WIFI-UHF TRANSCEIVER DESIGN FOR 650-680 MHZ TELEVISION WHITE SPACE (TVWS) SPECTRUM APPLICATION

by

KHAIRIL ANUAR KHAIRI
(1630812147)

A **thesis** submitted in **fulfillment** of the requirements for the degree of
Master of Science (Communication Engineering)

School of Computer and Communication Engineering
UNIVERSITI MALAYSIA PERLIS

2018

ACKNOWLEDGMENT

In the name of Allah, First of all, I thank to Allah for being with me, giving me the strength, health and patience to complete this thesis.

More acknowledgements to my supervisor, Professor Ir. Dr Mohd Faizal Jamlos for his intellectual and academic inspirations and excellent support, caring, guidance throughout my research work. Without his mentoring, support and cooperation, I could not have completed this research project.

Special thanks also go to all my friends, colleagues and staff at Advanced Communication Engineering Centre (ACE), School of Computer and Communication Engineering, UniMAP, for their help and sharing knowledge and ideas during working in my project as well as to those whoever has helped me either directly or indirectly.

Lastly my earnest thanks to my parents Khairi bin Mohammad Ariffin, Rohana binti Lazim and my mother-law Halimah binti Abdullah for their support, love and prayer. Special thanks to my beloved wife Tun Qurratul Ain Bt Yaacob for your unconditional love, understanding, trust and for giving me the strength and support to reach for the stars and go for my dreams through all these years. I also dedicated this thesis to my much-loved children Megat Muhammad Mustaqim, Megat Muhammad Muaz, Megat Muhammad Mukhlis and Megat Muhammad Mufeed and I hope that this can be used as an inspiration to all of you. Remember, success doesn’t just come and find you as you have to go out and get it.

Last but not least, I would also like to extend my appreciation and gratitude to all my siblings, brothers and sisters in-law for their support, love and prayer, without which I would not achieve my goal. The appreciation can hardly be expressed in words.

TABLE OF CONTENTS

CHAPTER 3 : METHODOLOGY 30

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADS	Advanced Design System
BPF	Band Pass Filter
BW	Bandwidth
CAD	Computer-aided Design
CR	Cognitive Radio
dB	Decibel
dBm	Decibel of Measured power referenced to 1 milliwatt (mW)
DUT	Device Under Test
EF	Error Function
FCC	Federal Communications Commission
HPF	High Pass Filter
IEEE	Institute of Electrical and Electronics Engineering
IF	Intermediate Frequency
ISM	Industrial, Scientific and Medical
LNA	Low Noise Amplifier
LO	Local Oscillators
LOS	Line of Sight
LPF	Low Pass Filter
NF	Noise Figure
PA	Power Amplifier
PCB	Printed Circuit Board
PLL	Phase-locked Loop
PN	Part Number
RF	Radio Frequency
RX	Receiver
SAW	Surface Acoustic Wave
SNR	Signal-to-noise Ratio
TX	Transmitter
TVWS	TV White Space Spectrum
UHF	Ultra High Frequency
VBPF	Variable Band Pass Filter
VCO	Voltage Control Oscillator
VNA	Vector Network Analyzer
Vctrl	Voltage Control
WB	Wide-Band
WLAN	Wireless Local Area Network

Wi-Fi	Wireless Fidelity
WUT	WIFI UHF Transceiver

LIST OF SYMBOLS

Ω	Ohm
ϵ_r	Relative Permittivity
η	Efficiency
ε	Permittivity
σ	Conductivity
c	Speed of light ($3 \times 10^8\ ms^{-1}$)
λ	Free space wavelength
C	Capacitance
R	Resistance
L	Inductance
ε_{eff}	Effective permittivity
λ_g	Guided Wavelength
Y	Admittance
f_c	Resonance frequency

Rekabentuk WiFi UHF Transceiver Untuk Aplikasi Spektrum Ruang Putih Televisyen 650-680 MHz

ABSTRAK

Penyelidikan telah mencetuskan minat untuk mengkaji secara lebih mendalam sekiranya wujud kemungkinan untuk memanfaatkan frekuensi daripada ruang putih telivisyen yang jarang digunakan dalam lingkungan band 470-770 MHz supaya dapat menggantikan Wi-fi frekuensi 2.4 GHz yang spectrum frekuensinya hampir habis digunakan. Reka bentuk, simulasi, fabrikasi, pembuktian secara eksperimen dan pengoptimuman terhadap litar didalam Wi-fi-UHF transceiver untuk mencapai kebolehan bagi membuat penukaran frekuensi secara menaikkan dan menurunkan frekuensi diantara 2.4 GHz dan band UHF adalah dipersembahkan didalam tesis ini. WUT yang mempunyai beberapa bahagian seperti penapis, pengadun, penguat dan pelemah direka secara menyeluruh melalui satu seni bina yang hanya menggunakan satu VCO-PLL untuk merealisasikan penaikkan dan penurunan signal RF diantara 2.4 GHz dan 650-680 MHz. Penurunan frekuensi diantara 2.4 GHz dan 650-680 MHz dilakukan semasa pemancaran signal RF manakala penurunan frekuensi berlaku sebaliknya. Dengan memprogramkan VCO-PLL kepada frekuensi tertentu sebagai pengayun setempat (LO) signal RF pada 2.4 GHz dapat diturunkan kepada mana mana frekuensi didalam lingkungan 650-680 MHz yang mana frekuensi tersebut akan dipancarkan menerusi antena ke udara. Pada laluan atau bahagian penerimaan frekuensi pula, penyelarasan keatas VBPF melalui potensiometer dapat membolehkan WUT menerima apa sahaja frekuensi didalam lingkungan 650-680 MHz yang akan bercampur dengan frekuensi LO tertentu daripada VCO-PLL yang sama untuk menghasilkan signal 2.4 GHz. Reka bentuk yang mempunyai mekanisma yang sebegini unik dapat membuka jalan agar WUT dapat berfungsi sebagai transceiver yang tidak memerlukan langsung pengubahsuaian keatas Wi-Fi modem yang sedia ada. ADS digunakan sebagai alat untuk membuat rekaan dan simulisasi terhadap bahagian-bahagian litar secara individu menurut speifikasi masing-masing sebelum kesemua bahagian-bahagian ini diintegrasikan menjadi satu sistem yang lengkap. Hasil simulasi membuktikan WUT berjaya menurunkan frekuensi daripada 2.4 GHz kepada 650-680 MHz dengan kenaikan 9.5dB manakala penaikan frekuensi daripada 650-680 MHz kepada 2.4 GHz juga berjaya dicapai. Begitu juga WUT yang sebenar dapat melakukan fungsi yang sama tetapi dengan penurunan 42.7dB untuk penaikan frekuensi dan 22.6dB untuk penaikan frekuensi.

WiFi UHF Transceiver Design For Television White Space (TVWS) Spectrum Application

ABSTRACT

Studies have sparked an interest to look further into the possibility of research to make beneficial of underutilized Television White Space (TVWS) frequency band of 470 MHz-770 MHz to substitute the 2.4 GHz Wi-Fi which has been running out of frequency spectrum. The design, simulation, fabrication, experimental validation and optimization of a Wi-Fi-UHF Transceiver (WUT) circuit to achieve a capability of up and down-conversion between frequency of 2.4 GHz and UHF band are presented in this thesis. The WUT which is consisted of subsections like filters, mixers, amplifiers and attenuators are comprehensively designed with an architecture of utilizing a single VCO-PLL to perform up-conversion and down-conversion of RF signals between 2.4 GHz and 650-680 MHz correspondingly. The down-conversion from 2.4 GHz to 650-680 MHz is performed during the RF transmission while up-conversion is the other way around. By programming VCO-PLL to certain frequency as local oscillator (LO), the 2.4 GHz RF signal can be down-converted to any frequency within 650-680 MHz which will be transmitted out from the antenna into the air. On the receiver path, pre-adjustment of the VBPF through potentiometer enabled WUT to receive any frequency within 650-680 MHz which will be mixed-up with certain LO frequency from the same VCO-PLL to generate the 2.4 GHz. Such unique design mechanism has paved the way for WUT to work as a transceiver without any change or modification required to the existing Wi-Fi modem. ADS is used as a tool to design and simulate the subsection circuits separately towards specific design goals prior to integration as complete WUT system. The simulation results shows that WUT is able to down-convert 2.4 GHz to 650-680 MHz with gain of 9.8 dB meanwhile the up-convert of 650-680 MHz to 2.4 GHz managed to have gain of 5.6 dB. Also the physical WUT is able to perform similarly, but with up-conversion gain of -42.7dB and down-conversion gain of -22.6dB.

CHAPTER 1 : INTRODUCTION

1.1 Project Background & Motivation

The growth of wireless communication relies on the availability of radio frequency for new services. More efficient spectrum allocations are required to serve the increasing data per user. The major regulatory bodies are formulating new spectrum management techniques to forge the growing spectrum scarcity. Exclusive use of spectrum is proved to be inefficient in many spectrum occupancy measurement campaigns. As a result, spectrum sharing methods are being considered.

Recently regulators, at various levels, are starting to devise new spectrum management methods to resolve the forthcoming spectrum crisis. The regulators are showing their willingness to solve this problem by sponsoring free radio channels as spectrum commons to allow opportunistic access for unlicensed devices. The Industrial, Scientific and Medical (ISM) radio bands in the 2.4GHz frequency are allocated freely for public use as spectrum commons. These bands showed tremendous success for short-range low power communication in Wireless Local Area Networks (WLANs). Another spectrum sharing technique, named opportunistic access, enables the unlicensed use of the idle portions of a licensed radio spectrum without harming the primary licensee. Regulators have been giving permission for wireless microphones to work in the occupied TV channels in interleave basis. After the digital switchover, new spectrum allocations are expected to complete in the coming years.

Studies have revealed that the TV broadcasting is not using the spectrum efficiently i.e. TV channels are not being used in some geographical locations (Maziar, 2010) (Harrison et al., 2010). The allocated UHF frequency band which is not being used for TV broadcasting in some geographic areas will create a coverage holes which known as Television Whitespace (TVWS). Both the industry and the regulators are investigating the capability of TVWS, as a potential source of spectrum for emerging wireless services which is considered to be the next potential immediate solutions for spectrum scarcity.

Television White Space (TVWS) Technology is a disruptive wireless broadband innovation which challenges a basic tenet of radio licensing: that radio spectrum should be sold or leased for exclusive use. TVWS is an inexpensive, light weight technology - priced closer to wireless broadband equipment than it is to the cellular equipment typically used to cover rural and remote communities. Through its use of television spectrum TVWS can allow broadband coverage far more effectively than technologies like Wi-Fi while emitting just four watts of power which is less than a typical cellular tower (Lei et al., 2012).

The Cognitive Radio (CR) technology is defined as a radio or a system that senses, or is aware of, its operational environment and dynamically and autonomously adjusts its radio operating parameters accordingly by collaborating wireless and wired networks. The CR technology is classified into two types according to its spectrum sensing method. One is a heterogonous type, in which a CR terminal selects appropriate existing wireless communication systems according to its environment. The other one is a white-space type, in which the CR terminal secondarily uses the frequency band allocated to primary users.

Especially, the latter one is expected to allow newly wireless communication systems without squeezing up a wide space from current crowded frequency bands. As one of the white-space type cognitive radio technologies, MCMC promotes the secondary use of the Ultra-High Frequency (UHF) band which is mainly allocated to the TV broadcast (Mitola et al., 1999).

This thesis developed a WIFI-UHF Transceiver (WUT) system for TVWS application. This device is considered to be a type of CR which is developed for TVWS to utilize the unused UHF frequency band.

1.2 Problem Statement

In the last decades there has been a huge revolution in the communications industry, producing notorious impact in economy and society. Wireless communications in particular, deserve special attention since they have experienced tremendous increase and have become part of daily lives being one of the main elements of economic development. Wireless and mobile communications offer a low cost, efficient way to connect rural areas and thus, telecommunications industry plays an essential role in development of a country.

However, due to the exponential increase on demand for technology and telecommunications, and since the number of users are enormously increasing, frequency spectrum is running out, see Figure 1.1. Meanwhile the investment to build a wireline network and multiple access points in rural or remote areas of low housing density would be much costly as shown in Figure 1.2. Huge areas like manufacturing plant, a transportation hub for courier operations, a refinery or a power plant needs multiple Wi-Fi access points to implement wireless network on its campus could cause a wireless interference. Multiple access points to cover a huge area or a plant will create blind spots, see Figure 1.4. These blind spots occur due to coverage limitation for a single access point.

Figure 1.1 Frequency spectrum is running out (receiving low signal) due to increasing number of users

Figure 1.2 Building wireline cable in rural area would cost much

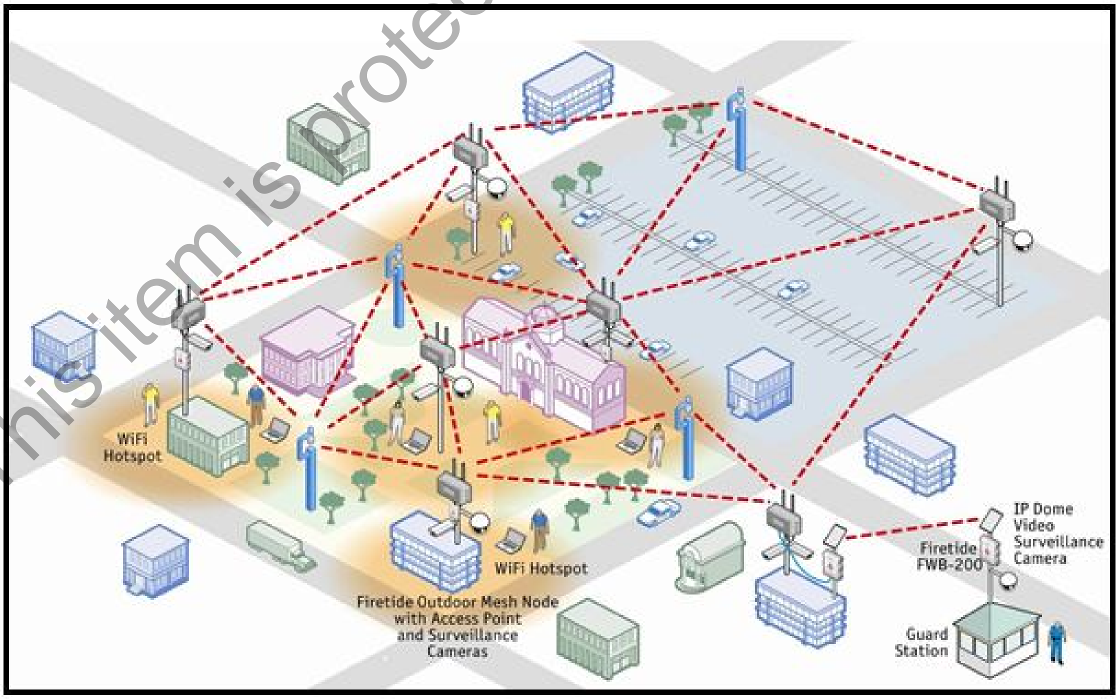


Figure 1.3 Huge campus needs multiple access points to do the wireless network

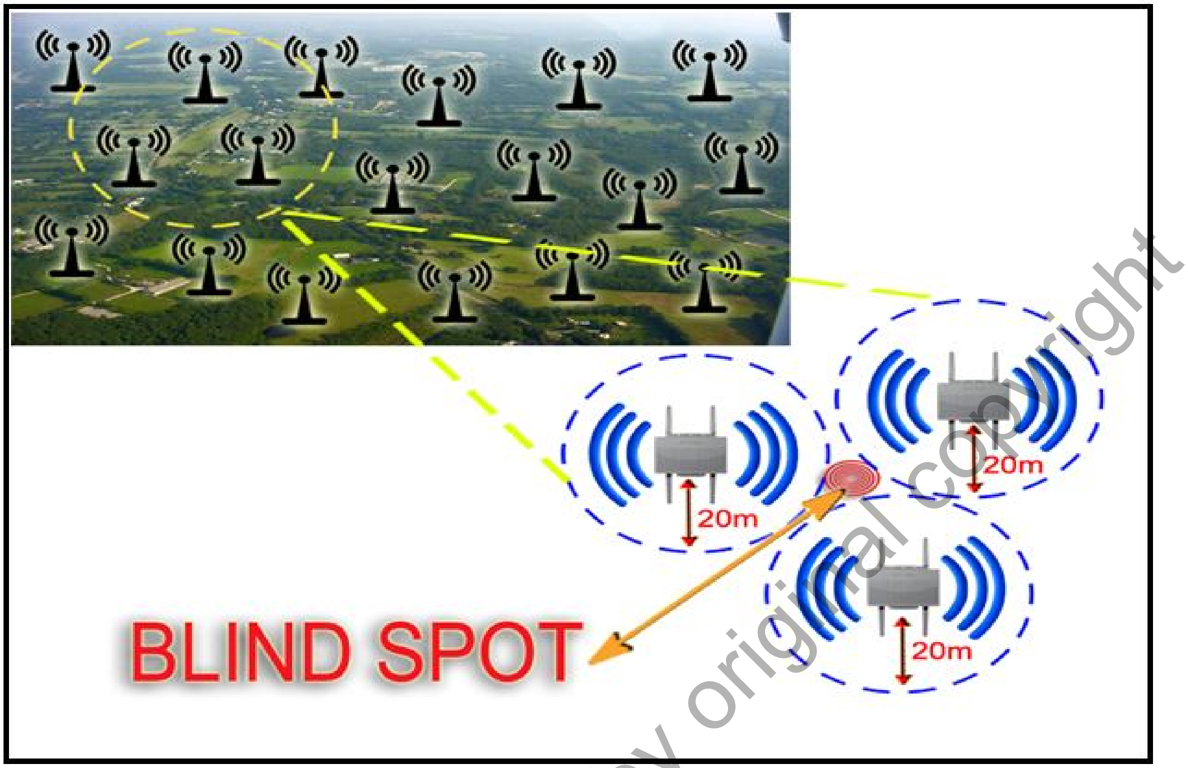


Figure 1.4 Using multiple access points in rural area can create blind spots

TVWS communications are of special interest because of two main reasons: first of all, their propagation characteristics with low propagation loss and high penetration range are particularly good for wireless communications where coverage is increased. Secondly, little and relatively cheap infrastructure is required for their implementation, making them well suitable for rural areas where previous infrastructure does not exist (Engelstad et al., 2011). UHF converter is the equipment used in TVWS technology which secondarily uses the allocated spectrum for primary users in TV band to transmit the converted Wi-Fi signal

TVWS communications would be much more optimum and meaningful if the UHF converter is not only able to transmit the converted Wi-Fi signal, but also it is able to receive the UHF signal converted from other Wi-Fi signal. This would turn the converter into a transceiver which will down-convert the Wi-Fi frequency to UHF during transmit and up-convert the UHF frequency to Wi-Fi during receive. However, the switching between transmit and receive has to be fast enough to prevent data loss over the rapid communication in which the current TVWS transceiver with a half-duplex communication mode might be prone to have a big concern about this. Apart from this, the receiver in transceiver shall not be designed with a wide passband as it tends to pick up an unwanted signal which frequency is close to the desired signal. Thus, the transceiver shall be designed to operate in a very limited or small frequency range even though the available frequencies in TVWS are between 470-770MHz.

1.3 Thesis Objectives

The main objectives of this study include:

i) To design architecture of WiFi-UHF Transceiver (WUT) which down-converts the Wi-Fi frequency signal (2.4GHz) to UHF band signal (650-680MHz) and up-converts UHF band signal to Wi-Fi frequency signal.
ii) To fabricate a WUT which includes all associated components as per design architecture and followed by characterization of individual components.
iii) To verify the WUT entirely as transmitter or receiver system based on output power level performance at transmit frequencies between 650-680 MHz and receive frequency of 2.4 GHz.

1.4 Scope of Work

Study has embarked on understanding the insight of TV white space technology which includes the frequency range coverage, the current utilization of the frequencies, the frequencies availability and the necessary frequency range to be used for WUT application as the design for a white band application might be too challenging and needs extremely huge efforts.

In order to improve the coverage of data communication over Wi-Fi, WUT deploys a concept which is quite similar to transceiver where the signal through the WUT will be up and down-convert to enable the data transfer between two Wi-Fi modems. Thus the design architecture of proposed WUT assembled a basic transceiver system which includes two main elements: transmitter and receiver consisting of sub-components such as RF filters, amplifiers, circulators, attenuators, mixers and VCO-PLL.

Chapter 3 is focusing on designing several sub-components e.g. RF filters from scratch and those like amplifiers, circulators, mixers and VCO-PLL are the customized parts or evaluation boards (off-the-shelf) purchased from the market. The choice of filter type, location and topology or design will be determined based on specific requirements explained in the next chapters. After the design is finalized, ADS will be used as a tool to build and simulate all the filters as ground work to achieve the preliminary goals determined for WUT. For amplifier evaluation boards, s2p data file provided by the manufacturer will be used in simulation to represent their measured response. Other customized parts or evaluation boards like circulator, mixers and VCO-PLL which do not have s2p file provided by manufacturer, the ideal components with definable parameter in ADS have to be used to exhibit an ideal response of them. Finally all components will be included and integrated in simulation to analyze the WUT performance as a system which will be divided into transmitter and receiver.

After WUT's results have been satisfied through simulation, fabrication of WUT will be in place where PCB gerber file is required. In order to generate the gerber file, the PCB has to be designed in regards to all lump components stated in build of material (BOM) and schematic. The BOM has been prepared in excel sheet whereas the schematic and PCB design have been created using Cadence Allegro. After the PCB board has been fabricated, all components per the BOM list have been placed and soldered on the board and the WUT commercial components have been assembled and integrated per the system architecture. After the assembly, all sub-components will be validated and characterized individually to learn and analyze their performance through measurement.

Chapter 4 addresses the characterization results of RF filters by comparing simulation to with measurement to correlate between them is as the call for optimization will be made upon this analysis. For the customized parts or evaluation boards, the characterization is nothing more than just a verification to learn how close the actual performance is compared to those stated in datasheet or displayed in ADS from the s2p file.

Optimization would expect to be a lengthy process as it needs number of attempts to rework the component of the RF filters on the prototype board with various values until the measured response becomes as close as possible to the simulation. Usually some kind of tweaking or tuning will be done in simulation prior to rework in order to get some idea or direction which particular component in the circuit shall be changed towards the improvement. All RF filters will be optimized individually until the specific design goal of each filter is met. After the optimization of all RF filters is complete, all sub-components of WUT including the optimized filters and evaluation boards will be integrated as a complete system as preparation for system performance evaluation. The evaluation will be performed separately for transmitter and receiver in which the output power will be the measure of quantifying the WUT performance similarly to how it was done in simulation.

Limited number of prototype board used for the verification and optimization is one of the limitations. The optimization by changing lump components e.g. inductor might be the limitation and concern since the physical inductor of the new value might be too small or big for the fabricated pad stack of the designated PCB. In order to address this, another prototype board with updated PCB layout needs to be fabricated and this seems to be costly.

CHAPTER 2 : LITERATURE REVIEW

2.1 Overview

Recently, high-speed and high-capacity wireless communication systems are realized with a progress of a wireless communication technology. However, now a serious problem is being experienced that the frequency bands might not be sufficient to accommodate the current and the future demand, since users and traffics are enormously increasing beyond expectation. This seems to be concerned especially for all frequency bands below 6 GHz, suitable for wideband mobile communication systems, which were already allocated to existing usages and the new wireless communication systems in Malaysia has no more frequency band available. A cognitive radio (CR) technology comes with very high potential to address such problem with frequency resource shortage and its early practical use is strongly expected (Sabbah et al., 2018).

CR technology like TVWS is an evolving technology with potential high impact in developing rural areas. They offer a low cost, high scope, state-of-the-art wireless broadband access to remote, isolated locations by dynamically accessing and managing underused spectrum frequency bands. Several initiatives currently takes place and some pilot TV White Space networks have been deployed worldwide, being Malaysia one of the pioneers with several research works are being take place. Adoption of TVWS communications will create several business opportunities and contribute to the economic growth of developing countries.

2.2 TV White Space

White space is the frequencies provided to a broadcasting service in telecommunications, but not for local use (Alonso et al., 2017). Different frequencies for specific uses are assigned by National and international bodies and mostly the rights to broadcast over these frequencies are licensed by them. The white space between used radio bands or channels are assigned to avoid interference for technical reason when a band plan is created for allocation process of this frequency. Specifically they are assigned for an objective, such as a guard band while the frequencies are not occupied in this case.

Since the existence of white spaces between used channels is expected, then transmissions assigned nearby to immediately adjacent channels might cause destructive interference to both. Also there is unused radio spectrum except the white space assigned for technical reason which has never been used or becomes available due to technical changes. Particularly, the migration to digital television would make large areas available between about 50 MHz and 700 MHz to pack digital transmissions into adjacent channels and this seems impossible for analog. This means the band is able to be "compressed" into several channels, while more transmissions are still allowed.

Figure 2.1 is showing the frequency spectrum allocation for analog TV and digital terrestrial broadcasting in Malaysia (SKMM, 2015). From this figure, there are total of 40 channels with 8MHz bandwidth starting from channel 21 up to channel 61 available in this UHF band. Figure 2.2 shows the list of TV broadcasters in Malaysia using VHF and UHF.

There only 4 channels are occupied by the broadcasters in UHF band and the remaining channels are being unused. These unused channels are called as white space channels or simply known as TV white space.

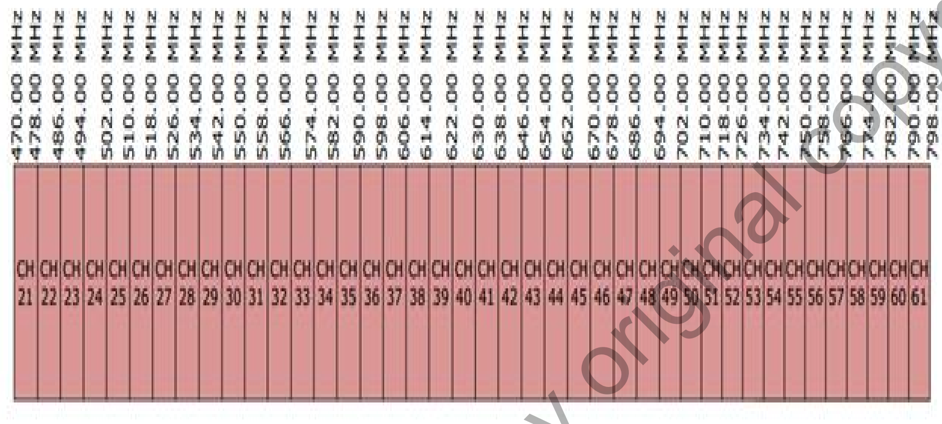
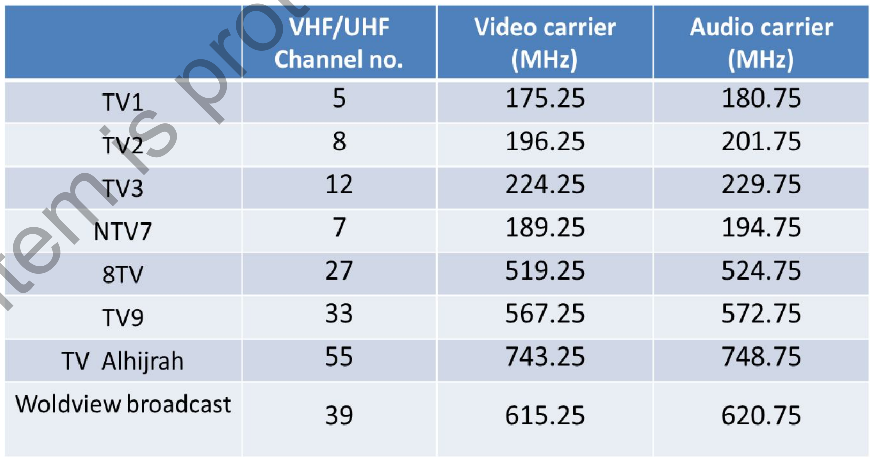


Figure 2.1 Frequency allocation for Analog TV & Digital Terrestrial TV Broadcasting
Source: SKMM (2015)



	VHF/UHF Channel no.	Video carrier (MHz)	Audio carrier (MHz)
TV1	5	175.25	180.75
TV2	8	196.25	201.75
TV3	12	224.25	229.75
NTV7	7	189.25	194.75
8TV	27	519.25	524.75
TV9	33	567.25	572.75
TV Alhijrah	55	743.25	748.75
Woldview broadcast	39	615.25	620.75

Figure 2.2 Malaysia’s analogue terrestrial television broadcasting using VHF and UHF
Source: SKMM (2015)

2.3 WiFi-UHF Transceiver (WUT)

The purpose of WUT is to offer a user-friendly, thus far flexible platform for the extension of IEEE 802.11 devices with CR features so they can have access to local TVWS spectrum resources. The baseband signals will not be directly accessed so that the compatibility with various commercial IEEE 802.11 hardware is achievable. Therefore WUT needs to move accessible at antenna output signals from the 2.4 GHz ISM band to the UHF bands (IEEE P802.11-REVmd/D1.0, 2018). The device shall have ability to support UHF output powers and legacy WLAN with different output powers because the regional regulatory constraints are not the same.

The high requirements of signal purity of IEEE 802.11 devices might give several challenges due to the increase of the noise levels and unwanted distortions at receiver and transmitter side by the WUT. The permissible interference must be minimized first from a TVWS link conversion in order to meet the standard specification’s limits. The impurities of signal from both the original chain of WLAN transceiver and the WUT needed for compensation make this particularly difficult. Most likely this will only contribute to a small error budget for low-quality WLAN adapters that need the considerably high quality of WUT.

The signal power in channels of the present broadcasting networks next to the whitespace devices channels of operation is a second practical issue. Without proper filtering plan, at the WUT there will be a huge threat of frontend desensitization. Networks become particularly apparent in urban regions due to fragmentation of nowadays broadcasting channel use (Lei et al., 2014). Here, TV channels are extended locally all over the entire UHF spectrum and only few channels within are unused. Hence it may be impossible for the transceiver to be tuned to channels from the broadcasting channels with high frequency offset. A mapping of UHF frequency to ISM band has to be made possible for the incumbent signal to be beyond the passband of a huge subset of the built-in filters in order to reduce harm from the incumbent.

2.4 Existing Projects

A few existing projects have been identified whereby the main objectives are to perform the frequency conversion between Wi-Fi and UHF for communication. Some of them have an intelligent feature such as sensing element or scanner which can detect the vacant or available frequencies within the UHF band and feedback to the system to automatically change the frequency of the communication as alternative solution.

2.4.1 UHF CR prototype using Field Programmable Gate Array (FPGA)

A big demand for prime (i.e. with good propagation characteristics) radio frequency (RF) spectrum has been created by the proliferation of wireless applications/devices. The usage of this spectrum varies significantly with time and space even though most of this spectrum is allocated. One would require a device that continuously scans the radio environment for vacant spectrum and uses it for its communication needs in order to increase the efficiency. These new class of devices which is referred to as Cognitive Radios (CRs), (Ying et al., 2013) will efficiently utilize the spectrum while the interference to the primary occupants of the spectrum is avoided. This demonstration will span all of the principal requirements of a cognitive radio while individual pieces of a cognitive radio platform in the UHF band have been demonstrated before: sensing at low levels, distributing coordination of available channel via beaconing and silence periods while maintaining QoS of the application. Conclusively these technologies look mature and can be transitioned into real products in a very short time.

Custom algorithms in some combination implemented on commercial off-the-shelf components and a Field Programmable Gate Array (FPGA) are used to build a CR prototype. Figure 2.3 shows the top-level block diagram of the CR prototype. Physical (PHY) layer functionality and the Medium Access & Control (MAC) are realized by a standard Wi-Fi card. The PHY operates in 5 MHz mode with extended MAC to include cognitive features and ad-hoc distributed architecture. A down- and up-conversion of the Wi-Fi signals to the desired channel in the UHF band is handled by a frequency conversion module. The detailed block diagram of the CR node is shown in Figure 2.4. The sensing module is composed of an FPGA evaluation board and a standard TV tuner. The TV tuner down-converts the signals to an IF, which will be sampled by ADC on the FPGA board at 100 MHz. In order to sense for digital and analog TV signals and wireless microphone signals, the digitized signals are processed in real-time in the FPGA.

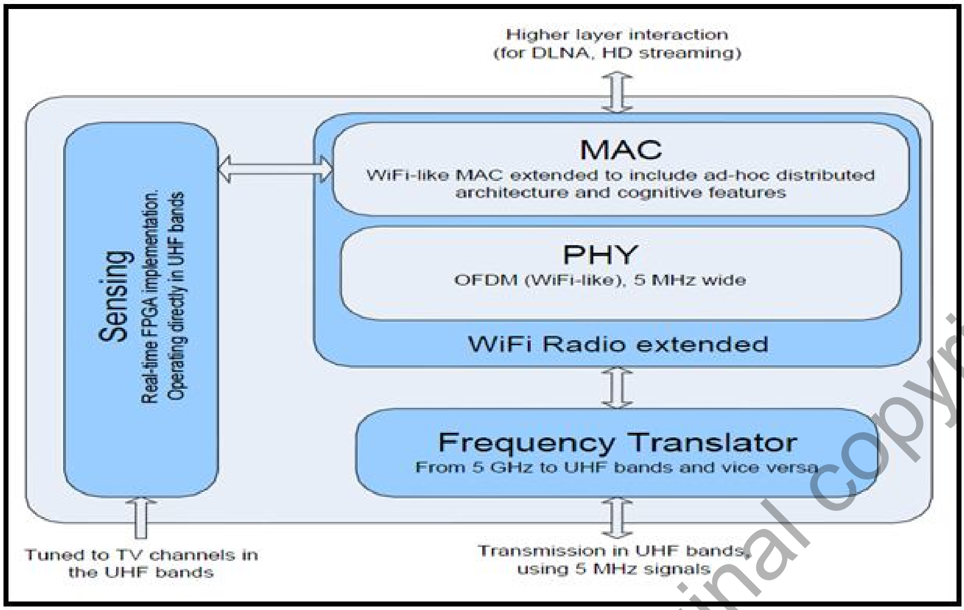


Figure 2.3 Top-level block diagram of CR prototype
Source: Iacobucci (2013)

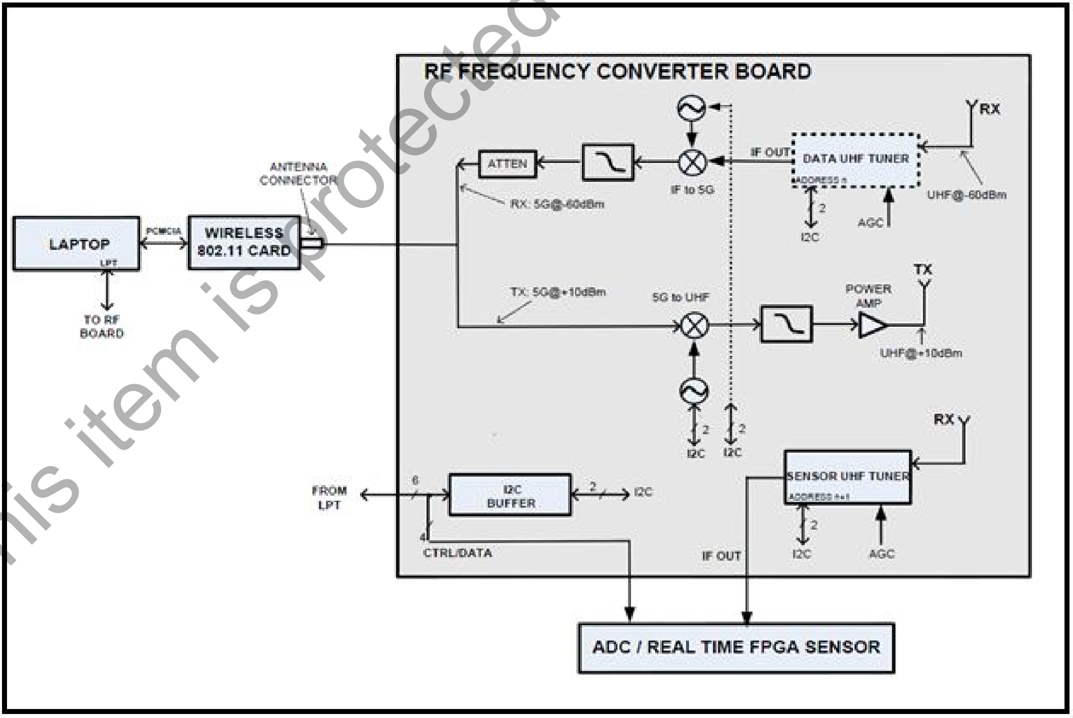


Figure 2.4 Block diagram of a UHF cognitive radio node
Source: Iacobucci (2013)

2.4.2 TV White Space Converter prototype for WLAN routers

There is no doubt that the realization of wireless networks with high-data rate for next generation will be up to spectrum availability amount. A future spectrum shortage is predicted by the dependency growth of society on reliable and fast wireless Internet access, and the rapid expansion of wireless devices which traffic devastates the networks. Several measurement campaigns have revealed the potentially underutilization of many licensed frequency bands (Tehrani et al., 2016). On an opportunistic basis spectrum the re-farming approaches and techniques of spectrum-agile cognitive radio (CR) have been proposed by secondary users to allow the leveraging of licensed spectrum so the spectrum is efficiently used. (Ying et al., 2013). A lot of attention has been given to the current UHF bands as potentially attractive bands reserved for TV broadcasting to implement new secondary radio technologies due to their encouraging propagation characteristics. These are known as TV whitespaces (TVWS) which are presently underutilized temporally and spatially in many regulatory domains.

Trials are currently in progress of quantifying the prospects of TVWS operations after the initial rulemaking by FCC (FCC, 2010) to allow secondary use in the US. It seems highly sensible using additional bands to enable legacy technologies in order to cut manufacturing costs and minimize radio overhead while the majority of personal communication devices such as tablets or smartphones comes with transceivers in multi-band, e.g. IEEE 802.11 WLAN

To promote a practical use of this technology, small size terminals operated in the UHF band is strongly required, thus, an architecture that enables a wireless communication in the UHF band by converting the frequency band of 2.4 GHz, which is originally used by an existing wireless local area network (WLAN) module based on IEEE 802.11b/g/n, to the UHF band has been prototyped. Also, a small size of UHF converter which can be implemented in a tablet terminal has been prototyped.

The architecture of the UHF Converter is shown in Fig 2.5. The UHF Converter is basing a transceiver architecture of high-IF in which a problem because of LO harmonics is not caused by unwanted spurious of RX band emissions. The transceiver is divided into transmit and receive in separate path to enable more fine-grained configuration of not the same components, thus the optimization for receiver sensitivity and transmit signal purity can be independently. Two fast SPDT RF switches help separate and unify the two paths, one (the RF switch) merges the signal paths for operation of single UHF antenna and the other one (the IF switch) is at the IF port to face the WLAN router.

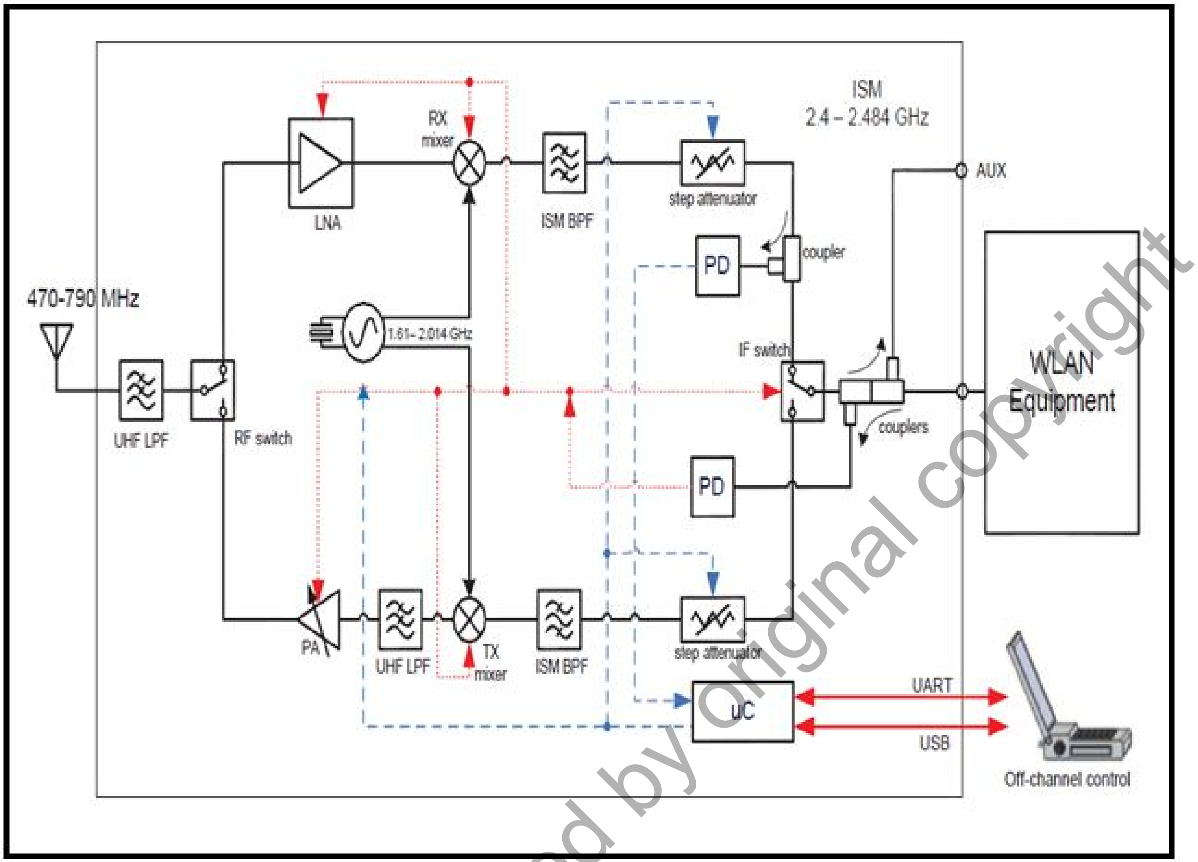


Figure 2.5 The complete block diagram of the UHF converter
Source: Ser et al. (2017)

Between the RF switch and the antenna port there is a single UHF low pass filter in combination with inherent selectivity of the antenna. A bandpass network is formed by the LNA's input matching network to reject the unwanted interference from the lower frequency of broadcast networks to prevent the LNA from desensitization. Also, the desensitization of the frontend is prevented by driving the LNA into low gain mode when a high power (> -20 dBm) of in-band interferer is present. The RF switches are controlled by coupling out a little portion of the WLAN transmit signal and feeding it into an RF power detector in the symmetric transceiver path between the router IF switch and RF port of the input side. The router signal (6 dB coupling) received has another small portion fed into a third, auxiliary RF connector for optional connectivity of further measurement equipment.

The transmit path starts after the switch separating Tx and Rx signal with a digital attenuator in signal chain as first element to allow tradeoffs between linearity and noise, and to accommodate different settings in router signal strength. Also, slow power-level control can be implemented over an interface of microcontroller (see below). Power backoff is provided by the attenuator up to 31 dB and the bandpass SAW filter of 2.4 GHz ISM attenuate from the WLAN router all possible spurs. Then the WLAN signal is translated by the mixer with highly linear down conversion into the desired UHF band via a local oscillator (LO) signal produced by the synthesizer. The unavoidable mixer spurs lying above the desired signal frequency degrades the resulting signal between 470-790MHz UHF band still. Hence, removing these nonlinearities is required for UHF low pass filter. The 30 dBm output power is capable by the power amplifier and power backoff is provided by the attenuator when in need. Through the RF switch, then the output signal amplified is injected to the antenna. The single-ended signal transmission is used by the whole signal processing path.

LNA is the first stage of the receiver with gain as high as 22 dB and noise figure (NF) as low as 0.45 dB. The rejection capabilities of superior noise are provided by the receiver chain as obvious from these key metrics. The desired UHF frequencies are translated by the up-conversion mixer into the 2.4 GHz ISM band. The spurs produced by any other contents of unwanted frequency and the mixer are removed by another ISM band pass filter. A small fraction of the UHF band is only chosen since 80 MHz is the bandwidth of this band pass filter. Any 80MHz band within the UHF band of target is chosen by tuning the synthesizer. Further channel selection is done through the WLAN device built in receiver chain.

The unwanted signal sources can also be suppressed by the ISM filter in the present broadcasting networks due to its attenuation characteristics by changing the preferred channels near the transition band of the ISM filter. The possibly wide variation of signal strengths causes the addition of digitally controllable attenuator included in the receive path. A power backoff here can be made possible for up to 31 dB. A method of detecting RF power is made available in the hardware since baseband decoding is not required by detecting broadcasts or PMSE users. This can also be an advantage for faster detection in hardware with some resources. Hence, the signal received from the attenuator moves to an RF power detector through coupling before the RF switch. Similarly, the receive path signal processing section is completely single-ended like transmit path.

The LO is comprised of an external loop filter used for the PLL, a wideband synthesizer chip and an external of reference crystal resonator to obtain a carrier signal with required phase noise performance. Both mixers can run at the same LO frequency since the WLAN router runs in TDD mode. The dynamic loops of the PLL are customized so the phase noise can be achieved at minimum level to maximize its performance. Moreover, PLL settings are made selectable to fulfil the required settling time to sense the spectrum.

Two mechanisms control the various parts in the signal chain. Firstly, in controller mode the router feeds the transmit signal to a power detector. Hereby, the converter turns to transmit mode when the input power hits the predefined threshold. 96 us is the shortest preamble packets of IEEE 802.11 whereas 150 ns is the RF switch's switching delay, which is short enough to avoid any loss of information. The WSC is returned to receive mode if the router power is detected lower than the threshold specified by user. Despite any mode, the unused blocks in the path of other signal are turned off to reduce local interference and to conserve power. The second mechanism is off-channel control realized through a microcontroller (an ATxMega32 from Atmel) which handles the settings of attenuation for both paths: receive and transmit. Also the analog voltage from the RF power detector is read by the microcontroller which uses this value to provides digital readout via both a USB port and a legacy serial port.

2.4.3 UHF Cognitive Radio prototype using scanner

Based on the recent measurements, TV bands still has a huge portion of unutilized licensed spectrum. For instance, in the US the use of TV broadcast bands is averagely low, 14% in 2004 which is in marked contrast to the congestion of wireless communications in ISM bands without license. The Federal Communications Commission (FCC) is looking at the option to allow unlicensed wireless communication in white spaces to address this disparity, i.e. TV bands portion inactively used at present by the TV operators. There are certain properties of radio frequency (RF) propagation in the lower frequency of TV bands unlike the higher frequency ISM bands, such as, better penetration, longer range and lower interference which are for data communication incredibly desirable. The initiatives by the FCC above are in the imagination of engineers and researchers to be taken into account in building systems with high-speed data communication in the white spaces to avoid interference with existing TV signals. There is no confirmation that this goal is achieved by any existing system. Furthermore, no complete system is able to dynamically incorporate signal from scanner output into radio with capability to perform high-speed data communication in TV bands even though the presence of a TV signal is detected in high-end scanner.

A hardware prototype has been designed per the objectives outlined above. An off-the-shelf commercial IEEE 802.11bg [22] (Wi-Fi) radio is coupled with a high resolution TV scanner by a hardware. The translation of the ISM band signals to the suitable TV band and vice versa is done by an up and down converter included in the front end of the Wi-Fi radio. The waveform of 22 MHz Wi-Fi OFDM is processed for the operation within one TV channel after going through an appropriate filter so the transmissions of the device are kept within one TV band.

More than 10 Mbps data rate is achieved in a 6 MHz TV band with this arrangement and the TV receivers is allowed to operate without interference Furthermore, to the extent possible, the system is designed to prevent from hidden terminal interference, even when the scanner was unable to "hear" a TV signal. The system's hardware prototype is developed in association with Metric Systems (www.metricsystems.com). To allow data communication of high speed in the TV bands, a two radio approach is used. A scanner is