平成27年度修士論文

Radio Environment Database considering Primary User Activity in Time Domain

プライマリユーザの時間的変化を考慮した電波環境データベース構築

学生番号	1431019
氏名	王 昊
情報・通信工学専攻	情報通信システムコース
主指導教員	藤井 威生 教授
指導教員	山尾 泰 教授
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専攻主任印	主指導教員印	指導教員印

修 士 論 文 の 和 文 要 旨

研究科・専攻	大学院　情報理工学研究科　情報・通信工学専攻　博士前期課程		
氏　　　名	王 昊	学籍番号	1431019
論 文 題 目	Radio Environment Database considering Primary User Activity in Time Domain		

要 旨

近年，周波数の枯渇問題を解消するための抜本的な対策として，周波数共用におけるコグニティブ無線技術が活発に研究を行われている．コグニティブ無線を用いた周波数共用において，周波数の二次利用者 (SU: Secondary User) は既存の周波数割り当てユーザ (PU: Primary User) への干渉を回避する必要がある．その中で自身の通信品質を確保するためには，正確な電波環境推定技術が重要である．従来研究では，本研究室がこれまで車載無線機やスマートフォンといった移動端末が観測した膨大な電波環境情報から構築される実測値に基づく電波環境データベースを提案してきた．テレビ帯域を対象とした実証実験により，従来の距離減衰モデルに基づく手法と比較して PU の平均受信電力値の空間的な分布を精度良く推定できることを明らかにしている．しかし，これまでは PU の通信状態の ON/OFF 遷移を考慮せずに観測値を一意に平均化していた．そのため，無線 LAN やセルラ通信のように観測期間内に状態遷移する可能性のあるシステムについては，最終的な平均結果と ON 状態の平均受信電力値に差が生じる恐れがあった．そこで本研究では，観測期間内に PU の通信状態が時間的に遷移する場合の電波環境データベースの構築における精度について検討を行う．1 回の観測期間内での受信電力に関する分布変化を検出することにより，PU の通信状態の遷移点を検出するアルゴリズムを提案する．その分布の変化検出に CUSUM アルゴリズムと GLR アルゴリズムが用いられ，２つの分布の累積対数尤度比の変化傾向から遷移点の検出が可能となる．検出した遷移点を用いて，通信を行なっている状態のみの有効期間から受信電力値の取り出しが可能となり，PU が通信を行なっている状態での平均受信信号電力値を精度良く推定できる．本研究では特に，状態遷移の検出性能及び受信電力値の推定性能に焦点を当てたシミュレーション評価を行ない，その有効性を示す．シミュレーションにより，提案手法を用いることで遷移点が精度よく検出され，受信電力値の推定誤差が状態遷移が考慮されていない従来手法より抑えることが可能である．

和文概要

近年，周波数の枯渇問題を解消するための抜本的な対策として，周波数共用におけるコグニティブ無線技術が活発に研究を行われている．コグニティブ無線を用いた周波数共用において，周波数の二次利用者 (SU: Secondary User) は既存の周波数割り当てユーザ (PU: Primary User) への干渉を回避する必要がある．その中で自身の通信品質を確保するためには，正確な電波環境推定技術が重要である．従来研究では，本研究室がこれまで車載無線機やスマートフォンといった移動端末が観測した膨大な電波環境情報から構築される実測値に基づく電波環境データベースを提案してきた．テレビ帯域を対象とした実証実験により，従来の距離減衰モデルに基づく手法と比較して PU の平均受信電力値の空間的な分布を精度良く推定できることを明らかにしている．しかし，これまでは PU の通信状態の ON/OFF 遷移を考慮せずに観測値を一意に平均化していた．そのため，無線 LAN やセルラ通信のように観測期間内に状態遷移する可能性のあるシステムについては，最終的な平均結果と ON 状態の平均受信電力値に差が生じる恐れがあった．そこで本研究では，観測期間内に PU の通信状態が時間的に遷移する場合の電波環境データベースの構築における精度について検討を行う．1 回の観測期間内での受信電力に関する分布変化を検出することにより，PU の通信状態の遷移点を検出するアルゴリズムを提案する．その分布の変化検出に CUSUM アルゴリズムと GLR アルゴリズムとピーク検出が用いられ，2 つの分布の累積対数確率密度比の変化傾向から遷移点の検出が可能となる．検出した遷移点を用いて，通信を行なっている状態のみの有効期間から受信電力値の取り出しが可能となり，PU が通信を行なっている状態での平均受信信号電力値を精度良く推定できる．本研究では特に，状態遷移の検出性能及び受信電力値の推定性能に焦点を当てたシミュレーション評価を行ない，その有効性を示す．シミュレーションにより，提案手法を用いることで遷移点が精度よく検出され，受信電力値の推定誤差が状態遷移が考慮されていない従来手法より抑えることが可能である．

Abstract

Recently, with the fast development of wireless communication technology, cognitive radio (CR) has been recognized as a promising solution to address the problem of impending spectrum scarity for improving the utilization of spectrum for various wireless applications. In a CR system, it allows the Secondary Users (SUs) to opportunistically utilize the temporal and/or spatial unused spectrum holes without harmful interference to Primary Users (PUs). While SUs can occupy avaliable spectrum holes as long as the corresponding PU is in active, they must immediately evacuate the band as soon as the corresponding PU appears. One of the main chanllenges is to intelligently determine ongoing PU activity to avoid interferece toward PU. SUs can evacuate the band without affecting PU 's activity and opportunistically access the spectrum to maximize the spectrum usage if the information about PU can be obtained in advance. Hence, more information about PU leads to more effective spectrum usage for SUs, and an external device for provding information of PU is necessary. In conventional database construction method, the activity of primary user is considered to be always ON when the sensor uses the spectrum sensing to calculate the received power at each place. However, a state transition may occur during the sensing period, which leads to a reliability degradation of the RED. In this thesis, an active period detection method of primary signal is proposed. In this method, transition point detection is used to detect a distribution change between ON and OFF state with applying CUSUM (cumulative sum) algorithm, GLR (Generalized Likelihood Ratio) algorithm and Peak Detection, which the cumulative sum of log probability density ratio value is calculated to detect the change between two different distribution. Then an active period is extracted by using the detected transition point. In this thesis, we focus on the transition point detection performance and received power detction performance. From simulation results, the transition point is well detected and the estimated received power is more accurate than the one using the conventional method.

Contents

Chapter 1

Introduction

In chapter 1, present spectrum scarcity problem as the background of this thesis and technology proposed for solution is described. Aslo, the overview of this thesis and purpose is described.

1.1 Background

Due to the rapid development of wireless communication systems, a demand on sprectrum resource for communication has increased explosively. Because the data rate and perfomance of the wireless communication system, such as mobile phone, are improved, it leads to a serious sprectrum scarcity problem.

From Fig. 1.1, reference [1] predicts that Global mobile data traffic will increase nearly tenfold between 2014 and 2019 and mobile data traffic will grow at a compound annual growth rate (CAGR) of 57 percent from 2014 to 2019, reaching 24.3 exabytes per month by 2019. In addition to the increasement of the data traffic, a fixed resource allocation method as the current spectrum allocation policy, which is utilized for avoiding harmful interference toward licensed systems with each other, is also considered as a major reason for the scarcity of the spectrum resource. As a reason, almost linear increasing demand on necessary bandwidth for communication leads to a difficult allocation for new systems. From Fig. 1.2 reported from Ministry of Internal Affairs and Communications(MIC) in Japan government [5], it is shown that most of the spectrum resources has already been allocated. Thus, the lack of spectrum resources has become a serious problem.

Since the finite spectrum resources are not able to fulfill the expoential growth of demand on traffic, it is necessary to review the present spectrum policy with fixed resource allocation for the next generation wireless communication sysytems and a effecient spectrum utilization turns to be a key problem.

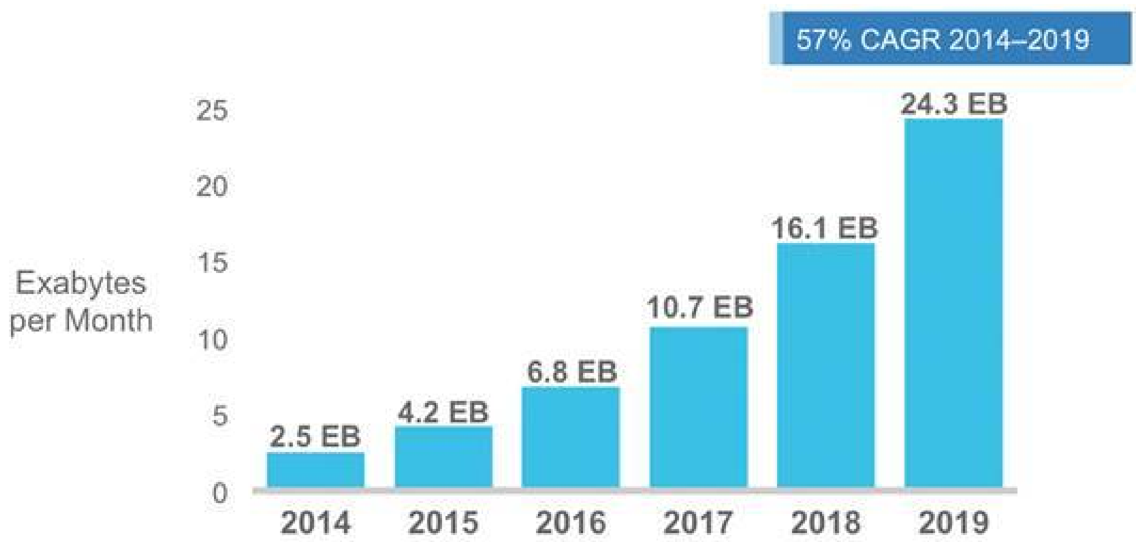

Figure 1.1: Cisco Forecasts 24.3 Exabytes per Month of Mobile Data Traffic by 2019

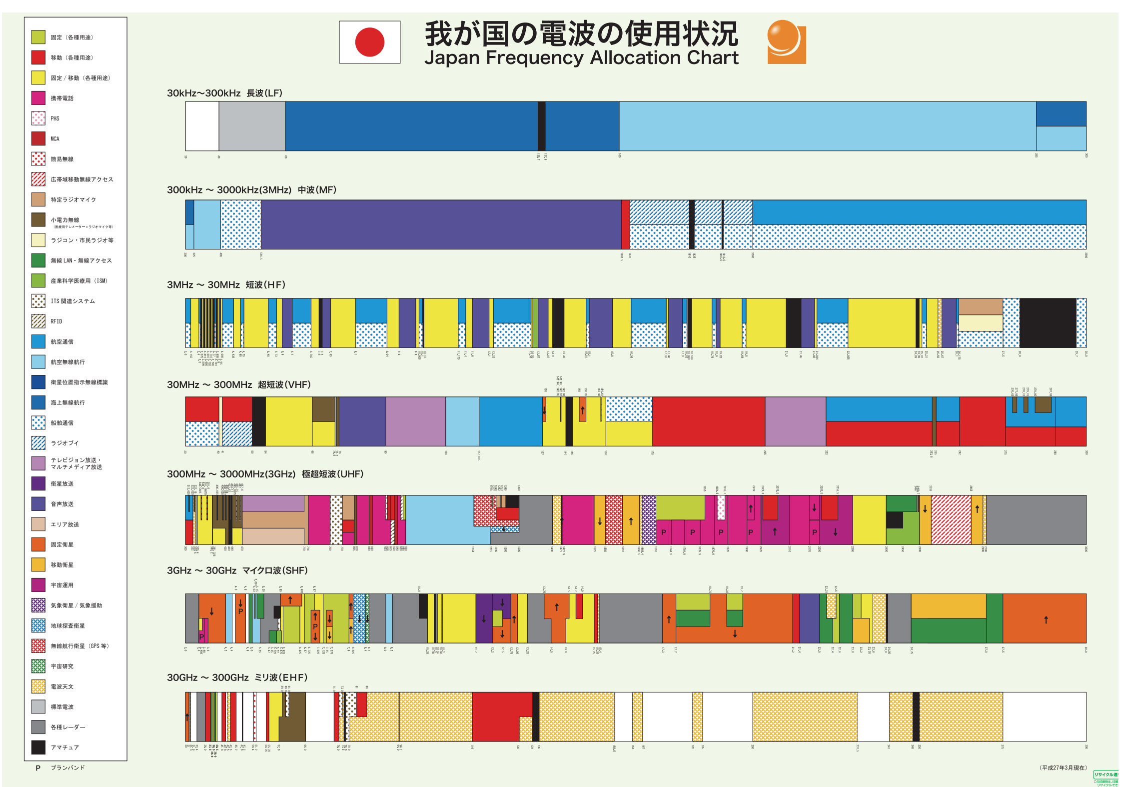

Figure 1.2: Japanese Frequency Allocation Chart.

There are 2 main methods to ensure the bandwidth for new systems. Firstly, a spectrum arrangement on the whole wireless communication systems is utilized to extend available bandwidth. In 2011, an arrangement on television broadcasting is executed with switching to digital television broadcasing. However, it is not available for supporting the expoential growth of the data traffic and the number of systems. Second, an efficient and dynamic utilization method of bandwidth is considered to extend the probability for the future wireless communication systems, which is attracted attention as effective solution to the shortage of spectrum resources.

According to the report [2] from Federal Communications Commission(FCC), actual spectrum usage on the licensed band is lack of balance in both temporal and spatial domain and instantaneous usage efficiency remains at 15%〜80% even under crowd environment, such as urban areas, which means that an unused White Space(WS) exists even under temporal and spatial varying envrionment. However, it is not allowed to utilize White Space by other licensed or unlicensed systems based on current radio regulations.

1.2 Spectrum Sharing Trend and Problem

Cognitive Radio(CR) [4] has been recognized as a promising solution to address the problem for improving the utilizetion of spectrum for various wireless applications. In a CR system from Fig.1.3 and 1.4, it allows the Secondary Users (SUs) to opportunistically utilize the temporal and/or spatial unused spectrum holes without causing interference to Primary Users (PUs). While SUs can occupy avaliable spectrum holes as long as the corresponding PU is inactive, they must immediately evacuate the band as soon as the corresponding PU appears.

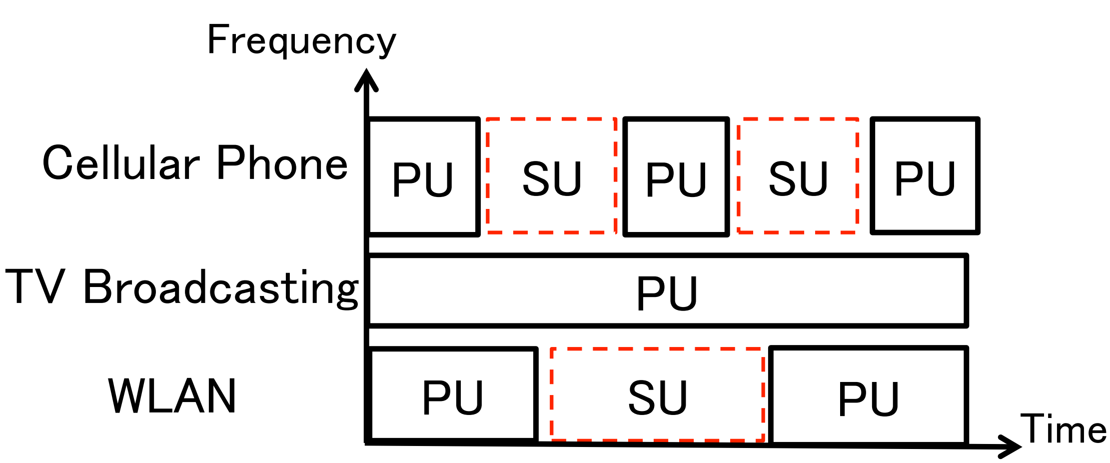

Figure 1.3: Coexsitance between PU and SU in time domain.

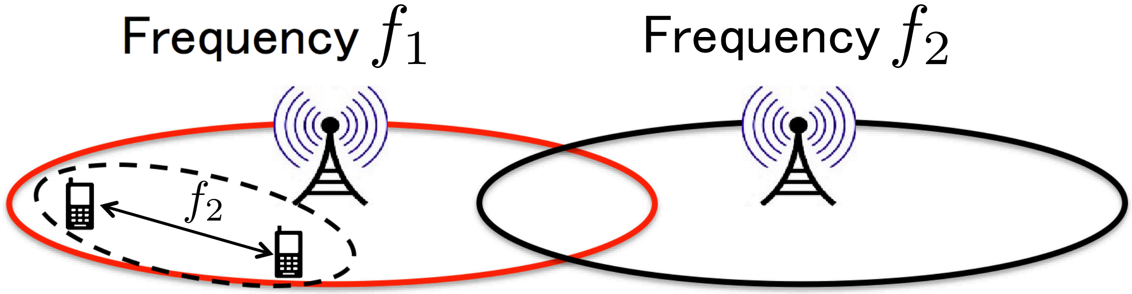

Figure 1.4: Coexsitance between PU and SU in space domain.

One of the main chanllenges is to intelligently determine ongoing PU activity to avoid interferece toward PU. SUs can evacuate the band without affecting PU 's activity and opportunistically access the spectrum to maximize the spectrum usage if the information about PU can be obtained in advance. Hence, more information about PU leads to more effective spectrum usage for SUs, and an external device for provding information of PU is necessary. One of the main chanllenges is to intelligently determine ongoing PU activity to avoid interferece toward PU. SUs can evacuate the band without affecting activity of PU and opportunistically access the spectrum to maximize the spectrum usage if the information about PU can be obtained in advance. Hence, more information about PU leads to more effective spectrum usage for SUs, and an external device for providing information of PU is necessary. However, it is difficult for SU to obtain the information about activity of PU individually according to the position of SU and it may leads a performation degradation on PU protection.

The idea of Spectrum Database has been studied for assisting SUs to effectively reuse the spectrum. SUs can access the database to obtain the surrounding radio environment information and optimize their own parameters, such as modulation, transmitting power and so on. Federal Comminication Committee (FCC) has been considered a propagation model-based spectrum database to provide the spectrum available information whether the spectrum locating SU can be used or not [3]. The model-based database has to set a large margin to avoid interference to PU because the realistic radio environment with considering the effect of surrounding obstacles cannot be considered. Therefore, there is a limit to improve the spectrum utilization efficiency.

Authors in [6] proposed a measurement-based spectrum database as a realistic method. The measurement-based database generates the database information by gathering the measuring received power at SUs, which are inactive for communication. Then the real radio propagation situation can be known and more accurate information at SU location can be provided. Then, SUs access to the database with their own location information and download the responding average received signal power at the SU location as shown in Fig.1.5.

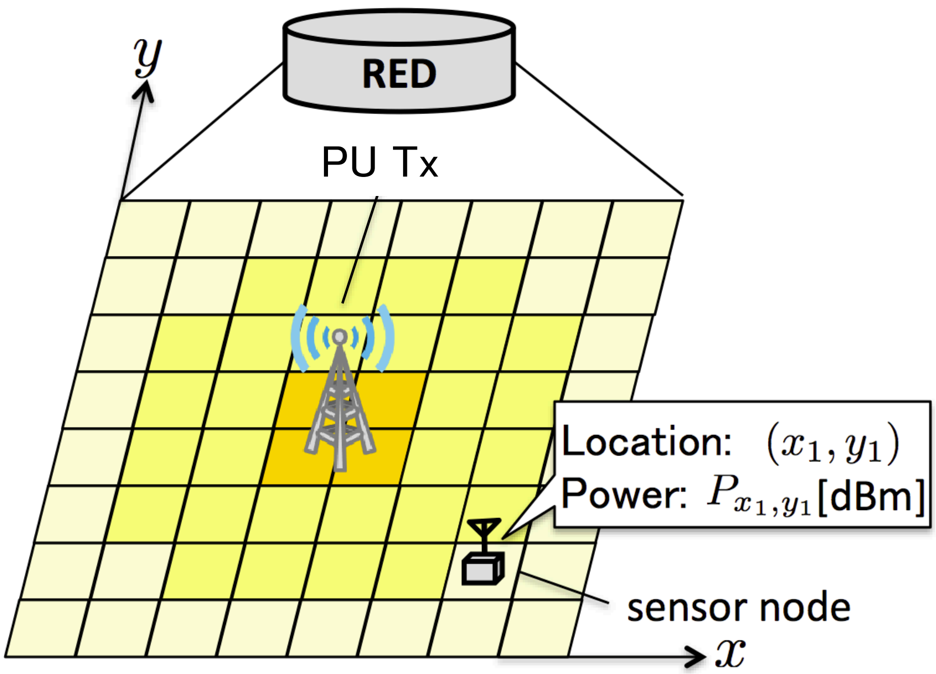

Figure 1.5: Measurement-based Spectrum Database.

The database is constructed by using reported measurement results of averaged sampling value in each sensor node like energy detection spectrum sensing algorithm to calculate the average received signal power at each location. However, it is only appropriate under the assumption that the PU status is always ON. For example, in [7] [8], the channel scenario is not considering primary user traffic during the sensing period. If there is a state transition from ON to OFF, sensor node will report the wrong received signal power to the database, which leads to low reliability and performance. Thus, it is necessary to detect PU 's state transition and extract the ON part only to the database to improve the reliability of database. In [9], single status change of primary user is focused.

1.3 Purpose

In this thesis, we focus on a distribution transition between the ON status and OFF status, CUSUM (cumulative sum) algorithm [16] and GLR (Generalized Likelihood Ratio) algorithm [17] are used to detect the rise up point and rise down point, which is status change point from OFF to ON and ON to OFF. Finally, only ON power can be extracted with using the detected transition point and the sensing error reduction is possible.

The remainder of this thesis is organized as follows. The overview of Cognitive Radio and Spctrum Sharing with Spectrum Database is introduced in Chapter 2. In Chapter 3 the basic sensing method for calculating the reported information is presented as a measurement-based spcetrum database construction metrics and the problem of Spectrum database construction is described in detail. Chapter 4 proposes the active period detection method of primary signal for spectrum database in detail and the simulation results and performance evaluation are discussed in Chapter 5. Finally, Chapter 6 concludes the thesis.

Chapter 2

Cognitive Radio

In Chapter 2, cognitive radio technology for spectrum sharing is described in detail. Also, as one of the applied technology, spectrum sharing with spectrum database is discussed.

2.1 Overview of Cognitive Radio

Cognitive Radio(CR) is defined as the technology that wireless communication devices are able to be aware of the surrounding environment and configure communication parameters autonomously. Frequency in use, Modulation method, Transmission power all can be treated as communication paramters. Because the adaptive parameter configuration can make an effective usage on White Space possible, it is expected as a solution to the shortage of the spectrum resources.

As a process for Secondary User communication, a series of algorithm named as Cognitive Cycle [3] is proposed by J.Mitola Ⅲ in 1999. With observing Outside World, Secondary User can obtain various informaiton. Next, after analysis is executed based on information from observation, results are oriented by priority and process is carried out depending on the determined oriented result. If the status has to be responded instantaneously, the appropriate Act needs to be reacted immediately with using the information obtained. For example, when the status of Primary User changes to ON, Secondary User has to stop transmission immediately. Otherwise, in the case that an urgent status exists, an act needs to be determined based on the information. As an example, when Secondary User has an effect on primary signal with huge interfernce power, it is necessary to move to the phase which is stopping transmission or lower the interferece power. If the priority is Normal, an optimised Plan is determined with a long-term observation. While the radio environment changes, the obversation will be observered again. At the end, the Cognitive Cycle is possible based on the process below.

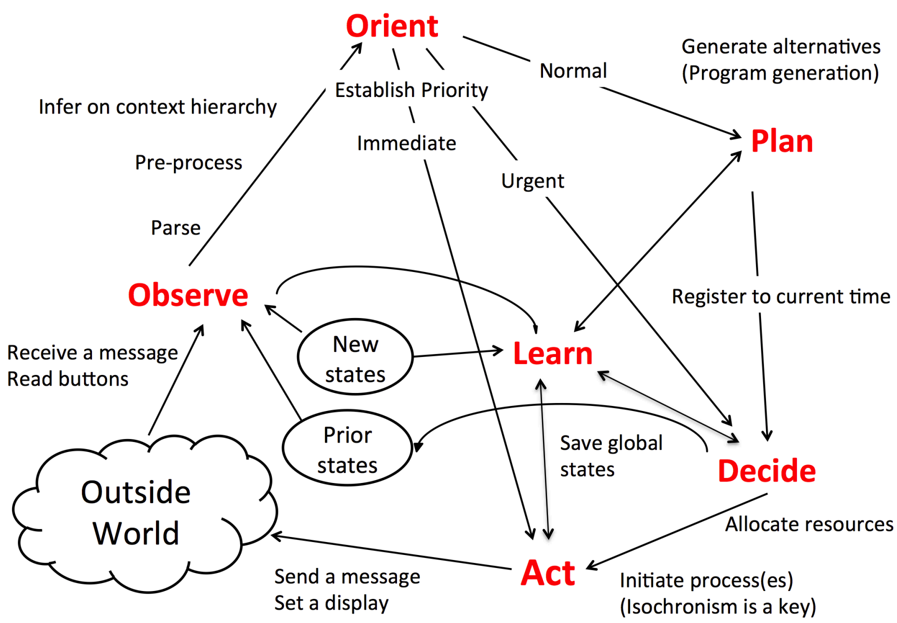

Figure 2.1: Cognitive Cycle.

The protection of Primary transmission is related to the observation and determination. The signal from Primary User, the own location information from Global Position System(GPS), and the sensing infromation from other nodes can be treated as the observation data. Next, the determination process is optimally executed according to the observation data. Whether the Primary User existence can be determined accurately plays an key role to the cognitive radio sysytems.

In this thesis, we focus on the observe and Orient process in the cognitive cycle for our proposed method.

2.2 Multi-mode System

Cognitive Radio technology which is researched actively is roughly divided into two tpyes: Multi-mode System and Dynamic Spectrum Access. In Multi-mode System as illustrated in Fig. 2.2, Secondary User is allowed to detect the temporally and spatially unused licensed band and utilize the spectrum with same behavior as Primary User. If the Quality of Service(QoS) is not able to be achieved from the certain spectrum band, Secondary User switches to another spectrum. While Multimode system is realized as a easier method than Dynamic Spectrum Access with the reason that the communication method has already been established, the spectrum usage efficiency is not remarkable due to the upper limitation on the communication scheme of Primary User.

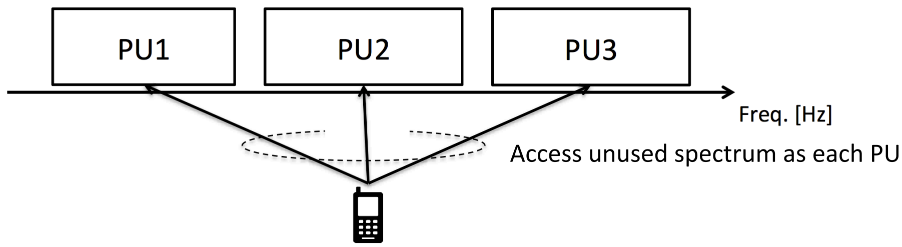

Figure 2.2: Multi-mode System.

2.3 Dynamic Spectrum Access for Spectrum Sharing

As Dynamic Spectrum Access is possible for more flexible spectrum utilization, huge spectrum usage efficency improvement In the Dynamic Spectrum Access, Secondary Users are able to detect the spectrum and access to it with lower priority than Primary User of that spectrum. As a constraint, harmful interference toward Primary User is not allowed. The method about how to access to the spectrum is composed of two types, which is defined as Overlay Spectrum Sharing [10] and Underlay Spectrum Sharing [11].

2.3.1 Overlay Spectrum Sharing

As illustrated in Fig.2.3, Unused White Space is utilized for communication in Overlay Spectrum Sharing. If the existence of Primary User in this spectrum is accurately detected by Secondary User, the protection of Primary User will be possible and the opportunity for Secondary User can be gained. In other words, the detection method on Primary User is the way to achieve Overlay Spectrum Sharing.

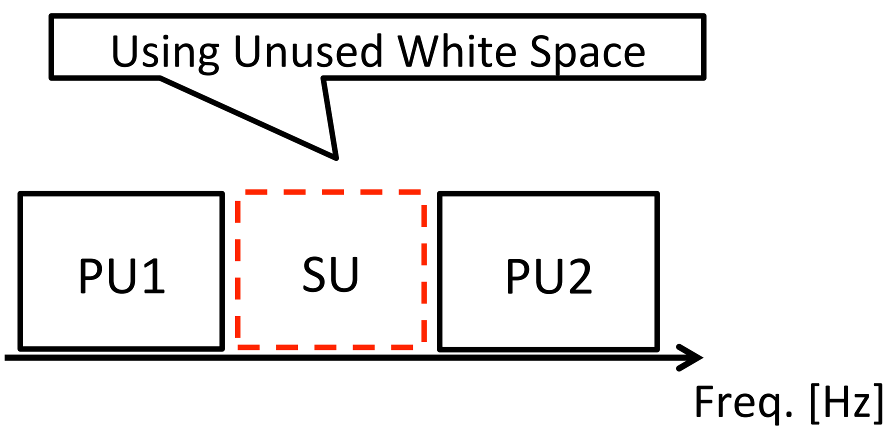

Figure 2.3: Overlay Spectrum Sharing.

2.3.2 Underlay Spectrum Sharing

Different with Overlay Spectrum Sharing, licenced band for Primary User is considered as usable spectrum for Secondary User as long as harmful interference towards Pirmary User is not existing. In other words, Both Primary User protection and own performance with using appropriate communication method should be ensured. Thus, it is more difficult to realize the Underlay Spectrum Sharing than overlay Spectrum Sharing.

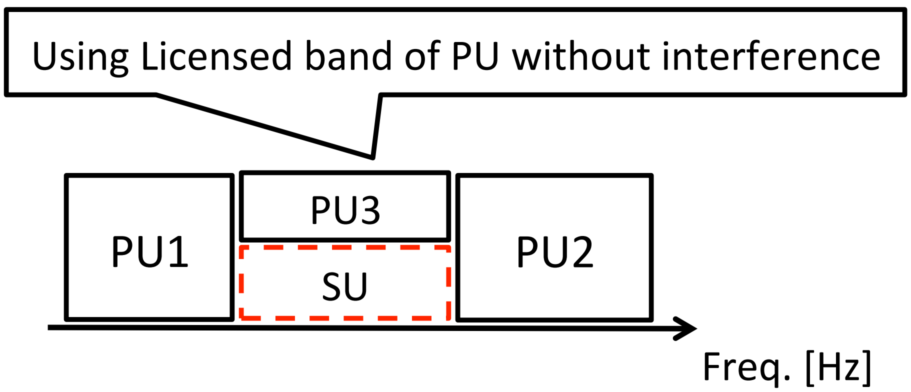

Figure 2.4: Underlay Spectrum Sharing.

Chapter 3

Spectrum Database

In Chapter 3, the overview of spectrum sharing with spectrum database and the measurement-based Spectrum Database proposed by our laboratory. And a problem of Spectrum Database Construction is described.

3.1 Overview of Spectrum Sharing with Spectrum Database

For further improving the performance for spectrum sharing, Federal Communications Commission(FCC), an independent agency of the United States government,proposed to fully utilize spectrum database for supporting spectrum sharing. Secondary User should obtain own postion by Global Position System(GPS) and access to database. FCC has already released the detailed rule of construction and managementfor TV broadcasting White Space and some service provider corporation have already established spectrum databases. [12–14]. However, FCC-defined Database is determined by following a specified propagation model and only stores the decision information whether the White Space can be utilized or not at each position based on the calculation result from the propagation model. Based on the information from GPS, Secondary User accesses to the spectrum database to obtain the White Space information. Because interference towards Primary User is designed by managing geographic White Space conservatively, FCC-defined Spectrum Database is only treated as overlay spectrum sharing. Consequently, as the interference margin is set too large, the calculation of interfernce power with following a detailed propagation model is not considered, which is described in Chapter 2 that the spectrum usage efficiency improvement has a upper limit.

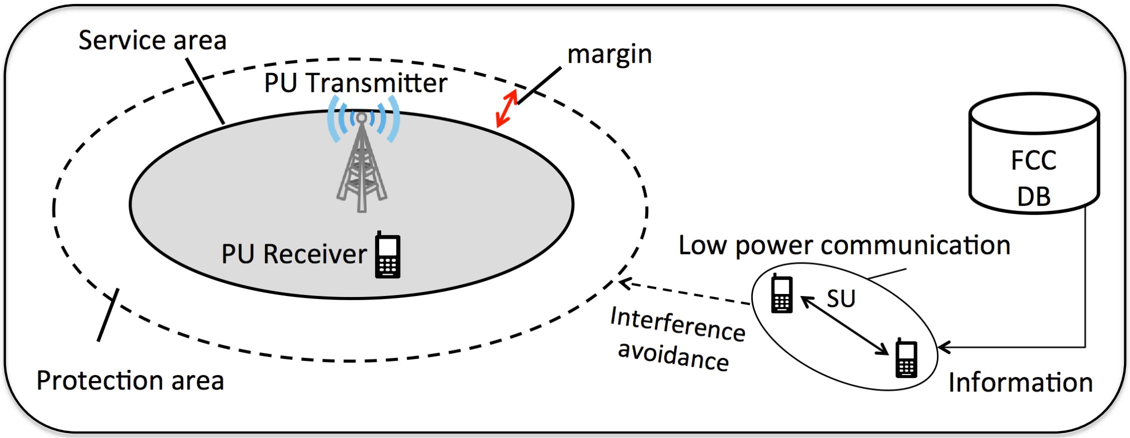

Figure 3.1: FCC-defined Spectrum Database.

3.2 Measurement-based Spectrum Database

To obtain a large improvement on spectrum usage efficiency, underlay spectrum sharing spectrum database should be considered instead of overlay type. Thus, a more advanced radio environment database besides FCC-defined spectrum database is required for providing not only the White Space information, but also the information about Primary, such as Modulation and Coding Scheme(MCS) and transmision power, a more detailed propagation model, estimation error and the position of Primary receiver and so on. As the Spectrum Database is contructed based on the observation on primary signal, high-speed communication is possible to be realized with adaptively determining the transmission power for avoiding interference towards Primary User based on the information obtained from the underlay spectrum sharing database.

The difference between FCC-defined Spectrum Database and measurement-based Spectrum Database is described as follows and Fig. 3.1 and 3.2. In FCC-defined Spectrum Database as illustrated in Fig.3.1, a service area is determined in advance, and the margin level is calculated for protecting Primary User receivers in this service area. Then, the transmission power and service area for Secondary User is limited for avoiding interference towards Primary User. Thus, only low power communication and limited service area is suitable for spectrum sharing. On the other hand, As Measurement-based Spectrum Database is possible to provide all information about Primary User,whiche leads to a more detailed service area, received power from Primary User at each position is known to Secondary User. Therefore, a highly accurate design of transmission power and timing can be realized. As a result, spectrum sharing performance with Primary User and opportunity for Secondary will be improved and the Quality of Service(Qos) for Secondary

User will be enhanced.

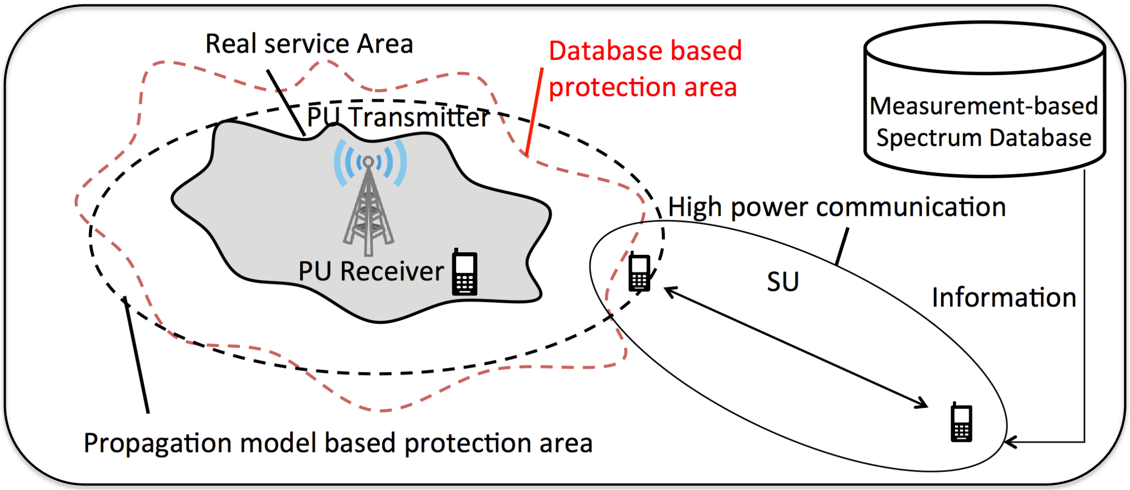

Figure 3.2: Measurement-based Spectrum Database.

3.3 Spectrum Datbase Construction based on Energy Detection

In this section, the measurement-based spectrum database considered in this research is described in detail. Fig. 3.3 shows the overview of how to construct the spectrum database. First, the spectrum database stores the radio environment information measured from Secondary User with mobility, such as vehicles and celluar phone. Secondary User receives the signal from Primary User when Secondary User moves without transmitting any signals. After that, Energy Detection(ED) [15], a simple and easy to implement spectrum sensing method, is adopted as a measurement method for uploading to the spectrum database. Energy Detection is considered as instantaneous primary signal sampling process during a sensing period T, and then N samples is obtained with determining a sampling frequency F. As a example, we assume that a series of samples $\{x_1, x_2, ..., x_N\}$are obtained by using energy detection, and then the received power P can be calculated as the following equation

$$P = \frac{1}{N}\sum_{i=1}^{N}(x_i)^2, \tag{3.1}$$

which is only the calculation of the average power of obtained samples. After Secondaray User finishes observation, the collect measurement will be uploaded to the spectrum database with its own position. Then, a statistical process of estimating the radio environment characterics of Primary User is executed to generate a radio environment map. However, Secondary User, as the source for spectrum database construction, requires highly accurate spectrum sensing performance. If measurment data including error may register to the database, the reliability of spectrum database may degrade. Therefore, the problem of spectrum database construction is explained in the next section.

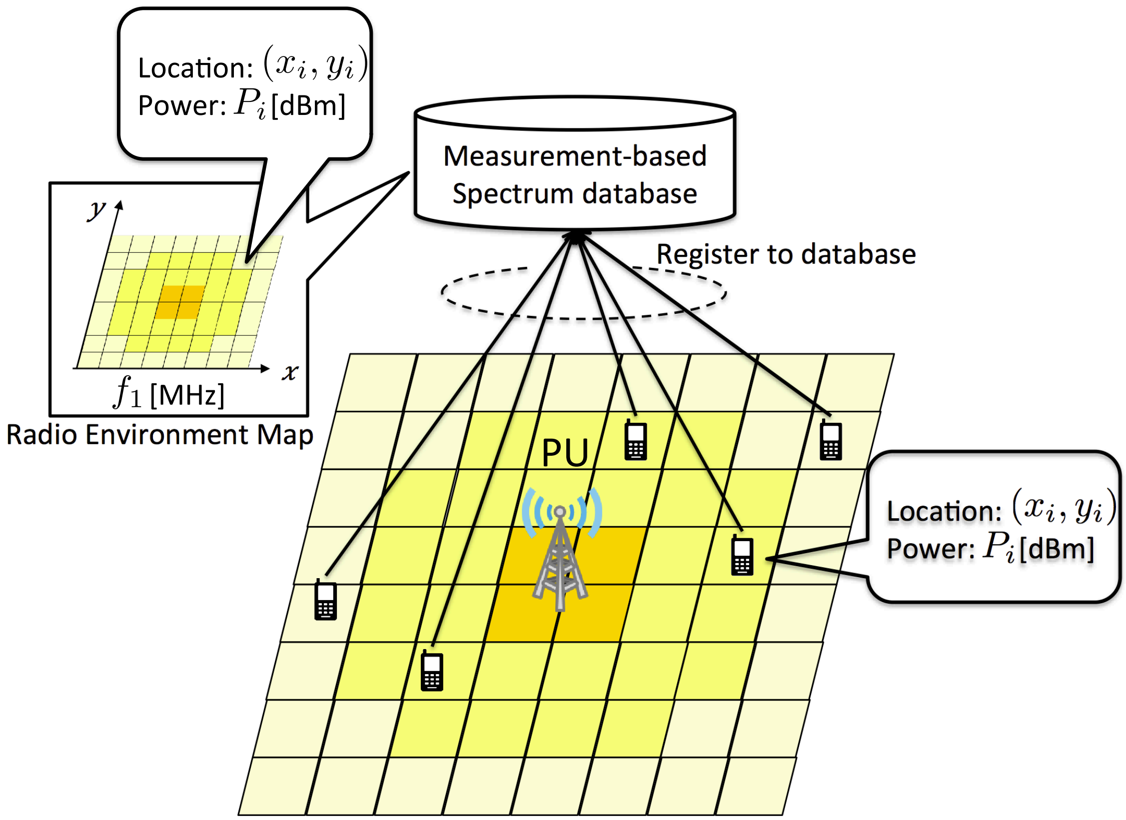

Figure 3.3: Measurement-based Spectrum Database Construction.

3.4 Problem of Spectrum Database Construction

As explained in the previous section, measurement-based spectrum database with spectrum sharing is constructed with considering received power value reported from Secondray Users at different position. However, since all received samples during the sensing period is utilized to calculate the received power value, the reported value may include noise component if a communication status transition of Primary User occurs during the sensing period. If the data with low accuracy are reported to the spectrum database, the reliability of the database degrades significantly. The problem discussed below will not cause any effect while the communication status of Primary User is always ON, such as Digital Television broadcasting system, while communication sysytems using Time Division Duplex(TDD) method or packet communication, such as Wireless LAN(WLAN) and celluar communication, may cause huge effect on the database. As illustrated in Fig 3.4, when the communication status is always ON during the sensing period, a correct received power can be reported to the database. On the other hand, when a transition from ON to OFF(which means that primary finishes transmission during the sensing period) occurs, samples including noise component are used to calculate the received power and are reported to the database. Because a noise including value is the correct received power we desire to obtain, the accurate propagation model is difficult to be estimated. Hence, from the viewpoint of the spectrum database construction, it is not appropiate to utilize all samples to calculate the received power and a transition point method to detect active period of primary user should be taken into account. In next chapter, a active period detection method is discussed for improving accuracy of spectrum database.

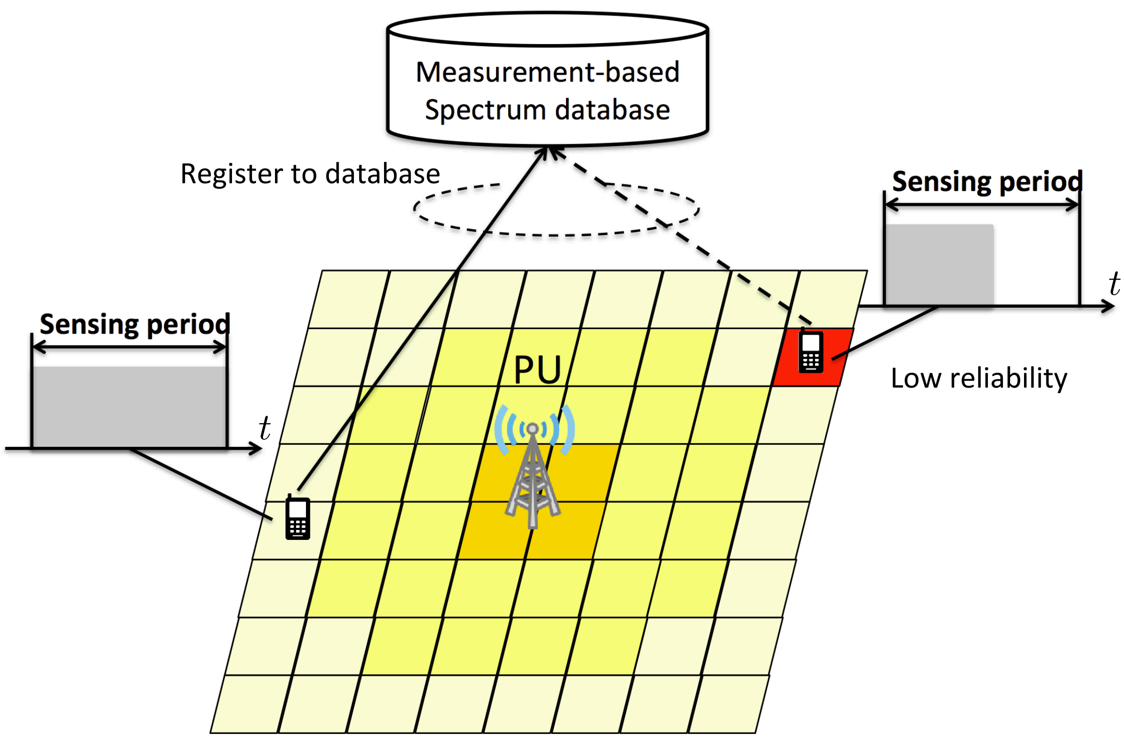

Figure 3.4: Problem of Measurement-based Spectrum Database Construction.

Chapter 4

Proposed Method

4.1 System model

We assume that a sensor node tunes to a frequency band and obtains samples $\mathbf{y} = \{y[1], y[2], ..., y[N]\}$ from a primary transmitter. N is the sample number during the sensing period. Since a multiple ON/OFF environment is considered, the sensing samples y is shown in Fig. 2 as follows

$$y[i] = \begin{cases} n[i], i = 1, ...\tau_1 - 1 \\ \\ x[i] + n[i], i = \tau_1, ..., \tau_2 - 1 \\ \\ n[i], i = \tau_2, .., N, \end{cases}$$

where τ_1 and τ_2 is the rise up point at which primary user starts to transmit and rise down point at which primary user stop transmitting respectively. If $\tau_1 = 1$ and $\tau_2 = N$, the primary user is always transmitting during the sensing period. On the other hand, if $\tau_1 = 1$ and $\tau_2 = 1$, the primary user is not at present during the sensing period. In this paper, we consider only the primary user starts and stops transmission during the sensing period. If the primary user is not transmitting, $y[i] = n[i]$, in which $n[i]$ is Addative White Gaussian Noise with mean 0 and variance σ^2. If the primary user starts transmitting, then $y[i] = x[i] + n[i]$, in which $x[i] = gs[i]$. g is the channel gain and the $s[i]$ is the signal of the primary user. Therefore, we assume $x[i]$ is white and Gaussian with mean 0 and variance P. P depends on the channel gain and the transmitter power of the primary user. In the wireless environment, the signal of the primary experiences pathloss and shadowing and multipath fading, so the value of P is not possible to be known accurately

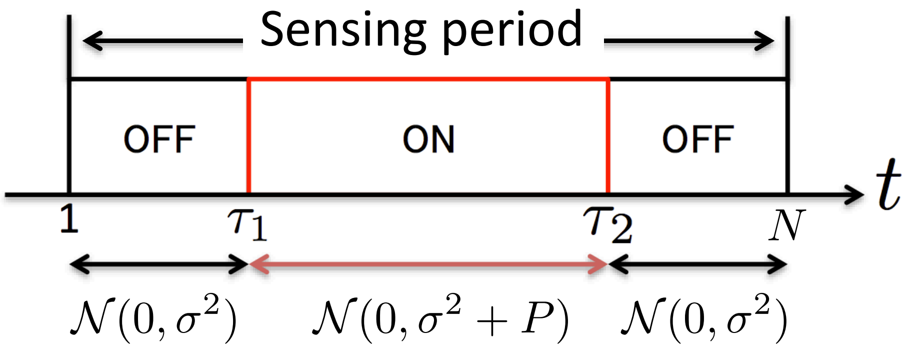

Figure 4.1: System model.

by the sensor. Thus, as a solution to received power detection problem, a transition point detection algorithm is considered.

4.2 Transition Point Detection Method under Multiple ON/OFF Environment

In this section, transition point detection algorithm for the status of primary user is introduced in detail. As the Fig. 4.2 is shown, the sample of the ON and OFF status follows a Gaussian distribution $\mathcal{N}(0, \sigma^2 + P)$ and $\mathcal{N}(0, \sigma^2)$ respectively. The probability density function(PDF) follows the eq. (4.1) is given by

$$\begin{cases} f_0(t) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{\mathrm{t}^2}{2\sigma^2}\right\} \\ \\ f_1(t) = \frac{1}{\sqrt{2\pi(\sigma^2+P)}} \exp\left\{-\frac{\mathrm{t}^2}{2(\sigma^2+\mathrm{P})}\right\}. \end{cases}$$

4.2.1 CUSUM algorithm

The cumulative sum (CUSUM) algorithm, which was first proposed by Page in [16], is used to detection the transition point when P and σ^2 is assumed to be known. The PDF $f_0(t)$ and $f_1(t)$ are fully specified. Thus, the log probability density ratio $l(y[i])$ is also fully defined by the eq. (4.1) and (4.2),

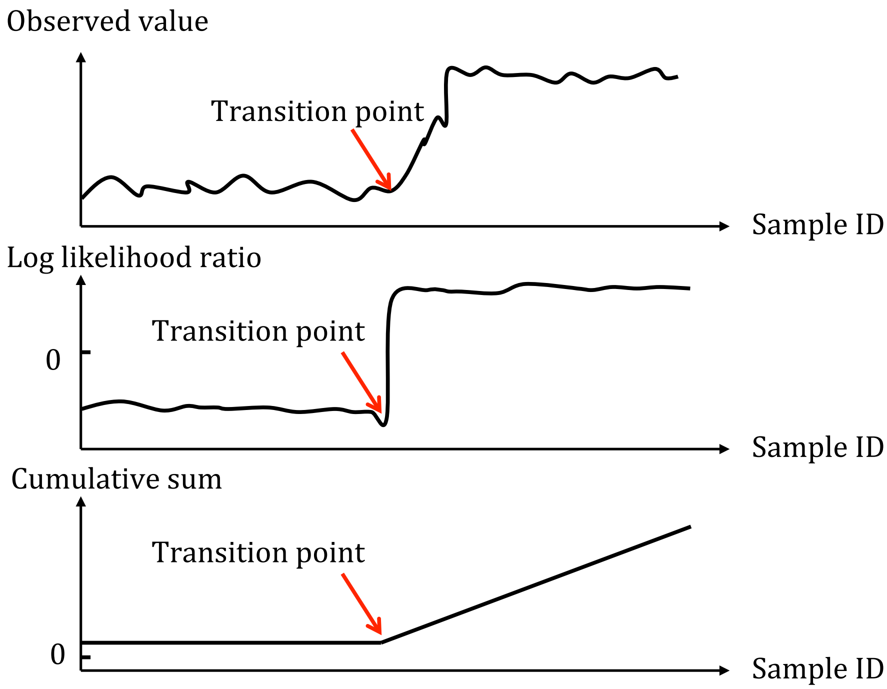

Figure 4.2: The image of cusum algorithm.

$$
\begin{aligned}
l_0(y[i]) &= \ln\left\{\frac{f_0(y[i])}{f_1(y[i])}\right\} \\
&= -\frac{2(P+\sigma^2)\sigma^2}{Py^2[i]} + \frac{1}{2}\ln\left\{\frac{P+\sigma^2}{\sigma^2}\right\},
\end{aligned} \tag{4.1}
$$

$$
\begin{aligned}
l_1(y[i]) &= \ln\left\{\frac{f_1(y[i])}{f_0(y[i])}\right\} \\
&= \frac{Py^2[i]}{2(P+\sigma^2)\sigma^2} + \frac{1}{2}\ln\left\{\frac{\sigma^2}{P+\sigma^2}\right\}.
\end{aligned} \tag{4.2}
$$

When the primary user is on the OFF and ON status, the average log probability density ratio can be calculated respectively using the eq. (4.3) and (4.4),

$$
\begin{aligned}
E_{f_0}\left\{l_0(y[i])\right\} &= -\int f_0(y)\ln\left\{\frac{f_0(y)}{f_1(y)}\right\}dy \\
&= -D(f_0||f_1) \le 0,
\end{aligned} \tag{4.3}
$$

$$
\begin{aligned}
E_{f_1}\left\{l_1(y[i])\right\} &= \int f_1(y)\ln\left\{\frac{f_1(y)}{f_0(y)}\right\}dy \\
&= D(f_1||f_0) \ge 0,
\end{aligned} \tag{4.4}
$$

where $D(f_0||f_1)$ is the Kullback-Leibler divergence of f_0 from f_1 and $D(f_1||f_0)$ vice versa, which is shown in eq. (4.5)

$$D(f_0||f_1) = \frac{P}{2(P+\sigma^2)} + \frac{1}{2}\ln\left\{\frac{\sigma^2}{\sigma^2+P}\right\}. \tag{4.5}$$

Hence, when the primary user is at present, which means the sample before primary user changes its status from OFF to ON, the probability density ratio $l(y)$ has a negative trend. After a change point from ON to OFF, $l(y)$ has a positive trend. Using the characterics discussed above, an algorithm for detecting a status transition (ON→OFF or OFF→ON) of the primary user can be defined as comparing,

$$g_t = \max_{k\le t}\left\{\sum_{i=1}^{t} l(y[i] - \sum_{i=1}^{k} l(y[i]))\right\} = \max_{k\le t}\sum_{i=k+1}^{t} l(y[i]), \tag{4.6}$$

with a threshold h. If g_t is larger than h, the existence of the primary user is declared. Since $l(y)$ has a positive trend during the ON status of the primary.

Also, the eq. (4.6) can be written as

$$\begin{aligned} g_{t+1} &= \max_{k\le t+1}\left\{\sum_{i=k+1}^{t+1} l(y[i])\right\} \\ &= \max\left\{\max_{k\le t+1}\left\{\sum_{i=k+1}^{t+1} l(y[i])\right\}, 0\right\} \\ &= \max\left\{\max_{k\le t+1}\left\{\sum_{i=k+1}^{t+1} l(y[i])\right\} + l(y[i]), 0\right\} \\ &= \{g_t + l(y[t+1])\}^+ . \end{aligned} \tag{4.7}$$

$\{.\}^+$means that the value must be postive. Hence, g_t can be computed recursively by setting $g_0 = 0$. To sum up, the CUSUM algorithm works as the following process:

i . compute $l(y)$ for each sample using eq. (4.1) or (4.2).

ii . compute the statistic g_t using eq. (4.7).

iii . compare the statistic g_t with a threshold h.

iv . If $g_t \ge h$, the existence of the primary user is declared.

4.2.2 GLR algorithm

In realistic wireless channels, the exact value of P is difficult to be known exactly. It is more reasonable to assume that P belongs to a range, that is $P \in [P_{\min}, P_{\max}]$. In this

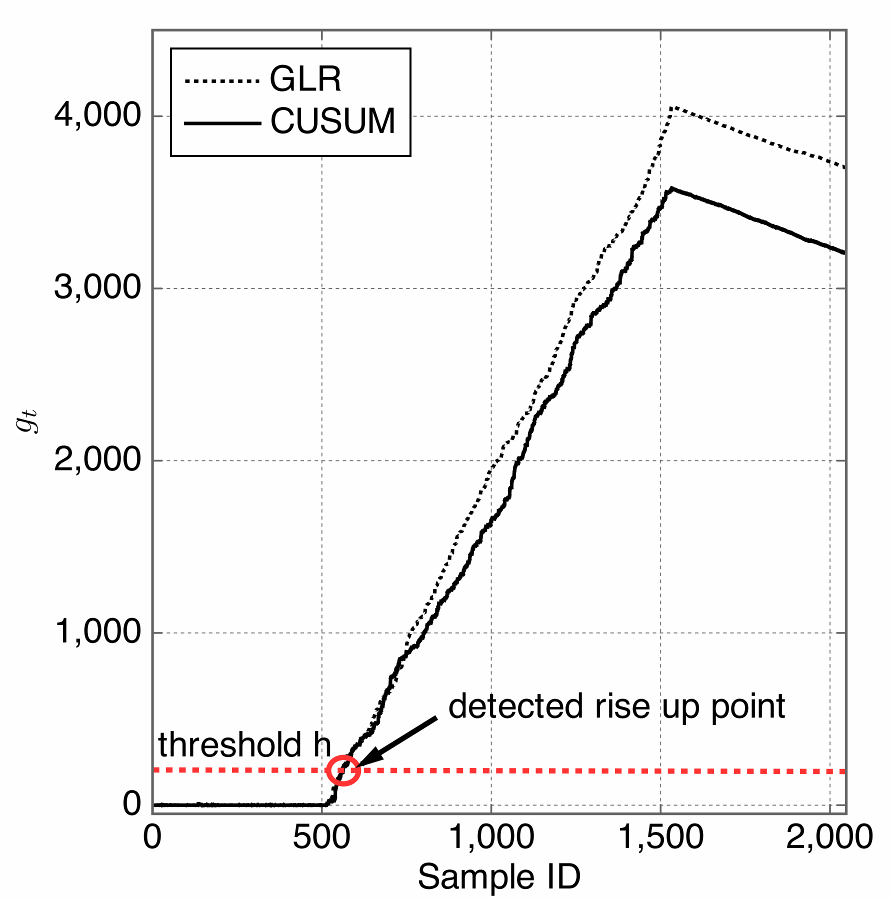

Figure 4.3: Statistic g_t using the probability density ratio $l_0(y)$ when the rise up point is 512th sample and the rise down point is 1532th sample.

case, a generalized likelihood ratio(GLR) algorithm [17] for transition point detection is applied. Since the value of P is unknown, the statistic g_t is defined as the following eq. (4.8),

$$\begin{aligned} g_t &= \max_{k \le t} \left\{ \sum_{i=k+1}^{t} l(y[i]) \right\} = \ln \left\{ \prod_{i=k+1}^{k} \frac{f_{1,P}(y[i])}{f_0(y[i])} \right\} \\ &= \max_{k \le t} \left\{ \sum_{i=k+1}^{t} \left\{ \frac{Py^2[i]}{2(P+\sigma^2)\sigma^2} + \frac{1}{2} \ln (\frac{\sigma^2}{P+\sigma^2}) \right\} \right\}, \end{aligned} \tag{4.8}$$

where $f_{1,P}(t)$ is the probability density function of the received signal when the varinace of the signal part is P. Therefore a function $f(P)$ defined as eq. (4.9) is used to calculate the statistic g_t,

$$\begin{aligned} f(P) &= \sum_{i=k+1}^{t} \left\{ \frac{Py^2[i]}{2(P+\sigma^2)\sigma^2} + \frac{1}{2} \ln (\frac{\sigma^2}{P+\sigma^2}) \right\} \\ &= \frac{P}{2(P+\sigma^2)\sigma^2} \hat{y} + (t-k) \frac{1}{2} \ln \left\{ \frac{\sigma^2}{P+\sigma^2} \right\}, \end{aligned} \tag{4.9}$$

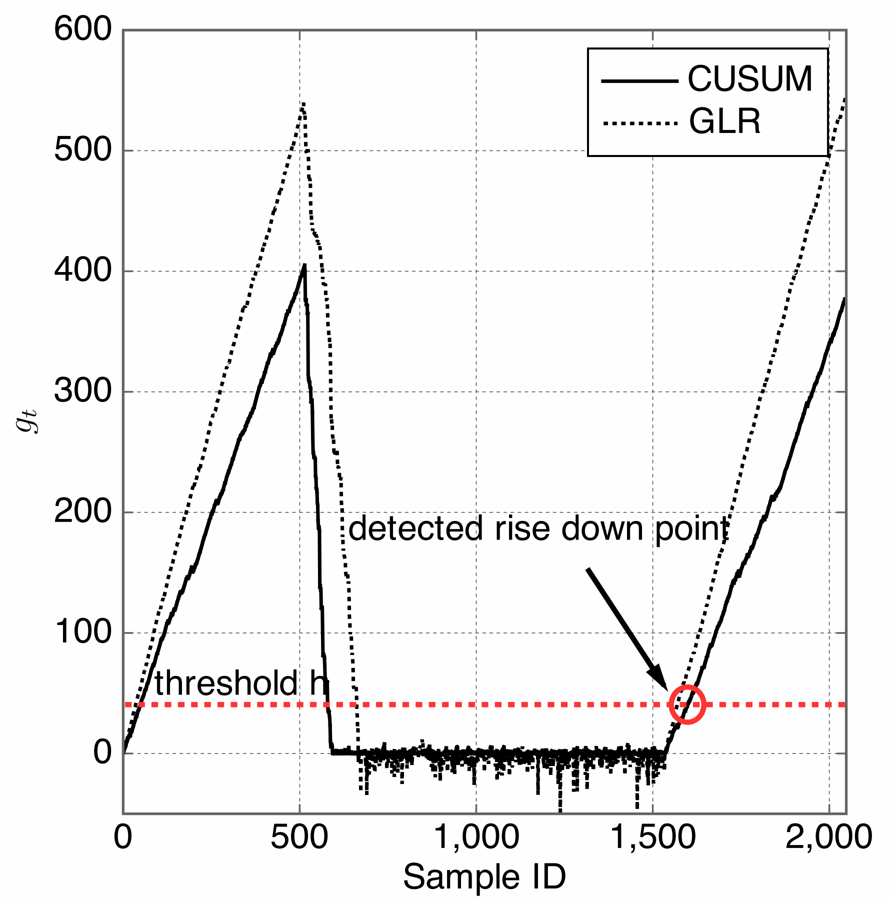

Figure 4.4: Statistic g_t using the probability density ratio $l_1(y)$ when the raise up point is 512th sample and the raise down point is 1532th sample.

where $\hat{y} = \sum_{i=k+1}^{t} y[i]^2$. To find a the power P^* that maximizes the function $f(P)$ over $P \in [P_{\min}, P_{\max}]$, it can be calculated as below,

$$P^* = \begin{cases} P_{\max}, & (t-k) \leq \frac{\hat{y}}{P_{\max}+\sigma^2}, \\ \frac{\hat{y}}{t-k} - \sigma^2, & \frac{\hat{y}}{P_{\max}+\sigma^2} \leq (t-k) \leq \frac{\hat{y}}{P_{\min}+\sigma^2}, \\ P_{\min}, & (t-k) \geq \frac{\hat{y}}{P_{\min}+\sigma^2}. \end{cases} \tag{4.10}$$

As a derivation, the the function $f(P)$ is differentiated with respect to P first and the eq. 4.11 is shown as follows,

$$f^{'}(P) = \frac{\hat{y}}{2}\frac{1}{(P+\sigma^2)^2} - \frac{t-k}{2(P+\sigma^2)}. \tag{4.11}$$

And then, $f^{'}(P) = 0$ is set to determine a extreme value and it is $P^* = \frac{\hat{y}}{t-k} - \sigma^2$, which P^* is assumed to be the extreme point of the function $f^{'}(P)$. Because the maximum of

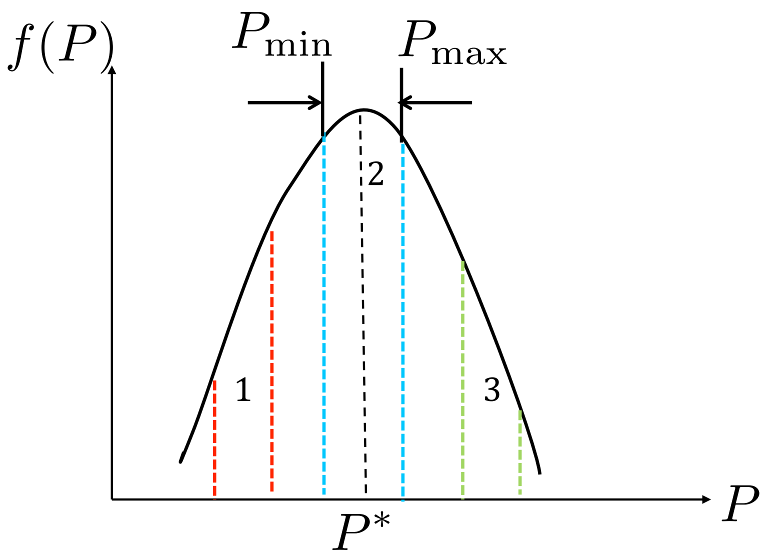

Figure 4.5: The image of funcition $f(P)$.

$f(P)$ is the final goal we want, the appropiate P should be determined during the the range $[P_{min}, P_{max}]$. As the function $f(P)$ is a concave function as shown in Fig. 4.2.2, the extreme value is the value when $P^* = \frac{\hat{y}}{t-k} - \sigma^2$ and 3 possible cases can be considered as follows,

$$\begin{cases} 1. \quad \max\{f(P)\} = f(P_{\max}), \quad P_{\max} < \frac{\hat{y}}{t-k} - \sigma^2, \\ \\ 2. \quad \max\{f(P)\} = f(P^*), \quad P_{\min} < \frac{\hat{y}}{t-k} - \sigma^2 < P_{\min}, \\ \\ 3. \quad \max\{f(P)\} = f(P_{\min}), \quad P_{\min} > \frac{\hat{y}}{t-k} - \sigma^2. \end{cases} \tag{4.12}$$

Finally, the maximum value of function $f(P)$ can be determined by eq.4.10 as shown before.

As same as the CUSUM algorithm, in the GLR algorithm the statistic value g_t is calculated in eq.(4.8) with choosing the a power P^* from the eq.(4.10), and is compared with the threshold h. Once $g_t > h$, the existance of the primary user is declared.

4.2.3 Threshold configuration for CUSUM and GLR algorithm

To set a threshold for the transition point detection, we first assume t_0 denotes the time when the statistic g_t exceeds the threshold h, and define $\bar{T}_0 = E[t_0]$ is the mean time to a false alarm. Following [18] and [19], some simple bounds on $\bar{T}_0$ can be derived.

For CUSUM algorithm, the relationship between the mean false alarm and threshold is as follows.

$$\bar{T_0} \geq e^h. \tag{4.13}$$

For GLR algorithm, the threshold is set to be $h = -\ln\left\{\frac{a}{b}\right\}$, where

$$b = 3\ln\left\{a^{-1}(1 + \frac{1}{D(f_1, P_{\min}||f_0)})^2\right\}, \tag{4.14}$$

and a follows the following inequality.

$$\bar{T_0} \geq \frac{1}{a}. \tag{4.15}$$

4.3 Peak detection for transition point

Except CUSUM and GLR algorithm, we propose a peak detection for transition point detection. As shown in Fig. 4.3 and 4.3, the cumulative sum of the log likelihood raito $l_1(y)$ and $l_0(y)$ will reach a peak value when a transition point between ON and OFF or OFF and ON. Therefore, instead of a threshold-based transition point detection method, a peak detection is adopted to detect transition point more accurately. Same as CUSUM and GLR algorithm, a detailed peak detetion process for transition point detecting is shown as follows.

i . compute $l(y)$ for each sample using eq. (4.1) or (4.2).

ii . compute the statistic g_t using eq. (4.7).

iii . detect the maximum of g_t as the peak value.

iv . If the peak value of g_t is detected, the sample ID associated with peak value is declared as the transition point, which is from ON to OFF or OFF to ON.

4.4 Avtive Period Detection

In this section, the proposed active period detection using the CUSUM and GLR algorithm and peak detection discussed above is introduced.

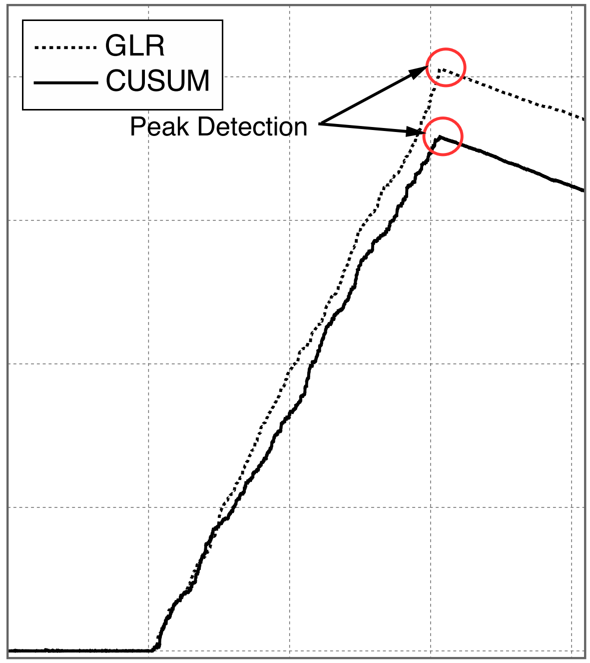

Figure 4.6: Peak detection image for rise up point.

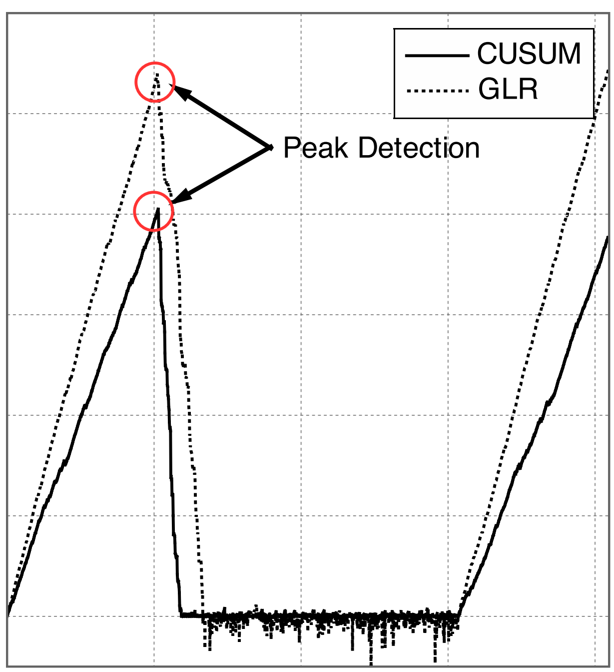

Figure 4.7: Peak detection image for rise down point.

First, the statistics g_t calculation results related to the sample ID using the probability density ratio $l_0(y)$ and $l_1(y)$ are shown in Figs.4.3 and 4.4, respectively. The rise up point is set to be the 512th sample and the rise down point is set to be 1532th sample. In Figure 4.3, when a status of the primary user from OFF to ON changes, the statistic g_t shows a increase trend, and when the status changes from ON to OFF, a decrease trend is shown. The reason is that if the probability density ratio $l_0(y)$ is used to calculate the statistics g_t, the ON samples show a positive trend and OFF samples a negative trend. Then in this case, the statistics g_t exceeds the threshold h, the rise up point is declared to be detected.

Samely, in Figure 4.4, when a status of the primary user from OFF to ON changes, the statistic g_t shows a increase trend, and when the status changes from ON to OFF, a decrease trend is shown. The reason is that if the probability density ratio $l_1(y)$ is used to calculate the statistics g_t, the ON samples show a negative trend and OFF samples a positive trend. Thus, the statistics g_t exceeds the threshold h, the rise down point is declared to be detected.

At last, as introduced in sec.4.3, the active period detection with peak detection utilizes the peak value of g_t to dectect the transition point to be Different from CUSUM and GLR algorithm.

Based on the detected rise up and rise down point, an active period of the primary user is extracted to calculate the received power. Since the only ON samples is detected to be used for calculating the received power, it may mitigate the sensing error compared with not considering ON sample extraction.

Chapter 5

Simulation

5.1 Performance evulation

In this section, we use computer simulation to evaluate the performance of transition point detection and the received power detection using CUSUM and GLR algorithm. The simulation parameters are shown in Table 5.1.

To vertify the performance of the received power, we evalate

1. the performance of the rise up point and the rise down point detection,
2. the CDF(Cumulative Distribution Function) of transition point.
3. the performance of the received power detection using the detected transition point.
4. the power difference in different ON percentage of primary user.

5.2 Simulation results

Figures 5.1 and 5.2 show the boxplot results of detected rise up point and rise down point respectively. The body of the boxplot consists of a box, which goes from the fisrt quartile to the third quartile. The line drawn at the box means the median of the detected transition point. The lines extended from the box called whiskers mean the smallest and the largest nonoutlier from the box. The real rise up point and rise down piont are fix on the 512th sample and 1532th sample. From the simulation results, we can see that in low SNR region the variation of transition point is large, howerver, in high SNR region the detected transition point converges to the real one.

Table 5.1: Simulation parameters

Parameter	Value
SNR	-10∼20[dB]
$[P_{\min}, P_{\max}]$	$[P/2, 2P]$
σ^2	1
sample number	2048
$\bar{T}_0$	10
transition partern	OFF $\rightarrow$ ON $\rightarrow$ OFF
rise up point	512th sample
rise down point	1536th sample
Number of trials	10,000

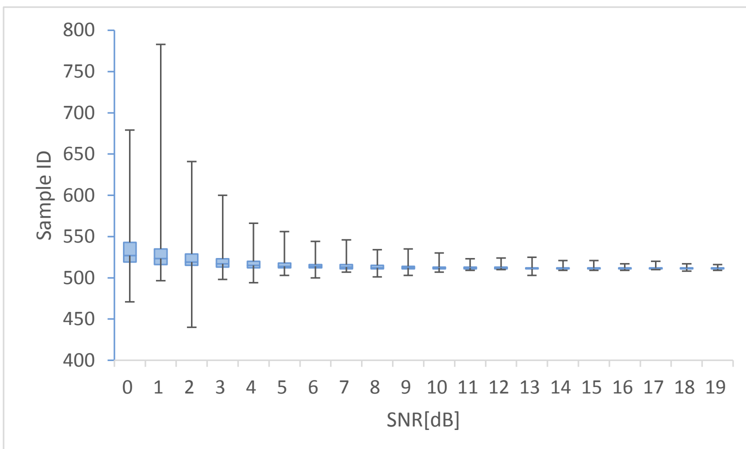

Figure 5.1: Boxplot result of the rise up point.

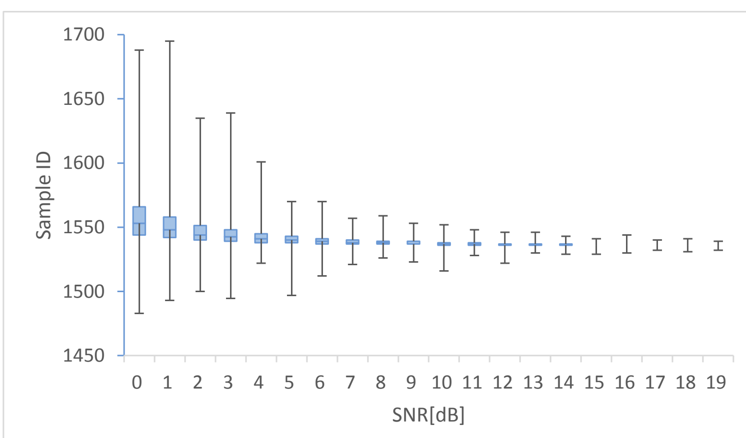

Figure 5.2: Boxplot result of the rise down point.

Figures 5.5 shows the performance of the power difference with the real power. The received power detection without considering ON/OFF transition during the sensing period, which means the all samples is used for calculating the received power, is considered as a conventional method for comparison. The dotted line means that the ideal case that the real received power is detected exactly. The power difference P_{diff} with real power is defined as follows,

$$P_{\text{diff}} = P - P_{\text{ON}}. \tag{5.1}$$

The simulation result shows that the proposed method for the received power detection using CUSUM algorithm and GLR algorithm and peak detection can obtain a better performance than the conventional method. In low SNR region, the proposed method can achieve 0.5[dB] gain than the conventional one, and in high SNR region, 1.3[dB] is improved.

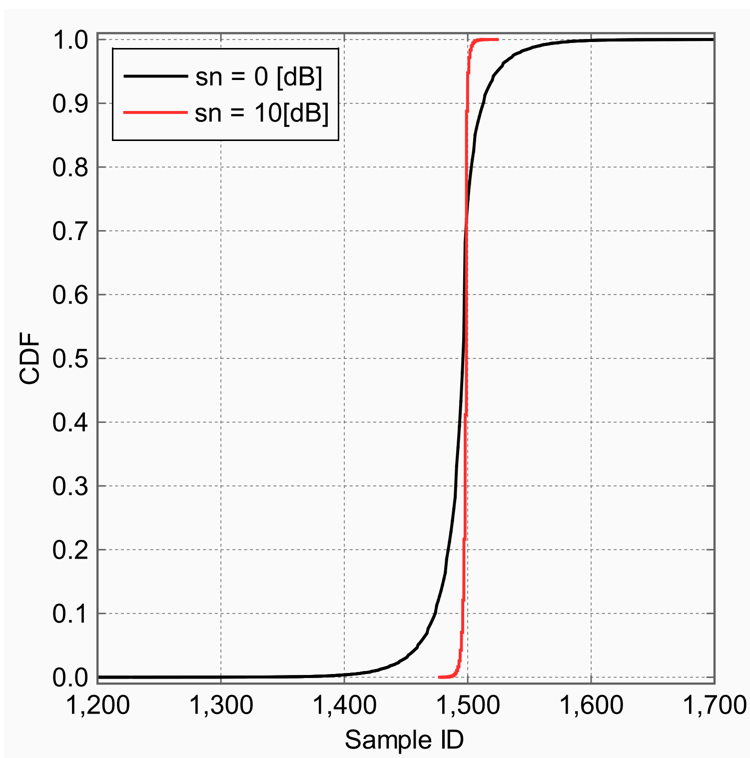

Figure 5.3: CDF of rise up point detection(rise up point is set to be 500th sample).

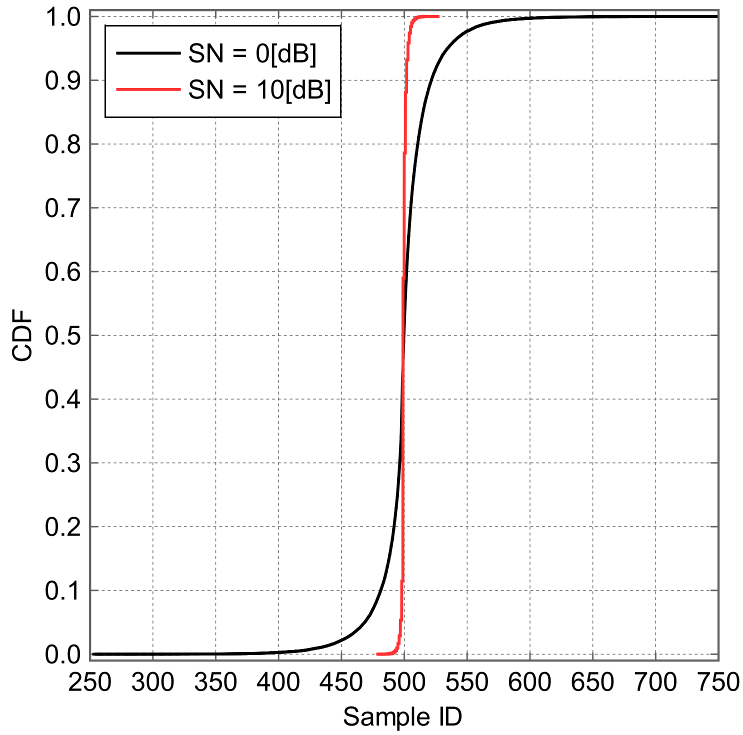

Figure 5.4: CDF of rise down point detection(risen down point is set to be 1500th sample).

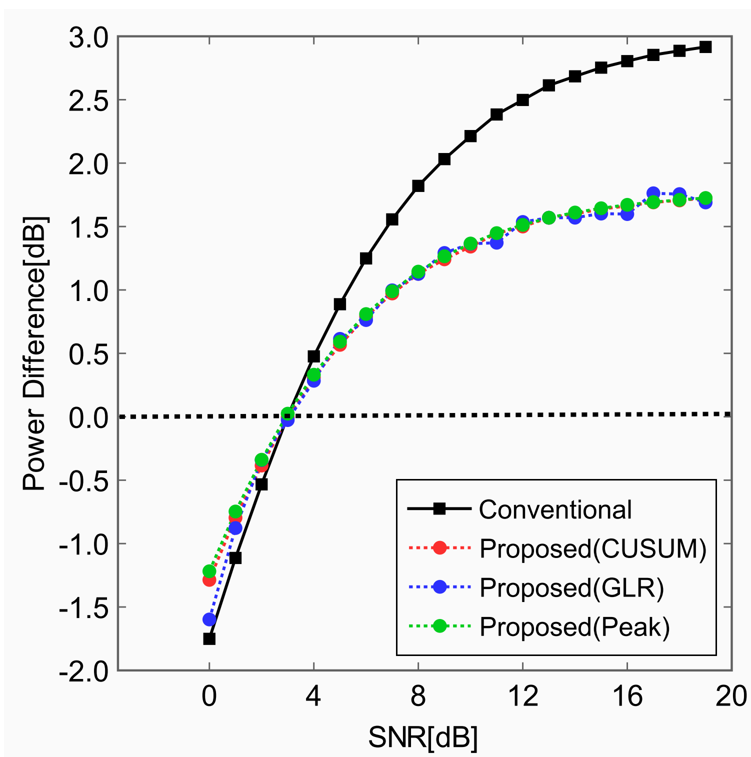

Figure 5.5: The power difference with the real power.

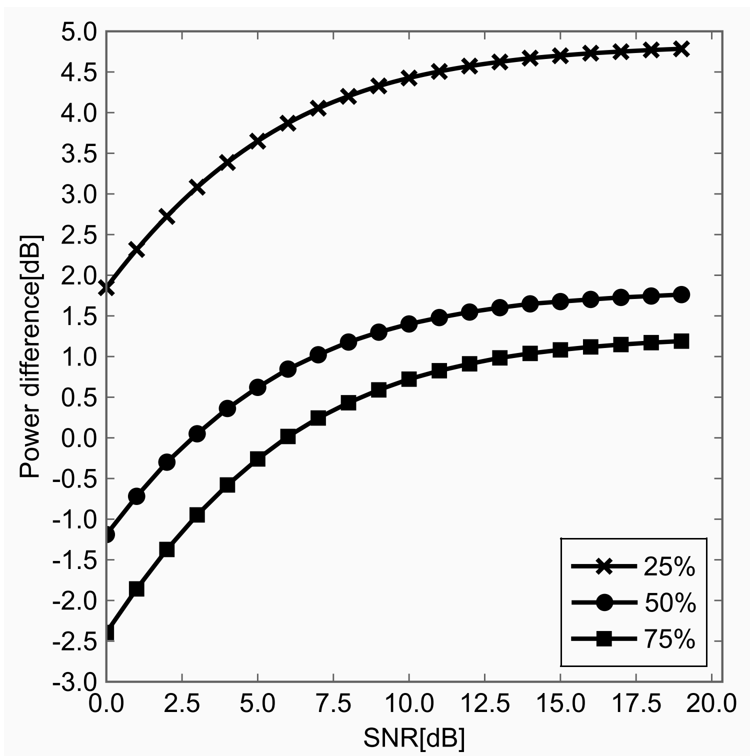

Figure 5.6: The power difference with the real power at different ON percentage during the sensing period.

Chapter 6

Conclusion

In this paper, as a solution to the sensing error under multiple ON/OFF environment for Spectrum Database, a transition point detection algorithm is applied for the received power detection. Based on the detected transition point of the primary user status by using CUSUM algorithm and GLR algorithm. an active period of the primary user can be extracted. Transition point is well-detected and an improvement of sensing error can be confirmed through simulation results.

Acknowledgments

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Appendix

From the next page, the program source is attached.