# 修士論文

## Measurement and Statistical Analysis of Frequency Utilization in Tokyo

東京都心における周波数利用率の測定と統計的解析

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## Abstract

The 3rd generation technology of mobile devices (3G) is supported by the wireless industry as a state of the art technology. It brings high-speed Internet and data transmissions to cell phones and increases the communication capacity for cell-phone applications. But a bottleneck exists there because of a shortage of available electromagnetic spectrum, what we call RF, to let next generation mobile systems roll out in the future. This work seeks to identify the keys in spectrum utilization and the means, by which more spectra can be available, and also how an effective dynamic utilization measurement and analysis can be conducted for the future mobile communication systems to improve the spectrum allocation and assignment activities and to enhance the heterogeneous network switching usage. In this master thesis, after introducing spectrum allocation and spectrum usage recent years, we will take a look at white space and other works related to spectrum management. Then, to our work, we will introduce the measurement we have deployed to measure the spectrum in downtown Tokyo, Japan for two years which collect a large amount of data by a long range of frequency. The second phase is the visualization phase of spectrum occupancy in which we show spectrum occupancy using our spectrum map system. And finally in the analysis phase, we show our quantitative analysis model to find an exact duty cycle of spectrum utilization, to know how spectrum is currently utilized in Tokyo and the spatiotemporal characteristic of spectrum as well as comparison with spectrum utilization in other countries.

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# Chapter 1

# Introduction

## 1.1 Background

The improving of wireless services have resulted in higher requirements for spectrum utilization, which prompts CR (Cognitive Radio [36]), Dynamic Spectrum Access (DSA [11–13; 19; 31] ) and Software Defined Radio [14; 18; 27] technology as an optimized solution to enhance effective spectrum usage [34] . In order to provide fundamental supports researches with the understanding of white space of CR as well as spectrum holders with probing into more valuable assets, we have condeucted many logical spectrum measurement at different sites as well as constructed a SpectrumMap system for spectrum visualization of downtown areas in Tokyo, which gives a deep investigation and understanding of spectrum occupancies in Japan. The work includes white space visualization as well as grass-roots data collections of RF (radio frequency) by enabling data publishers to expand their spectrum databases via web service. We show the current progress and the results of the work in this report. The related works including our detailed surveys will be provided firstly, then the prototype of the SpectrumMap system will be illustrated, followed by a RF data describe format. Finally, we show our long-term spectrum measurement in Tokyo at some distinctive locations, the main methods we have used to analyze our data, the results we have conducted and the conclusions.

## 1.2 Purpose

Cognitive Radio (CR [45–47] ) and Dynamic Spectrum Access (DSA [48] ) are technologies proposed to enhance spectrum utilization and to solve the issues of spectrum allocation such as spectrum scarcity. For long term spectrum monitoring studies, it would be crucial to determine spectrum hole (white space and gray space) and the possibility to estimate the utilization of spectrum using real RF data [9; 10; 21; 23; 35; 41; 44] . For these reasons, we have conducted a long-term spectrum measurement in Tokyo, Japan at several distinctive locations with a long range radio bandwidth to collect and measure spectrum data as well as analyze measured spectrum data to find specific clues used in CR and DSA in a near future. The measurement method mainly based on the energy detection (RSSI) using omnidirectional tri-axial antenna with SRM-3000 spectrum analyzer. The analyzed frequency data spreads from 75[MHz] to 3[GHz] and the resolution bandwidth (RBW) is 5[MHz].

In this paper, we present the spectrum measurement we held last two years, major conclusions for different spectrum bands and the comparisons of radio frequency utilization measurements that were held in other countries as Europe and China. We also figure out the spatiotemporal feature of spectrum intensity and summarize the spectrum utilization as well as spectrum utilization behaviors of main wireless communication systems in different time slots, the physical aspects of spectrum in Tokyo and correlations between spectrum occupancy at different locations. Finally, we analyze the real spectrum data to find the pattern of spectrum signal which is potential for cognitive radio technology and dynamic spectrum access in the future.

## 1.3 Thesis Organization

This thesis is organized as follows.

In Chapter 2, we took a look at surveys mainly on Radio Frequency (RF) and its applications. We will introduce what is RF and RF spectrum which are divided into many different types depend on RF spectrum's scope and scale. We especially focus on LAN and WRAN (with communication less from 15km to less than 100km, and the communication standard is IEEE 802.22) which are used widely in these years. In another part of this chapter, we deploy some surveys of spectrum assignments in 5 countries (US, Japan, Canada, United Kingdom, and France) which are considered to have a high occupancy of spectrum and the whitespace in spectrum sensing in recent years.

In Chapter 3, we introduce research works related to spectrum management. The first part of this chapter is Spectrum Measurement Framework which give some ideas of how researcher deploy an overall spectrum management from data definition, spectrum data collection, spectrum storage and spectrum analysis. These researches include works in Tokyo (The University of Tokyo) about Radio Inoformation Management for a Distributed Spectrum Sensing and the way they stored data in time-series sensor database to speed up the processing speed of spectrum database. The left part of this chapter, we show the works most related to our measurement framework. There are two trends of spectrum measurement, the first one is dynamic spectrum measurement which collecting spectrum data while moving along and the second one is static spectrum measurement which keep the spectrum analyzer at some specific locations and collect data for a long time at these points only. The benefit of dynamic spectrum measurement is it could cover a wide range of region with low cost and high flexibility of location arrangement. But it is lack of 24/7 operation, control management and number of data for one location which static measurement could do.

In Chapter 4, we introduce the Spectrum Map System we developed last year. This system could use the collected data and plot it on the Virtual Earth Map which is developed and enhance by Microsoft. We then show a prototype of the spectrum map system that aim to visualize location-based or time-based information of spectrum resources.

We depict a common data format which we originally develope for our measurement and our data description in chapter 5. In this chapter, we show why we need a common RF spectrum data exchange format and its features in our measurement system. We use WGS84 lat/long vocabulary in our XML format to represent our metadata. This semantic XML data also includes basic information of spectrum map data, device information and other specification as ownership, data, and time, etc.

In Chapter 6, we introduce our work on spectrum measurement. This is the pre-processing of a long-term spectrum measurement. This chapter shows some fundamental requirement of spectrum measurement as well as requirement of equipment (spectrum analyzer, GPS receiver, etc) to satisfy the spectrum measurement listed. We then introduce the measurement construction we deployed using SRM-3000 Spectrum Analyser and a USB GPS which is connected to a Windows XP PC which is synchronized using time slot with SRM-3000. We also mention the measurement location and the reasons why we choose those location for our long-term measurement setup.

Chapter 7 with chapter 6 and chapter 8 is one of the main part of our long-term measurement. In this chapter, we show which criteria and how we evaluate our collected spectrum data. And how it is different and original compared with previous work in Europe, US, and China. The main part of this chapter is how to find a precise threshold value for each spectrum band. But before defining a good threshold value, we have to know the noise level and False Alarm Rate (a non-target signal but defined as a target signal because the signal exceeds the dectection threshold) of spectrum data we collected. Choosing different noise level and FAR causes a crucial change of threshold value, and therefore changes the the final result of duty cycle of our measurement.

Chapter 8 is the final chapter after using methods we proposed in chapter 7 to find the precise duty cycle in Tokyo, Japan. This chapter shows the difference of duty cycle of spectrum in different measurement sites around Tokyo also the difference of duty cycle of the same place with various period of time. In this chapter, we not only take an overall of spectrum utilization but also a detail of spectrum utilization in various band in the long-range spectrum band. This chapter also focuses on WiFi band which could be used in not only coginitive radio technology and dynamic spectrum access, but also hetero-network technology.

# Chapter 2

# A Survey on RF Spectrum and Spectrum Allocation Policy

## 2.1 Introduction

The 3rd generation technology of mobile devices (3G) is supported by the wireless industry as a state of the art technology. It brings high-speed Internet and data transmissions to cell phones and increases the communication capacity for cell-phone applications. But a bottleneck exists there because of a shortage of available electromagnetic spectrum, what we call RF, to let next generation mobile systems roll out in the future. This work seeks to identify the keys in spectrum utilization and the means, by which more spectra can be available, and also how an effective dynamic utilization between government and private parties can be constructed for the future mobile communication systems.

## 2.2 What is RF and RF spectrum

The term radio frequency (RF) typically refers to the frequency from 3 kHz to 300 GHz that may be used for wireless communication. Wireless communication technology uses electromagnetic waves to transmit and receive data. For instance, television signals are modulated onto RF signals and then demodulated by a mobile device tuner.

Radio frequency spectrum (RF spectrum) refers to the full RF range from 3 kHz to 300 GHz as shown in Table Table 2.1 . Another way to categorize the different types of communication systems is by their scope or scale. From the historical reasons, the networking industry refers to nearly every type of area network. Common examples of area network types are shown in Fig. 2.1 . They are Personal Area Network (PAN, communication range usually less than 10m, IEEE 802.15), Local Area Network (LAN, less than 150m, IEEE 802.11), Metropolitan Area Network (MAN, less than 5km, IEEE 802.16), Wide Area Network (WAN, less than 15km, IEEE 802.20), Wireless Regional Area Network (WRAN, less than 100km, IEEE 802.22 [7] ).

LAN and WAN are the original categories of area networks, while the others have gradually emerged over many years of technology evolution. Especially, IEEE 802.22 [8], which has been proposed recently, is a standard for Wireless Regional Area Network (WRAN) using white spaces in the TV frequency spectrum. WRAN, whose speed can reach 18 to 24 Mbps through a wide communication range up to 100 km, is designed to operate by using the TV broadcast bands by the secondary users while assuring that no harmful interference is caused to the incumbent operators.

Table 2.1: Frequency Band, Range and Wavelength

| RF Band | Abbr. | Range | Wavelength |
|---|---|---|---|
| Extremely Low Freq. | ELF | 3-30 Hz | 100-10 Mm |
| Super Low Freq. | SLF | 30-300 Hz | 10-1 Mm |
| Ultra Low Freq. | ULF | 300-3000 Hz | 1000-100 km |
| Very Low Freq. | VLF | 3-30 kHz | 100-10 km |
| Low Freq. | LF | 30-300 kHz | 10-1 km |
| Medium Freq. | MF | 300-3000 kHz | 1000-100 m |
| High Freq. | HF | 3-30 MHz | 100-10 m |
| Very High Freq. | VHF | 30-300 Mz | 10-1 m |
| Ultra High Freq. | UHF | 300-3000 Mz | 100-10 cm |
| Super High Freq. | SHF | 3-30 HGHz | 10-1 cm |
| Extremely High Freq. | EHF | 30-300 GHz | 10-1 mm |

## 2.3 Spectrum Policy and Regulatory Structures

### 2.3.1 United States

In US, there are two main parties who get involved in the spectrum allocation. The first party is the National Telecommunications and Information Administration (NTIA). The second one is the Federal Communications Commission (FCC). These two parties have two different missions in which NTIA has responsibility for the usage of spectrum in federal sphere and NTIA has responsibility for the civil uses of spectrum. In NTIA, the Office of Spectrum Management (OSM) is consulted by the Interdepartment Radio Advisory Committee (IRAC) to carry out main tasks as issuing the spectrum usage policy, the spectrum assignment; maintaining spectrum usage databases, and reviewing the Federal telecommunications systems to verify the legal utilization of spectrum [4; 5; 38].

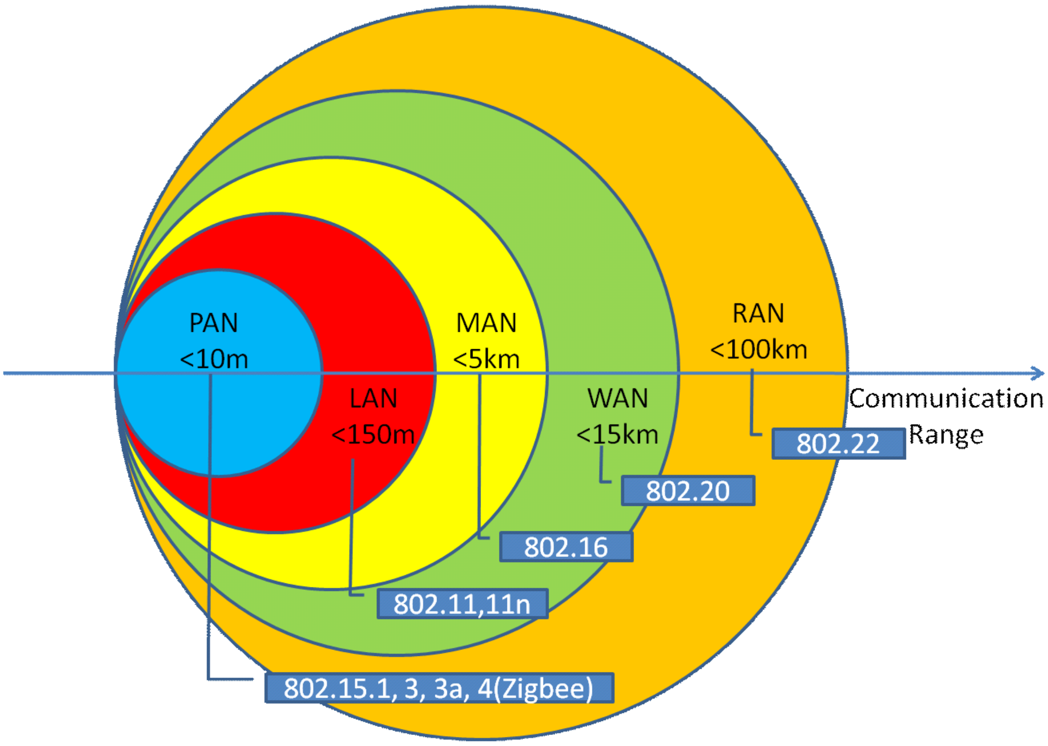



Fig. 2.1: Different types of communication networks

### 2.3.2 Japan

In Japan [51], all of the activities related to spectrum issues as RF spectrum allocations and assignments are decided by the Ministry of Internal Affairs and Communications (MIC) under the assistance of government, non-government parties and policy experts. By ensuring equitable and efficient use of radio waves, with the aim to promote the public welfare, MIC has been managing the radio frequency Telecommunications Law. And upon determining the standards and frequency management policies, to ensure transparency, the MIC solicits public comments to the spectrum allocation advisory council [37].

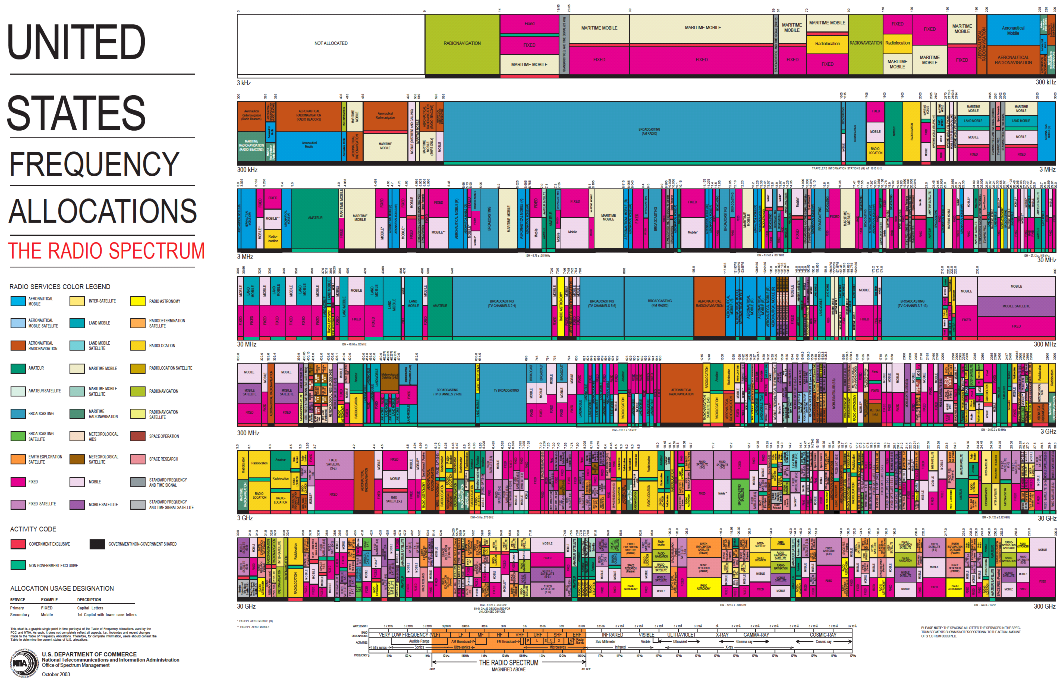



Fig. 2.2: Spectrum allocation in US [38]

### 2.3.3 Canada

A government department called Industry Canada has responsibility in establishing and issuing RF allocations and assignments authorities under the corporation of the Department of Industry Act, the Radio Communication Regulations in Canada. This party also has to develop plans for the new telecommunications systems and certify that there are still spectrum available for each slots they assign.

### 2.3.4 United Kingdom

In the UK [32], to dual with the issues for civil uses, the system is a bit different with other countries. There are two parties, one is Ofcom and another one is a committee organized by UK government. Ofcom has a mission to allocate the spectrum use, authorize the regular and negotiate

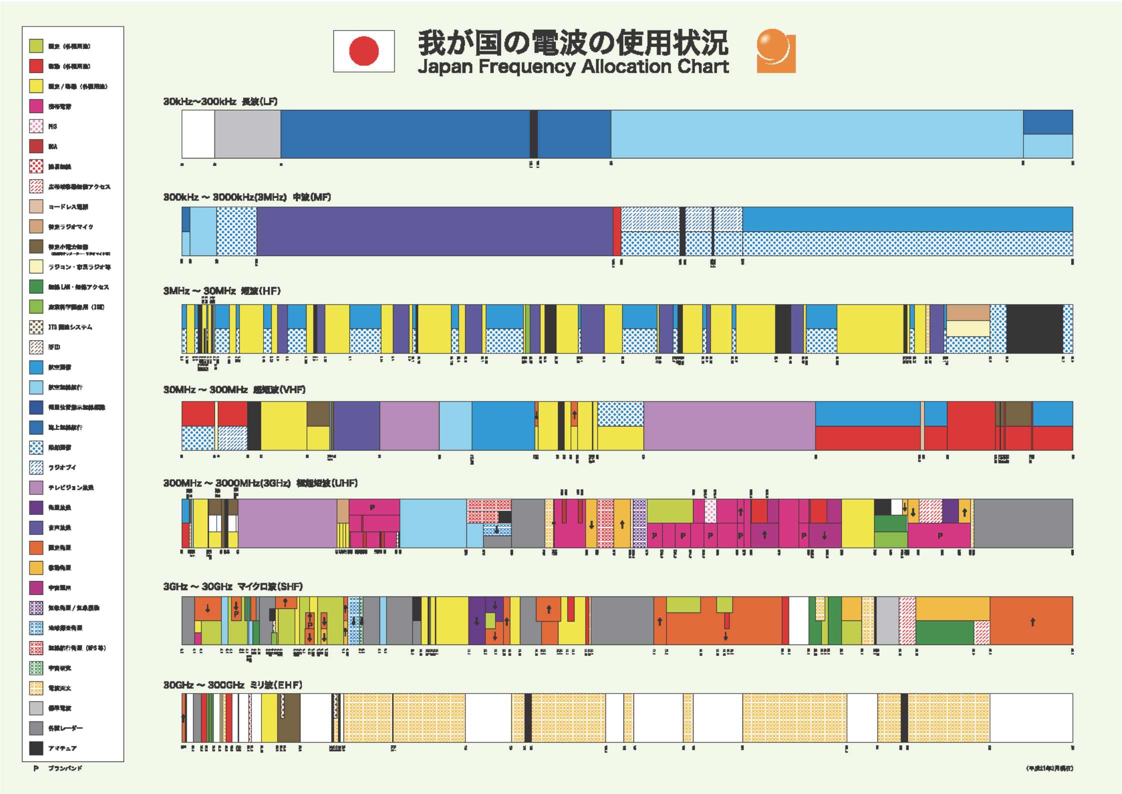



Fig. 2.3: Spectrum allocation in Japan [37]

as an international representation when it comes to a global decision in making rules.

### 2.3.5 France

In France, the Agence Nationale des Frequences (ANFR) is responsible for the spectrum allocation and policy decision. This agency is one of the offices of the French government. This agency covers the spectrum allocation and investigation, spectrum planning and assignments, domestic or international negotiations, etc.

### 2.3.6 Spectrum Allocations in US and Japan

Fig. 2.2 shows spectrum allocation in the U.S.[38] and Fig. 2.3 shows spectrum allocation in Japan [37]. In Japan, the Japanese government contributes to the spectrum assignments by allocating the spectrum for 3G mobile many times until now. The ministry of Internal Affairs and Communications is the main agency which is responsible for matching the operator candidates to the right spectrum segment. Though the spectrum allocation is not the best one in Japan now, as many experts already claimed but, compared with other countries, Japanese government contributed so far in both people and fund aspect.

## 2.4 Whitespace and Spectrum Sensing

Whitespace are frequencies allocated to a broadcasting service but not used locally at particular time in a particular location.

There are two main kinds of Whitespace. One is the free band (band-plan) rendered between the used frequency band to avoid the interference. We also call this space as a guard band. But nowadays, when modulation and demodulation technology come to development, we don't need a very wide range to transmit the signal at all, then this guard band seems unnecessary.

Another whitespace [1] is the really unused bands exist because of the lack of utilization. This is different with the guard band that has the technical reasons, this kind of whitespace appears due to the change of technology. It causes a lot of spectrum band vacant and abandon while a large number of wireless services are under scarcity of spectrum(as expressed in Fig.2.4).

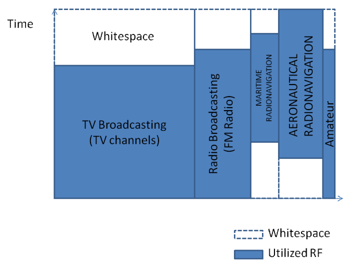



Fig. 2.4: Whitespace(unused spectrum band)

# Chapter 3

# Related Works of Spectrum Measurement in Other Countries

Spectrum Measurement Framework is a framework designed to measure, characterize and model spectrum utilization. There have been several surveys so far. In this section, we describe the following surveys of spectrum measurement and show what is the different we have done in our measurement to keep up with the environment in Japan and to preserve the accuracy of data collection in our measurement in next section.

## 3.1 Spectrum Measurement Framework

### 3.1.1 A Framework for Radio Frequency Spectrum Measurement and Analysis

The purpose of this system is to measure, analyze and model the spectrum utilization [41] . This framework used a sharing database schema that can handle with a large amount of data for a long term spectrum data usage and management. The framework 's implementation also supports spectrum data sharing among researchers (Fig. 3.1). The system is a combination of 4 steps: definition, collection, storage and analysis. These four steps are covered with a central archive technology (Fig. 3.2).

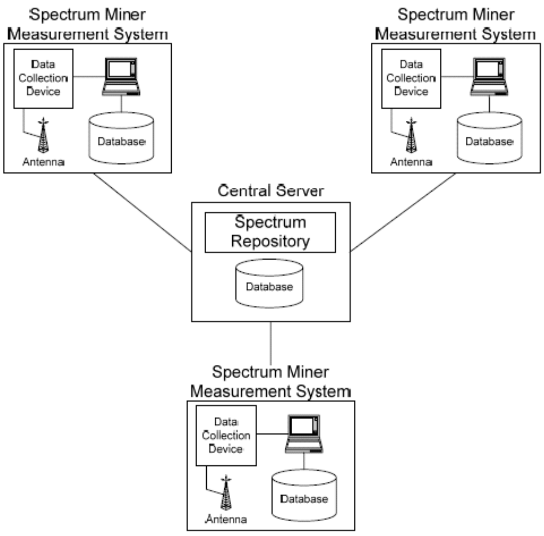



Fig. 3.1: Framework Structure [41]

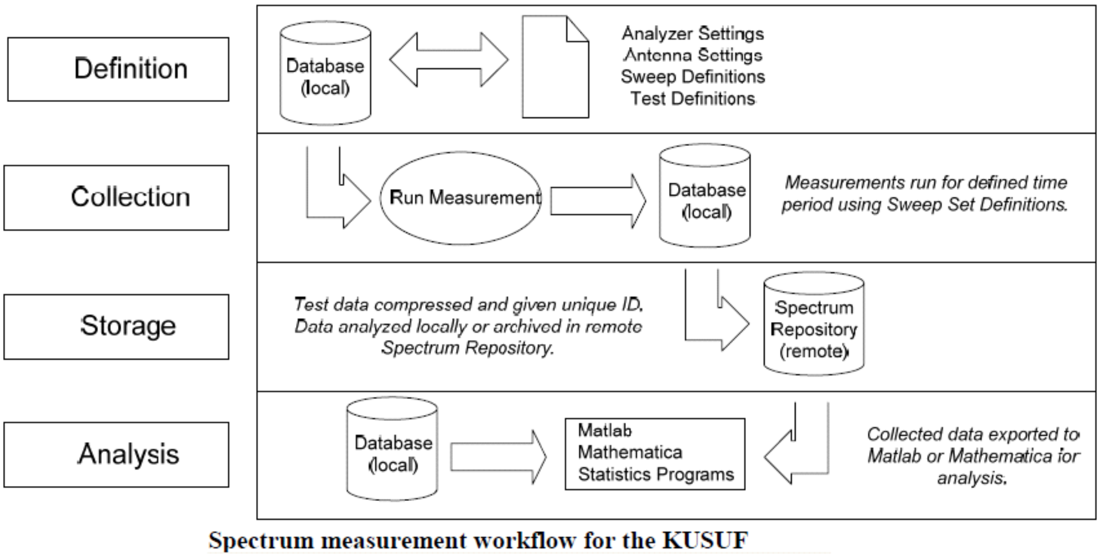



Fig. 3.2: Framework Flow [41]

### 3.1.2 A Study on Radio Information Management for a Distributed Spectrum Sensing (RCAST, The University of Tokyo)

In this Distributed Spectrum Sensing System [49; 50] , the RF data will be loaded from the front-end of a sensor node by a Collector and data will then be stored in a separated HDD by the Storage System (Fig. 3.3). Users who want to use the data can access to the data in the HDD by the central server. This system also includes a constraint of transmission capacity and storage volume concerning speeding up data transmission and mitigating the storage limitation of devices.

### 3.1.3 Initial Consideration of a Time-series Sensor Database System

The concept of this system [50] is to use a Time-series Sensor Database system, instead of using Stream Data Processing (SDP) which is very slow and not adequate for dealing with a huge amount of stored sensor data. In this system, the time-series sensor data will be stored in different Node Database (Fig. 3.4). When users use the application to retrieve data, the Query Manager will join the corresponding node from Meta Database with the right node in the Node Database.

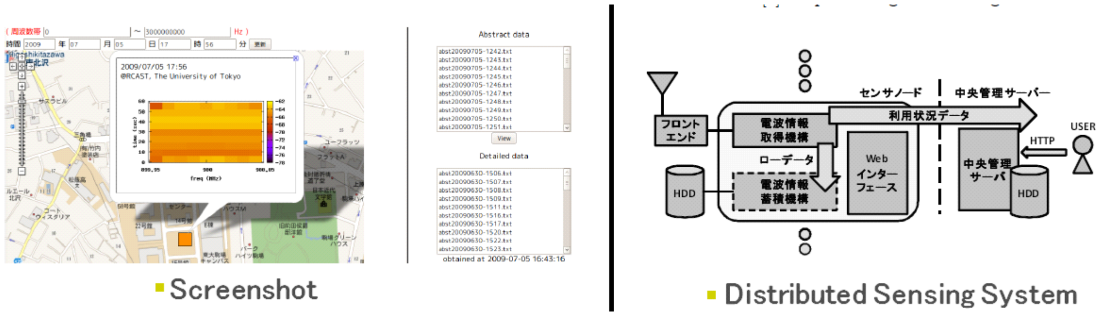



Fig. 3.3: RCAST Framework Structure [49]

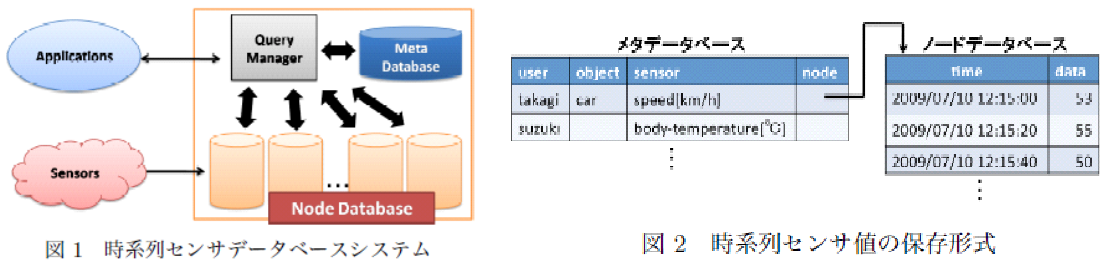



Fig. 3.4: Framework Structure [50]

### 3.1.4 Summary

- All of the related works above have some concepts and goals that are the same. First, they want to collect the RF data, store and share with other people to find the utilization and the effective models of RF spectrum. They have to deal with a huge amount of RF data, that 's the reason why a distributed system to process all of these data is necessary.
- However, every system or framework has its own function, including input sensor data, the processing strategy and the output data format. The parameters of different system will be different. It 's the most significant features of these frameworks, namely, " spectrum model ". The measurement locations and the devices are different, therefore we should propose a common data format to deal with this problem. Because without a common data format, it 's very difficult to exchange data with each other, a problem of data modeling.

- In order to improve the understanding of spectrum utilization effectively, especially for exploiting how much white space could be obtained, a visual system for spectrum is necessary.

## 3.2 Spectrum Utilization and Measurement Trends

There are two main spectrum measurement trends to collect data for spectrum utilization analysis. One is dynamic spectrum measurement and other is static spectrum measurement. In dynamic trend, researchers usually use vehicles containing the spectrum device to collect data while moving. In the other hand, researchers who use static method only put the spectrum device at some specific locations and collect data at one location only.

### 3.2.1 Dynamic Spectrum Measurement

CRFS, on behalf of Ofcom, has deployed 'Capture of Spectrum Utilization Information using Moving Vehicles 'project. This project was run from April 2008 to March 2009 and was a challenge for researcher to collect and monitor the spectrum data along UK by using moving vehicle fleet.This measurement covered a wide range of frequencies from 10 MHz to 5 GHz.The amount of data exceeded 4.2 million individual spectrum measurements, and occupied more than 200 GBytes of data. In all more than 65,000 km of driving in all parts of the UK contributed to the database.

The equipment is RFeye which was contained in standard car roof boxes. RFeye consists of 3 antennas collecting 3 different kinds of data. The parameters of 3 different antennas are shown in Table 3.1.

- Measurement Parameters

  The main purpose of the measurement was on collecting broadband data using the omnidirectional antenna(Scan 0) from 10MHz to 5GHz. However, data was also collected over the 800 MHz to 1 GHz frequency range from either side of the vehicles(Scan 1 and Scan 2). The objective of collecting the data from Scan 1 and Scan 2 data was to evaluate the usefulness of this in identifying specific transmission sources or base station. It can be obtained by comparing the relative power of a defined signal received by each antenna, an initial estimate

Table 3.1: Measurement Parameters

| Parameter | Detail |
|---|---|
| Freq. span | Scan 0: 10 MHz to 5 GHz (omnidirectional antenna) Scan 1: 800 MHz to 1 GHz (left directional antenna) Scan 2: 800 MHz to 1 GHz (right directional antenna) |
| Freq. resolution | 256 points (variable 128 to 4096 points) |

of the position of its source can be obtained and built up with each new vehicle position. By taking this information, and processing a number of samples from different locations as the vehicle moves down the road (and perhaps around the source), a better estimation of the signal source location can be achieved.

- Data collection process

  Data collected from each vehicle was automatically logged by the RFeye spectrum monitoring node with the following in one data set: unit ID, time (GPS derived), location (GPS derived).

  Data once collected will be logged into high-capacity USB memory sticks, and then the data subsequently loaded into the CRFS database for analysis.

- Data collection restrictions

  The same as in Japan where we cannot collect the RF spectrum data in some sensitive places, for example around the Emperor Palace. In UK, there are some places where the authorities do not want RF spectrum monitoring to be taken place for security reasons. Therefore, the CRFS spectrum management tool has a facility that will accept a list of GPS coordinates together with an exclusion zone radius (the zone that the data cannot be collected) around those coordinates to prevent data processing. A list of secure sites has been included in the CRFS spectrum management software and this list will be used to make the data in this coordinate being invalid.

- Analysis process

  The CRFS spectrum management provide the management of data and visualize the RF spectrum data in various ways including area processing, peak power over area, mean power over area, peak(mean) spatial utilisation over area, frequency processing, peak(mean) power over frequency, total integrated power over frequency, peak(mean, total) spatial utilisation over frequency.

### 3.2.2 Static Spectrum Measurements

1. The same with spectrum power measurements in 2G and 3G cellular phone bands during the 2006 football world cup in Germany [15] , spectrum survey in Singapore [16], in the U.S. public safety band for opportunistic spectrum access [17] and others [39; 42] , the Chicago project consisted of deploying a high dynamic range spectrum measurement system, a data collection and processing system and conducting spectrum occupancy measurements in all bands between 30 MHz and 3,000 MHz.

   The measurements were held in Washington, D.C., and New York City over a two-day period. These studies will indicate what bands have low utilization, when the bands should be used and these studies are crucial in developing new dynamic spectrum access(DSA) such as cognitive radio. The first goal of this project is to perfome a band by band measurement of the spectrum occupancy between 30 MHz and 3 GHz. This would provide information on:

   - What bands have low (and high) utilization,
   - What types of modulation , data rates, equipment characteristics, where and when, mobile or fixed device,

- The existing user's aggregate equipment parameters (signal bandwidth, modulation, power levels, etc),
- The number and location of transmitters in each band and
- The background noise level.

These parameters are necessary in DSA-deployment process used in CR technology. Some parameters as the utilization of spectrum bands can be directly known but some other parameters need to be interpreted in the analysis program.

- Measurement Locations and Equipment

  The measurement location for this study was the top of the 22 story IITRI Tower located at 35th St and South State Street roughly three miles south of the Chicago Loop, the business center of the city.

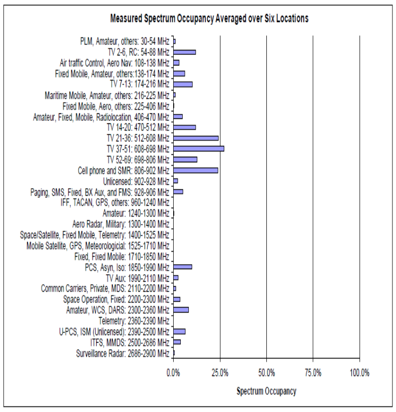
  The equipment used for measurement in this study consisted of a spectrum analyzer, a high linearity pre-selector, an omni-directional discone antenna, a small log periodic array (LPA) for frequencies greater than 1000 MHz, and a laptop computer. The antennas were connected to the pre-selector. A long RF cable, a control and power cable, and a pre-selector power cable connected the pre-selector box to a shielded Faraday cage enclosure . The shielded enclosure contained a 3 GHz spectrum analyzer, a laptop computer, and power supplies.

- Data Collection and Calibration.

  A pre-selector composed of filters, RF switches, preamplifiers and programmable RF attenuators was used to improve the measurement sensitivity and dynamic range. The upper path is used for signals from 30 MHz to 1000 MHz, and the lower path is used for 1000 MHz to 3000 MHz. The pre-selector was located at the base of the antennas and sealed in a plastic bag for weather protection.

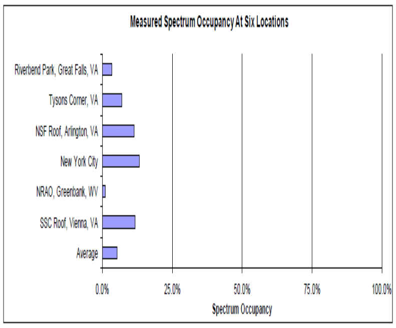
2. The project consisted of building a high dynamic range spectrum measurement system, a data collection and processing system and conducting spectrum occupancy measurements

at six locations.




**Spectrum occupancy in each band averaged over six locations.**

Fig. 3.5: Measured Spectrum Occupancy Averaged over Six Locations




**Spectrum occupancy at each location.**

Fig. 3.6: Measured Spectrum Occupancy at each location

The goal of this study was to determine the spectrum occupancy in each band at multiple locations. The bar graphs in Fig. 3.5 and Fig. 3.6 provide the average of the occupancy in each band and at each location. The average occupancy over all of the locations is 5.2%. The maximum occupancy is 13.1% (New York City) and the minimum occupancy is at the National Radio Astronomy Observatory (1%). These low occupancy levels show that there is significant spectrum for a Dynamic Spectrum Access Radio (DSA) to provide service.

In rural areas, there is enough unused spectrum for a DSS Radio to provide ten times the capacity of all existing wireless devices together.

### 3.2.3 Conclusion

- UK-wide frequency usage map of BBC DAB multiplex (225.648 MHz) is shown in Fig. 3.8 and, the spectral data and spectrogram data are shown in Fig. 3.7.

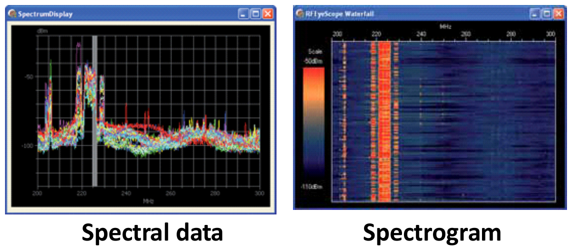



Fig. 3.7: Spectral dataand spectrogram data(BBC@225.648 MHz)

Fig. 3.8 shows that, on average the use of BBC@225.648 MHz is very high almost all of the time. Because the orange color stands for a high level usage of this spectrum. And we also can check this information from the spectral and spectogram data (Fig. 3.7). But when we take a look at other spectrum bands from 200MHz to 210 MHz or from 230 MHz to 300 MHz, we can see that they are vacant all the time. This is "white-space" that a cognitive technology could use.

- The result of measurement held in Chicago showed that the spectrum occupancy for the two day measurement period was 17.4%. It means that 82.6% of this completely allocated spectrum was unused for this period. This information is displayed in bar graph form in Fig. 3.9(left side) graphically showing the actual utilization of the spectrum over the various bands in Chicago and the real spectrum signal graph is displayed in Fig. 3.10 . This figure shows a vacant Whitespace of spectrum (unused spectrum) at 16:17:37 of the TV channel 4.

  The goal of this study was to determine the spectrum occupancy in each band at multiple locations. The bar graphs in Fig. 3.9(right side) provide the measured occupancy for each

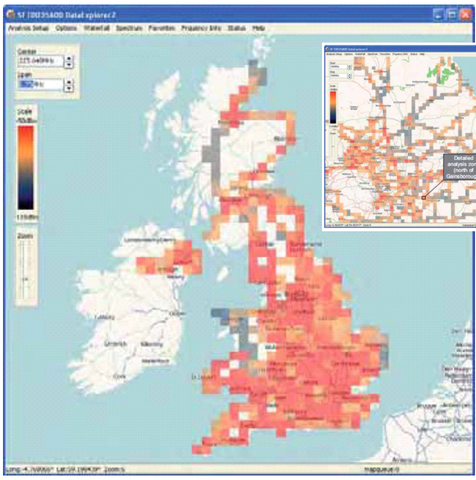


Fig. 3.8: UK-wide frequency usage map(BBC@225.648 MHz)

band for Chicago and for comparison New York City, arguably two of the most intensive users of wireless technology in the United States. As noted earlier, the over-all usage for the cities were 13.1% for New York and 17.4% for Chicago. These low occupancy levels show that there is significant spectrum for a DSA radio to provide service. In rural areas, there is a great deal more spectrum available, enough in fact to allow a DSA based radio to provide ten to one hundred times the capacity of all existing wireless devices in those regions.

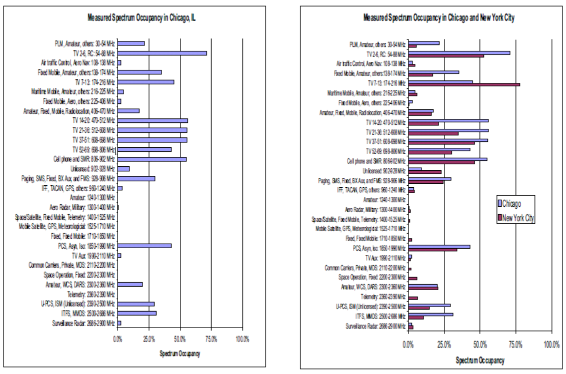



Fig. 3.9: Measured Spectrum Occupancy in Chicago and New York City

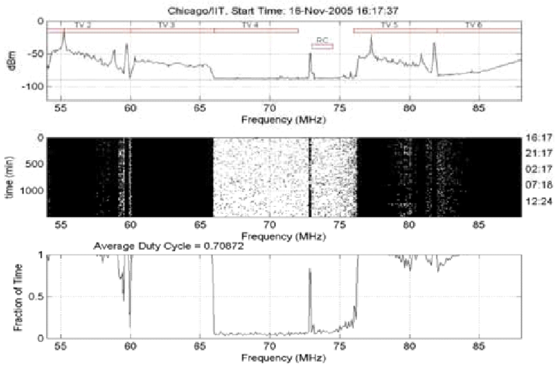



Fig. 3.10: Measured Spectrum Frequency in Chicago and New York City

- For those areas where a more detailed picture of spectrum usage is required on a regular basis, the use of static nodes(fixed nodes), is worth consideration. Dynamic nodes(mobile nodes) has some advantages and disadvantages and fixed nodes has so on as shown in Table 3.2 and to achieve the desired balance of geographical and spatial utilization measurements a hybrid (fixed and mobile) monitoring system is recommended, ideally with both networks using a common architecture and analysis methodology.

Table 3.2: Comparison Between Mobile Measurements and Fixed Measurements

| | Mobile Measurements | Fixed Measurements |
|---|---|---|
| Geographical Coverage | Excellent | Potentially good if large numbers of nodes used |
| Costs | Low | High-assuming the cost of fixed devices |
| Flexibility of location | Excellent | Poor-difficult to move |
| 24/7 operation | Dependant on carriers | Excellent |
| Control | Likely poor | High |
| Noise | More | Less |

# Chapter 4

# SpectrumMap System

Monitoring the spectrum utilization and capturing the available spectrum bands is the groundwork for the CR (Cognitive Radio) technologies. Because the spectrum management has been a politically as well as technically sensitive issue, it is usually very hard to access the open data of real spectrum usage. In this sense, we believe grass-roots data collections are important. For these collections to be worthy of spectrum investigations, we need to reduce several noises inserted during monitoring because of the diversity of measurement environments. In addition to this, data visualization must be provided end users with intuitive understandings about the results of the analysis. This chapter presents the basic requirements for the data format of grassroots spectrum data collections and the visualization process using Virtual Earth platform [26] to be accessed from the public. We then show a prototype system named SpectrumMap to aim at visualizing location-based or time-based information of spectrum resources and promoting a research on the future CR solutions with user-friendly interfaces. Integrating spectrum analyzer, GPS (Global Positioning System) and the Virtual Earth platform, a mashup of spectrum utilization is demonstrated.

## 4.1 Introduction

The radio wave is a precious common property. There is a springing-up argument of the effective use of frequency bands. However, little knowledge is known on the spectrum utilization, due to the insufficient public documents. Building a map from the point of spectrum usage would provide us with a revolutionary change of our comprehensions about the notional electric waves. In addition, an overall investigation and study of spectrum occupancy would recommend us an appropriate action to improve the frequency assignment. A large volume of spectrum database would provide potentially an early hint to spectrum utilization and contribute to spying candidate bands for CR technology.

The evolution of technology provides us with significant data captured in real time without inspecting stale data records. People tend to obtain information rapidly and joyfully with easy comprehension for underlying data rather than spending time and energy to deal only with numerical results. The data visualization can meet these challenges, mimicking people 's thinking pattern and endowing end users qualitative understandings. The service integration has boosted the development of content aggregation technologies, and data visualization technology is a growing trend in consumer and business environment. The Virtual Earth platform of Microsoft allows users to customize their visualization systems using mashup technology, interacting with topographically-shaded street maps, which embodies a mass of and built-in constituents such as universities, hospitals, subway stations, sight spots, tourist tracks, etc. The map control [25] of Virtual Earth platform can make sites discoverable with accurate map features, such as 2D and 3D city models and road model, and contribute to visualizing and gaining clarity and insight on our numerical data [24].

SpectrumMap [20] is a grass-roots spectrum data collection mashupped onto Virtual Earth, which we expect to provide a fundamental database for CR technology. To realize spectrum visualization, the system needs to provide not only grass-roots data collections but also a flexible and userfriendly interface design. However, this was difficult because spectrum measurement is usually done with propriety measurement devices and visualization platform [9] or just with general measurement devices without a visualization platform. The closed architecture in the former case is inadequate for the grass-roots data collections since everybody must be able to access the spectrum database. As for the latter case, we have to build an internet accessible server to provide collected data to the public visually. In our research, we overcome this by introducing Virtual Earth platform for grass-roots spectrum data collections to be accessed flexibly, noting the requirements for the data format of grass-roots spectrum collections.

The remainder of the part is organized as follows. Section 4.2 presents the definition of SpectrumMap and its requirements. In Section 4.3, we give a description about the prototype of the SpectrumMap, including spectrum data collection, distributed data processing, and the detail GUI of SpectrumMap. Section 4.3.5 concludes this part.

## 4.2 SpectrumMap and Its Requirements

SpectrumMap is a mashup database to visualize the spectrum utilization at each geographical location, founded on the collection of spectrum usages as well as the mashup technology of Virtual Earth map control. A possible usage is to investigate the spectrum utilization at a certain location and at a certain time, e.g., showing the spectrum during a peak traffic period around Tokyo Tower on some Sunday afternoon. The spectrum visualization will be effective to improve our comprehension of what to expect in our wireless environment at deploying short-range communication systems like IEEE 802.11b/g/n, which meet with the peak system capacity. The spectrum data should be collected in a grass-roots manner due to its shortage, which requires the scalability of the data description format on account of large volume data sets. The data include the average frequency occupancy over all the locations, its maximum / minimum, and signals which cross a power threshold in given locations. In addition, an overview of wide area spectrum utilization requires a large number of data formats at multiple locations, such as longitude, latitude, frequency value and power, which demands SpectrumMap to have high scalability and flexibility for data storage and analysis.

SpectrumMap should satisfy the following requirements.

Spectrum visualization modes: The basic data element of spectrum information is 6-dimensional, including time, location, frequency band and spectrum intensity. The following functions should be installed to visualize a more easy-to-understand spectrum. A) Alter the measuring location and get the 3D spectrum at each position, with time (second), frequency (GHz) and spectrum intensity (V/m); B) Keep the measuring location fixed, while capturing the other 3D variations, i.e. time (second), frequency (GHz) and spectrum intensity (V/m); C) Given the desirable or specified value of spectrum intensity (V/m), then hunt all the satisfied cases expressed by the other 5D spatial elements, i.e. location, time (second) and frequency band (GHz). D) Given the desirable or specified values for both spectrum intensity (V/m) and time (second), then hunt all the satisfied cases expressed by the other 4D spatial elements, i.e. location, frequency (GHz).

Location Identification: Even though Differential GPS (DGPS) is used, the accuracy of GPS is influenced by many factors, such as GPS devices, multipath effect, topographical changes, poor satellite reception and so on. To avoid multipath error, we should design the data format to characterize building density, since GPS signals would be reflected from nearby objects before reaching the antenna. Other kinds of data formats, such as GPS devices used, satellite view and postal address of the monitoring location, should be used as metadata to compensate the GPS location. Another important parameter is altitude, since the SpectrumMap would be able to illustrate spectrum behavior according to the features of 3D scenes (e.g. building floors, elevators) and describe the difference of radio waves along with the altitude. Due to the invalidity of GPS in indoor environments, the data format should also include the building height in the altitude or the floor number.

The Diversity of Radiation Meter: The specifications of the radiation meter should be written in the metadata, which could be a model name of the device. A radiation meter may be composed from antennas and a spectrum analyzer. In this case, the specifications or model names of these devices should be included to declare the radiation meter consisting of these devices. The information such as directional / omnidirectional antennas, RBW (resolution bandwidth), the frequency stability of a spectrum analyzer could be included if the model name is not enough to distinguish them.

Time synchronization of location information and spectrum data: In some environments, since the measurement tools are separate devices, the time synchronization among these devices is required.

More interactive supplements to show numeric data: It is insufficient to support spectrum information related with CR only by visual graphs. The digital raw data should be obtained as supplement, e.g., the visual graphs should be quick to indicate end users explicit and clear values of frequency band, time and spectrum intensity.

Set triggers for real-time data of spectrum: Visualize spectrum resources in a real-time manner and set triggers that could indicate the optimal spectrum bands and wireless communication mode to CR users. The data should be described as metadata in XML (Extensible Markup Language) to enhance the scalability and robustness of the SpectrumMap.

## 4.3 Prototype of SpectrumMap

The spectrum map is designed in a web-based access form to be flexibly interacted with the public with authority permission and it contains three basic processes, data collection, data processing and data visualization / analysis. A brief architecture is given in Fig. 4.1.

### 4.3.1 Data Collection

Considering building a huge spectrum database, we proposed the prototype of the spectrum data collection to be grass-roots mode, which would enable related researchers to exchange or share spectrum information more effectively and agilely. Measurement noise during this process is a key factor due to multiplicities of measuring methods. Basically, RF monitoring is realized by spectrum analyzer with additional aided tool like GPS (Global Positioning System) for spatial-temporal synchronization. Narada SRM-3000 (Selective Radiation Meter [29]) is adopted in our measurement to evaluate the frequency electromagnetic fields since it can preserve the successive variation of the absolute value of E-field intensity in time axis and a USB-GPS receiver is integrated with a mobile PC capturing geographical information by time stamp linked with the measured RF contents.

Note that we expect grass-roots data collections, which could also be comprehended according to the system architecture. It is obvious that we facing several challenges in this process.

・Validity of spectrum measurement: Instabilities of RF measurement would have an impact on the real situation of power distribution of spectrum, and this could be caused by distinct measurement modes, such as fixed or mobile measurement, including diversity of used spectrum analyzers and antennas. Namely, the collected data accuracy should be guaranteed to a certain extent, which is a crucial issue especially under the scenario of grass-roots data collection.

・Compatibility of spectrum metadata: In order to endow the platform the quality of being agile to support different spectrum metadata, we should provide effective data processing for absorbing varieties existed within measured RF contents before visualizing them by map control. In other words, XML files should be designed as middle component to enhance the scalability and robustness of the spectrum map.

### 4.3.2 Distributed Data Processing

Hadoop Distributed File System (HDFS) is a distributed file system designed to run a distributed processing on commodity hardware. Hadoop has some significant differences with other existing systems, though it also has some basic features that other existing distributed file systems have. First, HDFS is simplified, highly fault-tolerant and is designed to be deployed on low-cost hardware. Second, HDFS provides high throughput access to application data and is suitable for applications that have large data sets. There are two processes to do with the HDFS, the Map process and the Reduce process, which consist of one job tracker and one task tracker.

In our system,

・The raw data of RF spectrum will be copied and stored in the HDFS Storage in a specified

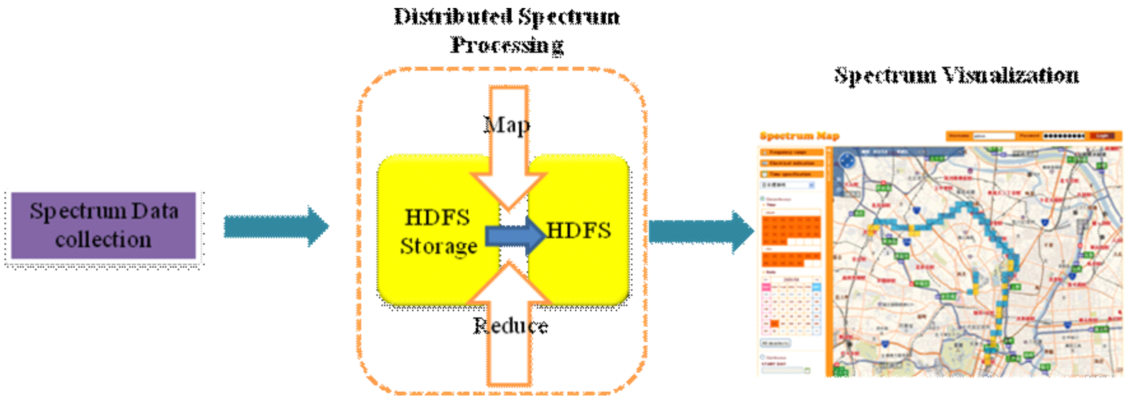



Fig. 4.1: System architecture of the spectrum map

format. The specified format is defined as follow.

All individual data files including a certain observational data during a day are assumed to be a text (.txt) form. The first line is composed by the file header with the index to the relevant data, and the line since the second line corresponds to the data of the observation time respectively.

The index contained in the file header consists of byte offset in the file to the first character of the line where the value at the second in which the observation time is indicated and the data of the time are described. All time where the observational data exists is delimited by the comma and this index is arranged.

The line that shows the data of every the second starts from the header line and the colon following it, is delimited the electric power data observed at that time by the comma, and continues. As for the line header, the number of data and the meta data are delimited by the comma respectively and composed at frequency intervals between the frequency of a number of seconds, latitude, and a longitude and the first data and each data. The meta data has the registration date with the user. All lines are divided according to single line-feed character (
n).

・ The data then will be processed by Map and Reduce and stored in the output folder of HDFS. The output folder of HDFS has the index key so that the data will be easy to retrieve.

・The processed data then will be used to plot on the map or to be analyzed by CR researchers.

・ A group of clusters in NII (National Institute of Informatics) was adopted to deploy our spectrum map system (Fig. 16). Because we couldn 't access to NII side by normal access except the ssh connection. We use one machine in NII as a tunneling server so that we could communicate with all of the other machines in NII, then we set up a server in our lab. The server in our lab which we called Hongo side server will serve as a web server and the client from all over the world could access to our hadoop nodes through this web server. The server was allocated a global IP address and people can access to this web server every time they want.

### 4.3.3 Principle Functions

We gave the basic definitions of the calculation algorithm for the maximum and minimum value of E-field intensity, average E-field intensity, and the average E-field utilization.

- Maximum and minimum value of E-field intensity

$$X_{ij} = \max(X_{ijk}), i \in (1,n), j \in (1,m), k \in (1,l) \tag{4.1}$$

$$X_i = \max(X_{ij}), i \in (1,n), j \in (1,m) \tag{4.2}$$

$$X_{\max} = \max(X_i), i \in (1,n) \tag{4.3}$$

- Average E-field intensity

$$X_{ij} = \frac{1}{l}\sum_{k=1}^{l} X_{ijk}, i \in (1,n), j \in (1,m), k \in (1,l) \tag{4.4}$$

$$X_i = \frac{1}{m}\sum_{j=1}^{m} X_{ij}, i \in (1,n), j \in (1,m) \tag{4.5}$$

$$X_{ave-i} = \frac{1}{n}\sum_{i=1}^{n} X_{ij}, i \in (1,n) \tag{4.6}$$

- Average E-field utilization(Fig. 4.2)

$$X_{ij} = \frac{sumvalueofRFabovethreshold}{allofRFvalue} \tag{4.7}$$

$$X_i = \frac{1}{m}\sum_{j=1}^{m} X_{ij}, i \in (1,n), j \in (1,m) \tag{4.8}$$

$$X_{ave-u} = \frac{1}{n}\sum_{i=1}^{n} X_{ij}, i \in (1, n) \quad (4.9)$$

$X_{max}, X_{ave-i}, X_{ave-u}$ is maximum value, average E-field intensity and average E-field utilization respectively

k: number of data selected from start-frequency to end-frequency for one scan(from 1 to l)

j: number of scan fo one point(from 1 to m)

i: number of measurement points in one grid on the map(from 1 to n)

### 4.3.4 GUI of SpectrumMap

We use the map control of VE (Virtual Earth) to visualize spectrum usage by interactive web applications based on ASP.Net of Microsoft Company (Fig. 4.2). ・ Measurement route We collected data by train around Yamanote Line and subway ranged from Ikebukuro Station, Tokyo Station, Hongo - Sanchome Subway Station and the hongo campus of the University of Tokyo (Table 4).

・ GUI components of the spectrum map The Spectrum Map consists of two main panels, the control panel and the visualized panel which contains the map (Fig. 17). The visualized panel use Visual Earth of Microsoft and was overlaid by a transparent color tie layer which shows the power of the RF spectrum of the corresponding area on the virtual earth map. The corresponding area was obtained by associating the coordinates of the virtual earth map with the GPS information we got from the real measurement.

The control panel consists of

A) The method of calculation: Avg: the average value of spectrum intensity. Max: the max value of the spectrum intensity. Sum: the sum value of the spectrum intensity.

B) The Frequency Range pop up: This function was included in the control panel so that user can choose the range of frequency they want to know. Typical frequency bands include TV bands, mobile phone, etc.

C) The intensity level: The bar was painted by different levels of color from white to red as shown. The red color shows the most strong spectrum power while the white color expresses the


Fig. 4.2: Average Spectrum Utilization at Tokyo station from 2.4GHz to 2.6GHz at 14:00:00 on Sat.

”white space ” of the frequency bands or the frequency that we haven ’t measured yet.

D) Date field: Users can choose the date they want to learn by selecting the begin and the end of the date range or choose from the calendar below.

E) The calendar panel: Using this panel, users can choose the date easily.

F) Spectrum View button: This button is used to decide to show the spectrum intensity level on the map.

・Possible contribution of SpectrumMap to CR researchers From this map CR researchers could easily come to understand the areas where white space appears. With the varieties of the value to be calculated (avg, max, sum), the CR researchers could learn about the power distribution of RF, which would benefit the deployment of CR networks.

### 4.3.5 Summary

Data visualization makes it possible to provide beneficial solutions for the spectral resource allocation. In this chapter, we have discussed the details of SpectrumMap system that would visualize spectrum resources, based on grass-roots data collections, by the Virtual Earth map control in time-varying and space-varying domains.

# Chapter 5

# Data Description Format for SpectrumMap

" Cognitive radio "is emerging as a promising technology to cope with the spectrum scarcity as well as with the spectrum underutilization problem in the next generation systems. There have been several previous broadband spectrum surveys [25, 27] up to now, but they all had their own specific data formats and the usage of collected data was limited by them. Additionally, the amount of spectrum data is very small and insufficient for a world-wide cognitive radio technology. Hence, for long term spectrum monitoring studies, it would be crucial to develop a new spectrum monitoring system that can handle a huge amount of data in different data formats from many different kinds of measurement equipment. This requires a universal data exchange format to be defined. In this paper, we propose efficient criteria for spectrum meta data, using typical XML. We briefly revise fundamental features of a data exchange form in section 4.1, and the way the state-of-the-art WGS84 Geo Positioning is implemented as a standard XML vocabulary for geo-location in section 4.2. Finally, in section 4.3 we propose a data exchange format for RF spectrum map based on XML schema.

## 5.1 RF Spectrum Data Exchange Format

The RF spectrum data collected from the surveys or projects included millions and millions of records, and the features of data varied from measurement to measurement, of which the observers used. For instance, in the project of " Capture of Spectrum Utilization Information using Moving Vehicles " [24], CRFS (on behalf of Ofcom - British Office of Communications) equipped a fleet of vehicles travelling in all parts of the United Kingdom to monitor and collect details of spectrum usage over a wide range of frequencies from 10 MHz to 5 GHz. The amount of data exceeded 4.2 million records and occupied more than 200 Gigabyte of memory. The Chicago project in [25] deployed a high dynamic range spectrum measurement system to collect the data in all bands between 30 MHz and 3 GHz. The devices the two projects used are different, therefore the formats are also different. It is necessary for them to use a common RF spectrum data exchange format if they want to share their own data with each other.

The data formats of RF spectrum measurement devices include specific features of the devices that were used to collect them. But the common features include the minimum and maximum value of frequency, the resolution bandwidth, the threshold of the device and the scale of the data range. This information is very basic and necessary to specify and analyze the collected data. In addition, the information relevant to the owner, the type of the device and antenna, cable and calibration is also necessary but not an essential condition for the RF data format. Because these features vary from device to device, we should find an appropriate data exchange format and implement all the necessary information into this format so that every user can use it and share their data.

## 5.2 Using WGS84 lat/long Vocabulary in Our XML

WGS84 lat / long [39] is a very basic XML vocabulary used in Semantic Web service with a basic namespace for representing latitude, longitude and other spatial information (Fig.17). In our proposal, we used WGS84 vocabulary to express the location information because you can add some additional tags as location address to figure out the latitude or longitude afterwards in case you don 't have a GPS receiver. Additionally, every country has their own geodetic system, and it is necessary for them to convert the collected GPS data into the standard worldwide GPS system as WGS84 to share with other users from other countries. We also use Dublin Core [40] metadata element set to express owner and other basic information, and define our own namespace for the spectrum data.

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
        xmlns:geo="http://www.w3.org/2003/01/geo/wgs84_pos#">
  <geo:Point>
    <geo:lat>25.090</geo:lat>
    <geo:long>19.830</geo:long>
  </geo:Point>
</rdf:RDF>
```

Fig. 5.1: A basic standalone RDF

## 5.3 Our Proposal

First, we define vocabularies representing basic information of spectrum map data, the device information and other specification (ownership, date, time, etc). These vocabularies include the unique URIs in the namespace. Then, we publish our namespace so that every user can use it and share it with other users without any trouble in converting data into their own data format.

XML is one of the representations for the metadata because of its applicability to metadata representation, and an infrastructure that enables the encoding, exchange and reuse of structured metadata. Hence, in our proposal, we use XML data format with three namespaces as identifiers to

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
        xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
        xmlns:geo="http://www.w3.org/2003/01/geo/wgs84_pos#"
        xmlns:dc="http://purl.org/dc/elements/1.1/"
        xmlns="http://akg.t.u-tokyo.ac.jp/">
<Person>
 <name>Vasileios</name>
 <homepage dc:title="Vasileios's Spectrum map page"
              rdf:resource="http://danbri.org/"/>
 <based_near geo:lat="25.090" geo:long="19.830"/>
 <rdfs:seeAlso rdf:resource="http://akg.t.u-tokyo.ac.jp/specsMap"/>

 <!--more geoExtension-nonGWS84 RDF here, using any RDF vocabularies-->

</Person>
</rdf:RDF>
```

Fig. 5.2: GeoExtension-nonWGS84 Proposal

differentiate three separate sections of grouped data in the same document. The xmlns: attribute declares the namespace for an XML document. The attributes that declare namespaces can be placed in the root element of the document, as in this case, or in any nested element (Figs. 18, 19).

The format is divided into three separate sections: one for the ownership and GEO information listing, which will be identified by the geo and dc namespace, one for the information of measurement device, which uses the sd namespace prefix, and one for the data list, which is also identified by the sd namespace prefix. For instance, the prefix for the device type looks like this:

```
<sd:dev-type>SRM-3000</sd:dev-type>
```

An example of device information including device type, serial, firmware version, cable name, cable serial, antenna name, antenna serial, calibration is defined as in Fig. 20.

## 5.4 Summary

In this chapter, we propose a data exchange format, enabling data exchange of RF spectrum measurement. We believe this exchange data format is one of the efficient approaches toward spectrum data sharing.

The next plan of the work will be: Enhance the accuracy for hunting white space The current SpectrumMap system enables a user to decide threshold value for judging white space appropriately by themselves. A) In order to provide accurate white space, we plan to use a real time spectrum analyzer to make a 24-ours observation for multiple days, which would furnish us the minimum value of received signal power recorded in an observed band, then a proper threshold value would be yielded by setting a certain dB (3 6 dB) higher than the obtained minimum history value [41]. B) Due to noise uncertainty, fading, and shadowing, we plan to take into count cooperative spectrum measurements, which use multiple spectrum analyzers to take parallel measurement at adjacent locations and in the same time, to further improve the accuracy of white space by cooperative decision.

Implement effective data exchange format The compatibility of spectrum metadata requires the SpectrumMap system to provide flexible functions to handle the diversity of spectrum data exchange.

Validate spectrum data: Due to the diversity during the process of spectrum data collection, how to ensure the accuracy of obtained spectrum resources, especially under the environment of grass-roots data collection, is still a challenge. An effective security model needs to be addressed.

### 5.4.1 The Location Metadata for Spectrum Map

```
$GPGGA,043635.0,3501.538,N,13546.857,E,1,06,1.20,00056,M,034,M,,*5C
$GPGLL,3501.538,N,13546.857,E,043635.0,A*35
$GPVTG,351.8,T,358.3,M,000.0,N,000.1,K*4D
$GPGSA,M,3,01,04,07,13,10,24,,,,,,,2.48,1.20,2.16*01
$GPGSV,2,1,8,01,25,048,41,04,66,012,45,07,47,170,42,13,53,083,42*46
$GPGSV,2,2,8,10,19,246,41,24,38,310,42,11,47,000,,30,47,000,*47
$GPRMC,043635.0,A,3501.538,N,13546.857,E,000.0,351.8,250501,06.5,W*44
$GPZDA,043635.2,25,05,2001,,*52
```

Fig. 5.3: GPS information output from Pathfinder Pocket

Table 5.1: The Location Metadata for Spectrum Map

| **Data** | **ID** |
|---|---|
| Time | rdf:Time |
| Lontitude | rdf:Lon |
| Latitude | rdf:Lat |
| Altitude | rdf:Alt |
| Number of satelite | sat:Num |
| Satelite No. | sat:No |
| Address | rdf:Add |

# Chapter 6

# Long-term Spectrum Measurement

Cognitive radio was first proposed by Mitola J. III[28] then the RF spectrum has been regulated by principle organizations and the governments. There are some technologies used to occupy the free-band frequency including dynamic spectrum access (DSA) and the Cognitive Radio (CR). These technologies enhance a flexible transmission and reception of RF signal by software or hardware to utilize the unused or underutilized RF with incumbent licensed users and therefore solves the spectrum utilization problem and the scarcity of spectrum. In this paper, we show our dynamic long-term spectrum measurement and a statistical analysis of spectrum utilization using real data from multiple places in downtown Tokyo.

## 6.1 Measurement Requirement

To measure the entire long-range spectrum band, we followed some basic requirement that makes the analysis result preciser: (a) Focus on 5MHz bandwidth from 75MHz to 3GHz, with 2.5MHz sweep interval each. (b) E-Field intensity for each frequency should be calibrated absolute value, NOT relative value. (c) For each single sweep, a pair of corresponding GPS information and corresponding time should be recorded and attached. (d) Also, if possible the other RBW (less than 5MHz) of spectrum data from 75MHz to 3GHz with 2.5MHz sweep interval of reference data should be attached to be compared.

## 6.2 Measurement Equipment

To meet the above requirement, in our measurement, we used a hand-held selective measuring device SRM-3000 Spectrum Analyzer ( SRM-3000 Selective Radiation Meter ) to measure RF and microwave electromagnetic fields from 75 MHz to 3 GHz, and we used GPS USB (LS23068 Dongle $\mu$podR) to collect GPS information used in synchronizing afterward (Fig. 6.1 ). The resolution bandwidth of SRM-3000 is 5 MHz and the sweep time is from 200 [ms] to 1 [s] and the result type is ACT (the current actual spectrum value) for each frequency. The antenna is an E-field triaxial antenna with dynamic range from 0.25 [mV/m] to 200 [V/m] connected with the device by an N connector (50[$\Omega$]).

## 6.3 Measurement Construction

In our measurement, as shown in Fig. 6.2 USB GPS receiver was connected to a PC (Windows XP) to collect spectrum data at the same time with SRM-3000. First, the spectrum signals from SRM's omni-directional antenna were scanned and recorded continuously from 2.4[GHz] to 2.6 [GHz] with a sweep time from 200ms to 2s. On the other hand, simultaneously with the above operation, the USB GPS receiver connected to a PC received position information from satellites, and saved data as a text format in that PC. Then, in the later stages of analysis, these data will


Fig. 6.1: Measurement Equipment (Upper) SRM-3000 (Lower) USB GPS

be used with time sequence as a key to be synchronized with data from SRM-3000.

SRM-3000's data stored in the device is binary data, each measurement data for each day then will be converted to text format, and saved in local PC as a fundamental data for analysis. Fundamental data then will be transferred to SpectrumMap database and used to visualized on that map and analyzed in next phase.

## 6.4 Measurement Location

We tried to measure almost all kinds of distinctive data in Tokyo, and these are some criteria we followed to meet our goal, (a) Spectrum data should be observed in downtown, business district, the main terminal station, resident district. (b) At each location, making a continuous sweep of more than 10 minutes per session. (c) Choose three different distinctive times to measure for each observation location. (d) Choose three different distinctive days per week to measure for each observation location. (e) Multiple measurements should be held for each set listed above.

We chose Akihabara and Shibuya as the main two downtown area to measure because these are two typical place where a lot of people and communication devices are presented here. These two locations do not only represent one of the most crowded area in Tokyo but also the culture of

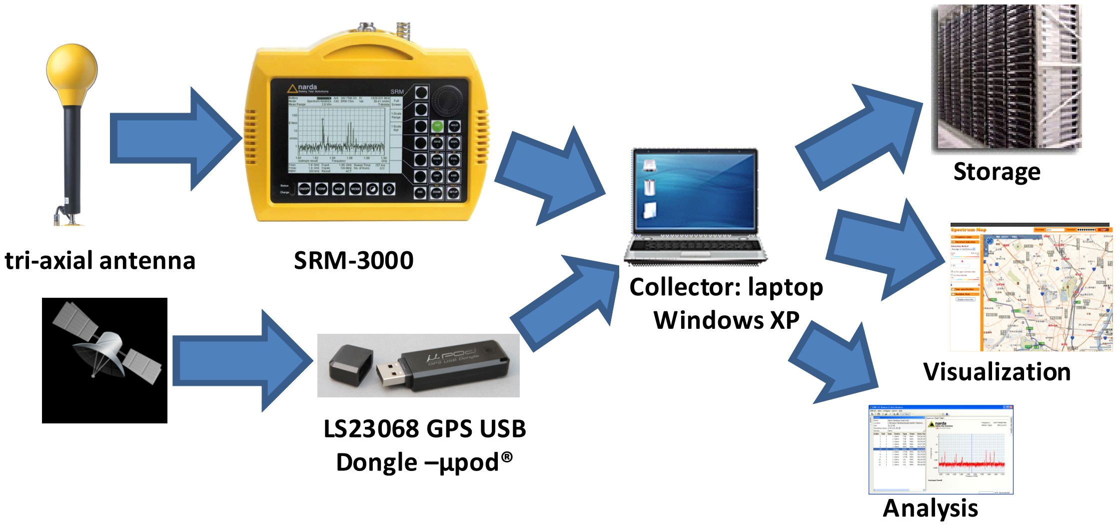



Fig. 6.2: Measurement Setup

communication in Japan. Roppongi Hills and Tokyo Station were chosen as the business area for its representation of Japan offices. Shibuya and Tokyo Station (waiting room) were also measured as the main terminal station in Tokyo and Ikebukuro residental area near Kami-Ikebukuro was chosen as the typical residence(Fig. 6.3) .

| Location | Type | Day Type 1 (Weekdays) | Day Type 2 (Friday) | Day Type 3 (Weekends) |
|---|---|---|---|---|
| **Akiahabara** | downtown | Tue. (08:30, 12:00, 18:00) | Fri. (08:30, 12:00, 18:00) | Sat .(08:30, 12:00, 18:00) |
| **Roppongi Hills** | business district | Tue. (09:30, 14:00, 19:00) | Fri. (09:30, 14:00, 19:00) | Sat. (09:30, 14:00, 19:00) |
| **Tokyo Station (Yaesu Side)** | business district | Wed. (09:00, 14:00, 19:00) | Fri. (09:00, 14:00, 19:00) | Sat. (09:00, 14:00, 19:00) |
| **Tokyo Station Shinkansen Waiting Room （Without GPS）** | main terminal station | Wed. (09:30, 15:30, 19:30) | - | - |
| **Shibuya Station (near ハチ公)** | downtown | Tue. (10:30, 15:00, 20:00) | Fri. (10:30, 15:00, 20:00) | Sat. (10:30, 15:00, 20:00) |
| **Ikebukuro Station Resident Place** | residence | Wed. (08:00, 15:00, 23:00) | Fri . (08:00, 15:00, 23:00) | Sat. (08:00, 15:00, 23:00) |

Fig. 6.3: Measurement Time Table and Locations

# Chapter 7

# Principles and Methodologies of Spectrum Utilization Analysis

### 7.0.1 Analysis Method

The parameter we used to evaluate the utilization of RF spectrum is duty cycle. This parameter specifies the time the frequency band is used to the total time. Duty cycle is calculated as the ratio between number of samples $P$ superior to the threshold value $N_{P>threshold}$ and the number of samples $N_{total}$ as following.

$$DutyCycle = \frac{N_{P>threshold}}{N_{total}} \tag{7.1}$$

To specify duty cycle [43] , a power threshold value must be defined. A high threshold value may lead to a missing awareness of potential spectrum, but with a too low threshold may cause interference with primary users. Threshold value is considered as a value of average noise level and the false alarm rate corresponding to the appropriate frequency band.

### 7.0.2 Noise Floor and Threshold Value

Noise floor is defined as the unexpected signal within the whole measurement environment. It is considered as the sum of all the noise sources and random signals in the air. Threshold value includes this noise floor and False Alarm Rate [3; 6; 22; 30; 33] .

$$FAR(P_T) = \frac{1}{N_{total}} \sum_{i=1}^{N_{total}} S_i(P_R \geq P_T) \tag{7.2}$$

Here, $FAR$ refers to a non-target signal but defined as a target because the signal exceeds the detection threshold. $P_R$ and $P_T$ are RF powers of real data and threshold value respectively.

$$S_i = 1, \text{ if } (P_R \geq P_T) \text{ else } S_i = 0$$

Threshold values changed according to RF bands, hence we should choose a reasonable value for False Alarm Rate for our measurement. In our measurement, we took about 1.5 million samples from these 6 places. In each sample, we stored the signals from 75 [MHz] to 3000 [MHz] and then for each frequency, we took the average value of minimum RSSI to evaluate the noise floor corresponding to each frequency bands. To verify the noise level of our measurement accurately, we firstly identify the signal of non-communication spectrum band. The band should be chosen from spectrum that is vacant for all of the measurement time. Those bands are different from country to country, hence, we have to choose a proper band in Japan. The band we have selected is satellite-to-satellite communication bands which is allocated at [2025∼2110][MHz] and [2200∼2290][MHz] as shown in Fig. 8.2 to Fig. 8.5, and the RSSI probability of this band as in Fig. 8.42. After approximate this RSSI probability with Gaussian Distribution (7.3), we got mean $\mu = 60.79461 \times 10^{-4}$ and variance $\sigma = 17.90778 \times 10^{-4}$, therefore the threshold value should be larger than $\mu + 3\sigma = 114.48795 \times 10^{-4}$ to avoid the margin error of noise level.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{7.3}$$

# Chapter 8

# Analysis Results of Spectrum Utilization in Tokyo, Japan

## 8.1 Noise Channel Distribution

To verify the noise level of our measurement accurately, we firstly identify the signal of non-communication spectrum band (Fig. 8.1). The band should be chosen from spectrum that is vacant for all of the measurement time. Those bands are different from country to country, hence, we have to choose a proper band in Japan. The band we selected is satellite-to-satellite communication bands which is allocated at [2025∼2110][MHz] and [2200∼2290][MHz].

The reason we selected this frequency band because it is currently allocated to satellite and

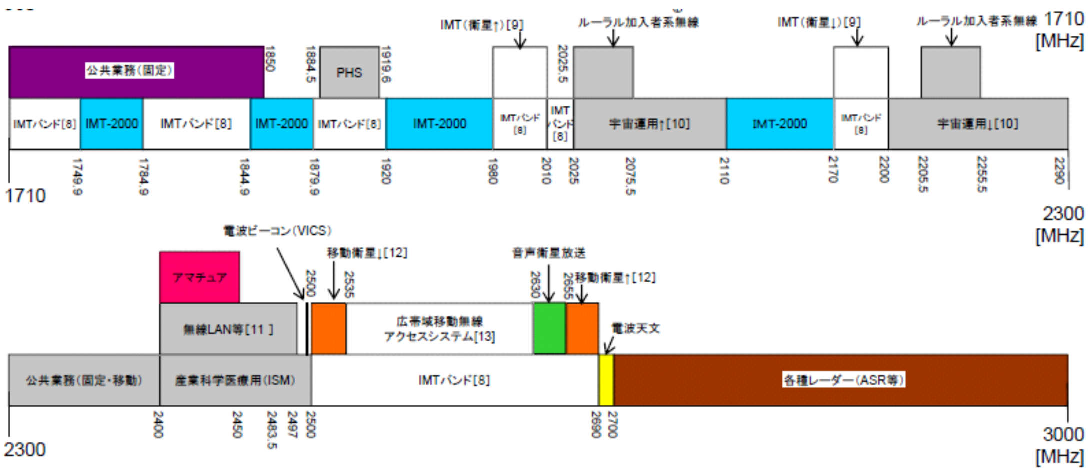



Fig. 8.1: Table of Frequency from 1700∼3000[MHz]

satellite that the signal usually becomes weaker under the atmospheric boundary layer (ABL) and its strength can be considered as 0 at ground. Hence, the signal at this band is not a sensitive signal at all, what we called a noise level.

To understand the noise level of all of the measurement data, we took maximum, minimum and average values for this frequency band and then, find the probability of the RSSI signal to find the statistically accurate value of threshold.

### 8.1.1 Maximum, Minimum and Average Values of Noise Channel

First of all, we will show an overall spectrum of 4 noise channels we chose. The noise channel 2075∼ 2110[MHz], 2255∼2290[MHz], 2500∼2535[MHz], 2655∼2690[MHz] were chosen because it cover the WiFi channel at the middle.

Looking at those graph, we could see that the signals of noise level do not change a lot while considering specific aspect of it, e.g. average values. But we could not know the change of these graphs together. But actually, signal power seems increasing due to the increasing of frequency. This was caused because the amplifier adjusted the signal level of frequency due to the different of signal level of different frequency. This could be verified by next section.

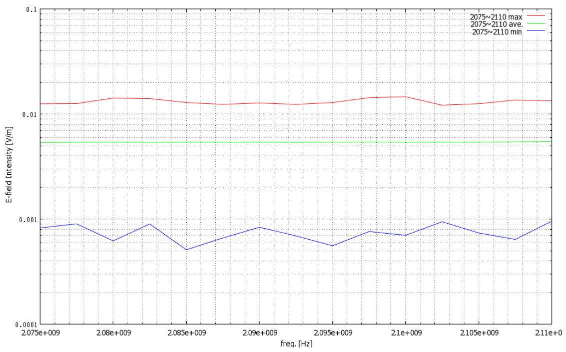


Fig. 8.2: Maximum, Minimum and Average Values of Noise Channel at [2075∼2110][MHz]

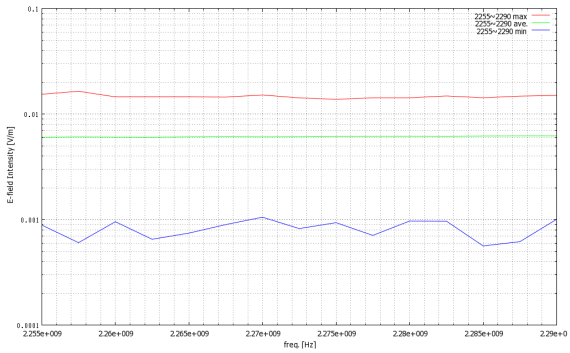


Fig. 8.3: Maximum, Minimum and Average Values of Noise Channel at [2255∼2290][MHz]

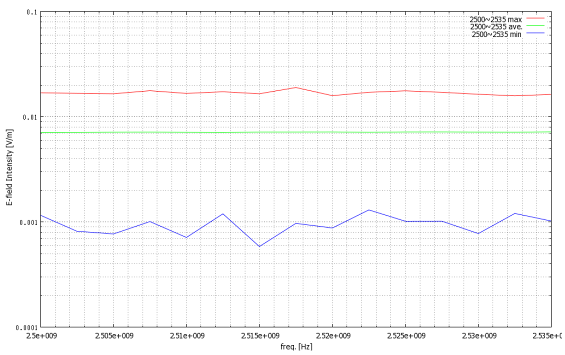


Fig. 8.4: Maximum, Minimum and Average Values of Noise Channel at [2500∼2535][MHz]

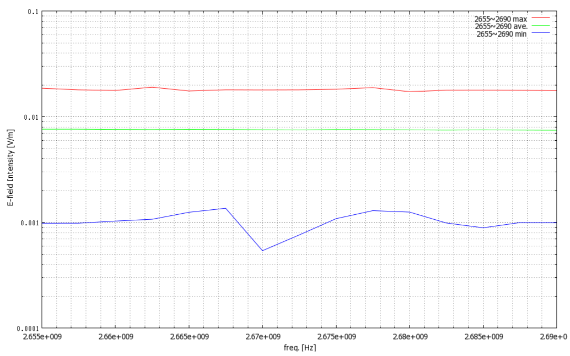


Fig. 8.5: Maximum, Minimum and Average Values of Noise Channel at [2655∼2690][MHz]

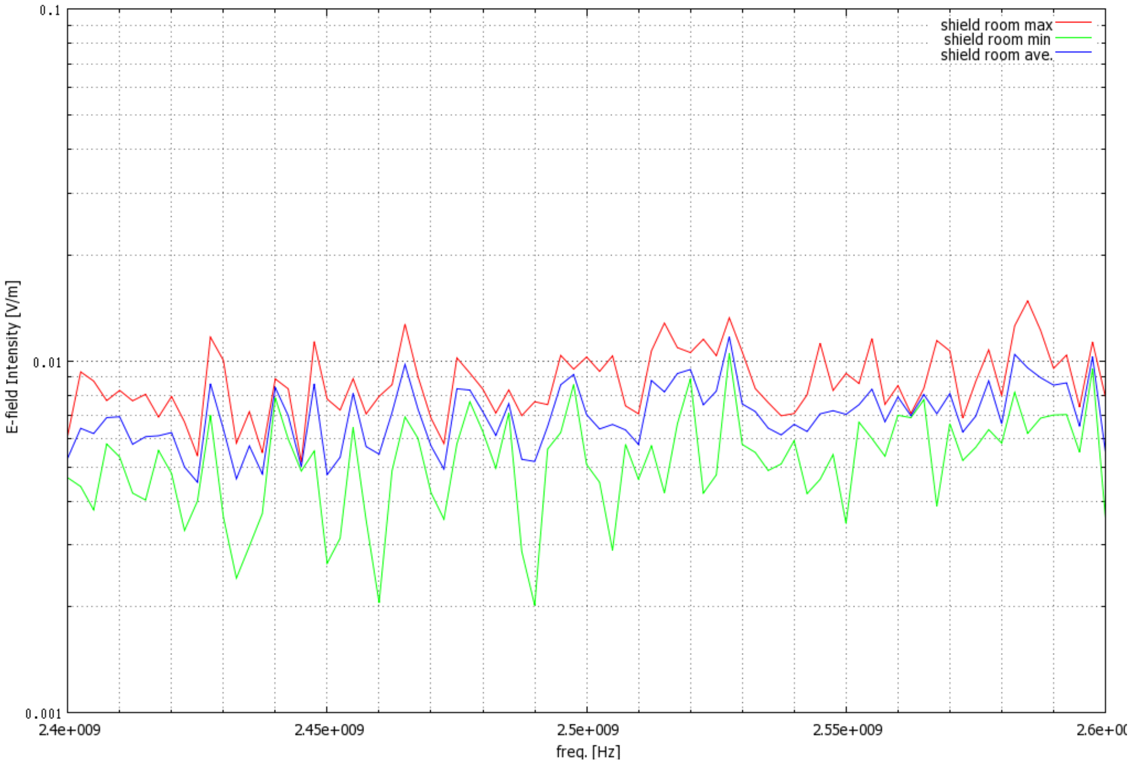



Fig. 8.6: Maximum, Minimum and Average Values in Shield at [2400∼2600][MHz]

We also concerned the affects of noise without the signals in the air, then we measured the signals in the shield room at the WiFi channel. The result is shown in Fig. 8.6. We could see the antenna of SRM did not receive any signals in the air. But the signal slightly increase when the frequency grow up. This should be taken into account and we will mention in next section.

### 8.1.2 RSSI Probability of Noise Channel

In this section, we aimed to quantitatively find the difference of average values and variance values of noise channels because we realized the increasing of power level according to the increasing of frequency range. First we took samplings of our measured signal in noise bands, then count the number of signal having the same powers in that bands and find the percentage of power of

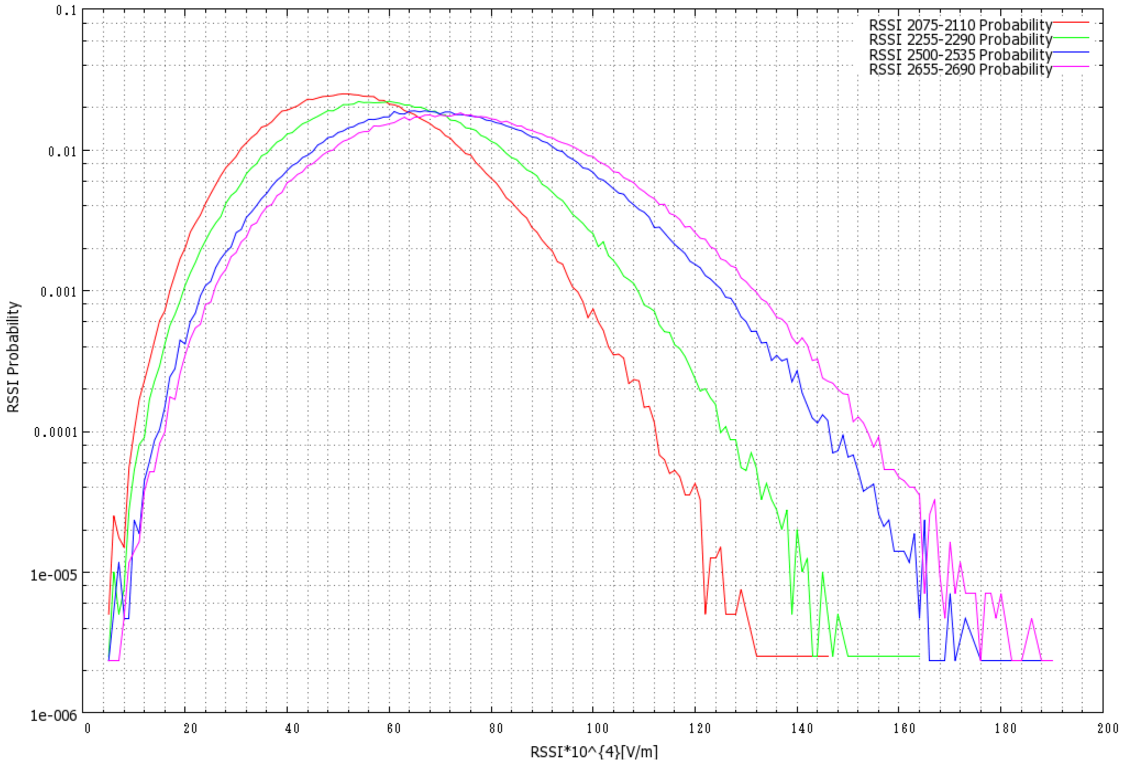



Fig. 8.7: RSSI Probability of Noise Channels

that noise channel. This is called probability of RSSI power for noise channel and shown in Fig. 8.7. First, this figure showed us there are difference even in noise channel, the signal power level increase according to frequency increasing.

Second, we plotted these noise channel RSSI probability in log scale of y axis. But when we took a look at the normal scale of y axis, it is a Gaussian distribution. To prove this, and to find the average and varian quantitatively, we approximate these noise channel with Gaussian distribution as shown in Fig. . This is an evidence to turn the hypothesis of [2] up side down, that the average value does not change, and they just calculated the average value of one noise channel and used it as the criteria to evaluate the noise level, and therefore threshold value of other frequency channels.

### 8.1.3 Noise Channel Distribution and its Averages, Variances

We approximate RSSI probability in last section wih a Gaussian distribution as shown in Fig. 8.8, Fig. 8.9, Fig. 8.10 and Fig. 8.11.

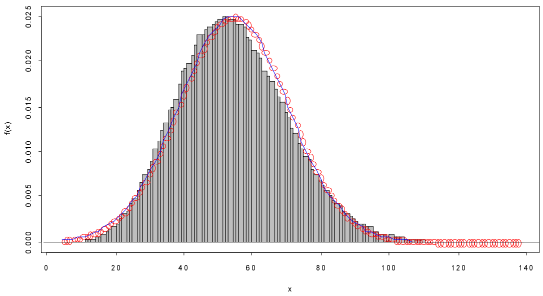



Fig. 8.8: Approximation of Noise Channel RSSI Distribution at [2075∼2110][MHz]

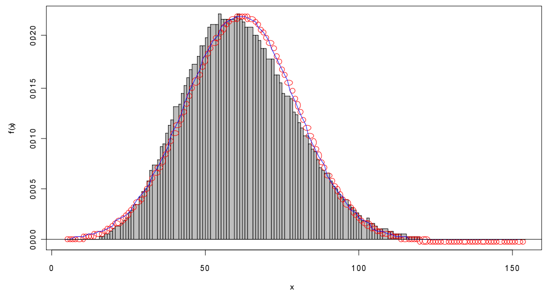



Fig. 8.9: Approximation of Noise Channel RSSI Distribution at [2255∼2290][MHz]

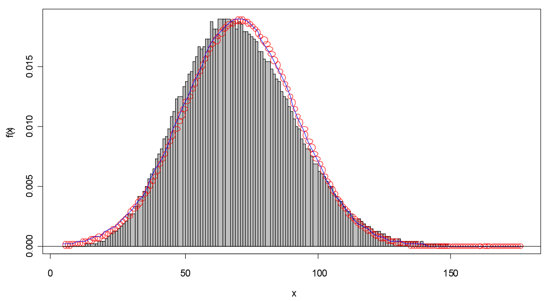



Fig. 8.10: Approximation of Noise Channel RSSI Distribution at [2500∼2535][MHz]

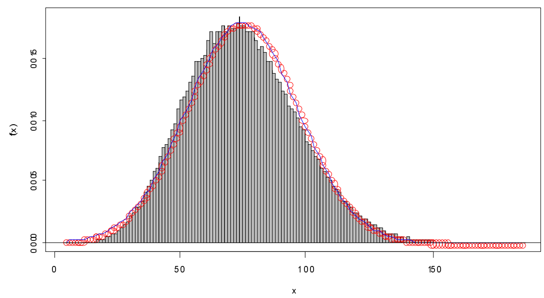



Fig. 8.11: Approximation of Noise Channel RSSI Distribution at [2655∼2690][MHz]

The averages, variances is summarized in Table. 8.1.

But in this case, we consider the RSSI distribution of a range of spectrum (E.g. from 2075∼2110[MHz]), then to find the correlation between these noise channel, we should find the center frequency of approximation results. This is shown in Table 8.2.

Table 8.1: Averages, Variances of Noise Channel

| RF Frequency | Average [$10^4$V/m] | Variance [$10^4$V/m] |
|---|---|---|
| 2075∼2110][MHz] | 54.22865 | 15.977 |
| 2255∼2290][MHz] | 61.38566 | 18.079 |
| 2500∼2535][MHz] | 70.47988 | 21.05 |
| 2655∼2690][MHz] | 74.57577 | 22.285 |

Table 8.2: Averages, Variances of Noise Channel at Center Frequency

| RF Frequency [MHz] | Average [$10^4$V/m] | Variance [$10^4$V/m] |
|---|---|---|
| 2092.5 | 54.22865 | 15.977 |
| 2272.5 | 61.38566 | 18.079 |
| 2517.5 | 70.47988 | 21.050 |
| 2672.5 | 74.57577 | 22.285 |

After transform this RSSI distribution into this phase, we find the common points of average and variance and find that this distribution average and variance increase linearly according to the frequency (Fig. 8.12). We approximated this linear feature of noise RSSI distribution into a linear function,

$$Y = aX + b \tag{8.1}$$

and find a, b constance in this case to model this linear feature (Fig. 8.13). The result of this function constance is a=0.0354584, b=-19.5338. The same for variance term, we approximate this with a linear function Y=a'X+b' and got the result a'=0.0110838, b'= -7.12876 (Fig. 8.14).

Finally, we obtained the final result for average and variance linear function as follow.

$$Y = aX + b \tag{8.2}$$

$$Average : Y = 0.0354584X - 19.5338 \tag{8.3}$$

$$Variance : Y = 0.0110838X - 7.12876 \tag{8.4}$$

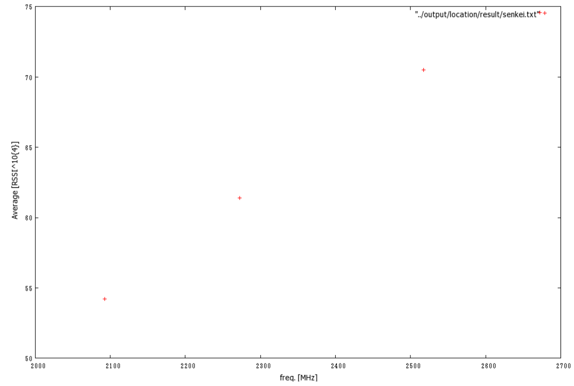



Fig. 8.12: Linear Feature of Noise Channel RSSI Distribution Average

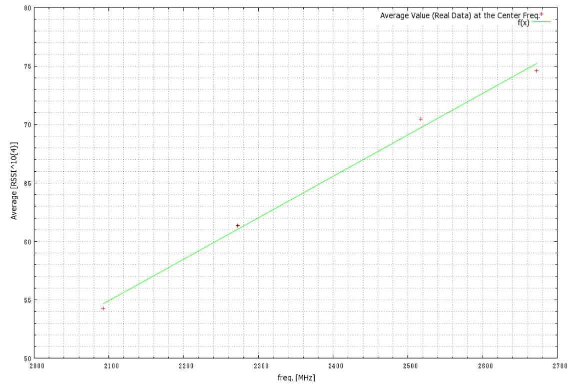



Fig. 8.13: Linear Feature of Noise Channel RSSI Distribution Average

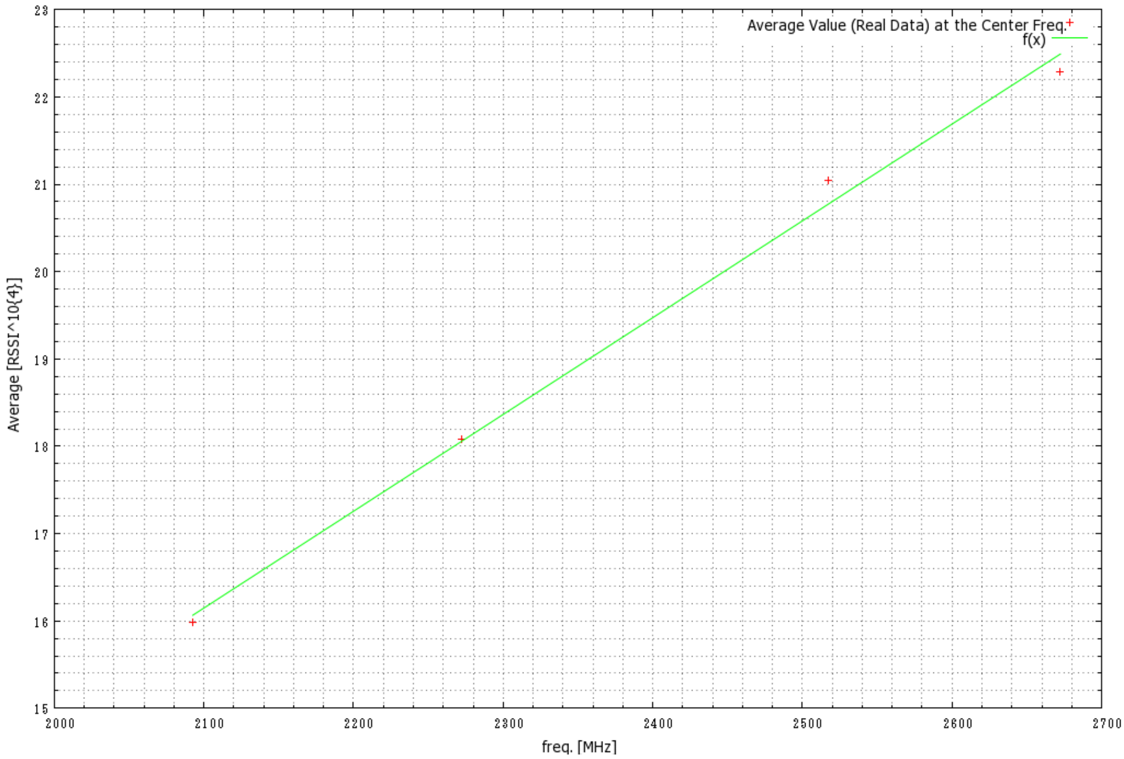



Fig. 8.14: RSSI Probability Variance Linear Feature of Noise Channels

Notice that the frequency we chose are at the both side of WiFi channel from 2.4GHz∼2.5GHz then we could find the noise average and variance of noise channel in WiFi channel because the average and variance are linear values and the second reason is because we could not find the average value from the distribution of WiFi channel itself as shown in Fig. 8.15. The reason is this distribution is a linear combination of noise distribution and Poisson distribution as follow.

$$f(\mu,\lambda) = \frac{\lambda^{\mu} e^{-\lambda}}{\mu!} \tag{8.5}$$

$e$ is the base of the natural logarithm (e = 2.7183)
$\mu$ is the number of occurrences of RF signals
$\mu!$ is the factorial of k
$\lambda$ is a positive real number, equal to the expected number of occurrences of RF signales that occur during the given interval. This make the overall distribution of WiFi channel a long-tail distribution.

We, therefore don't use the total distribution of WiFi signal but use the approximation of equation 8.2 (Fig. 8.13, and Fig. 8.14). But because the WiFi channels overlap each other (8.16) then we could not split WiFi channel into 13 slices. We now used the non-overlapped channels of 1 (center frequency=2.412GHz), channel 6 (center frequency=2.437GHz) and channel 11 (center frequency=2.462GHz).

After substituting these channel frequencies into equation 8.2, we got,

$$X = 2.412 \quad , \quad AVE = \mu = 0.035X - 19.534 = (0.035 * 2412) - 19.534 = 65.992 \tag{8.6}$$

$$VAR = \sigma = 0.011X - 7.129 = (0.011 * 2412) - 7.129 = 19.605 \tag{8.7}$$

$$X = 2.437 \quad , \quad AVE = \mu = 0.035X - 19.534 = (0.035 * 2437) - 19.534 = 66.878 \tag{8.8}$$

$$VAR = \sigma = 0.011X - 7.129 = (0.011 * 2437) - 7.129 = 19.882 \tag{8.9}$$

$$X = 2.462 \quad , \quad AVE = \mu = 0.035X - 19.534 = (0.035 * 2462) - 19.534 = 67.764 \tag{8.10}$$

$$VAR = \sigma = 0.011X - 7.129 = (0.011 * 2462) - 7.129 = 20.159 \tag{8.11}$$

Now we have already known the average value and variance of 3 frequencies we want to analyze. Next we should use the transformation formula to change this Gaussian distribution into Standard

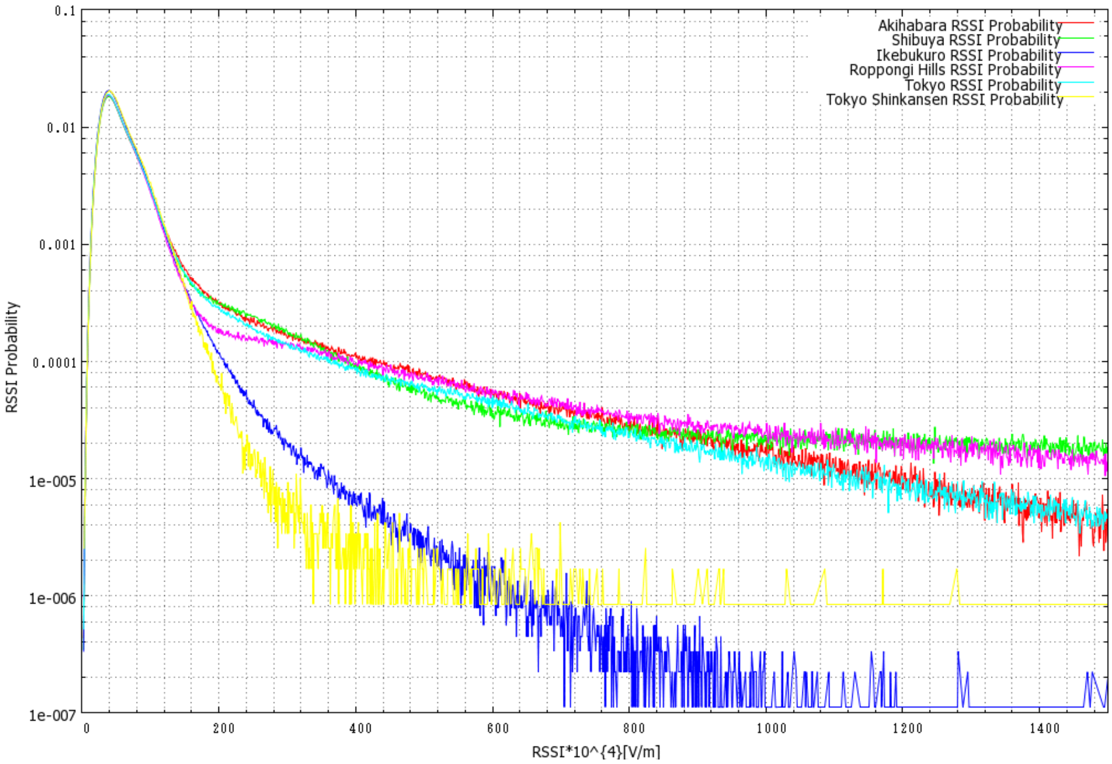



Fig. 8.15: RSSI Probability of Noise Channel at All 6 Locations

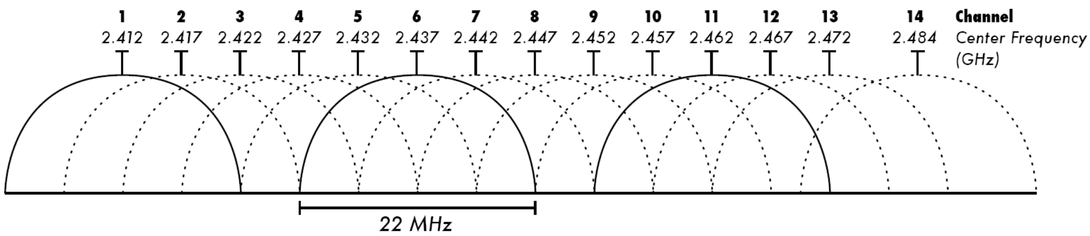



Fig. 8.16: WiFi Channels

Normal Distribution (Z distribution Fig. 8.17) by

$$Z = \frac{X - \mu}{\sigma} \tag{8.12}$$

$$X = Z\sigma + \mu = threshold \tag{8.13}$$

Table 8.3: FAR, T and Z

| FAR | T=(1-2FAR)/2 | Z |
|---|---|---|
| 0.01 | 0.49 | 2.33 |
| 0.03 | 0.47 | 1.88 |
| 0.05 | 0.45 | 1.64 |

Here, FAR(False Alarm Rate) should be defined by FAR=(1-2T)/2, and finally we could find the

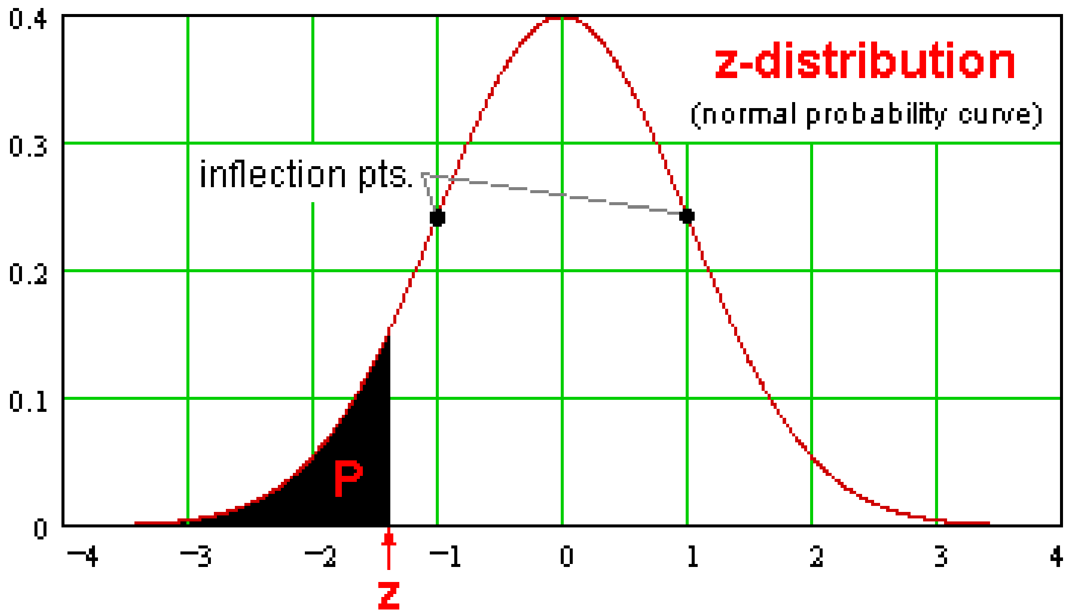



Fig. 8.17: Standard Normal Distribution

threshold value for each FAR. We choose three tolerant FAR value of 0.01, 0.03, 0.05 to evaluate our measurement data.

The threshold value for each FAR level is shown in Table 8.4, Table 8.5, Table 8.6 respectively.

The spectrum utilization using threshold values of channel 1, channel 6 and channel 11 is shown

Table 8.4: Threshold with Different FAR based on $\mu$ and $\sigma$ of WiFi channel 1

| FAR | $\mu$ | $\sigma$ | Z | Threshold [$10^4$V/m] |
|---|---|---|---|---|
| 0.01 | 65.9918608 | 19.6053656 | 2.33 | 111.672363 |
| 0.03 | 65.9918608 | 19.6053656 | 2.05 | 106.18286 |
| 0.05 | 65.9918608 | 19.6053656 | 1.88 | 102.849948 |

Table 8.5: Threshold with Different FAR based on $\mu$ and $\sigma$ of WiFi channel 6

| FAR | $\mu$ | $\sigma$ | Z | Threshold [$10^4$V/m] |
|---|---|---|---|---|
| 0.01 | 66.8783208 | 19.8824606 | 2.33 | 113.204454 |
| 0.03 | 66.8783208 | 19.8824606 | 1.88 | 104.257347 |
| 0.05 | 66.8783208 | 19.8824606 | 1.64 | 99.4855562 |

in Fig. 8.18, 8.20, 8.19 respectively.

Focusing on 2.42 GHz band in Fig. 8.20, we saw that duty cycle is 0.1 therefore in this case, signal just appeared 90% of the entire time slot. But this also includes the noise which is considered as signal (which is related to FAR).

FAR = 0.01, dcycle = 0.11

FAR = 0.03, dcycle = 0.14

FAR = 0.05, dcycle = 0.166

Hence, it push the duty cycle 0.9*0.01=0.009 upper, which causes the final observed duty cycle to be 0.109. With FAR=0.03, the upper-pushed level of signal is 0.9*0.03=0.027 and the observed duty cycle is 0.127. And FAR=0.05 will lead to an upper 0.9*0.05=0.045 of duty cycle and give a result of duty cycle to 0.145. In other words, duty cycle of FAR = 0.03, 0.05 cause the increasing of the contribution and is quite likely noise. FAR=0.01 seems to be over-taken for signal in WiFi band, but FAR=0.03 is still lightly high, therefore we chose FAR=0.02 as our false alarm rate used in evaluation of spectrum.

When we took FAR=0.02 in channel 6 (the middle channel of WiFi), then we have T=(1 -

Table 8.6: Threshold with Different FAR based on $\mu$ and $\sigma$ of WiFi channel 11

| FAR | $\mu$ | $\sigma$ | Z | Threshold [$10^4$V/m] |
|---|---|---|---|---|
| 0.01 | 67.7647808 | 20.1595556 | 2.33 | 114.736545 |
| 0.03 | 67.7647808 | 20.1595556 | 1.88 | 105.664745 |
| 0.05 | 67.7647808 | 20.1595556 | 1.64 | 100.826452 |

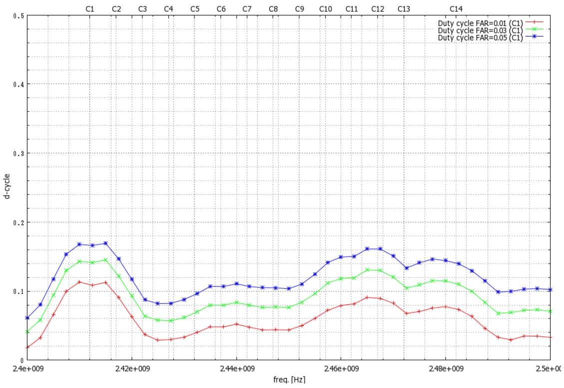



Fig. 8.18: Duty Cycle (FAR=0.01, 0.03, 0.05) based on Channel 1's $\mu$ and $\sigma$

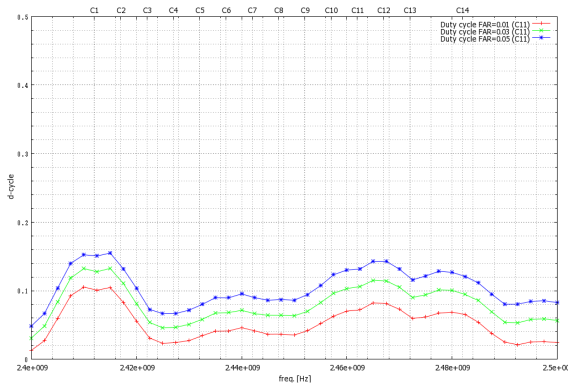



Fig. 8.19: Duty Cycle (FAR=0.01, 0.03, 0.05) based on Channel 11's $\mu$ and $\sigma$

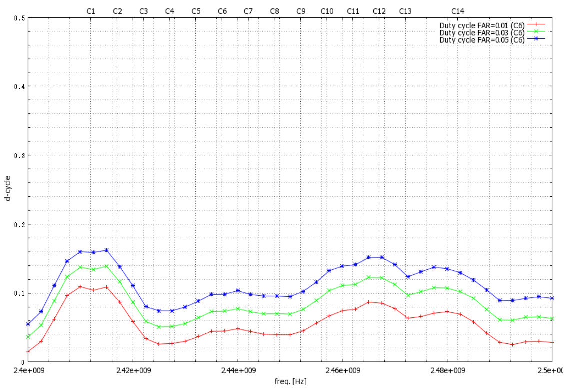



Fig. 8.20: Duty Cycle (FAR=0.01, 0.03, 0.05) based on Channel 6's $\mu$ and $\sigma$

(0.02 * 2)) / 2 = 0.48. Looking up this T in Standard Normal Distribution Table, we found

Z=2.05. The we used this Z value in threshold = $\mu + Z\sigma$=66.8783208 + (19.8824606 * 2.05) = 107.637365[$10^{-4}$V/m]. This is the final threshold value we chose to evaluate WiFi spectrum in our paper.

## 8.2 Summary and Conclusions

### 8.2.1 Duty Cycle of WiFi channel at Distinctive Locations

In this section, we used the final threshold value we have already decided in last section (TH=107.637 [$10^{-4}$V/m]) to evaluate the threshold value of the same location at different time slot, and of the different locations to compare them together. Among 6 locations we took measurement, we selected four different locations to compare in this section. They are measurement results at Akihabara measurement site, Roppongi Hills measurement site and Ikebukuro Residental measurement site and Shibuya Hachiko measurement site.

#### Weekdays at Four Locations

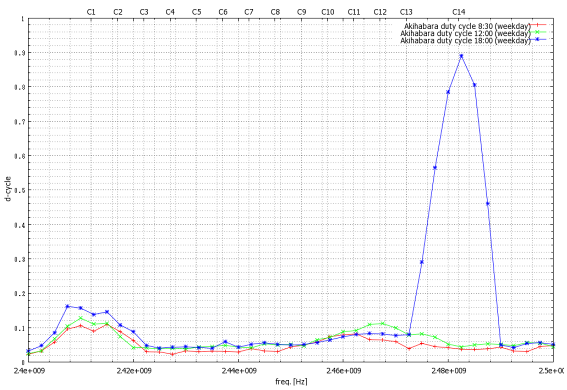



Fig. 8.21: Spectrum Utilization at Akihabara on weekdays

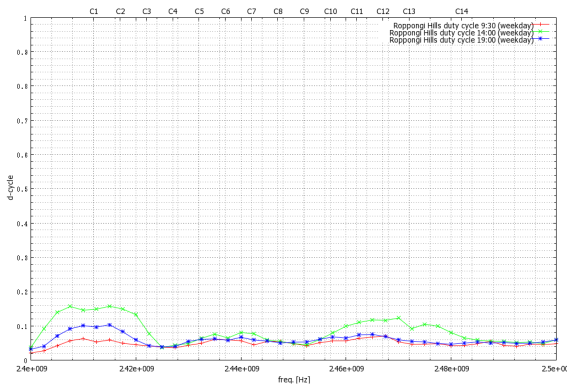



Fig. 8.22: Spectrum Utilization at Roppongi Hills on weekdays

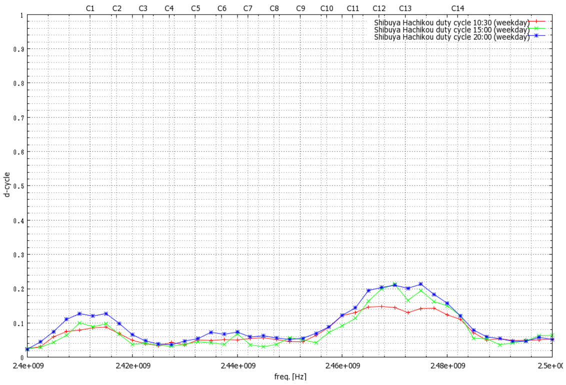



Fig. 8.23: Spectrum Utilization at Shibuya Hachiko on weekdays

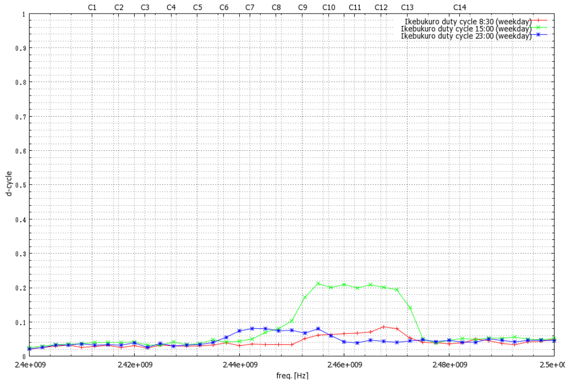



Fig. 8.24: Spectrum Utilization at Ikebukuro Residence on weekdays

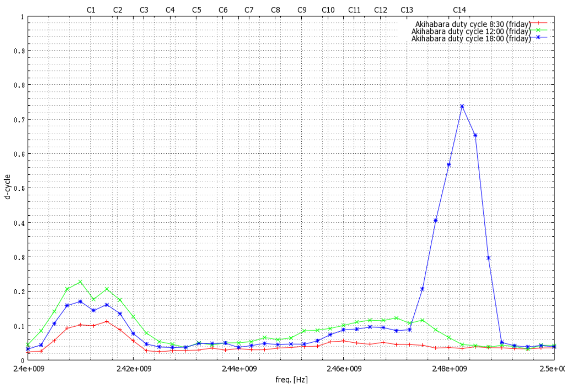



Fig. 8.25: Spectrum Utilization at Akihabara on Fridays

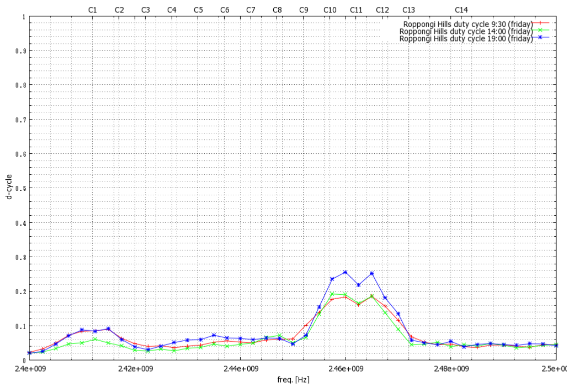



Fig. 8.26: Spectrum Utilization at Roppongi Hills on Fridays

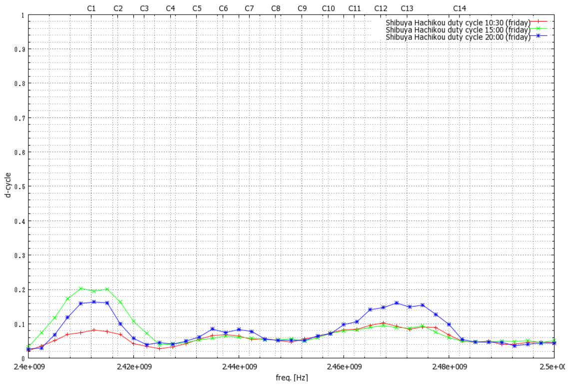



Fig. 8.27: Spectrum Utilization at Shibuya Hachiko on Fridays

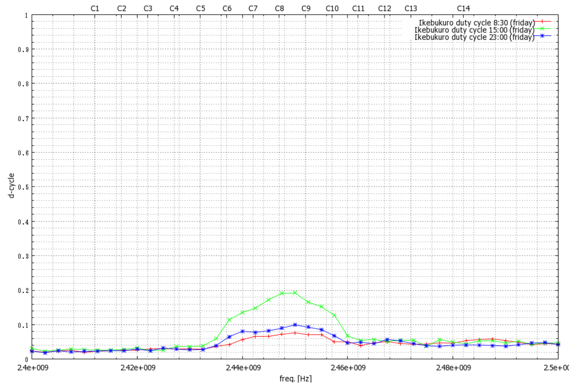



Fig. 8.28: Spectrum Utilization at Ikebukuro Residence on Fridays

**Fridays at Four Locations**

**Weekends at Four Locations**

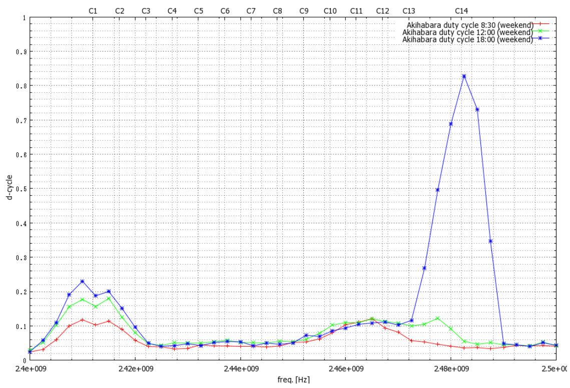



Fig. 8.29: Spectrum Utilization at Akihabara on weekends

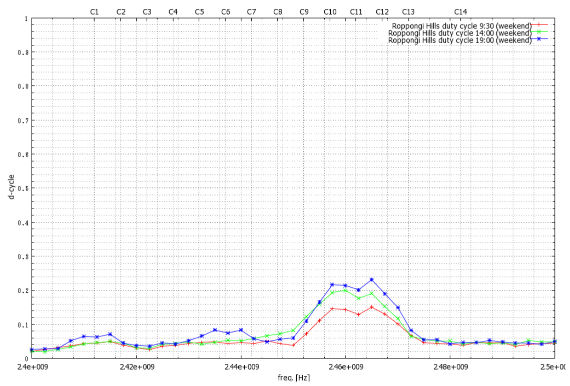



Fig. 8.30: Spectrum Utilization at Roppongi Hills on weekends

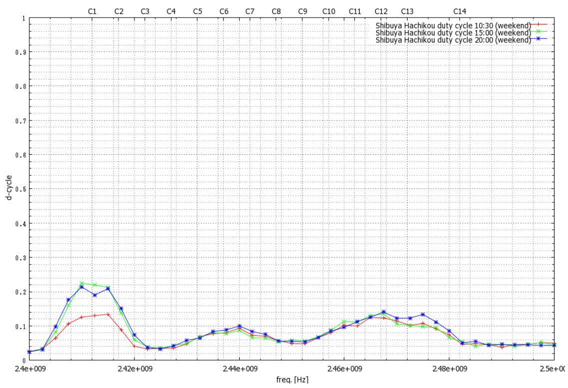



Fig. 8.31: Spectrum Utilization at Shibuya Hachiko on weekends

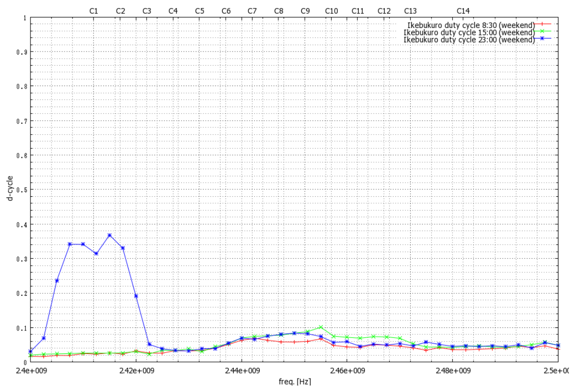



Fig. 8.32: Spectrum Utilization at Ikebukuro Residence on weekends

### 8.2.2 Comparison with Other Spectrum Utilization Results

In other paper as in [2], they firstly figured out the Maximum, Minimum and Average Values of spectrum. After that, they found the gap between Minimum and Maximum value in noise channel then applied this gap (in dB) to other bands (not noise). They could use it because they supposed that average noise channel is a constance at every frequency bands.

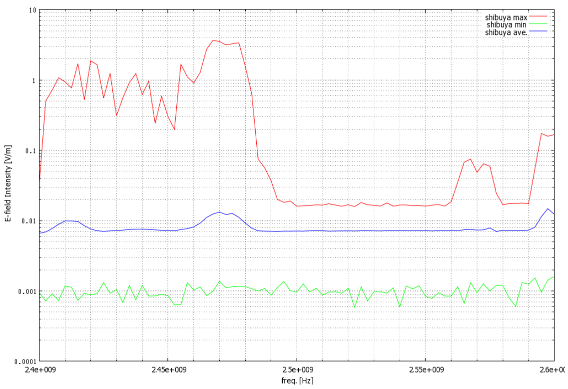



Fig. 8.33: Maximum, Minimum and Average Values of All Channel at Shibuya [2400∼2600][MHz]

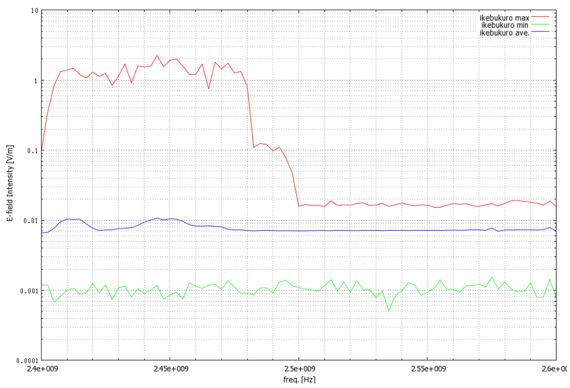



Fig. 8.34: Maximum, Minimum and Average Values of All Channel at Ikebukuro [2400∼2600][MHz]

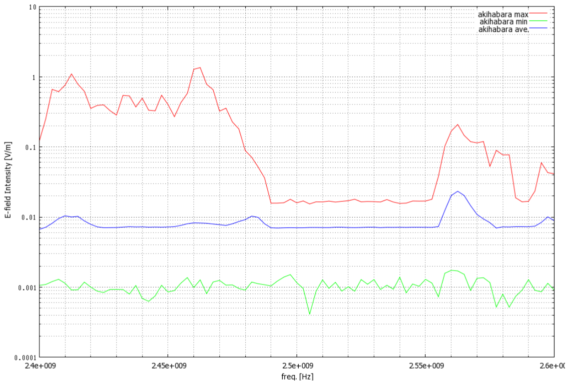



Fig. 8.35: Maximum, Minimum and Average Values of All Channel at Akihabara [2400∼2600][MHz]

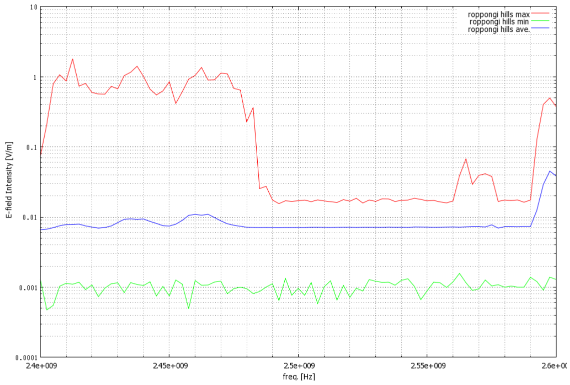



Fig. 8.36: Maximum, Minimum and Average Values of All Channel at Roppongi Hills [2400∼2600][MHz]


Fig. 8.37: Maximum, Minimum and Average Values of All Channel at Tokyo Station [2400∼2600][MHz]

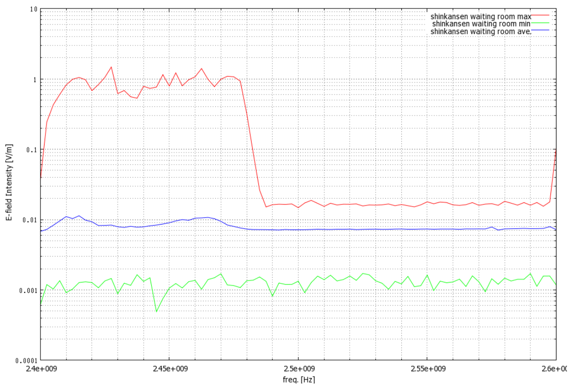



Fig. 8.38: Maximum, Minimum and Average Values of All Channel at Tokyo Shinkansen Waiting Room [2400∼2600][MHz]

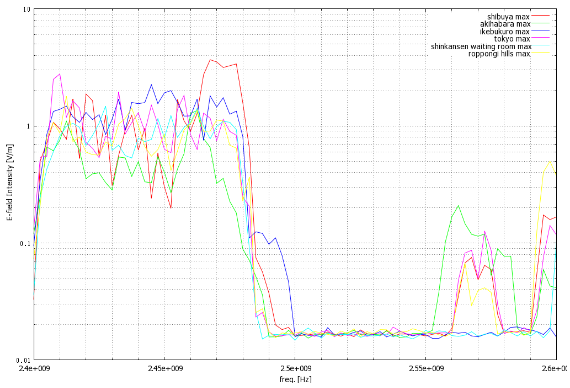



Fig. 8.39: Maximum Values of All Channel at All Locations [2400∼2600][MHz]

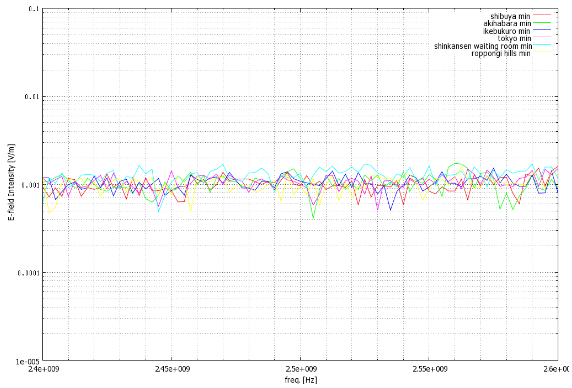



Fig. 8.40: Minimum Values of All Channel at All Locations [2400∼2600][MHz]

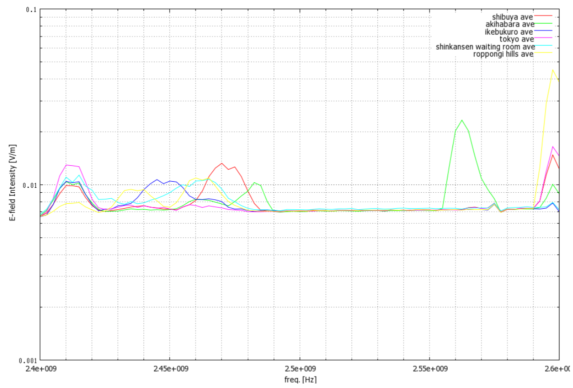



Fig. 8.41: Average Values of Noise Channel at All Locations [2400∼2600][MHz]

To compare with these papers, we also took max, min and average of 6 locations as shown from Fig. 8.33 to Fig. 8.41. From these figure and the numbers, we conducted the result that in these two bands, the minimum value is always 24.78dM (using 5MHz RBW) lower than maximum value. The same for [2500∼2535][MHz] band and [2655∼2690][MHz] band which are assigned to Mobile Satellite Communications. This value then will be used as a criteria to evaluate the threshold of [75∼3000]MHz band. The threshold for each band will be defined as the value which is 24.78dB (5MHz RBW) above the minimum of threshold in that band in comparison with other papers. But the result of threshold we found is 0.017[V/m]. This value is so high and this could not catch the WiFi that has low power level as IEEE802.11b channels.

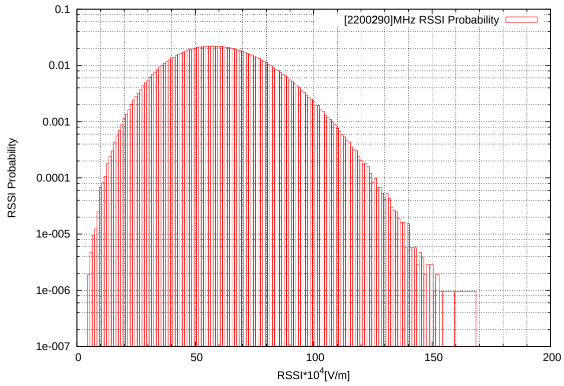



Fig. 8.42: RSSI Probability of Noise Channel at [2200∼2290][MHz]

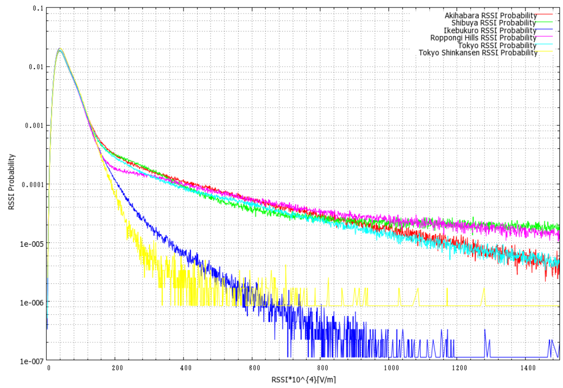



Fig. 8.43: RSSI Probability of Noise Channel at All 6 Locations [75∼3000][MHz]

The second reasons that previous paper did not mention is the difference of noise level at different frequency bands. We could see from Fig. 8.43, Fig. 8.45 and Fig. 8.44 the average value increase according to the increasing of spectrum. As shown in Fig. 8.43 , the patterns of RSSI power probability change depends on the environment. This also turns the assumption of [? ] upside down that the RSSI doesn't depend on locations. We noticed the RSSI of Ikebukuro (residential measurement site) and Tokyo Shinkansen Waiting Room are similar to each other. This could be explained of the rare usage ratio of spectrum (especially 3G, WiFi and WiMAX) at these two special locations. The remains are all crowded measurement sites located at Akihabara, Shibuya, Roppongi Hills, and near Tokyo Station which have the same trend.

### 8.2.3 Spatiotemporal Characteristic of Spectrum in Tokyo

Fig. 8.46 showed 5 minute sample of Shibuya Station on 2010/11/12 from 20:00:11. We can easily see that the spectrum is strong (over 0.3[V/m]) at some bands but not all of the band in this 5 minute period. To know more about temporal characteristic we plotted two more histograms of the same place ( Shibuya Station) in Fig. 8.47 .

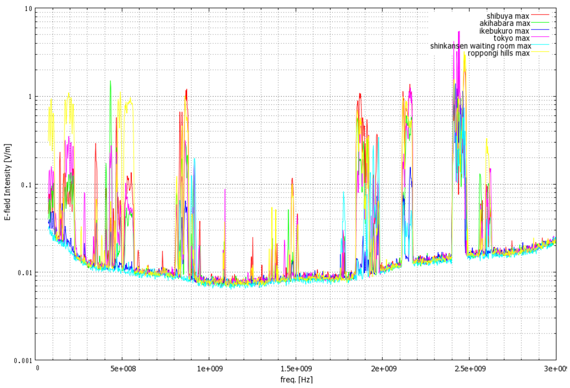



Fig. 8.44: Maximum RSSI of All Channels at All 6 Locations [75∼3000][MHz]


Fig. 8.45: Minimum RSSI of All Channels at All 6 Locations [75∼3000][MHz]

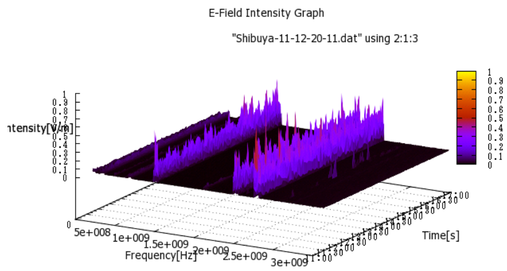
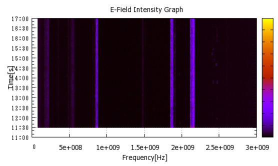



Fig. 8.46: Shibuya Spectrum Histogram (3D) on Friday night

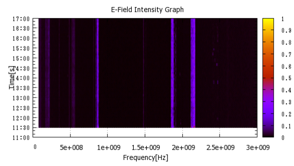
Using more than one million samples of data evaluation, we found some fundamental statistical results for WiFi channel signals shown in Fig. 8.48. This figure showed the main channels used for WiFi is 1, 6 and 11 channel. Even though channel 6 is not popular as channel 1, and 11 with just 2.4% of duty circle. This value is less than half of the duty cycle of channel 1 (7.5%) and channel 11 with 4.1%.

### 8.2.4 Duty Cycle of Different Locations

Fig. **??** is a plot of measurement in Shibuya in 2009 and 2010 (b) and comparison between Shibuya and Akihabara this year (a) . The difference between last year and this year is the underutilization




(a) at 17:20:21




(b) at 17:25:36

Fig. 8.47: E-field Intensity Histogram at Shibuya Station

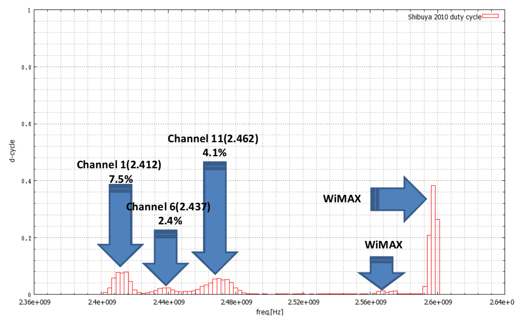



Fig. 8.48: Main Used WiFi Channels and WiMAX

of last year WiFi due to the measurement time period. Last year, we took measurement basically from 15:00 for 15 to 30 minutes. This graph shows the fact that in general, there's utilization of WiFi in Shibuya but at some specific time periods as at 15:00, the spectrum is usually underutilized.

We divided the spectrum into some main bands which have the same specification and apply the method mentioned above to find the duty cycle. There are six main bands we have divided; FM and VHF low band [76∼108][MHz] which is used for FM radio transmission (Fig. 8.49, average utilization 3.15%) ; VHF-TV and cable TV transmission band [176∼468][MHz] (Fig. 8.50, 1.71%); UHF TV band [470∼770][MHz] (Fig. 8.51, 3.84%) which is used for TV broadcasting, cell phone band [815∼890][MHz] (Fig. 8.52 , 8.04%); Fixed/Mobile band [1759∼2170][MHz] (Fig. 8.53, 7.91%) and WiMAX band [2500∼2600][MHz] (Fig. 8.54 , 1.08%).

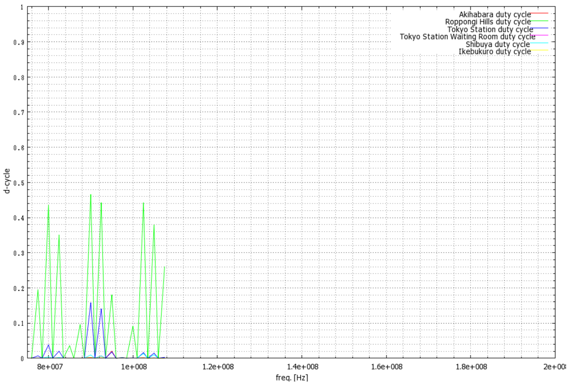



Fig. 8.49: Duty Cycle of FM and VHF low Band [76∼108][MHz]

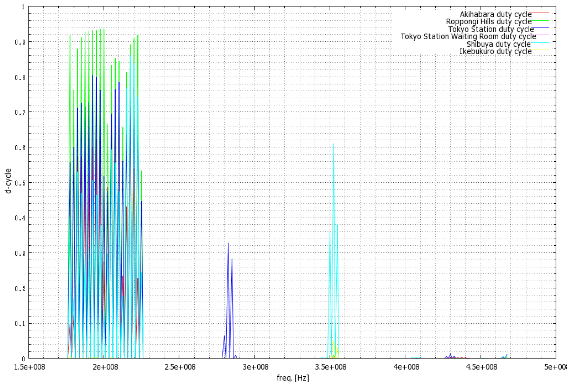



Fig. 8.50: Duty Cycle of VHF and cable TV Band [176∼468][MHz]

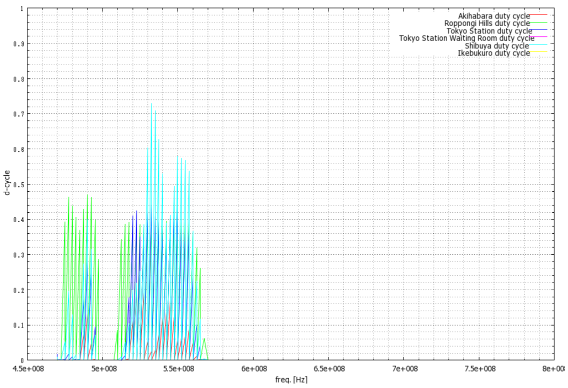



Fig. 8.51: Duty Cycle of Japan UHF TV Band [470∼770][MHz]

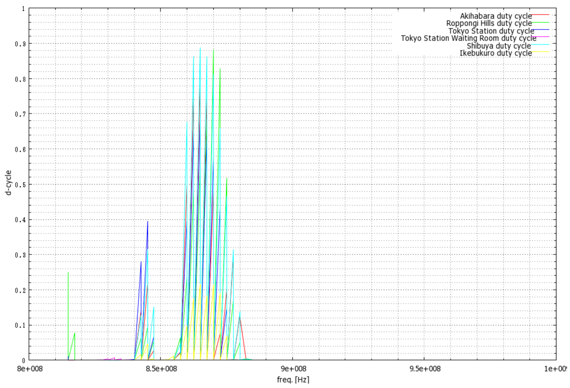



Fig. 8.52: Duty Cycle of Cell Phone Band [815∼890][MHz]

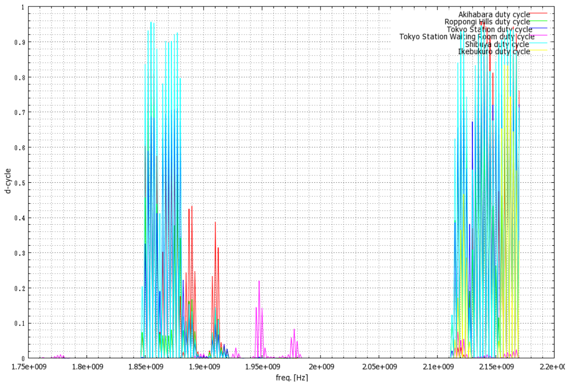



Fig. 8.53: Duty Cycle of Fixed/Mobile Band [1759∼2170][MHz]

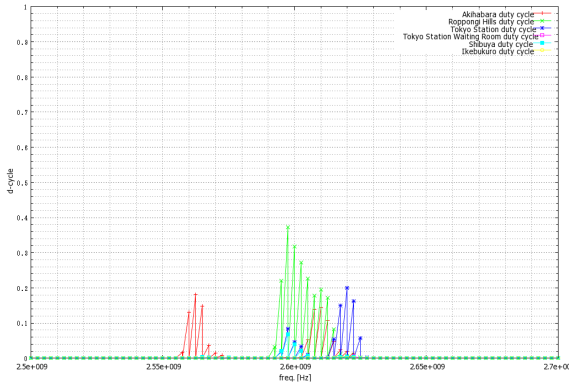



Fig. 8.54: Duty Cycle of WiMAX Band [2500∼3000][MHz]

### 8.2.5 Comparison with Other Countries

There are some spectrum utilization surveys in other countries. One of them is measurement in Czech (which is supported by French Government [40]) and the average spectrum utilization of all band [400MHz∼3GHz] at all 3 locations is reported as about 8.3%. This value is 5.11% in Tokyo. This value may change according to the threshold value of settings, but overall the spectrum utilization in both Tokyo and Czech and other counries is still lower than 10% according to the result conducted by these paties.

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[2] Y. Li, T. T. Quang, Y. Kawahara, T. Asami, and M. Kusunoki: " Building a Spectrum Map for Future Cognitive Radio Technology, " Proc. ACM MobiCom '09 Workshop on Cognitive Radio Networks (CoRoNet), pp.1-6, Beijing, China, 2009/09

[3] T. T. Quang, Y. Li, Y. Kawahara, and T. Asami: " A Statistical Analysis of Spectrum Utilization using Long Term Measurement RF Data, " Proc. IEICE Society Conference, BS-7-17, 2010/09

[4] Y. Li, T. T. Quang, Y. Kawahara, T. Asami, and M. Kusunoki: " Visualizing Spectrum Utilisation of Tokyo Area, " 信学ソ大, BS-10-24, 2009/09

[5] 加藤拓也, T. T. Quang, 楠慶, 川原圭博, 浅見徹: " スペクトル情報可視化システムの設計と実装, " 信学ソ大, B-7-39, 2010/09

[6] Y. Li, T. T. Quang, Y. Kawahara, and T. Asami: " Fast White Space Decision for a Tiled Region of a SpectrumMap Based on Spectrum Data Fusion, " 信学ソ大, BS-7-16, 2010/09

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