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FAST SPECTRUM SENSING IN WRAN (802.22)

An Application using Cognitive Radio method

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Halaman Pernyataan Orisinalitas

Skripsi ini adalah hasil karya saya sendiri, dan semua sumber yang dikutip maupun dirujuk saya nyatakan benar

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Tanda Tangan	**:**
Tanggal	**: Desember 2009**

Statement of Authorship

The work contained in this project report has not been previously submitted for a degree or diploma at any other tertiary educational institution. To the best of my knowledge and belief, the project report contains no material previously published or written by another person except where due reference is made.

Signed ....

Date ....

Lembar Pengesahan

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Program Studi : Teknik Elektro Internasional

Judul Skripsi : Fast Spectrum Sensing in WRAN (802.22)

Telah berhasil dipertahankan dihadapan dewan penguji dan diterima sebagai bagian persyaratan yang diperlukan untuk memperoleh gelar Sarjana Teknik pada program studi Teknik Elektro Internasional, Fakultas Teknik Universitas Indonesia.

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Abstract

Current spectrum management model, command and control, is creating a fundamental cause to drop the spectral efficiency of the radio spectrum in time and space by granting a right to Radio Access Technology (RAT) to access exclusively. In order to solve the spectrum scarcity, a number of bodies, headed by the FCC, have been taking actions to make new paradigm of spectrum management. Recently, the FCC announced a very interesting report (1). It pointed out that more than 7000 of radio spectrums are underutilized in certain times or geographic locations. This means that spectrum scarcity is not due to fundamental lack of spectrum instead because of wasteful static spectrum allocations. Hence, various spectrum sharing schemes which can raise spectrum utilization are investigated by research institutes. In this context, IEEE 802.22 WG which was organized in November 2004 has a purpose to provide wireless internet service to WRAN (Wireless Regional Area Network) user (or secondary user) using idle or unused TV spectrums not to disturb VHF/UHF TV band users (primary user). Since there are two types of users in terms of spectrum access priority, this coexistence is regarded as vertical sharing (2) that the secondary user utilizes licensed spectrums by opportunistic manner. The outstanding advantage of this sharing is to be realizable by little modifications of current spectrum regulation. Therefore, IEEE 802.22 activities have received a plenty of attentions.

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List of Abbreviation

RAT	-	Radio Access Technology
QoS	-	Quality of Service
xG	-	next Generation
LAN	-	Local Area Network
WRAN	-	Wireless Regional Area Network
CDMA	-	Code Division Multiple Access
U-NII	-	Unlicensed National Information Infrastructure
DFS	-	Dynamic Frequency Selection
BS	-	Base Station
CPE	-	Costumer Premise Equipment
OFDMA	-	Orthogonal Frequency-Division Multiple Access
OFDM	-	Orthogonal Frequency-Division Multiplexing
PHY Layer	-	Physical Layer
MAC Layer	-	Medium Access Control Layer
SCH	-	Superframe Control Header
RFE	-	Radio Frequency Front End
IF	-	Intermediate Frequency
RSSM	-	Received Signal Strength Measurement
MRSS	-	Multi-Resolution Spectrum Sensing
AWGN	-	Additive White Gaussian Noise

Supplementary Material

1. Abstract
2. Project Plan
3. Poster
4. MATLAB Code Files
5. Presentation slides
6. MATLAB simulation results files

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I would like to acknowledge all those who have assisted and supported me through the course of this project. In particular I would like to extend a big thank you to Dr. Dhammika Jayalath, my project supervisor for his weekly (sometimes many times a week) assistance and guidance. Without his help, I would not have been able to complete this project to its current standard. I would also like to thank my friends, my family and my loved ones, Noor Melissa Putri for their endless support throughout the making for this project. Last but not least, a big thank you to everyone else who assisted me on this project, especially Asim Anwar who assisted me tremendously to do the programming part.

Thank you everyone for your support.

Chapter 1 Introduction

Current spectrum management model, command and control, is creating a fundamental cause to drop the spectral efficiency of the radio spectrum in time and space by granting a right to Radio Access Technology (RAT) to access exclusively. In order to solve the spectrum scarcity, a number of bodies, headed by the FCC, have been taking actions to make new paradigm of spectrum management. Recently, the FCC announced a very interesting report (1). It pointed out that more than 7000 of radio spectrums are underutilized in certain times or geographic locations. This means that spectrum scarcity is not due to fundamental lack of spectrum instead because of wasteful static spectrum allocations. Hence, various spectrum sharing schemes which can raise spectrum utilization are investigated by research institutes. In this context, IEEE 802.22 WG which was organized in November 2004 has a purpose to provide wireless internet service to WRAN (Wireless Regional Area Network) user (or secondary user) using idle or unused TV spectrums not to disturb VHF/UHF TV band users (primary user). Since there are two types of users in terms of spectrum access priority, this coexistence is regarded as vertical sharing (2) that the secondary user utilizes licensed spectrums by opportunistic manner. The outstanding advantage of this sharing is to be realizable by little modifications of current spectrum regulation. Therefore, IEEE 802.22 activities have received a plenty of attentions.

Since the QoS (Quality of Service) of privileged primary users must be guaranteed, in the secondary spectrum usage approach, one of the critical parts is spectrum sensing. Thus, low complexity with high sensitive detection technique is needed in the secondary user system. In IEEE 802.22, for example, if the DTV signal is a primary user, a secondary user has to detect up to -116 dBm signal. To meet the time and sensitivity requirements, two stage spectrums sensing which consists of coarse and fine detection has been suggested (3). The key functionality of each stage is to select multiple unoccupied candidate channels, and to identify the signal type and detect the weak signal respectively.

The development of the IEEE 802.22 WRAN Standard (4) is aimed at using cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the television broadcast service, on a non interfering basis, to bring broadband access to hard-to-reach-low-population-density areas typical of rural environments, and is therefore timely and has the potential for wide applicability worldwide. IEEE 802.22 WRANs are designed to operate in the TV broadcast bands while ensuring that no harmful interference is caused to the incumbent operation (i.e., digital TV and analog TV broadcasting) and low-power licensed devices such as wireless microphones.

In this report, student focus on the coarse detection part which selects multiple unoccupied candidate channels by the energy detection method. The swapping time is more important than the sensing sensitivity at this stage. Thus, we propose the fast spectrum sensing algorithm based on the discrete wavelet packet transform. Although the wavelet packet transform has almost the same complexity as the Fast Fourier Transform (FFT), the proposed wavelet based algorithm reduces the complexity and makes spectrum sensing faster. In the proposed scheme, furthermore, it is not necessary to confirm whether spectrums are unused or not because of the fundamental property of the proposed algorithm. Student verifies these advantages by simulations and complexity analysis.

The student contribution of this report including the comprehensive literature survey on spectrum sensing for cognitive radio as well as detailed study for IEEE 802.22 (WRAN), brief overview on IEEE 802.22 Standard and suggesting fast sensing method for MAC layer in WRAN by using wavelet energy detector.

The remainder of this report is organized as follows. Section I is the introduction of the project Section II briefly describes the Cognitive Radio and its main functions as well as the fundamental things for it. The application of Cognitive Radio in 802.22 and related works proposed by IEEE 802.22 WG are explained in section III. In section IV, the wavelet based energy detector is proposed. The simulation environments and results are provided in section V, and section VI concludes the paper.

Chapter 2 Cognitive Radio

2.1 Introduction

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. Dynamic spectrum access using cognitive radio techniques offers the capability to share the spectrum in an opportunistic manner. Dynamic spectrum access allows the cognitive radio to operate in the best available channel[1] [2].

The advantages of cognitive radio are to senses Radio frequency environment and modify frequency, power or modulation, allow for real time spectrum management, and significantly increase spectrum frequency (5). In this cognitive radio adhoc network[3], a node may not be able to transmit immediately and as soon as it detects the presence of the neighbouring nodes. This fact seems to be the biggest disadvantage of cognitive radio adhoc network and this differentiates the cognitive radio adhoc network from the adhoc networks. But on the other hand they are provided with an end-to-end routing. This makes it superior when compared to the adhoc networks.

The application of cognitive Radio including LAN devices (WRAN included), CDMA networks, Cordless phones, U-NII/DFS (Europe) (5).

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[1] Depending on the parameter considered to decide the transmission and reception changes we can distinguish two types of cognitive radio: Full Cognitive Radio or 'Mitola Radio', where every possible parameter apparent by wireless node or network is considered and Spectrum Sensing Cognitive Radio, in which only the radio frequency spectrum is considered.

[2] Depending on what element of the spectrum is available for cognitive radio, we can distinguish: Licensed Band, where cognitive radio is capable of using bands, apart from unlicensed band and Unlicensed Band, in which can only use unlicensed parts of radio frequency spectrum.

[3] Cognitive radio adhoc networks are an advanced network that operates over a wide range of frequencies in the spectral band. They are unlikely and highly improbable to have a complete and fully accomplished topology information so they lead to interference among the cognitive radio users and as well as the collision among the primary users.

2.2 Main Functions of Cognitive Radio

More specifically, the cognitive radio technology will enable the users to: (6)

1. Determine which portion of the spectrum is available and detect the presence of licensed users when a user operates in licensed band and sharing spectrum without negative interferences with other users (*spectrum sensing*),
2. Select the best available channel to meet user communication requirements (*spectrum management*),
3. Coordinate access to provide fair spectrum scheduling method with other users (*spectrum sharing*), and
4. Vacate the channel to maintain seamless communication requirements during the transition to better spectrum when a licensed user is detected (*spectrum mobility*).

Once a cognitive radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum.

These functionalities of next generation networks enable spectrum-aware communication protocols. However the dynamic use of the spectrum causes undesirable effects on the performance of conventional communication protocols, which were developed considering a fixed frequency band for communication.

2.2.1 Spectrum Sensing

An important condition of the next generation network is to sense the spectrum holes; cognitive radio is designed to be responsive and sensitive to the changes in its surrounding. The spectrum sensing function enables the cognitive radio to adapt to its environment by detecting spectrum holes. The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range. But, in reality, it is difficult for a cognitive radio to have direct measurement of a channel between a primary receiver and transmitter. Thus, the most recent work focuses on primary transmitter detection based on local observation. In general, the spectrum sensing method can be classified as:

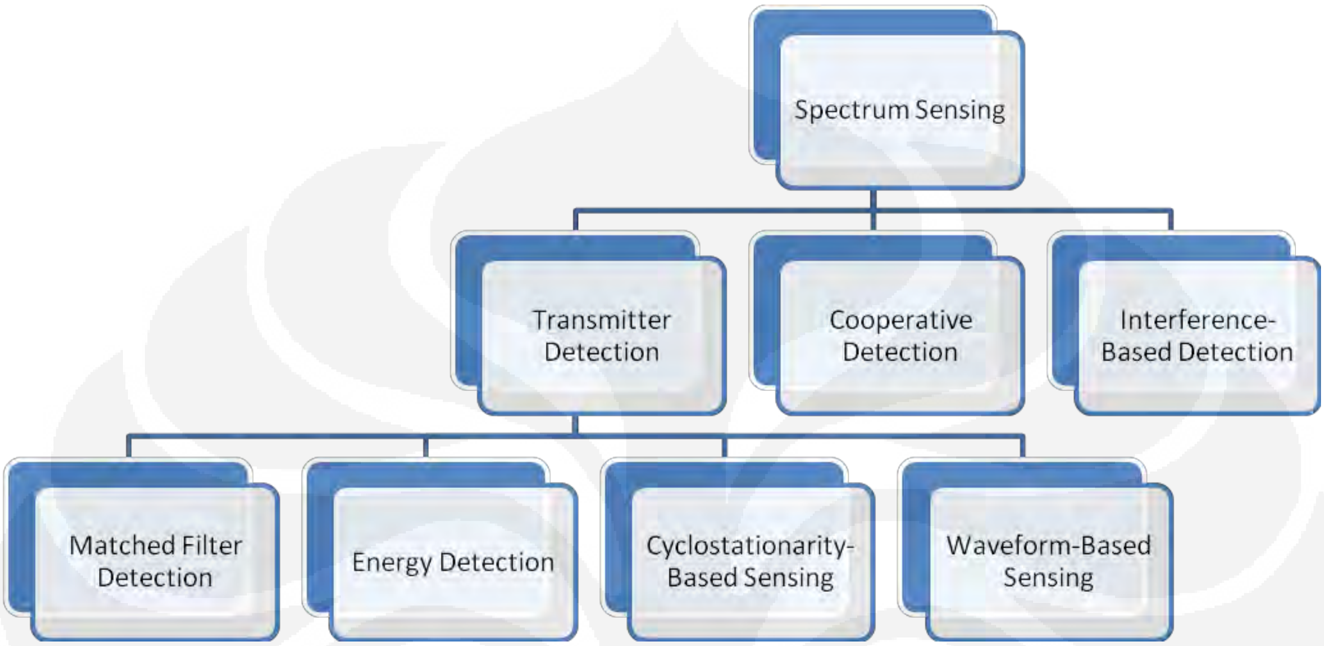

Figure 1 Classification of spectrum sensing techniques.

2.2.1.1 Transmitter Detection (Non-cooperative Detection)

The cognitive radio should distinguish between used and unused spectrum bands. Thus, the cognitive radio should have the capability to determine if a signal from primary transmitter is locally present in a certain spectrum. Transmitter detection approach is based on the detection of a weak signal from primary transmitter through the local observation from users.

2.2.1.1.1 Matched filtering detection

Matched filtering is known as the optimum method for detecting primary user when the transmitted signal is known. The main advantage of the matched filtering detection is the short time to achieve certain probability of false alarm or the probability of miss detection as compared to other methods that will be discussed later. However, the matched filtering detection requires the cognitive radio to demodulate signals, and thus requires perfect knowledge of the primary users signalling features such as bandwidth, operating frequency, modulation type and order, pulse shaping, frame format, etc. What's more since cognitive radio needs receivers for all signal types, implementation complexity of sensing unit is inconveniently large. Another disadvantage is large power consumption as various receiver algorithms need to be executed for detection.

2.2.1.1.2 Energy detector-based detection

Energy detector-based approaches, also known as radiometry or periodogram, are the most common ways of spectrum sensing because of their low computational and implementation complexities. Moreover, they are the most standard as receivers do not need any knowledge on the primary users' signals. The signal is detected by comparing the output of energy detector with a threshold which depends on the noise floor. Some of the challenges with energy detector-based sensing include selection of the threshold for detecting primary users, inability to distinguish interference from primary users and noise, poor performance under low Signal-to-Noise-Ratio (SNR) values, and does not work efficiently for detecting spread spectrum signal. (7)

2.2.1.1.3 Cyclostationarity- based detection

Cyclostationarity feature detection is a method for detecting primary user transmission by exploiting the cyclostationarity features of the received signals. Cyclostationarity features are caused by the periodicity in the signal or in its statistics like mean and correlation value. Instead of Power Spectral Density (PSD), cyclic correlation function is used for detecting signals present in given spectrum. The cyclostationarity-based detection algorithm can differentiate noise from primary users' signals. This is as a result of the fact that noise is Wide Sense Stationary (WSS) with no correlation while modulated signals are cyclostationarity with spectral correlation due to the redundancy of signal periodicities. Cyclic frequency can be assumed to be known or they can be extracted and used as features for identifying transmitted signals. (8)

2.2.1.1.4 Waveform-Based Sensing

Waveform-Based Sensing is working on familiar pattern and usually utilized in wireless systems to support synchronization. Familiar pattern such as preambles and mid ambles is sensed by performing correlation to the known signal. This sensing may only appropriate to systems with familiar patterns. The waveform-based sensing is superior to the energy detector-based sensing in terms of reliability and convergence time. Moreover, it is revealed that the performance of this sensing algorithm increases as the duration of known signal pattern increases.

2.2.1.2 Cooperative Detection

The assumption of the primary transmitter detection is that the locations of the primary receivers are unknown, this happen due to the absence of signalling between users. Therefore, the cognitive radio should rely on only weak primary transmitter signals based on the local observation of the user. However, mostly the network is separated from the primary network and so there is no interaction between them. Hence, with the transmitter detection, user cannot avoid detection due to the lack of primary receiver's information. A cognitive radio transmitter can have a good line of sight to a receiver, but may not be able to detect the transmitter due to shadowing. As a result, sensing information is essential for more precise detection.

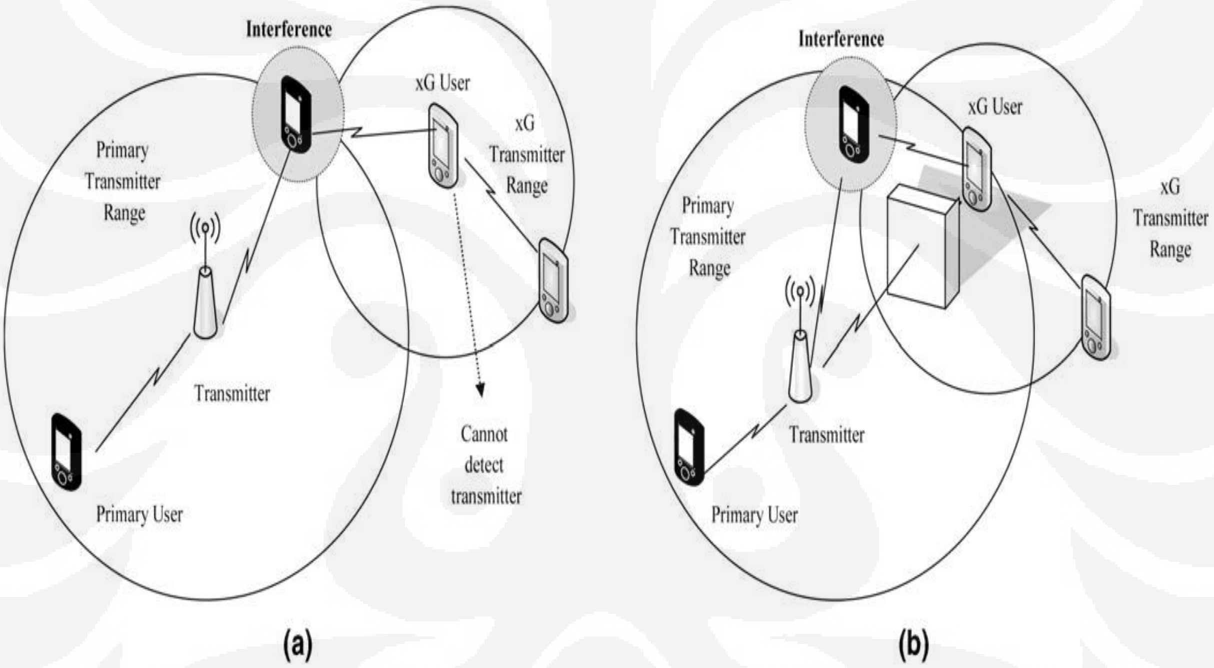

Figure 2 Transmitter detection problems

Cooperative detection can be implemented either in centralized or in a distributed method.

2.2.1.2.1 Centralized method

In centralized method, the cognitive radio base-station plays role to gather all sensing information from users and detect the spectrum holes.

2.2.1.2.2 Distributed method

In distributed method, the cognitive radio base-station requires exchange of observations among the cognitive radio users.

Cooperative detection among unlicensed users is theoretically more accurate since the uncertainty in a single user's detection can be minimized (9). In addition, the multipath fading and shadowing effect are the main factors that degrade the performance of primary user detection methods. Nevertheless, cooperative detection schemes allow justifying the multipath fading and shadowing effects, which improves the detection probability in heavily shadowed environment. While cooperative approaches provide more accurate sensing performance, the also cause negative effect on resource constrained network due to additional operations and overhead traffic. Additionally, the primary receiver location knowledge is still unsolved in the cooperative sensing. (9)

2.2.1.3 Interference-based detection

Due to the problems in cooperative detection such as additional operations, overhead traffic and primary location knowledge, Interference-based detection is introduced. Interference is typically regulated through the radiated power, the out-of-band emissions and location of individual transmitter. Nonetheless, interference is in reality occurs at the receivers. And thus, a new way to measure interference is introduced. This new model is called interference temperature and designed to operate in a range at which the received power approaches the level of the noise floor. Unlike the traditional transmitter approach, the interference temperature model manages interference through the temperature limit. In other words, the interference temperature model accounts for the cumulative Radio Frequency technology energy from multiple transmissions and maximum cap as long as the users do not exceed this limit by their transmissions, they can use this spectrum band.

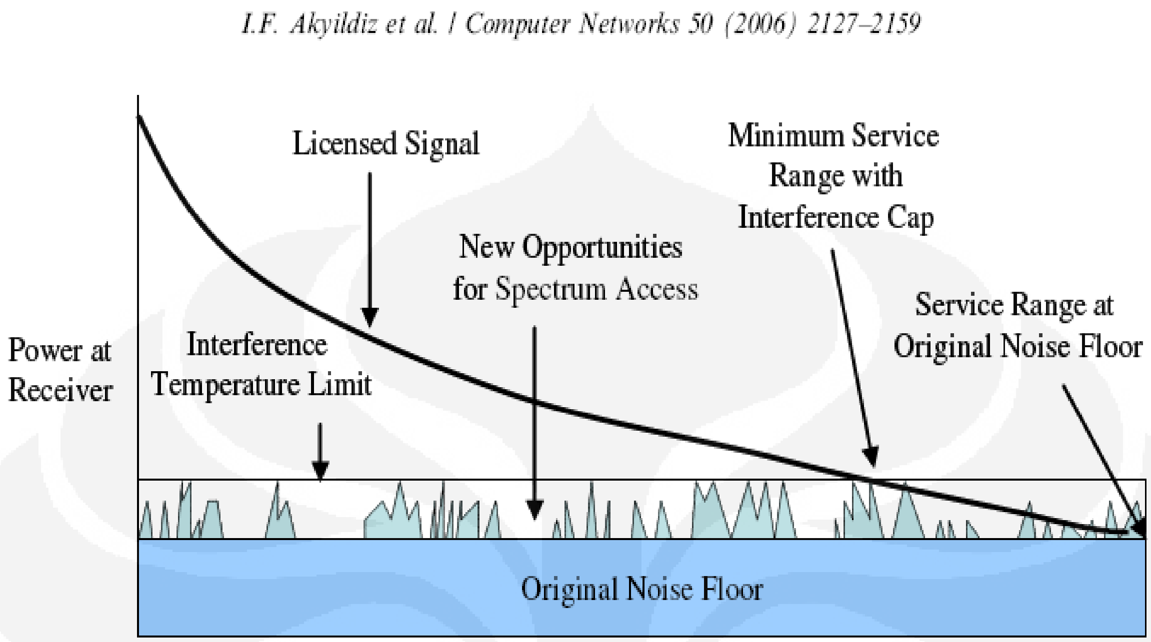

Figure 3 Interference temperature model

However, there exist some limitations in measuring the interference temperature. This method consider factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed users (10). Moreover, if the users are unaware of the location of the nearby primary users, the actual interference cannot be measure using this method.

2.2.2 Spectrum Management

Spectrum management is needed to capture the best available spectrum to meet user communication requirement. Cognitive radios should decide on the best spectrum band to meet the QoS requirement over all available spectrum bands (11).

Management function classified as:

2.2.2.1 Spectrum analysis:

In cognitive radio, the available spectrum holes show different characteristics which vary over time. Since the users are equipped with the cognitive radio based physical layer, it is important to understand the characteristics of different spectrum bands. Spectrum analysis enables the characterization of different spectrum bands, which can be exploited to get the spectrum band appropriate to the user requirements. In order to describe the dynamic nature of cognitive radio, each spectrum hole should be characterized considering not only the time-varying radio environment and but also the primary user activity and the spectrum band information such as operating frequency and bandwidth. Hence, it is essential to define parameters such as interference level, channel error rate, path-loss, link layer delay, and holding time that can represent the quality of a particular spectrum band as follows (6):

- Interference
- Path Loss
- Wireless Link Errors
- Link Layer Delay
- Holding Time

2.2.2.2 Spectrum decision

Once all available spectrum bands are characterized, appropriate operating spectrum band should be selected for the current transmission considering the QoS requirements and the spectrum characteristics. Thus, the spectrum management function must be aware of user QoS requirements. Based on the user requirements, the data rate, acceptable error rate, delay bound, the transmission mode, and the bandwidth of the transmission can be determined. Then, according to the decision rule, the set of appropriate spectrum bands can be chosen. In (12) five spectrum decision rules are presented, which are focused on fairness and communication cost. However, this method assumes that all channels have similar throughput capacity. In (13), an opportunistic frequency channel skipping protocol is proposed for the search of better quality channel, where this channel decision is based on SNR. In order to consider the primary user activity, the number of spectrum handoff, which happens in a certain spectrum band, is used for spectrum decision (14).

2.2.3 Spectrum Sharing

Spectrum sharing in cognitive radio will provide the fair spectrum scheduling method. Spectrum sharing corresponds to MAC problems existing in the systems, and therefore remains as major challenge in open spectrum usage (11).

The existing solutions for spectrum sharing in cognitive radio can be mainly classified in three aspects: i.e., according to their architecture assumption, spectrum allocation behaviour, and spectrum access technique as shown in fig 4. In this section, we describe these three classifications and present the fundamental results that analyse these classifications. The analysis of cognitive radio spectrum sharing techniques has been investigated through two major theoretical approaches. While some work uses optimization techniques to find the optimal strategies for spectrum sharing, game theoretical analysis has also been used in this area. The first classification for spectrum sharing techniques in xG (neXt Generation) networks is based on the architecture, which can be described as follows (6):

- Centralized Spectrum Sharing
- Distributed Spectrum Sharing
- Cooperative Spectrum Sharing
- Overlay and Underlay Spectrum Sharing

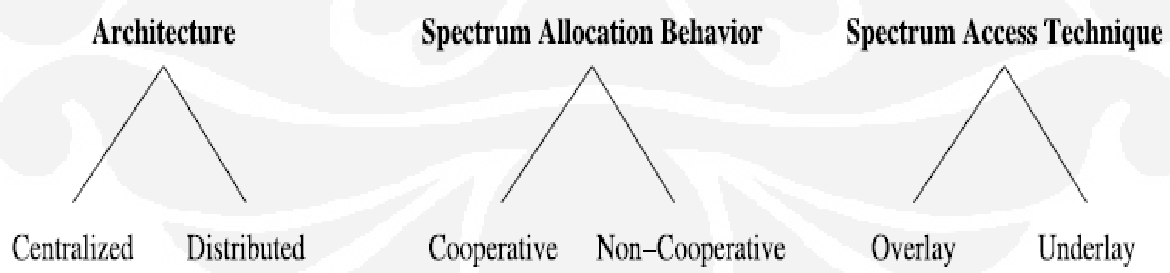

Figure 4 Classification of spectrum sharing in cognitive radio networks based on architecture, spectrum allocation behaviour, and spectrum access

2.2.4 Spectrum Mobility

Spectrum mobility is the process where a cognitive radio user exchanges its frequency of operation. Spectrum mobility uses the spectrum in a dynamic manner by allowing the frequency radio terminals to operate in the best available frequency band. Seamless requirement communication requirements during the transition to better spectrum must be maintained (11).

Cognitive radio networks target to use the spectrum in a dynamic manner by allowing the radio terminals, known as the cognitive radio, to operate in the best available frequency band. This enables us to get the *best-available-channel* concept for communication purposes. To realize the concept, a cognitive radio has to capture the best available spectrum.

Multi-layer mobility management protocols are required to accomplish the spectrum mobility functionalities. These protocols support mobility management adaptive to different types of applications. For example, a TCP connection can be put to a wait state until the spectrum handoff is over. Moreover, since the TCP parameters will change after a spectrum handoff, it is essential to learn the new parameters and ensure that the transition from the old parameters to new parameters is carried out rapidly. For a data communication e.g., FTP, the mobility management protocols should implement mechanisms to store the packets that are transmitted during a spectrum handoff, whereas for a real-time application there is no need to store the packets as the stored packets, if delivered later, will be stale packets and cannot be used by the corresponding application (6).

Chapter 3 WRAN (802.22)

3.1 Introduction

IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) utilizing white spaces[4] in the TV frequency spectrum on a non-interference basis (15). The intent of this standard is to provide broadband access in rural and remote areas with performance comparable to DSL and cable modems. The television spectrum was selected for this application due to its propagation characteristics. Cognitive radios will reuse fallow TV spectrum in an opportunistic way by detecting if the channel is occupied before using it. Different approaches proposed:

- Centralized servers provide information on available channels in the area of access point (AP)
- Local spectrum sensing only, where the AP would decide which channels are available
- Combination of the previous approaches

Figure below will show us the range and speed expected for WRAN network, which is < 100 KM with speed ranges from 18-24 Mbps, that is compared by WAN, MAN, LAN or PAN providing the farthest range, however on the downside this network is has the slowest speed connection compared to other area network.

[4] In telecommunications, white spaces refer to frequencies allocated to a broadcasting service but not used locally. In the United States, it has gained prominence after the FCC ruled that unlicensed devices that can guarantee that they will not interfere with assigned broadcasts can use the empty white spaces in spectrum.

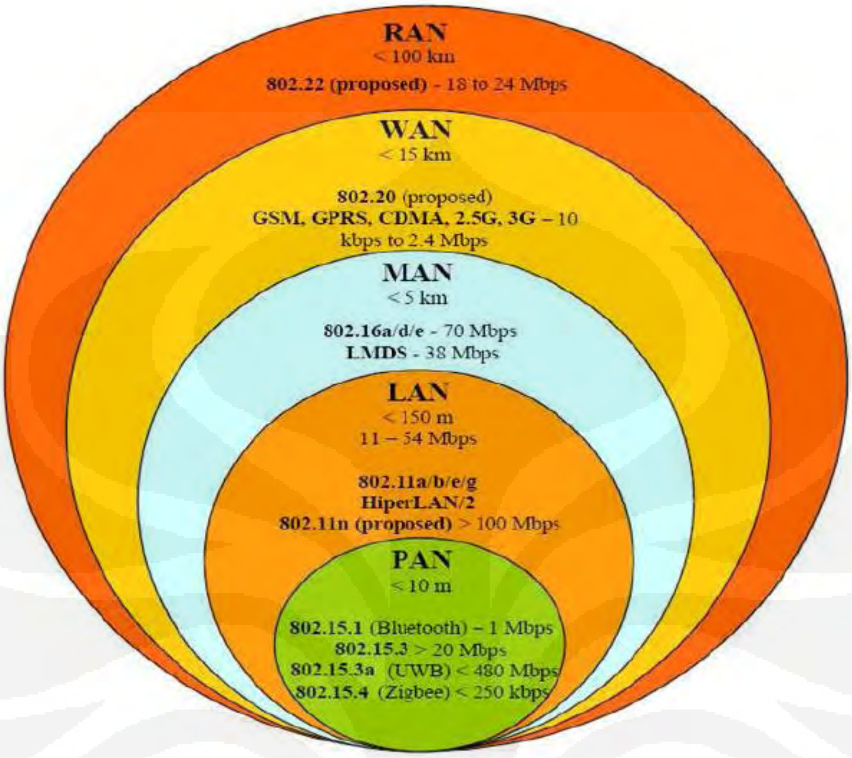

Figure 5 Area Network Ranges and Speed

3.2 802.22 Topology

The topology for the WRAN is a fixed point-to-multipoint[5] wireless air interface. Where the Base Station (BS) Manage its own cell and all associated Consumer Premise Equipment (CPEs[6]). Base Station is responsible of:

- Medium Access Control (MAC)
- Managing distributed sensing by instructing the CPEs to perform measurements of different channels
- Based on feedback, deciding which steps to take

[5] Point-to-multipoint communication is a term that is used in the telecommunications field which refers to communication which is accomplished via a specific and distinct type of multipoint connection, providing multiple paths from a single location to multiple locations

[6] Customer-premises equipment or customer-provided equipment (CPE) is any terminal and associated equipment located at a subscriber's premises and connected with a carrier's telecommunication channel(s) at certain point. CPE usually refers to telephones, DSL modems or cable modems, or purchased set-top boxes for use with Communications Service Providers' services

One key feature of the WRAN Base Stations is that they will be capable of performing a distributed sensing. This is that the CPE's will be sensing the spectrum and will be sending periodic reports to the BS informing it about what they sense. The BS, with the information gathered, will evaluate whether a change is necessary in the channel utilized, or on the contrary, if it should stay transmitting and receiving in the same one.

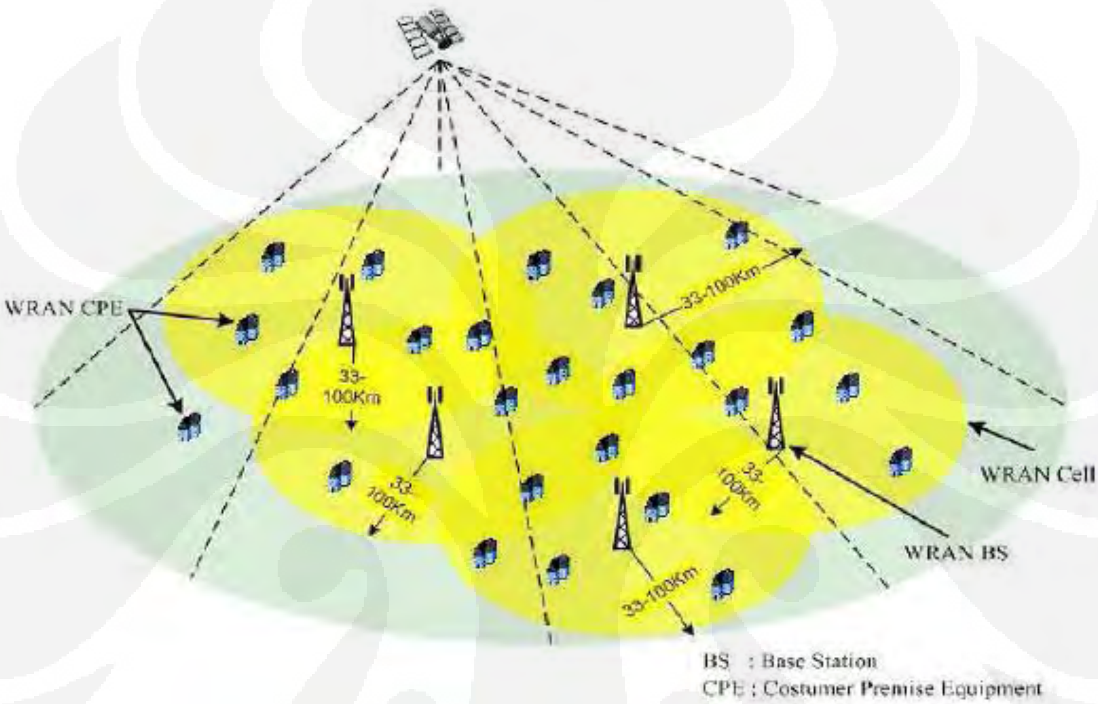

Figure 6 WRAN 802.22 Topology

3.3 802.22 PHY Layer

Physical (PHY) Layer must be able to:

Adapt to different conditions:

- Be flexible for jumping from channel to channel without errors in transmission or losing clients (CPEs)
- Dynamically adjust the bandwidth, modulation and coding schemes

Orthogonal Frequency-Division Multiple Access (OFDMA), a multi-user version of Orthogonal Frequency-Division Multiplexing (OFDM) digital modulation scheme, will be the modulation scheme for transmission in Uplink and Downlink. The approximate transmission by using just one TV channel is 19Mbit/s at a 30 km distance, and still not enough to fulfil the requirements of the standard. The feature Channel Bonding[7] deals with this problem. Channel Bonding consists in utilizing more than one channel for Tx / Rx. This allows the system to have higher bandwidth which will be reflected in a better system performance. In PHY Layer, channel bonding utilizes more than one channel allowing the system to have a larger bandwidth and higher throughput.

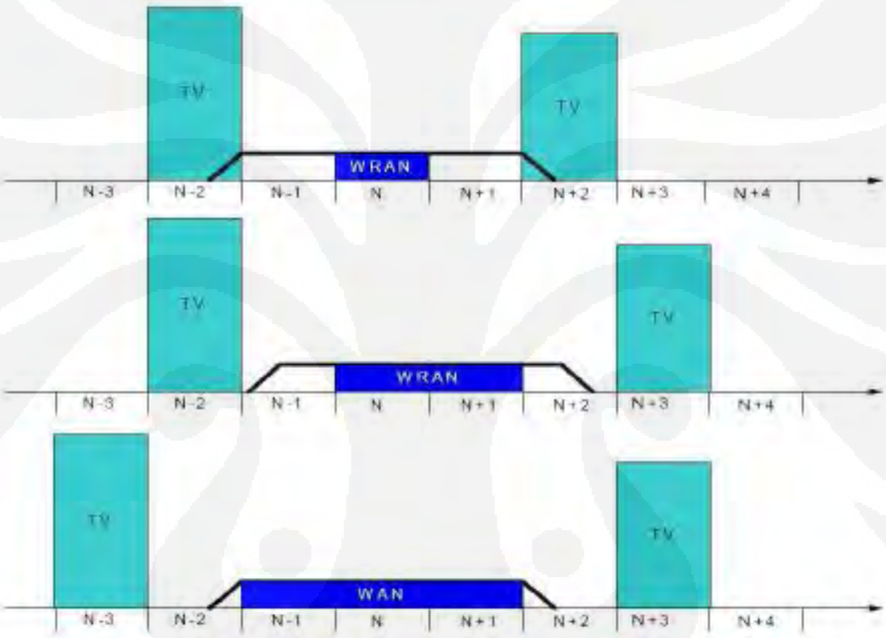

Figure 7 PHY layer channel bonding

3.4 802.22 MAC Layer

The MAC layer of WRAN is based on cognitive radio technology. The layer's is basically consists of two structures: Frame and Superframe. A Superframe will be formed by many frames. The

[7] **Channel bonding** (also known as "Ethernet bonding") is a computer networking arrangement in which two or more network interfaces on a host computer is combined for redundancy or increased throughput.

Superframe will have an SCH (Superframe Control Header) and a preamble. These will be sent by the BS in every channel that it's possible to transmit and not cause interference. When a CPE is turned on, it will sense the spectrum, find out which channels are available and will receive all the needed information to attach to the BS

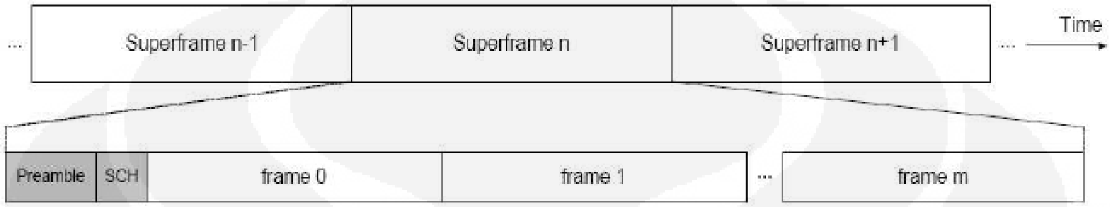

Figure 8 WRAN MAC layer

MAC Layer properties:

- No pre-determined channel (frequency, time) for CPE to look for BS
- At start-up CPE scans the TV Channels and build a spectrum occupancy map
- This information may be later sent to BS and is also used by the CPE to determine where to look for BS

MAC layer will perform sensing in either in-band or out-of-band measurements. These measurements are divided into:

- Fast sensing (under 1ms per channel)
- Fine sensing (about 25ms per channel) is done if the BS feels that more detailed sensing is needed

Figure 9 MAC layer fine and fast sensing

We will focus the fast sensing algorithm within the next chapter.

Chapter 4 Fast Spectrum Sensing Algorithm for 802.22 WRAN Systems

4.1 Related Works in 802.22 Standard

In the proposal (3), they suggested the two way stage sensing architecture as shown in figure 9. The procedure of the architecture is the followings. Use a wideband antenna and wideband RF front-end[8], the coarse detection based on energy detection schemes is first performed to select unoccupied candidate channel, and then one of the channels is examined by the fine/feature sensing to identify the incoming signal type and detect weak signals.

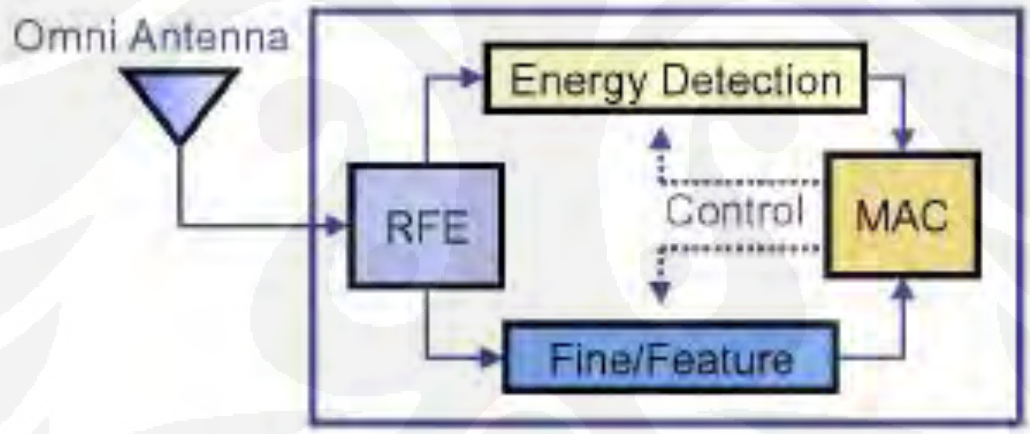

Figure 10 Two Stage Sensing Architecture

4.1.1 Energy Detection

Student suggested following schemes that can be used in 802.22 WRAN systems:

[8] RF front end (RFE) is a generic term for everything in a receiver that sits between the antenna and the intermediate frequency (IF) stage.

- Received Signal Strength Measurement (RSSI): it is the scheme that selects unoccupied candidate channels using received signal strength. One possible implementation is converting the energy in an interested band to the input signal strength, or
- Multi-Resolution Spectrum Sensing (MRSS): MRSS is the scheme which can sense an interested band in the analog domain using a wavelet transform that can be a basis of Fourier Transform. Since it is performed in the analog domain, spectrum sensing can be reduced.

Since the energy detection schemes are performed in the wide band and have to compare their results with a specific threshold, fast sensing and determination of the threshold are important parameters of the energy detection schemes.

4.1.2 Fine/feature Sensing

Signal feature sensing detection and cyclostationary feature detection are proposed in this sensing stage. Common disadvantage of these schemes is that we previously have to know the features of possible incoming signals. Student doesn't specifically explain about this scheme because our concern is in energy detection, fast sensing detection.

4.2 Wavelet Based Energy Detector

The energy detection schemes that can be used in IEEE 802.22 WRAN systems have to sense radio spectrums faster and determine the threshold. Thus, student suggests a possible energy detector for IEEE 802.22 WRAN systems using the discrete wavelet packet transform to alleviate these problems.

4.2.1 Power Measurement using Wavelet

Power measurements are explained in. If the received signal, *r(t)*, is a periodic signal T then, the power signal is computed by :

$$P = \frac{1}{T}\int_0^T r^2(t)dt \qquad (1)$$

Since *r(t)* can be represented as

$$r(t) = \sum_k c_{jo}, k\phi, k(t)(t) + \sum_{j \geq jo} \sum_k dj, k\psi, k(t) \qquad (2)$$

Where c_{jo}, k and dj, k are scaling coefficients and wavelet coefficient respectively. We can easily compute the power of received signal like following equation using orthogonal wavelet and scaling functions properties

$$P = \frac{1}{T}\int_0^T r^2(t)dt$$

$$= \frac{1}{T}\left[\int_0^T \left\{\sum_k c_{jo}, k\phi, k(t)(t) + \sum_{j \geq jo} \sum_k dj, k\psi, k(t)\right\}^2\right]$$

$$= \frac{1}{T}\left[\int_0^T \left\{\sum_k c_{jo}, k\phi, k(t)(t)\right\}^2 + \int_o^T \left\{\sum_{j \geq jo} \sum_k dj, k\psi, k(t)\right\}^2\right]$$

$$= \frac{1}{T}\left[\sum_k c_{jo,k}^2 + \sum_{j \geq jo} \sum_k dj, k\right] \qquad (3)$$

It means that the power of each sub band can be calculated using scaling and wavelet coefficients

4.2.2 Complexity of Wavelet analysis

Analysis of the number of mathematical operations, considering just multiplication, shows the complexity of the schemes. In discrete wavelet transform, there is *log2 N* level decomposition and only the output of low pass filter goes through the next operation. Therefore the complexity can be calculated as

$$Complexity = 2LN + 2\frac{LN}{2} + \ ... + 2LN/2^{(log2\,N-1)}$$

$$= 2LN\,(2^0 + 2^1 + \ ... + 2^{(log2\,N-1)}$$

$$= 4LN - 4L \qquad (4)$$

Where L is the length of high-pass and low-pass filters, if L<<N the complexity reaches 0(N). In the discrete wavelet packet transform, the outputs of high pass filter go through the next operation. This is the main difference between discrete wavelet transform and discrete wavelet packet transform.

4.2.3 The Algorithm Description

The discrete wavelet packet transform can separate the given frequency band into a low-frequency sub band and a high-frequency sub band. The proposed wavelet based energy detector is designed based on this fact and it maintains the two stage sensing architecture. Before commenting about the idea, student first assume that *Bi* and *Bc* are the interested frequency band (or scanning range) and the bandwidth of each channel respectively. Also, we assume that the ratio of between *Bi* and *Bc* is power of 2. The procedure of the idea, wavelet based energy detector, is shown in figure 11.

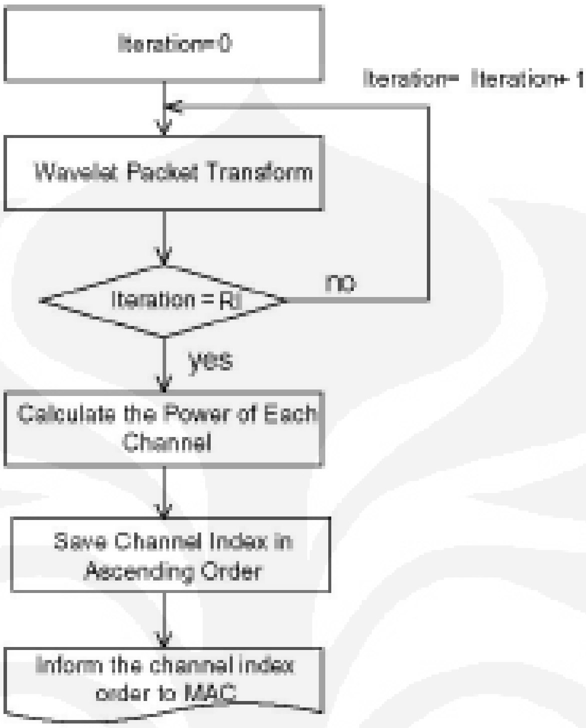

Figure 11 The flow chart of the wavelet based energy detector

The explanation of the flow chart:

1) Initialize the iteration parameter to zero.

2) Perform the 1-level discrete wavelet packet transform.

3) Compare the iteration parameter with *RI*. *RI* represents required iteration number of wavelet packet transform and is calculated by log2 (*Bi*). If the iteration parameter equals to RI, it goes to the next step. If not, the 1-level discrete wavelet packet transform is performed again with increasing iteration parameter by 1.

4) Compute the power of each channel.

5) Sort the channels in the ascending order based on the power of each channel.

6) Inform the order of sorted channel index to MAC to process the second sensing stage, fine/feature sensing.

4.2.4 The anticipated performance of the Algorithm

The proposed algorithm has two improvements for the energy detection schemes:

- It can easily select the unoccupied candidate channels without confirming whether channels are unused or not. This is accomplished by sorting the channels in the ascending order based on the power of each channel and it is rational due to the fact that the channel with low power has high probability due to be an unoccupied channel.
- Reducing complexity. Specifically, it performs the discrete wavelet packet transform not to the final level but to the RI level and its complexity becomes

$$Complexity = 2LN + \frac{2.2LN}{2} + \ldots . + 2.2^{(RI-1)} - 2^{(RI-1)}$$

$$= 2LN + 2LN + \cdots + 2LN$$

$$= 2LN \, . \, RI \qquad (5)$$

Where RI is the required iteration number of the discrete wavelet packet transform, *L* and *N* are the length of the wavelet filter and input signal respectively.

Chapter 5 Simulations and Result

In this section, we identify whether the proposed scheme senses primary (or licensed) users or not, and examine its whole procedure.

5.1 Simulation Environment

As shown in figure 12, the simulation environment is vertical sharing scenario. Specifically, there exist 3 primary users and 1 Customer Premise Equipment (CPE) that can sense the interested frequency band (or scanning range) for the secondary user. If we assume that each primary user's signal is sinusoid, the received signal at the CPE is numerically represented by

$$r(t) = a1 \sin(2\pi f1t) + a2 \sin(2\pi f2t) + a3 \sin(2\pi f3t) + n(t) \qquad (6)$$

Where *aj* and *fj* represent attenuation factor and canter frequency of each primary user's signal respectively, and *n(t)* is AWGN[9] with zero mean unit variance. Moreover we assume that each primary user uses different channel, the interested frequency band, *Bi*, is 1.6MHz and there are 16 channels in the frequency band, *Bi*.

[9] AWGN (Additive White Gaussian Noise) channel model is one in which the information is given a single impairment: a linear addition of wideband or white noise with a constant spectral density (expressed as watts per hertz of bandwidth) and a Gaussian distribution of noise samples

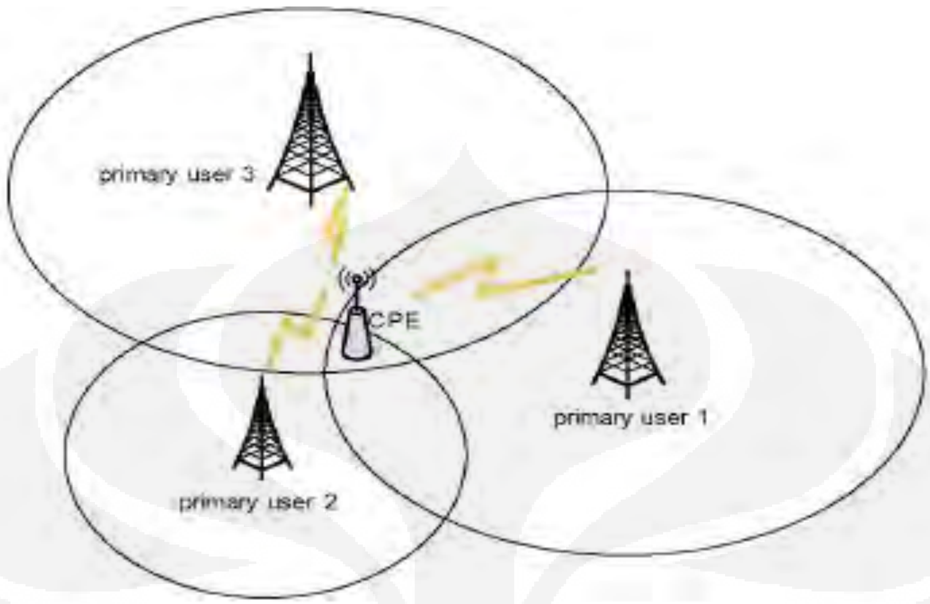

Figure 12 Simulation Environment Scenario

Fig 12 shows the procedure of separation of the interested frequency band based on the above simulation environments. Since there are 16 channels in Bi, B, is 100 KHz and 4-level discrete wavelet packet decompositions has to be performed. For simplicity we put indexes to channels in the ascending order. From this figure, we can infer that if a primary user's centre frequency exists in the frequency band 0 – 100 KHz, the power of the channel 1 has to be larger than other channels. "db20" wavelet is used in the simulation and fig 13 shows the magnitude characteristic of the wavelet filter.

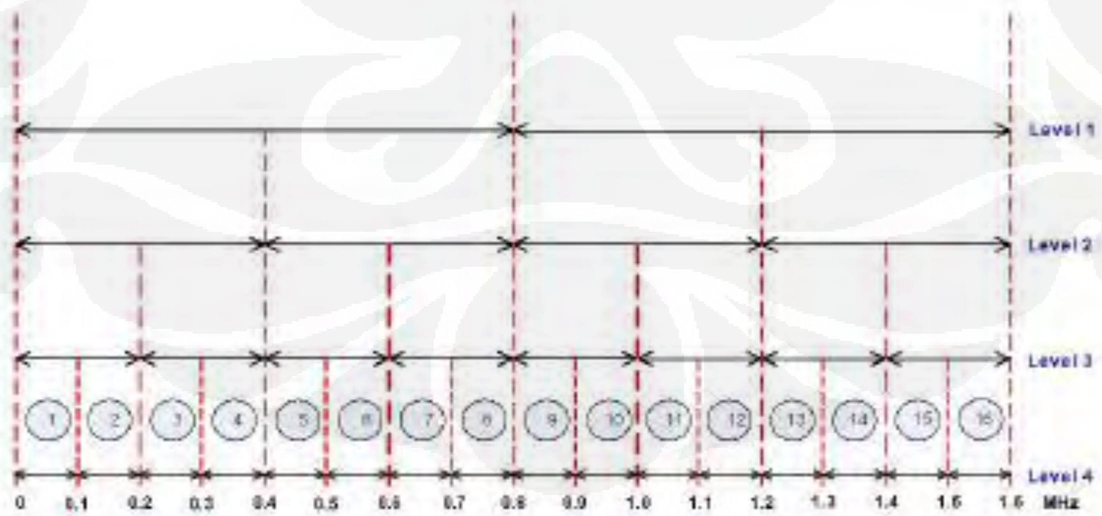

Figure 13 Separation of the interested frequency band using proposed scheme

5.2 Implementation of Algorithm in Matlab Codes

We can simulate the algorithm above with Matlab software by using the wpdec toolbox. Assuming that each primary user uses different channel, the interested frequency band, *Bi*, is 1.6MHz and there are 16 channels in the frequency band, *Bi*, the received signal at the CPE is numerically represented by the equation (6) with its attenuation factor for this example is 1 and canters frequencies are 200, 500 Hz for f1, f2 respectively, (student change the 3rd frequency, f3, with 600 Hz for yellow line, 900 Hz with red line and 1350 Hz with black line in order to notice the different in power for each channel) and the signal is AWGN with zero unit variance.

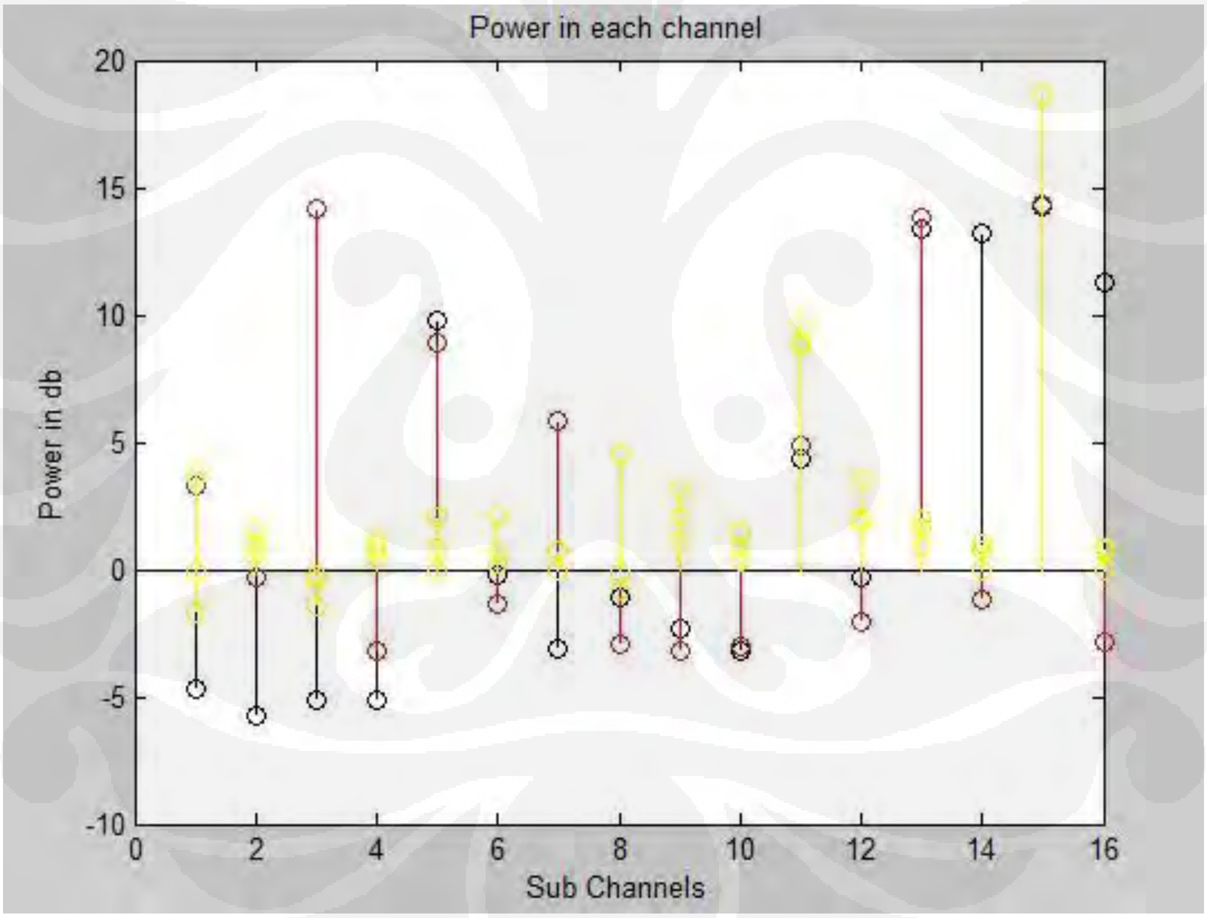

Figure 14 Power in each Channel by using Matlab

The 1-wavelet packet transform [10]is performed in the received signal to generate the figure above We can see that with the changes of frequency in f3, the power in each sub channel variates, according to the frequency. The tree decomposition showing how the method for Discrete Wavelet Transform works is shown in figure below.

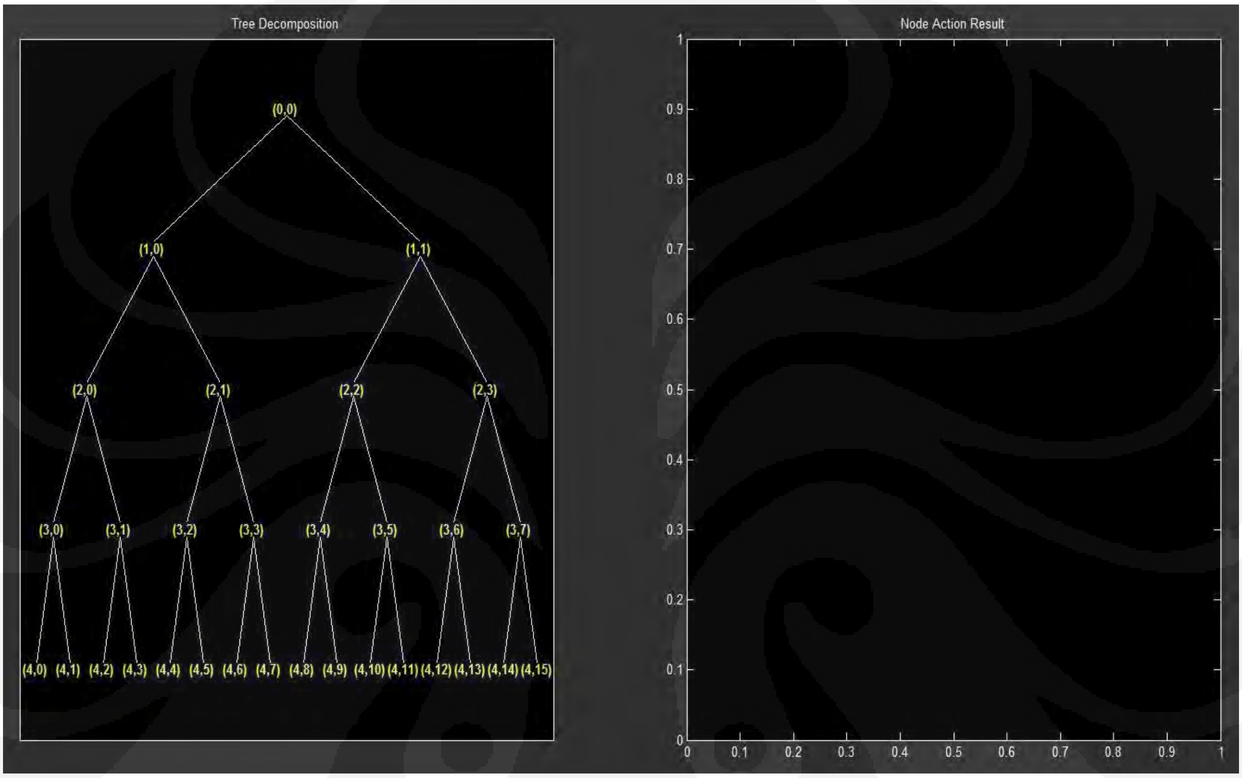

Figure 15 Tree Decomposition for Discrete Wavelet Transform

[10] The wavelet packet method is a generalization of wavelet decomposition that offers a richer signal analysis. Wavelet packet atoms are waveforms indexed by three naturally interpreted parameters: position and scale as in wavelet decomposition, and frequency.
For a given orthogonal wavelet function, a library of wavelet packets bases is generated. Each of these bases offers a particular way of coding signals, preserving global energy and reconstructing exact features. The wavelet packets can then be used for numerous expansions of a given signal.
Simple and efficient algorithms exist for both wavelet packets decomposition and optimal decomposition selection. Adaptive filtering algorithms with direct applications in optimal signal coding and data compression can then be produced.
In the orthogonal wavelet decomposition procedure, the generic step splits the approximation coefficients into two parts. After splitting we obtain a vector of approximation coefficients and a vector of detail coefficients, both at a coarser scale. The information lost between two successive approximations is captured in the detail coefficients. The next step consists in splitting the new approximation coefficient vector; successive details are never re-analysed.
In the corresponding wavelet packets situation, each detail coefficient vector is also decomposed into two parts using the same approach as in approximation vector splitting. This offers the richest analysis: the complete binary tree is produced in the one-dimensional case or a quaternary tree in the two-dimensional case.

5.3 Simulations for Test Cases using Matlab

The simulations in this paper consider two cases which are different with centre frequency and *SNR*.

1. Case 1: Centre frequencies of 3 primary users' signal and their SNR are fixed as *fi* = 250, *f2* = 650, *f3* = 1550 KHz and *SNR* = 0,-5.-10dB in this simulation. Since the centre frequencies are 250, 650, 1550KHz, we can anticipate the powers of channel 3, 7 and 16 are larger than other channels. Figure 16 shows the original received signal x(t).

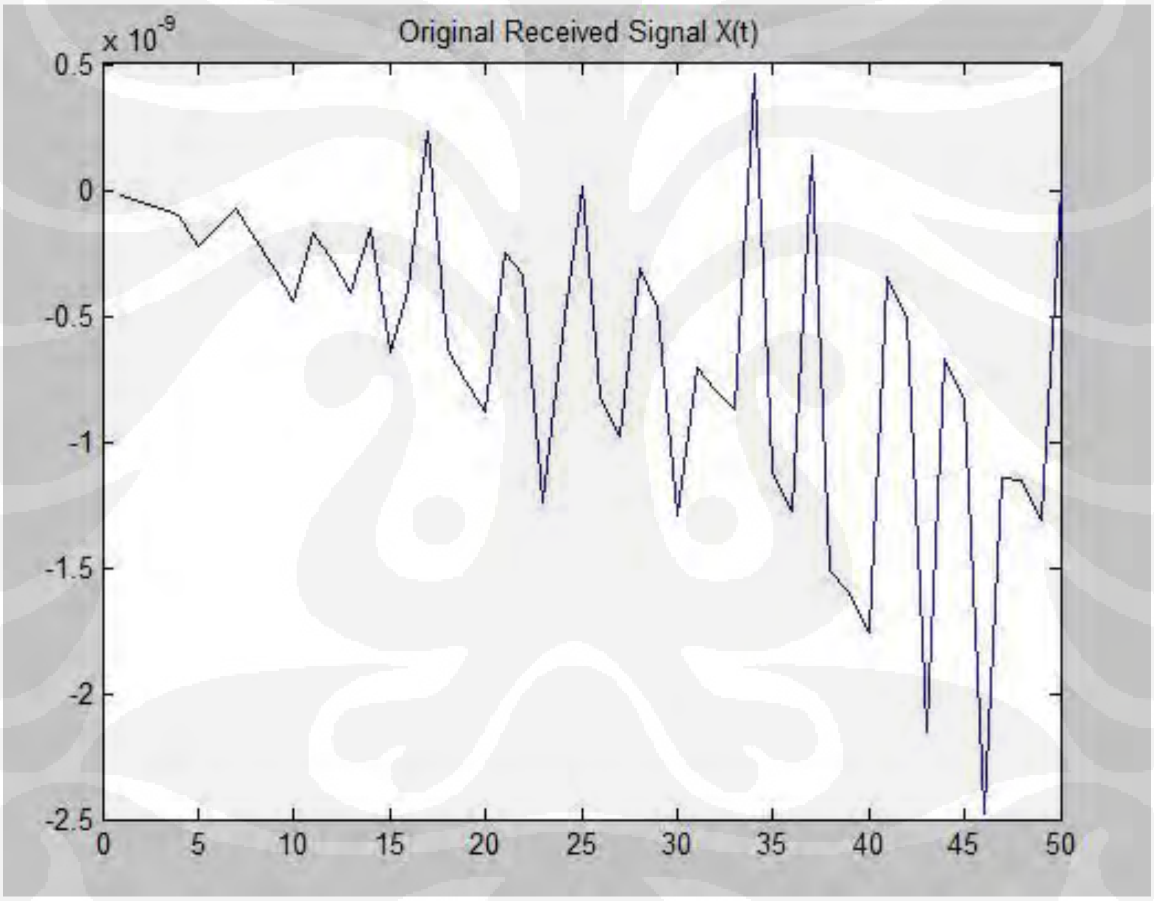

Figure 16 Original Received Signal x(t)

By applying the simulation using the 1-Level the Discrete Wavelet Transform in Matlab, we can see the power in 16 channels varies for each channel as shown figure 17

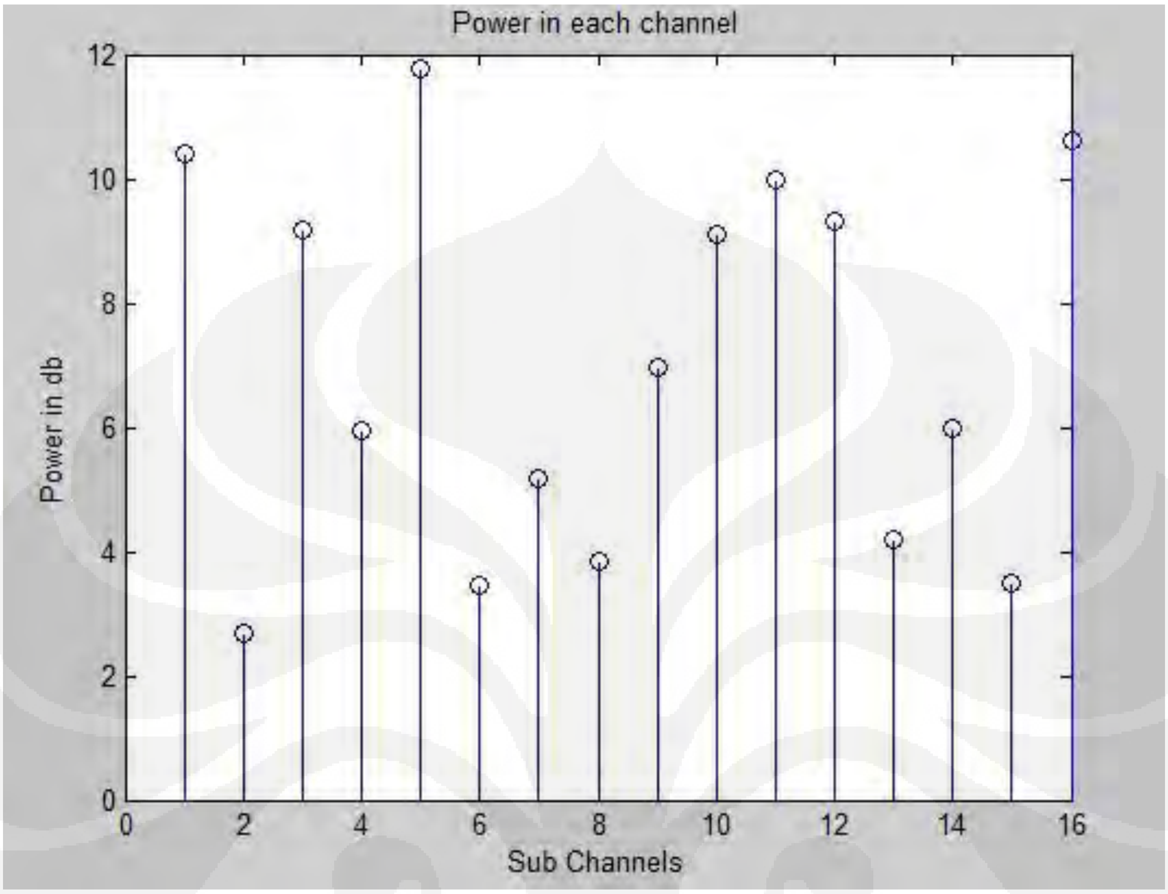

Figure 17 Power in each Channel

As shown in figure above channel 2 has the lowest power, meanwhile channel 5 has the highest power in dB, which means that there's high probability that channel 2 is not used whilst channel 5 is most likely to be used. We can see the sorted channel in figure 18 and the frequency response for the "dB20" Wavelet Filter in figure 19.

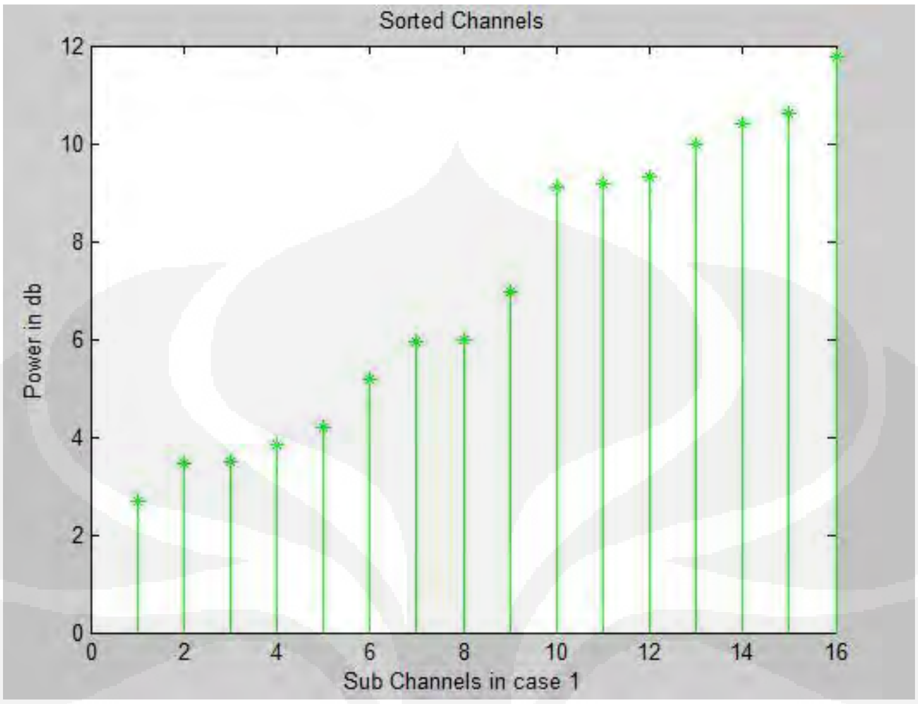

Figure 18 Sorted Channel for Test Case 1

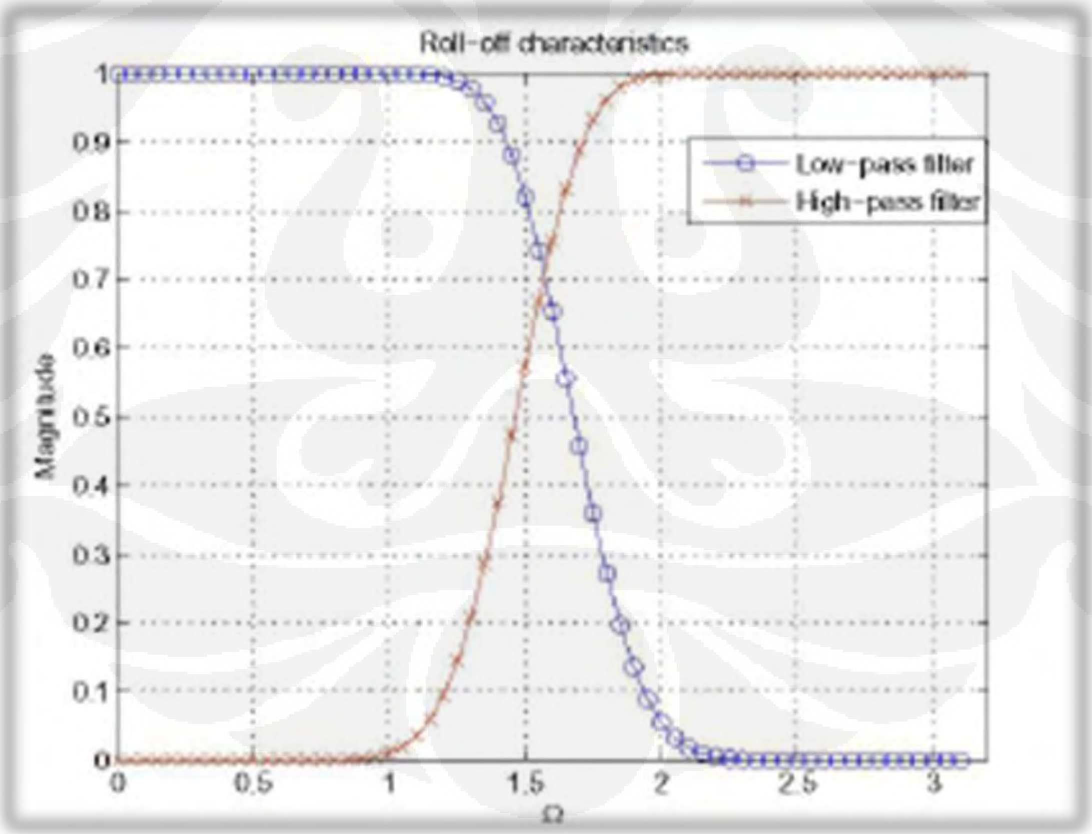

Figure 19 Frequency Response of the "dB20" Wavelet Filter

2. Case 2: Centre frequencies of 3 primary users signal and their *SNR* are fixed as *f1* = 50, *f2* = 950, *f3* = 1450 KHz and *SN*R = 0, 15, 20dB in this case. Since the centre frequencies are 50, 950, 1450KHz, we can anticipate the powers of channel 1, 10 and 15 are larger than other channels. In both cases, the final outputs, sorted channel indexes, are sent to the MIAC. This makes possible for the proposed scheme select the unoccupied channel candidates without confirming whether spectrums are unused or not. From above simulation results, furthermore, the proposed scheme is verified to identify the channels which primary users exist in. Since RI = 4 in these simulations, the complexity of the proposed scheme is 8LN using equation 5. Figure 20 shows the original received signal y(t).

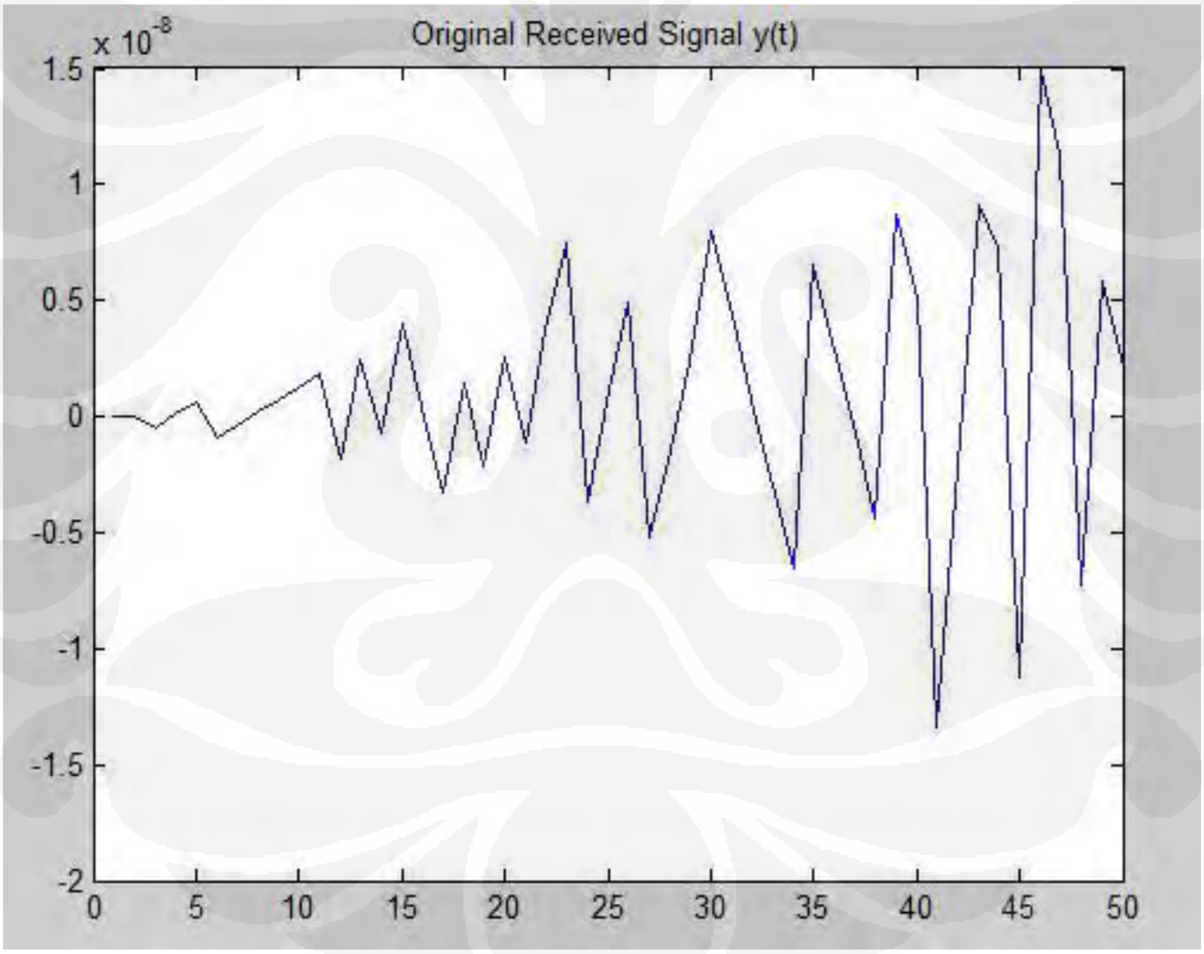

Figure 20 Original Received Signal y(t)

By applying the simulation using the 1-Level the Discrete Wavelet Transform in Matlab, we can see the power in 16 channel varies for each channel as shown figure 17

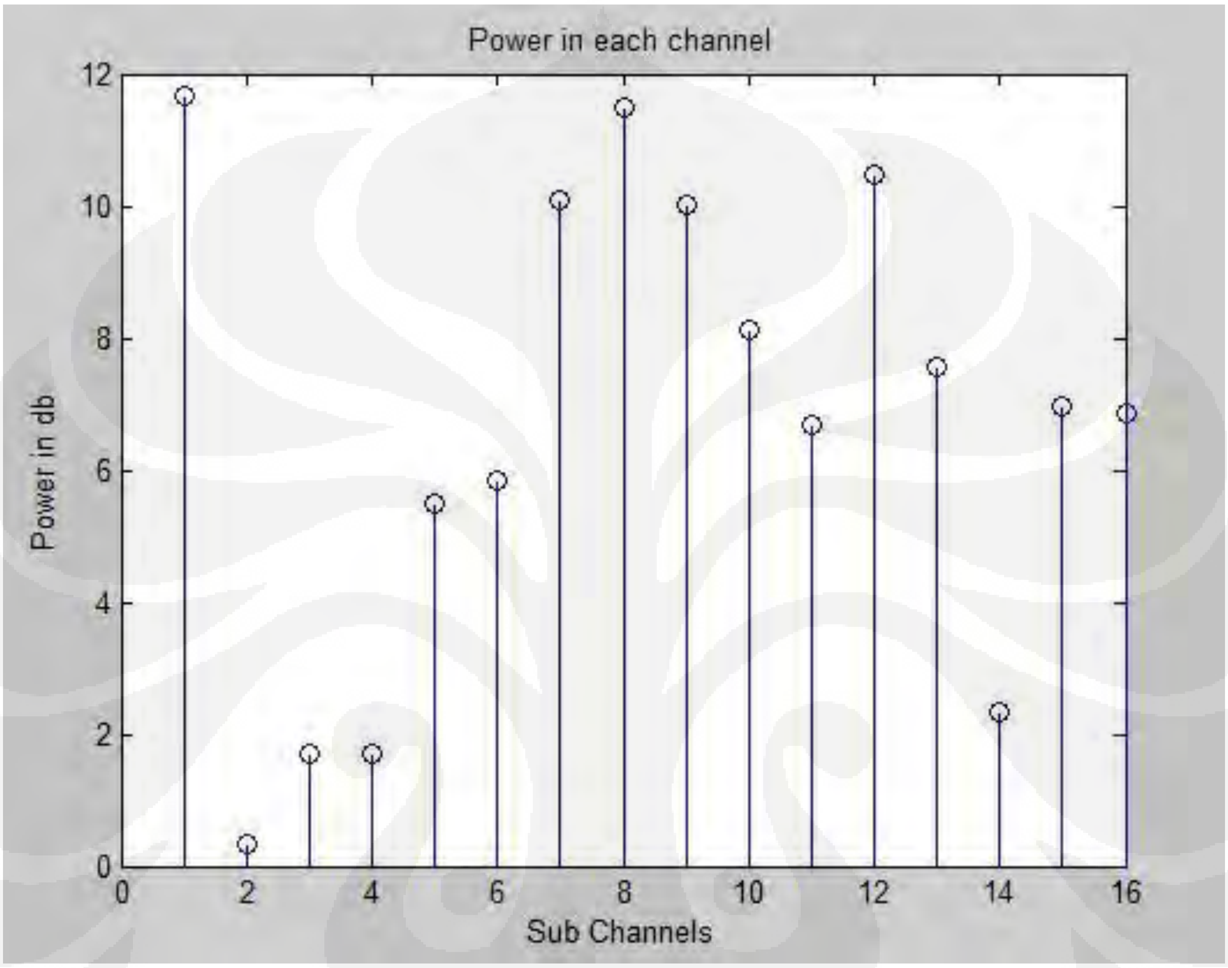

Figure 21 Power in each Channel

Since the centre frequencies are 50, 950, 1450KHz, we can anticipate the powers of channel 1, 10 and 15 are larger than other channels. In both cases, the final outputs, sorted channel indexes, are sent to the MIAC. This makes possible for the proposed scheme select the unoccupied channel candidates without confirming whether spectrums are unused or not. From above simulation results, furthermore, the proposed scheme is verified to identify the channels which primary users exist in. Since RI = 4 in these simulations, the complexity of the proposed scheme is 8LN using equation 5.

As shown in the figure above channel 2 has the lowest power, meanwhile as expected channel 1, 10 and 15 are larger than other channels, which means that there's high probability that channel 2 is not used by user whilst channel 1, 10 and 15 are larger than other channels and is most likely to be used. We can see the sorted channel in figure 22.

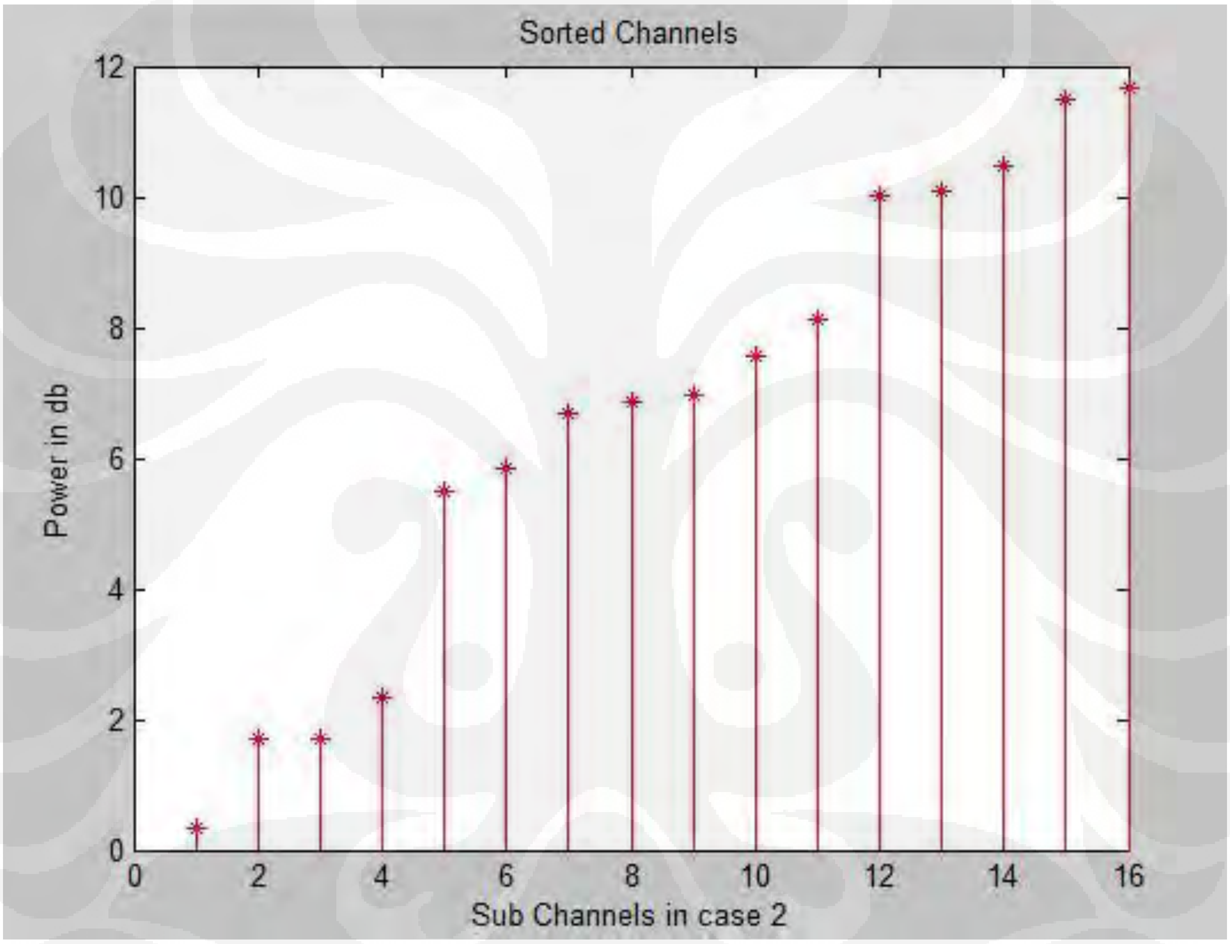

Figure 22 Sorted Channel for Case 2

Chapter 6 Summaries and Conclusion

The secondary spectrum has been issued because of improving spectra efficiency. In this context, IEEE 802.22 WG was organized in November 2004. Its critical technology is spectrum sensing not to interfere with licensed users. Thus, in this paper, we propose the fast spectrum sensing algorithm based on the discrete wavelet packet transform focusing on the coarse detection. Basically, since the proposed algorithm reduces complexity, it makes spectrum sensing faster. Furthermore, it is not necessary to confirm whether spectrums are unused or not because of the fundamental property of the proposed algorithm. Therefore, the proposed scheme can be an alternative energy detector of two stage spectrum sensing in IEEE 802.22 WRAN systems.

The proposed algorithm has two improvements for the energy detection schemes:

- It can easily select the unoccupied candidate channels without confirming whether channels are unused or not. This is accomplished by sorting the channels in the ascending order based on the power of each channel and it is rational due to the fact that the channel with low power has high probability due to be an unoccupied channel.
- Reducing complexity. Specifically, it performs the discrete wavelet packet transform not to the final level but to the RI level and its complexity becomes

$$Complexity = 2LN + \frac{2.2LN}{2} + \ ....+ 2.2^{(RI-1)} - 2^{(RI-1)}$$

$$= 2LN + 2LN + \cdots + 2LN$$

$$= 2LN \, . \, RI$$

Where RI is the required iteration number of the discrete wavelet packet transform, *L* and *N* are the length of the wavelet filter and input signal respectively.

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Appendix A Matlab Codes

1. Implementation of Algorithm for Wavelet Packet Transform

```
% *******************************************************************
% *****************Wavelet Packet Transform Algorithm*****************
% *******************************************************************

% Part of MAB 889-2 Final Year Project Report
% Queensland University of Technology, Brisbane, Australia.
% School of Engineering System
% Faculty of Built Environment and Engineering

% Created by Djaka Kesumanegara
% Student Number N6459188

clear
clc
Bi=1.6*10^6;
Bc=100*10^3;

% STEP 1: Initialize the iteration parameter to zero.
IP=0;

% STEP 2: Perform the 1-level discrete wavelet packet transform
% STEP 3: Compare the iteration parameter with RI. RI represents required
% iteration number of wavelet packet transform and is calculated by log2
% (Bi).If the iteration parameter equals to RI, it goes to the next step.
% If not, the 1-level discrete wavelet packet transform is performed again
% with increasing iteration parameter by 1.

% RI is the required iteration number
RI=log2(Bi/Bc);

% Attenuating Cooefficents
a1=0.01;
a2=0.05;
a3=0.025;
```

```matlab
% Frequencies for users
f1=200*10^3;
f2=700*10^3;
f3=1350*10^3;

syms 't';
t=1:50;
x(t)=a1*sin(2*pi*f1*t) + a2*sin(2*pi*f2*t) + a3*sin(2*pi*f3*t);

% Received Signal
r(t)=awgn(x,1);

% Wavelet Packet Transform Decomposition and comparison with RI (STEP 2&3)
if IP~=RI
  for i=1:RI;
    wpt = wpdec(r,IP+1,'db20','shannon');
    if IP==RI
      break;
    end
    IP=IP+1;
  end
end

% STEP 4 : Compute the power of each channel.
E = wenergy(wpt);
pdb = 10*log10(E);
stem(pdb)
c=pdb;
d=pdb;
n=length(pdb);
index=ones(1,n);
for i=1:n

  for j=1:n

    if(pdb(i) < c(j))
      pdb(i)=c(j);
      j;
      pdb(j)=c(i);
      c=pdb;

     end

  end

end
```

```
% STEP 5: Sort the channels in the ascending order based on the power of
% each channel.
% STEP 6 : Inform the order of sorted channel index to MAC to process the
% second sensing stage, fine/feature sensing.

m=0;
for k=1:1:16
   for l=1:16
   if( pdb(k)==d(l))
      m=m+1;
      index(m)=l;
   end
   end

end

% Plotting the Results
t=1:16;
subplot(1,1,1), plot(wpt)
subplot(1,1,1), stem(t,pdb,'b*'), xlabel('Sub Channels'), ylabel('Power in db'), title('Sorted Channels')
```

2. Simulation for Test Case 1

```
% ******************************************************************************
% *********************Simulation for Test Case 1*********************************
% ******************************************************************************

% Part of MAB 889-2 Final Year Project Report
% Queensland University of Technology, Brisbane, Australia.
% School of Engineering System
% Faculty of Built Environment and Engineering

% Created by Djaka Kesumanegara
% Student Number N6459188
clear
clc
Bi=1.6*10^6;
Bc=100*10^3;

IP=0;
syms 't';
t=1:50;

%RI is the required iteration number
RI=log2(Bi/Bc);

%Attenuating Cooefficents for case 1
a11=0.01;
a12=0.05;
a13=0.025;

%Frequencies for users in Case 1
f11=250*10^3;
f12=650*10^3;
f13=1550*10^3;

x(t)=a11*sin(2*pi*f11*t) + a12*sin(2*pi*f12*t) + a13*sin(2*pi*f13*t);

%Received Signal in case 1
r1(t)=awgn(x,0);

%Wavelet Packet Transform Decomposition and comparison with RI (Steps 1,2
and 3)
if IP~=RI
    for i=1:RI;
        wpt = wpdec(r1,IP+1,'db20','shannon');
        if IP==RI
            break;
        end
        IP=IP+1;
    end
end
```

```
%Power calculation of channels and sorting chanenls in ascending order on
%power measurement basis(Step4)
E1 = wenergy(wpt);
pdb1 = 10*log10(E1);
%stem(pdb1)
c=pdb1;
d=pdb1;
n=length(pdb1);
index1=ones(1,n);
for i=1:n

    for j=1:n

        if(pdb1(i) < c(j))
            pdb1(i)=c(j);
            pdb1(j)=c(i);
            c=pdb1;

         end

    end

end

%Channel Index (Steps 5 and 6)
m=0;
for k=1:1:16
    for l=1:16
    if( pdb1(k)==d(l))
        m=m+1;
        index1(m)=l;
    end
    end

end

%Plots
s=1:16;
subplot(1,1,1), plot(wpt)
subplot(1,1,1), stem(s,pdb1,'g*'), xlabel('Sub Channels in case 1'),
ylabel('Power in db'), title('Sorted Channels')
```

3. Simulation for Test Case 2

```
% ***********************************************************************
% *********************Simulation for Test Case 2**********************
% ***********************************************************************

% Part of MAB 889-2 Final Year Project Report
% Queensland University of Technology, Brisbane, Australia.
% School of Engineering System
% Faculty of Built Environment and Engineering

% Created by Djaka Kesumanegara
% Student Number N6459188clear

clear
clc
Bi=1.6*10^6;
Bc=100*10^3;

IP=0;
syms 't';
t=1:50;

%RI is the required iteration number
RI=log2(Bi/Bc);

%Attenuating Cooefficents for case 2
a21=1;
a22=0.5;
a23=0.25;

%Frequencies for users in Case 2
f21=50*10^3;
f22=950*10^3;
f23=1450*10^3;

y(t)=a21*sin(2*pi*f21*t) + a22*sin(2*pi*f22*t) + a23*sin(2*pi*f23*t);

%Received Signal in case 2
r2(t)=awgn(y,-15);

%Wavelet Packet Transform Decomposition and comparison with RI (Steps 1,2
and 3)
if IP~=RI
    for i=1:RI;
        T = wpdec(r2,IP+1,'db20','shannon');
        if IP==RI
            break;
        end
        IP=IP+1;
    end
```

```
end

%Power calculation of channels and sorting chanenls in ascending order on
%power measurement basis(Step4)
E2 = wenergy(T);
pdb2 = 10*log10(E2);
stem(pdb2)
e=pdb2;
f=pdb2;
n=length(pdb2);
index2=ones(1,n);
for i=1:n

    for j=1:n

        if(pdb2(i) < e(j))
            pdb2(i)=e(j);
            pdb2(j)=e(i);
            e=pdb2;

         end

    end

end
%Channel Index (Steps 5 and 6)
m=0;
for k=1:1:16
    for l=1:16
    if( pdb2(k)==f(l))
        m=m+1;
        index2(m)=l;
    end
    end

end

%Plots
s=1:16;
subplot(1,1,1), plot(T)
subplot(1,1,1), stem(s,pdb2,'r*'), xlabel('Sub Channels in case 2'),
ylabel('Power in db'), title('Sorted Channels')
```