 18% perbezaan antara pengukuran dan simulasi. Oleh itu, dapat disimpulkan bahawa terdapat kesamaan yang baik antara pengukuran dan simulasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ALGORITHMS

LIST OF ABBREVIATIONS

USRP	-	Universal Software Radio Peripheral
SDR	-	Software Defined Radio
IDE	-	Integrated Development Environment
FSPL	-	Free-Space Path Loss
GRC	-	GNU Radio-Companion
ED	-	Energy Detection
FCC	-	Federal Communications Commission
ISM	-	Industrial, Scientific and Medical
SNR	-	Signal to Noise Ratio
LED	-	Light Emitting Diode
PC	-	Personal Computer
CR	-	Cogitive Radio
AWGN	-	Additive White Gaussian Noise
FFT	-	Fast Fourier Transform

LIST OF SYMBOLS

P_D	-	Probability of detection
P_F	-	Probability of false alarm
P_{MD}	-	Probability of missed detection
p_{th}	-	Threshold
$y(n)$	-	Received signal
$s(n)$	-	Primary user signal
$w(n)$	-	Additive white gaussian noise
H_0	-	Hypothesis zero
H_1	-	Hypothesis one
M	-	Decision matrix
N	-	Number of sample
σ_s^2	-	Primary user signal variance
σ_n^2	-	Noise signal variance
$Q(.)$	-	Complementary distribution function of standard gaussian
P_t	-	Transmit power
P_r	-	Received power
G_t	-	Transmit gain
G_r	-	Received gain
d	-	Distance
λ	-	Wavelength
L	-	Losses
s_1^2	-	Sample one variance
s_2^2	-	Sample two variance
df_1	-	Degree of freedom sample one
df_2	-	Degree of freedom sample two

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Cognitive Radio is defined by the Federal Communications Commission (FCC) as a radio system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify the system operation, such as maximize throughput, mitigate interference, facilitate interchangeability, access secondary markets, etc [4].

Cognitive Radio networks can also be represented as an innovative approach to wireless engineering in which radios are designed with an unprecedented level of intelligence and agility. Cognitive Radio have the ability to monitor, sense and detect conditions of their operating environment, and dynamically reconfigure their own characteristics to best match those conditions. This technology enables radio devices to use the frequency spectrum in entirely new and sophisticated ways, and can be a solution to the spectral congestion problem by introducing the opportunistic usage of the frequency bands that are not occupied by licensed users [4–6].

According to Federal Communications Commission (FCC), the spectrum utilization in the 0 to 6 GHz band varies from 15% to 85%, this has prompted the FCC to propose the opening of licensed bands to unlicensed users and given birth to Cognitive Radio [6, 7]. Nowadays some frequency in the Industrial, Scientific and Medical (ISM) band is not efficiently used due to the fact that some developers tend to use the same frequency for their product [8]. For example, WiFi frequency is widely used by the product developer because of the availability on cheap WiFi transceivers in the market. Congestion in that particular frequency will result in data corruption, data collision, and data lost [8].

1.2 Problem Statement

Reconfigurable antenna is an antenna that can change its properties such as operating frequency. The reconfigurable antenna operating frequencies are tuned using radio frequency switches such as pin diode and varactor diode [9–12]. Wideband to narrowband reconfigurable antenna is one example of reconfigurable antenna that can change its operating frequency. The reconfigurable antenna can be used with a software defined radio (SDR) to achieve the full Cognitive Radio concept. However, the SDR such as Universal Software Radio Peripheral B200 (USRP B200) does not come with a software algorithm that can change the operating frequency of reconfigurable antennas like the wideband to narrowband and narrowband to narrowband reconfigurable antenna due the specific design of the antennas. In order to solve this problem, antennas switching algorithm for the reconfigurable antennas need to be developed.

Spectrum sensing is one of the task in Cognitive Radio concept. The simplest type of spectrum sensing is energy detection. Energy detection can be implemented in the SDR to measure the performance of the energy detection with reconfigurable antenna, however due to the different varieties of the energy detection and specific needs, it is not included in the software. So, to overcome this problem energy detection algorithm that can work with the reconfigurable antenna need to be developed in the software.

The performance of the energy detection usually compared between theory and simulation for examlple in [13–15]. There are few measurements on the performance of the energy detection algorithm with reconfigurable antenna like in [16]. So, the performance of the reconfigurable antennas with energy detection spectrum sensing need to be measured.

1.3 Objectives

The objectives of this research are as follows:

1. To implement energy detection algorithm at 2-5 GHz frequency range that can be used with reconfigurable antenna.
2. To develop wideband to narrowband reconfigurable antenna and narrowband to narrowband reconfigurable antenna switching algorithm.
3. To validate the performance of the wideband antenna, wideband to narrowband and narrowband to narrowband reconfigurable antenna in term of energy detection.

1.4 Scope and Significance of Study

This research covers on the development of the energy detection spectrum sensing algorithm that can work with the reconfigurable antenna. The programming languages used were C, C++ and Python for software development in GNU Radio environment. USRP B200, by Ettus Research were used as the SDR platform for experimentation.

The frequency range used in this research was from 2 to 5 GHz, this was due to the specific design of the wideband antenna, wideband to narrowband reconfigurable antenna and narrowband to narrowband reconfigurable antenna. Additionally, two reconfigurable antenna switching alogrithm were developed. The algorithm can be used to change the operating frequency of the reconfigurable antenna in the software. Furthermore, the SDR can be programmed to search any suitable frequency automatically. Moreover, the developed algorithm can increase the efficiency of the frequency usage, as it can sense the availability of the frequency or white space. With the improvement, the completed system can be commercialized for everyday use.

1.5 Contributions

The main contribution of this research is in term of software development of the energy detection spectrum sensing for the reconfigurable antenna to change its frequency properties via software using micro-controller, thus removing the need of manual switches. Three algorithms were developed during the course of this research; the energy detection algorithm, the wideband to narrowband reconfigurable antenna switching algorithm and narrowband to narrowband reconfigurable antenna switching algorithm. Other contributions include the performance measurement of the energy detection algorithm with the reconfigurable antenna that can be used for future research work.

1.6 Thesis Outline

A brief overview to Cognitive Radio and spectrum sensing, problem statement, objective of research, scope and significance of the study are presented in chapter 1.

In chapter 2, the background knowledge on Cognitive Radio, spectrum holes and conventional energy detection and its related equation are discussed. Previous work on energy detection and Cognitive Radio system with antenna are reported and summarized.

In chapter 3, the methodology of research is discussed. The flow of research are presented and the three stages of research work are described. The first stage which is software implementation are described, followed by second stage, energy detection flowchart overview. Third stage, measurement setup and its parameters are discussed.

In chapter 4, development on energy detection algorithm, wideband to narrowband reconfigurable antenna algorithm, and narrowband to narrowband reconfigurable antenna algorithm are presented. Additionally, the types of antenna used, graphical user interface, switch timing, and free space path loss simulation are discussed.

In chapter 5, measurement and simulation result on the performance of energy detection algorithm with wideband antenna, wideband to narrowband reconfigurable antenna, and narrowband to narrowband reconfigurable antenna are presented, compared and discussed thoroughly.

Finally, chapter 6 concludes the thesis and suggestion for future research work.

REFERENCES

1. Akyildiz, I. F., Lee, W.-Y., Vuran, M. C. and Mohanty, S. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks*, 2006. 50(13): 2127 – 2159. ISSN 1389-1286. doi:http://dx.doi.org/10.1016/j.comnet.2006.05.001. URL `http://www.sciencedirect.com/science/article/pii/S1389128606001009`.
2. Seshukumar, K., Saravanan, R. and Suraj, M. Spectrum sensing review in cognitive radio. *Emerging Trends in VLSI, Embedded System, Nano Electronics and Telecommunication System (ICEVENT), 2013 International Conference on*. 2013. 1–4. doi:10.1109/ICEVENT.2013.6496549.
3. Ma, J., Li, G. and Juang, B.-H. Signal Processing in Cognitive Radio. *Proceedings of the IEEE*, 2009. 97(5): 805–823. ISSN 0018-9219. doi: 10.1109/JPROC.2009.2015707.
4. FCC. Notice of proposed rule making and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. 2008: ET Docket No. 03–108.
5. Mitola, J. and Maguire, J., G.Q. Cognitive radio: making software radios more personal. *Personal Communications, IEEE*, 1999. 6(4): 13–18. ISSN 1070-9916. doi:10.1109/98.788210.
6. Mitola, I., J. Software radios: Survey, critical evaluation and future directions. *Aerospace and Electronic Systems Magazine, IEEE*, 1993. 8(4): 25–36. ISSN 0885-8985. doi:10.1109/62.210638.
7. FCC. Spectrum Policy Task Force report. 2002. ET Docket No. 02-155.
8. Chen, H.-S. and Gao, W. Spectrum Sensing for TV White Space in North America. *Selected Areas in Communications, IEEE Journal on*, 2011. 29(2): 316–326. ISSN 0733-8716. doi:10.1109/JSAC.2011.110205.
9. Yu, Y., Xiong, J., Li, H. and He, S. An Electrically Small Frequency Reconfigurable Antenna With a Wide Tuning Range. *Antennas and Wireless*

Propagation Letters, IEEE, 2011. 10: 103–106. ISSN 1536-1225. doi: 10.1109/LAWP.2011.2113390.

10. Tawk, Y. and Christodoulou, C. A New Reconfigurable Antenna Design for Cognitive Radio. *Antennas and Wireless Propagation Letters, IEEE*, 2009. 8: 1378–1381. ISSN 1536-1225. doi:10.1109/LAWP.2009.2039461.

11. Majid, H., Rahim, M. K. A., Hamid, M. and Ismail, M. Reconfigurable wide to narrow band antenna for cognitive radio systems. *RF and Microwave Conference (RFM), 2011 IEEE International*. 2011. 285–288. doi:10.1109/RFM.2011.6168750.

12. Majid, H., Rahim, M. K. A., Hamid, M. and Ismail, M. A Compact Frequency-Reconfigurable Narrowband Microstrip Slot Antenna. *Antennas and Wireless Propagation Letters, IEEE*, 2012. 11: 616–619. ISSN 1536-1225. doi:10.1109/LAWP.2012.2202869.

13. Dalai, J. and Patra, S. Spectrum sensing for WLAN and WIMAX using energy detection technique. *Emerging Trends in Computing, Communication and Nanotechnology (ICE-CCN), 2013 International Conference on*. 2013. 620–624. doi:10.1109/ICE-CCN.2013.6528574.

14. Lehtomaki, J., Juntti, M., Saarnisaari, H. and Koivu, S. Threshold setting strategies for a quantized total power radiometer. *Signal Processing Letters, IEEE*, 2005. 12(11): 796–799. ISSN 1070-9908. doi:10.1109/LSP.2005.855521.

15. Atapattu, S., Tellambura, C. and Jiang, H. *Energy Detection for Spectrum Sensing in Cognitive Radio*. SpringerBriefs in Computer Science. Springer New York. 2014. ISBN 9781493904945.

16. Wanuga, K., Pfeil, D., Gonzalez, D. and Dandekar, K. A software defined testbed for reconfigurable antenna cognitive radio. *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on*. 2012. ISSN 2166-5370. 1–6.

17. Cabric, D., Mishra, S. M. and Brodersen, R. W. Implementation issues in spectrum sensing for cognitive radios. *Proc. Asilomar Conf. Signals, Syst., Comput.*, 2004. 1: 772–776.

18. Liang, Y.-C., Chen, H.-H., Mitola, J., Mahonen, P., Kohno, R., Reed, J. and Milstein, L. Guest Editorial - Cognitive Radio: Theory and Application. *Selected Areas in Communications, IEEE Journal on*, 2008. 26(1): 1–4. ISSN 0733-8716.

19. Liang, Y.-C., Chen, K.-C., Li, Y., Mahonen, P. and Niyato, D. Guest Editorial

Advances in Cognitive Radio Networking and Communications (II). *Selected Areas in Communications, IEEE Journal on*, 2011. 29(4): 673–675. ISSN 0733-8716.

20. Liang, Y.-C., Chen, K.-C., Li, Y., Mahonen, P. and Niyato, D. Guest Editorial - Advances in cognitive radio networking and communications (I). *IEEE Journal on Selected Areas in Communications*, 2011. 29(2): 273–275. ISSN 0733-8716.

21. Haykin, S. Cognitive radio: Brain-empowered wireless communications. *Selected Areas in Communications, IEEE Journal on*, 2005. 23: 201–220.

22. Mitola, J. *Cognitive Radio — An Integrated Agent Architecture for Software Defined Radio*. DTech thesis. Royal Institute of Technology (KTH), Kista, Sweden. 2000. URL `http://web.it.kth.se/~{}maguire/jmitola/Mitola_Dissertation8_Integrated.pdf`.

23. Thomas, R., DaSilva, L. and MacKenzie, A. Cognitive networks. *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*. 2005. 352–360. doi:10.1109/DYSPAN.2005.1542652.

24. Mitola, J., Attar, A., Zhang, H., Holland, O., Harada, H. and Aghvami, H. Achievements and the Road Ahead: The First Decade of Cognitive Radio. *Vehicular Technology, IEEE Transactions on*, 2010. 59(4): 1574–1577. ISSN 0018-9545.

25. Zhao, Y., Mao, S., Neel, J. O. and Reed, J. Performance Evaluation of Cognitive Radios: Metrics, Utility Functions, and Methodology. *Proceedings of the IEEE*, 2009. 97(4): 642–659. ISSN 0018-9219. doi:10.1109/JPROC.2009.2013017.

26. Ganesan, G., Li, Y., Bing, B. and Li, S. Spatiotemporal Sensing in Cognitive Radio Networks. *Selected Areas in Communications, IEEE Journal on*, 2008. 26(1): 5–12. ISSN 0733-8716. doi:10.1109/JSAC.2008.080102.

27. Ghasemi, A. and Sousa, E. Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs. *Communications Magazine, IEEE*, 2008. 46(4): 32–39. ISSN 0163-6804. doi:10.1109/MCOM.2008.4481338.

28. Lu, L., Wu, H.-C. and Iyengar, S. A Novel Robust Detection Algorithm for Spectrum Sensing. *IEEE Journal on Selected Areas in Communications*, 2011. 29(2): 305–315. ISSN 0733-8716. doi:10.1109/JSAC.2011.110204.

29. Yucek, T. and Arslan, H. A survey of spectrum sensing algorithms for

cognitive radio applications. *Communications Surveys Tutorials, IEEE*, 2009. 11(1): 116–130. ISSN 1553-877X. doi:10.1109/SURV.2009.090109.

30. Liang, Y.-C., Zeng, Y., Peh, E. and Hoang, A. T. Sensing-Throughput Tradeoff for Cognitive Radio Networks. *Wireless Communications, IEEE Transactions on*, 2008. 7(4): 1326–1337. ISSN 1536-1276. doi:10.1109/TWC.2008.060869.

31. Wyglinski, A. M., Nekovee, M. and Hou, T. *Cognitive radio communications and networks: principles and practice*. Academic Press. 2009.

32. IEEE Standard for Information Technology–Telecommunications and information exchange between systems - Wireless Regional Area Networks (WRAN)–Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications:Policies and Procedures for Operation in the TV Bands - Amendment 2: Enhancement for Broadband Services and Monitoring Applications. *IEEE Std 802.22b-2015 (Amendment to IEEE Std 802.22-2011 as amended by IEEE Std 802.22a-2014)*, 2015: 1–299. doi:10.1109/IEEESTD.2015.7336461.

33. Zhou, Y., Zhou, Z. and Zhang, S. An Improved Spectrum Sensing Method: Energy-Autocorrelation-Based Detection Technology. *Circuits, Systems, and Signal Processing*, 2013. 32(1): 273–282. ISSN 0278-081X. doi:10.1007/s00034-012-9451-9. URL `http://dx.doi.org/10.1007/s00034-012-9451-9`.

34. Yang, Y., Wen, Z., Wu, Y. and Zhang, X. A Study of Spectrum Sensing Algorithm for Ultra High Speed WLAN. *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*. 2011. ISSN 2161-9646. 1–4. doi:10.1109/wicom.2011.6036640.

35. A Rashid, R., Sarijari, M. A., Fisal, N., Lo, A., Yusof, S., Kamilah, S. and Mahalin, N. Spectrum sensing measurement using GNU Radio and USRP software radio platform. *ICWMC 2011, The Seventh International Conference on Wireless and Mobile Communications*. 2011. 237–242.

36. Zhu, J., Xu, Z., Wang, F., Huang, B. and Zhang, B. Double Threshold Energy Detection of Cooperative Spectrum Sensing in Cognitive Radio. *Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on*. 2008. 1–5. doi:10.1109/CROWNCOM.2008.4562451.

37. Choi, K. W. Adaptive Sensing Technique to Maximize Spectrum Utilization in

Cognitive Radio. *Vehicular Technology, IEEE Transactions on*, 2010. 59(2): 992–998. ISSN 0018-9545. doi:10.1109/TVT.2009.2036631.

38. Labrador, M. and Wightman, P. *Topology Control in Wireless Sensor Networks: with a companion simulation tool for teaching and research*. Springer Netherlands. 2009. ISBN 9781402095856.

39. Seybold, J. *Introduction to RF Propagation*. Wiley. 2005. ISBN 9780471743682.

40. Balanis, C. *Antenna Theory: Analysis and Design*. Wiley. 2012. ISBN 9781118585733.

41. Burbank, J., Kasch, W. and Ward, J. *An Introduction to Network Modeling and Simulation for the Practicing Engineer*. The ComSoc Guides to Communications Technologies. Wiley. 2011. ISBN 9781118063644.

42. Eren, H. *Wireless Sensors and Instruments: Networks, Design, and Applications*. CRC Press. 2005. ISBN 9781420037401.

43. Navidi, W. *Statistics for Engineers and Scientists*. McGraw-Hill Education. 2014. ISBN 9781259251603.

44. Kirk, R. *Statistics: An Introduction*. International student edition. Cengage Learning. 2007. ISBN 9780534564780.

45. LeBlanc, D. *Statistics: Concepts and Applications for Science*. No. v. 2 in Statistics: Concepts and Applications for Science. Jones and Bartlett. 2004. ISBN 9780763746995.

46. Gardner, P., Hamid, M., Hall, P., Kelly, J., Ghanem, F. and Ebrahimi, E. Reconfigurable Antennas for Cognitive Radio: Requirements and Potential Design Approaches. *Wideband, Multiband Antennas and Arrays for Defence or Civil Applications, 2008 Institution of Engineering and Technology Seminar on*. 2008. ISSN 0537-9989. 89–94.

47. Gardner, P., Hall, P., Hamid, M. and Ghanem, F. Reconfigurable antennas for cognitive radio. *Antennas and Propagation in Wireless Communications (APWC), 2011 IEEE-APS Topical Conference on*. 2011. 1225–1228. doi: 10.1109/APWC.2011.6046836.

48. Christodoulou, C., Doyle, D., Woehrle, C., Costantine, J. and Tawk, Y. Reconfigurable antennas for cognitive radio and space applications. *Antennas Propagation Conference (LAPC), 2015 Loughborough*. 2015. 1–3. doi: 10.1109/LAPC.2015.7366126.

49. Majid, H., Rahim, M., Hamid, M. and Ayop, O. Reconfigurable wideband to

narrowband antenna using tunable EBG structure. *Applied Physics A*, 2014. 117(2): 657–661.

50. Ismail, M. F., Rahim, M. K. A. and Majid, H. A. Wideband to narrowband frequency reconfiguration using PIN diode. *Microwave and Optical Technology Letters*, 2012. 54(6): 1407–1412.

51. Majid, H. A., Rahim, A., Kamal, M., Hamid, M., Murad, N. and Ismail, M. Frequency-reconfigurable microstrip patch-slot antenna. *Antennas and Wireless Propagation Letters, IEEE*, 2013. 12: 218–220.

52. Majid, H. A., Abd Rahim, M. K., Hamid, M. R. and Ismail, M. F. Frequency reconfigurable microstrip patch-slot antenna with directional radiation pattern. *Progress In Electromagnetics Research*, 2014. 144: 319–328.

53. Majid, H. A., Rahim, M. K. A., Hamid, M. R. and Ismail, M. F. Frequency and Pattern Reconfigurable Slot Antenna. *Antennas and Propagation, IEEE Transactions on*, 2014. 62(10): 5339–5343.

54. Majid, H. A., Abd Rahim, M. K., Hamid, M. R., Yusoff, M. F. M., Murad, N. A., Samsuri, N. A., Ayop, O. B. and Dewan, R. Wideband Antenna with Reconfigurable Band Notched Using EBG Structure. *Progress In Electromagnetics Research Letters*, 2015. 54: 7–13.

55. Majid, H. A., Kamal, M., Rahim, A., Hamid, M. R., Murad, N. A., Asmawati Samsuri, N., Fairus Mohd Yusof, M. and Ayop, O. Reconfigurable notched wideband antenna using EBG structure. *Microwave and Optical Technology Letters*, 2015. 57(2): 497–501.

56. Majid, H., Rahim, M. K. A., Hamid, M. R., Ismail, M. *et al.* A compact frequency-reconfigurable narrowband microstrip slot antenna. *Antennas and Wireless Propagation Letters, IEEE*, 2012. 11: 616–619.

57. Majid, H., Rahim, M., Hamid, M. and Ismail, M. Frequency reconfigurable circular patch antenna. *RF and Microwave Conference (RFM), 2013 IEEE International*. IEEE. 2013. 450–453.

58. Majid, H., Rahim, M., Ayop, O., Hamid, M., Murad, N., Samsuri, N. and Yusoff, M. Frequency reconfigurable wideband monopole antenna using EBG structures. *Antennas and Propagation (EuCAP), 2014 8th European Conference on*. IEEE. 2014. 1906–1908.

59. Majid, H., Rahim, M., Hamid, M., Murad, N., Samsuri, A. and Ayop, O. Reconfigurable band notch UWB antenna using EBG structure. *Applied Electromagnetics (APACE), 2014 IEEE Asia-Pacific Conference on*. IEEE. 2014. 268–270.

60. Wang, Y., Wang, Y., Coon, J. and Doufexi, A. Antenna selection based spectrum sensing for cognitive radio networks. *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*. 2011. ISSN pending. 364–368. doi:10.1109/PIMRC.2011.6139983.

61. Singh, A., Bhatnagar, M. and Mallik, R. Cooperative Spectrum Sensing in Multiple Antenna Based Cognitive Radio Network Using an Improved Energy Detector. *Communications Letters, IEEE*, 2012. 16(1): 64–67. ISSN 1089-7798. doi:10.1109/LCOMM.2011.103111.111884.