Distributed Spectrum Sensing Utilizing Heterogeneous Wireless Devices and Measurement Equipment

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***Abstract*—A suitable spectrum policy is essential to allow efficient use of the radio spectrum. The Japanese government currently employs a Command and Control (C&C) regime, but measures must be taken to speed up governmental decisions. The first step is to obtain spectrum utilization data which can form the basis of such decisions. This paper describes the design, implementation and evaluation of a distributed spectrum sensing system that continually measures spectrum utilization at multiple locations. The system has an architecture that enables it to utilize a wide range of existing wireless devices and measurement equipment, which can be used as sensing nodes to rapidly expand the coverage area. By focusing on the way to easily expand the measurement coverage, our work complements previous spectrum measurements, which have been conducted with high accuracy in the context of cognitive radios.**

I. Introduction

Due to recent rapid developments in wireless communication technology, the radio spectrum has become a precious resource, and appropriate spectrum management policies are required to allow innovation of existing industries and creation of new ones. Market mechanisms and spectrum commons have been proposed as alternative spectrum policy regimes to the conventional Command and Control (C&C) regime [1]–[5]. However, these alternatives have several shortcomings such as coexisting with public or non-profit systems and "The Tragedy of the Commons" [6], in which the spectrum band is devastated due to the selfish behavior of users. The C&C regime therefore continues to play an important role in determining the efficient use of the radio spectrum.

C&C, however, has a problem in that governmental decisions, such as approval of new systems and retrieval of unused spectrum bands, are delayed. In order to speed up the C&C process, it is essential to continually collect detailed spectrum utilization data which is the basis for governmental decisions. At present, the Japanese government obtains spectrum utilization information by requesting license holders to fill out a questionnaire [7]. In addition, in order to obtain more realistic data, spectrum measurements have been conducted worldwide [8]–[35]. These previous measurement have been conducted with high accuracy and played an important role in the context of cognitive radios.

In this paper, we describe a distributed spectrum sensing system which complements these related studies by focusing on the way to easily expand the measurement coverage. The contributions of this paper are as follows: First, we demonstrate the necessity of distributed spectrum sensing for the efficient use of the radio spectrum. Second, we show that the key to implementing a distributed spectrum sensing system is to utilize heterogeneous wireless devices and measurement equipment as sensing nodes. Third, we define the interface between software components based on an abstraction of the spectrum utilization into binary information. Also, we propose a new file format named the Tiny Spectrum Format (TSF) which enables binary information to be stored at a high compression ratio. Finally, we verify the feasibility of the system through implementation and measurement using 3 types of sensing nodes: a spectrum analyzer, a WLAN module, and a software defined radio (SDR) front-end.

The remainder of the paper is organized as follows: in Section II, we demonstrate the necessity of speeding up the C&C process. Then, we describe the importance of collecting spectrum utilization data and the problems that still remain to be solved. Based on an analysis of previous studies, we present our approach and describe the system architecture that utilizes heterogeneous wireless devices and measurement equipment in Section III. Implementation of the system is described in Section IV. In Section V, we perform an evaluation of the proposed system using several types of measurements. Finally, we summarize this paper in Section VI.

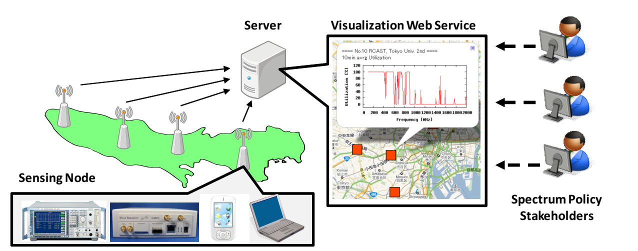

Fig. 1. Overview of system

II. Efficient use of radio spectrum

A. Spectrum policy

Due to rapid developments in wireless communication technology, the radio spectrum resource has become a precious resource. However, recent measurements have revealed the existence of licensed but unused spectrum bands. These facts highlight the need for more efficient management of the radio spectrum.

In Japan, the radio spectrum is under the control of the Japanese government. Thus, government policy has a large impact on how efficiently the spectrum is utilized. At present, the government employs the Command and Control (C&C) regime, under which the government determines spectrum allocation and a licensed band is exclusively utilized by a license holder. In the C&C regime, relatively long-term discussions take place before the government makes a decision on issues such as the usage of a particular band and the licensee, in order to guarantee fairness and the validity of the decision. In reality, these delays lead to inefficient use of the radio spectrum. For example, it is difficult to quickly assign a spectrum band to a new wireless system emerging from the development of wireless technology. Also, it is time-consuming to make decisions concerning retrieval of unused spectrum bands.

To address the problem, two alternative spectrum policy regimes have been proposed to date. The first regime involves market mechanisms, an example of which is a spectrum auction [1]. A government announces a new assignment of a spectrum band, operators who wish to use that band bid for it, and the highest bidding operator acquires it. The introduction of an auction system allows the government to choose operators who have sufficient funding and business motivation to use the spectrum band.

Another example of a market mechanism is to allow secondary trading of spectrum bands [2], [3]. Under the status quo, the Japanese government prohibits license holders from transferring their license to others, which leads to low liquidity of the spectrum bands. If secondary trading was allowed, unused spectrum bands could be easily transferred to more competitive operators. As a result, more efficient use of the radio spectrum is expected.

Market mechanisms, however, can not be adopted for all spectrum bands because of problems such as auction costs that might exhaust operators, the difficulty in keeping spectrum bands for public safety networks and non-profit systems, the potential danger of a monopoly being created due to the buying up of a large number of spectrum bands, and an unfairness to new operators in comparison to existing operators who acquired spectrum bands before the start of the auction system.

Another alternative spectrum policy regime is referred to as spectrum commons [4]. Spectrum commons abolishes the spectrum licensing system entirely. Because anyone can then freely use the radio spectrum, new operators or manufacturers can more easily enter the market, thereby increasing the efficiency of the radio spectrum use.

Spectrum commons, however, is prone to a potential danger known as "The Tragedy of the Commons" [6] by which the radio spectrum may be devastated by the selfish behavior of users. Even though a method of self regulation by users has been proposed [5], public safety networks such as police, fire department, and military need to operate under perfectly guaranteed spectrum bands.

As explained above, neither market mechanisms nor spectrum commons can act as a perfect substitute for the conventional C&C regime. The coexistence of the market mechanism, the spectrum commons, and the C&C is a practical solution. Therefore, it is critical for efficient spectrum use to speed up the C&C process.

The first step is to provide a means for the government to continually obtain detailed spectrum utilization data. Currently, the Japanese Ministry of Internal Affairs and Communication conducts surveys of spectrum utilization using questionnaires [7]. In a survey, the ministry requests each license holder to answer questions including the type of wireless station being operated, the number of wireless stations, their availability and operating hours. Such surveys are, however, conducted only once every 3 years, and more frequent updates are necessary. There are also three additional problems.

First, only registered wireless systems are surveyed. Wireless systems that can operate without a license or registration are not surveyed because the ministry can not send the request. In the case where a wireless system operates under a comprehensive license, which allows multiple terminals to operate with a single license, the spectrum utilization of each terminal can not be surveyed.

Second, the actual spectrum occupancy can not be determined because only the operation hours is surveyed. For example, even in the case of sparse transmissions with a low spectrum occupancy, the questionnaire will indicate total utilization of the spectrum band as long as a wireless device is turned on. Waiting time is also classified as spectrum utilization.

Third, there is a possibility of false answers in the questionnaires because the survey depends on self-enumeration. An operator who is afraid of blame for inefficient spectrum use might report operation hours that are longer than the actual utilization.

B. Related Work

In order to obtain continuous and detailed spectrum utilization data, measurements based on radio signal observations in real environments are necessary. This would also avoid the time cost of sending, collecting and evaluating questionnaires. Also, such an approach could reveal the spectrum utilization of unregistered wireless systems and also vacancies due to sparse transmissions and receiver waiting time.

The spectrum utilization have been conventionally studied in the context of cognitive radios which is a part of spectrum policy issues [8]–[35]. These related studies have played an important role in the technology developments and the policy discussions by providing the in-depth analysis of the actual spectrum utilization. Our work complements these related studies by focusing on the way to easily expand the measurement coverage.

A large number of spectrum utilization studies have already been carried out based on the installation of a single measurement system in a single location [8]–[15]. In most of these studies, the measurement system comprised an antenna, a spectrum analyzer or a receiver, and a PC. Measurement sites were chosen to be representative of a typical radio environment. Bacchus et al. [15] installed a system consisting of antennas, a spectrum analyzer, a radio scanner, and a PC on a rooftop of a building with a downtown view. They measured the spectrum utilization of land mobile radios and public safety networks over several months. The results identified seasonal/event-driven variations such as weekdays, weekends, New Year holidays, and Christmas holidays.

A single site measurement using a single system, however, is insufficient because spectrum utilization varies by location. For example, low-energy devices operating indoors or underground can not be detected by a measurement system installed outside. There are also cases in which buildings or mountains block radio propagation so that radio signals can not reach the measurement system. In addition, artificial noise from vehicles can strongly affect the measurement results, especially near roadsides.

In order to obtain more accurate spectrum utilization data, multi-site measurements and a comparison among measurement sites are important. One way to achieve this is to sequentially perform measurements in different locations [16]–[26]. McHenry [18] conducted sequential measurements in 6 U.S. locations using a system consisting of an antenna, a spectrum analyzer, and a laptop. The results showed that the maximum occupancy was 13.1%, the minimum occupancy was 1%, and the average occupancy was 5.2% over the 6 locations.

The systems used in [16]–[26], however, can not carry out measurements simultaneously in the time and space domains. If measurements are conducted at different locations, the measurement time per location must be shortened. Conversely, if the measurement time per location is long, it is more difficult to perform measurements at many locations. In addition, comparisons among different locations are not entirely accurate because each measurement must be conducted at a different time.

To simultaneously obtain temporal and spatial data allowing accurate comparisons among locations, multi-site measurement using multiple systems is necessary [27]–[35]. Qaraqe et al. [27] installed measurement systems at 4 locations in an urban area and found that spectrum utilization varied between 4% and 15% across these locations. While a similar trend was found for all 4 locations, a location-specific event that was a jamming signal in this case was also partially observed.

The coverage areas of the measurement systems used in [27]–[35], however, can not be easily extended due to cost problems. These systems use an antenna, a spectrum analyzer, and a laptop, of which the spectrum analyzer is most expensive, and usually costs from thousands of dollars to hundreds of thousand of dollars.

Because of the cost, a spectrum analyzer performs beyond the essential requirement for spectrum utilization measurement. For example, the output is exactly calibrated, the linearity is guaranteed, and a large number of functions are available. Also, recent wireless systems have the capability to correctly decode received signals with very low SNRs thanks to an achievement of coding gain or improvements in modulation techniques. This means that the signal level that will be recognized as spectrum occupancy is quite low. Consequently, a more sensitive spectrum analyzer will be required if spectrum occupancy is determined only by signal strength.

III. Distributed Spectrum Sensing System

Although previous studies have mainly used the power spectrum as an indicator of spectrum utilization, it is sufficient to measure only binary information, which means occupancy or vacancy, for the purposes of supporting governmental decision making. The most important governmental decision is an assignment of a spectrum band. Such assignment is based on evaluations such as an abandoned spectrum band that needs to be re-allocated, the necessity of an additional band assignment due to heavy congestion, the possibility of co-existence of different wireless systems in the same band, and a possible regional license based on geo-locational white-spaces. These are derived from statistical factors such as the spectrum utilization ratio (or duty cycle) which can be calculated using only binary information.

Not only a spectrum analyzer but also various type of wireless devices and measurement equipment can produce binary information. For instance, a WLAN module embedded on a laptop can measure spectrum utilization at 2.4 GHz band, and a DTV tuner can measure spectrum utilization at TV bands. Therefore, our system employs an architecture that utilizes not only a spectrum analyzer but also heterogeneous wireless devices and measurement equipment.

This allows us to include existing devices and measurement equipment owned by research organizations, industrial companies, and individuals to form a wide-area spectrum measurement system. Purchase of expensive spectrum analyzers can also be minimized. In addition, we can collect data from many types of locations as wireless terminals move around with their users.

A. Overview of System

Figure 1 depicts an overview of the distributed spectrum sensing system. The system consists of numerous sensing nodes and a server. We utilize heterogeneous wireless devices and measurement equipment as sensing nodes. Each sensing node measures the spectrum utilization at that location, and then sends this data to the sever.

Figure 2 depicts the software architecture of the system. The server sends commands to each sensing node for remote control, and receives the measurement data coming from these nodes. It also provides data search and visualization functions to various users interested in spectrum policy: government, commercial companies, and citizens.

A sensing node consists of 3 components: the Web Interface, Data Manager, and Device Controller. The design principles of the interface of each component are based on abstractions of the spectrum utilization into binary information with respect to 3 axes such as location, time, and frequency, as shown in Fig. 3.

To achieve remote control, the Web Interface receives commands from the server and transfers them to the Device Controller. To achieve data collection, the Web Interface uploads the data files written by the Data Manager to the server. In addition, the Web Interface is aware of the location of a sensing node based on a positioning system such as GPS. This means that the sensing node location in physical world is abstracted into just location information by Web Interface. The Web Interface transfers this location information to the Data Manager.

The Data Manager receives outputs from both the Device Controller and the Web Interface and saves this data in storage. Because it is important to reduce consumptions of storage and network capacity especially in resource-limited devices such as smartphones, we employ Tiny Spectrum Format (TSF). TSF achieves a high compression ratio by leveraging the abstraction of spectrum utilization into binary information.

The Device Controller provides two abstractions to allow the use of heterogeneous wireless devices and measurement equipment. First is an abstraction of both the time and frequency axes, which is achieved in the form of a common command set to control a wireless device or measurement equipment. Second is an abstraction of the spectrum utilization into binary information, which is achieved by generating binary information based on various forms of data acquired from a wireless device or a measurement equipment.

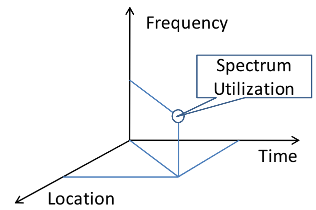

Fig. 3. Abstraction of the 3 axes and spectrum utilization.

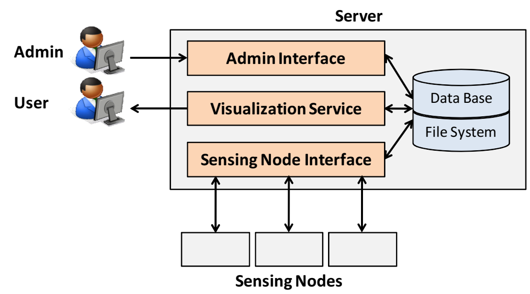

Fig. 4. Server software components

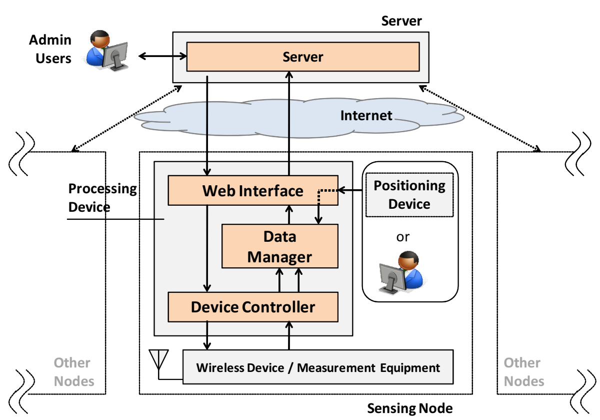

Fig. 2. System architecture

B. Server

The server provides functions to issue commands, collect data, and visualize data. Figure 4 depicts the structure of server components. The server consists of the Admin Interface, Visualization Web Service, and Sensing Node Interface. Each component exchanges the necessary information through the database and file system.

The Admin Interface provides a user interface to issue commands to control the sensing node. The command is temporarily stored in the database until it is read out when a sensing node accesses the server. The Visualization Web Service allows search and visualization of the data based on user inquiries on location, time, and frequency. The Sensing Node Interface communicates with sensing nodes to send commands and receive measurement data. The received data is registered in the database and stored in the file system.

C. Web Interface

The Web Interface operates on a sensing node to provide a communication channel for command retrieval and data uploading using HTTP POST based polling. In the first polling, the Web Interface sends a HTTP POST request with sensing node information set in the HTTP POST arguments. Table I lists the sensing node information. It consists of information on hardware organization and measurement performance such as hardware type, model, and frequency range. The server registers the sensing node information in the database, and then issues an ID number. In the second and later pollings, the sensing node sends a HTTP POST request in which the ID number is set in a HTTP POST request argument. The server replies with a HTTP Response that holds the commands that are issued by the administrator. Uploading of measurement data is achieved by attaching a measurement data file to a HTTP POST argument.

HTTP POST based polling has two advantages. First, sensing nodes can be installed in any network where HTTP is available. Even if the network is inside a firewall and

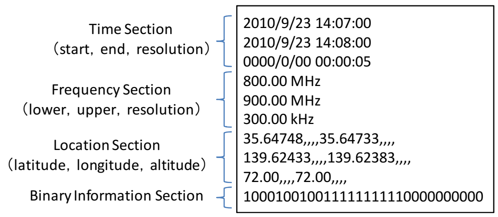

Fig. 5. TSF (Tiny Spectrum Format)

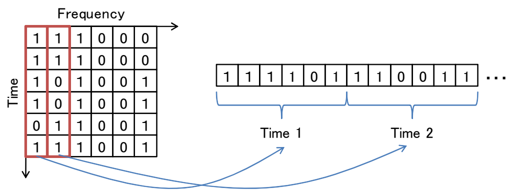

Fig. 6. Binary 2D array written as a single line

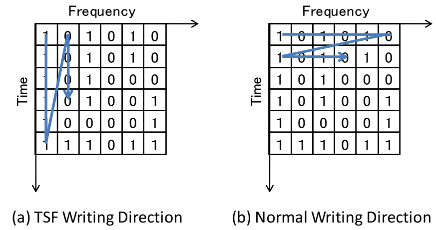

Fig. 7. Writing direction of binary 2D array

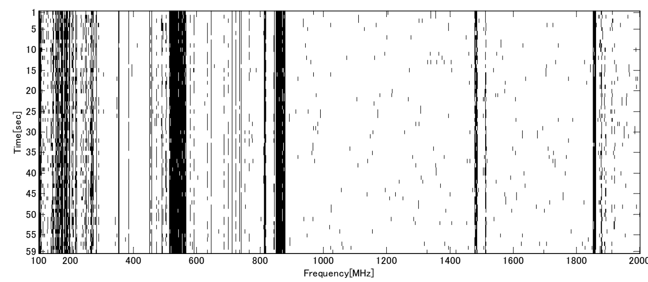

Fig. 8. Real spectrum utilization data.

connections from outside to inside are prohibited, a sensing node can communicate with the server. Second, on the server side, we can employ load balance techniques developed in web service domains such as DNS round-robin and load-balancer in order to mitigate traffic congestion or overloading.

The location information is acquired using a positioning system such as GPS. In addition, the Web Interface supports input from a sensing node owner if the sensing node is a fixed type and rarely moves. The acquired location information is transferred to the Data Manager.

D. Data Manager

The Data Manager receives the output of the Web Interface and Device Controller to save measurement data in a TSF file. Figure 5 shows an example of the contents of a TSF file. It has 4 information sections that are time, frequency, location, and binary information. In the time section, the start time, end time, and time resolution are written. In the frequency section, the lower bound frequency, upper bound frequency, and frequency resolution are written. In the location section, samples of latitude, longitude, and altitude are written in a time series. When the value of the location does not vary since the previous sample, only a comma is written, omitting the value. In the binary information section, a 1 is written for occupancy, and a 0 is written for vacancy.

The TSF has 3 features that allow it to achieve a high compression ratio. The first is that binary information is written in a single line. When the binary information has a start point, end point, resolution on the time and frequency axes, it can be handled as a 2D array as shown in Fig. 6. Thus, we don't have to write all the values of time and frequency corresponding to the binary information samples. Also, writing out the binary information in a single line removes line feed codes which degrades the compression performance of run-length and dictionary compression algorithms.

The second feature is that the binary information is written out in the time direction as shown in Fig. 7(a). The real spectrum utilization tends to have a series of identical samples in the time sequence within a frequency band as shown in Fig. 8, so that writing the binary information in the time direction helps run-length compression work more effectively. If the normal method was used, and the binary information was written at each sampling, i.e., in the frequency direction as shown in Fig. 7(b), this would degrade the compression performance.

The third feature is to separate the binary information section from the location section as different lines. Normally, it is natural to write both binary information and the location in a single line at each sampling. However, since the location data contains characters other than 1 and 0, the mixture of these characters degrades the compression performance. On the other hand, TSF separates the binary information from the location information to improve the compression performance.

E. Device Controller

The Device Controller provides a common command set to control wireless devices and measurement equipment. The command set specifies a start point, an end point, and a resolution on the time and frequency axes. Table II lists the common command set. Each command has a command name and an argument. The argument is the value that an administrator wishes to set. For example, to measure the frequency range from 100 MHz to 1 GHz, the issued command would be `FREQ_LOWER 100M` and `FREQ_UPPER 1G`.

When executing the commands, the Device Controller transforms each command into unique operations depending on the wireless device or the measurement equipment that the sensing node is equipped with. This command transformation totally depends on the type and model of the wireless device or

TABLE I
SENSING NODE INFORMATION

Parameter Name	Meaning	Range of Value or Example Value
frequency:min	Lower bound of measurable frequency[Hz]	e.g., 100M
frequency:max	Upper bound of measurable frequency[Hz]	e.g., 3.0G
frequency:resolution:min	Minimum frequency resolution [Hz]	e.g., 100k
frequency:resolution:max	Maximum frequency resolution [Hz]	e.g., 100k
time:resolution:min	Minimum time resolution [sec]	e.g., 0.1
time:resolution:max	Maximum time resolution [sec]	e.g., 60.0
equipment:type	Device or equipment type	spectrum_analyzer, sdr_frontend, tuner, ...
equipment:model	Device or equipment model	e.g., USRP2, R&S FSL 6
source:type	Type of raw data	spectrum, iq, sound, channel_quality, ...
source:available	Availability of raw data	1, 0
source:decision_method	Method to judge spectrum occupancy	decodability, threshold, ...
antenna:type	Antenna type	discone, logperiodic, ...
antenna:model	Antenna model	e.g., DS-3100
antenna:directional	Antenna directionality	1, 0
antenna:azimuth	Antenna azimuth	0, . . . , 360 or rotate
antenna:elevation	Antenna elevation	0, . . . , 90
antenna:height	Antenna height [m]	e.g., 5.0
positioning:type	Method to get location information	GPS, user, ...
positioning:model	Positioning device model	e.g., SONY GPS-CS1

measurement equipment. We show example implementations in Section IV.

As a result of command execution, the Device Controller obtains information related to spectrum utilization in various forms. Based on this information, the Device Controller judges the spectrum occupancy and outputs the binary information. The techniques to be used to judge the spectrum occupancy depend on the type of wireless device or measurement equipment. We present an overview of the judgment strategy here, and example implementations are described in Section IV.

Figure 9 shows the classification of the information generated from wireless devices and measurement equipment. There are two major categories of information: logical information and physical information.

Logical information is that obtained only after reading decoded signals. Logical information includes content such as audio, images, and data, channel quality factors, and the payload of a packet or a frame. The Device Controller can judge the spectrum occupancy based on whether the logical information is available or not.

Physical information is that obtained without any decoding. Physical information includes frequency domain information such as the power spectrum, and time domain information such as the base band signal, RF signal, and IF signal. The Device Controller can judge the spectrum occupancy based on physical information by applying spectrum sensing techniques pertaining to cognitive radio such as energy detection, feature detection, and matched filter detection [36].

IV. IMPLEMENTATION

A. Server

Server software is implemented using MySQL, PHP5, HTML/CSS, JavaScript, Gnuplot [37], and Google Maps API [38]. Figure 10 is a screenshot of the command terminal for administrators provided by the Admin Interface. Figure 11 is a screenshot of the Visualization Web Service. Each sensing node is represented as a icon, and the list of measurement

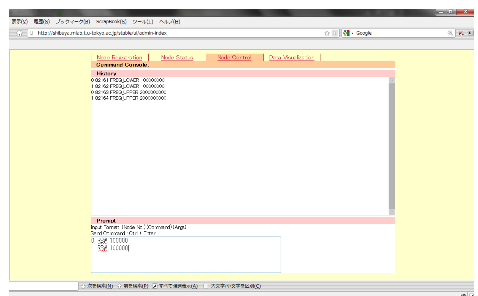

Fig. 10. Screenshot of the Admin Interface.

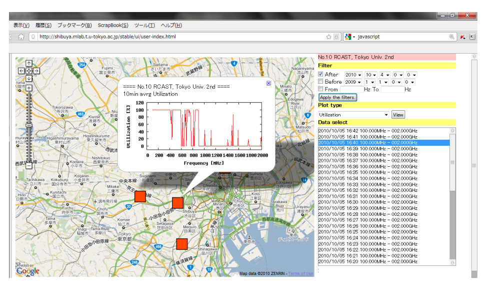

Fig. 11. Screenshot of the Visualization Web Service.

data appears when a user clicks the icon. Selecting the data, the user can see the plot of the spectrum utilization ratio.

B. Sensing Node Hardware

To verify that our architecture can utilize heterogeneous wireless devices and measurement equipment as sensing nodes, we implemented 3 types of sensing node using a spectrum analyzer Rohde & Schwartz FSL 6, a WLAN module Intel 5300 embedded on a Lenovo X200, and a SDR front-end USRP2. Figure 12, Figure 13, and Figure 14 show photos of the sensing nodes. In each node, we used a Lenovo X200 for data processing and hardware control. We used a discone

TABLE II
COMMON COMMAND SET.

Command Name	Meaning
FREQ_LOWER	Set the upper bound for measurement frequency range
FREQ_UPPER	Set the lower bound for measurement frequency range
RBW	Set frequency resolution
TIME_RESOLUTION	Set time resolution
START	Start a measurement
STOP	Stop a measurement

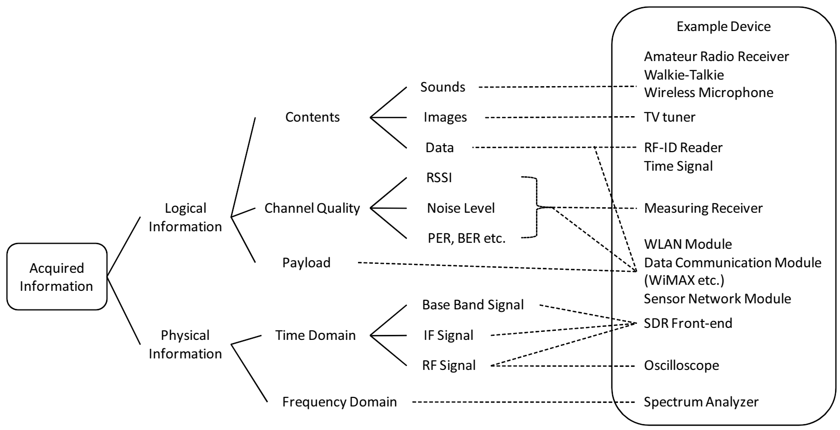

Fig. 9. Classification of information generated from various wireless devices and measurement equipment.

antenna DS-3100 with the spectrum analyzer and SDR front-end.

The spectrum analyzer, the WLAN module, and the SDR front-end respectively produce the frequency domain signal in physical information, the channel quality in logical information, and the time domain signal in physical information as shown in Fig. 9.

C. Web Interface

We implemented the Web Interface in PHP 5. It is independent of the type of wireless device or measurement equipment so that it is common to the 3 types of sensing node. We used the PHP extension pecl_http for HTTP POST. We also implemented inter-process communications using UDP for data exchange with the Data Manager and Device Controller.

D. Data Manager

We implemented the Data Manager in C. Since it is independent of the type of wireless device or measurement equipment, it is also common to the 3 types of sensing node. The Data Manager receives binary information from the Device Controller and location information from the Web Interface via UDP. It stores the received data in a TSF file and compresses the file using libbzip2. One TSF file is generated per minute. The Data Manager also monitors the storage capacity of the sensing node, and deletes the oldest file if it detects a shortfall in capacity.

E. Device Controller

Implementation of the Device Controller depends on the type of wireless device or measurement equipment that a sensing node is equipped with. For references, we implemented 3 versions of the Device Controller, for the spectrum analyzer, the WLAN module, and the SDR front-end.

Spectrum Analyzer R&S FSL 6 : Figure 15(a) shows a schematic circuit of a typical spectrum analyzer. A spectrum analyzer consists of local oscillators, mixers, filters, and an energy detector. The spectrum is obtained by detecting the power of the signals that are down-converted from RF to base band or IF, while sweeping the local oscillators' frequency. The Device Controller can judge the spectrum occupancy based on the strength of the spectrum.

In a spectrum analyzer, FREQ_LOWER and FREQ_UPPER corresponds to the start and end of the sweep, respectively. TIME_RESOLUTION corresponds to the time taken for a single sweep. RBW corresponds to the bandwidth of the band-pass filter in front of the energy detector. RBW also determines ΔF_{LO}, which is the increment of the frequency when sweeping. RBW and ΔF_{LO} are usually independent of each other. However, in the case that RBW is wider than ΔF_{LO}, a gap where the signal is not measured appears as shown in Fig. 15(b). To prevent this, the Device Controller automatically chooses a ΔF_{LO} that satisfies $\Delta F_{LO} <= \texttt{RBW}$.

To generate the binary information, we utilize the energy detector which compares the power of each spectrum bin to a predetermined threshold.

We connected the R&S FSL 6 and the Lenovo X200

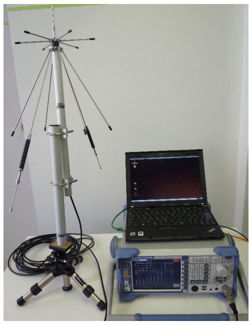

Fig. 12. Spectrum Analyzer R&S FSL6

Fig. 13. WLAN module Intel 5300 (embedded on Lenovo X200)

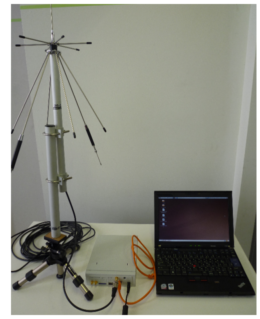

Fig. 14. SDR front-end USRP2

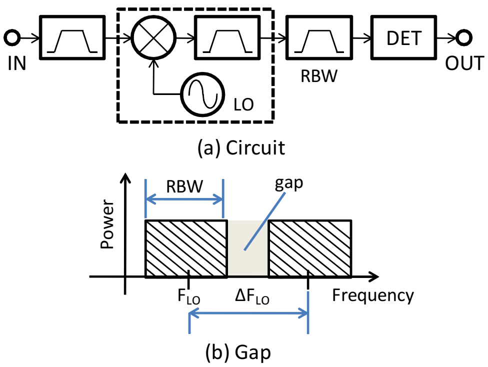

Fig. 15. Measurement using a spectrum analyzer

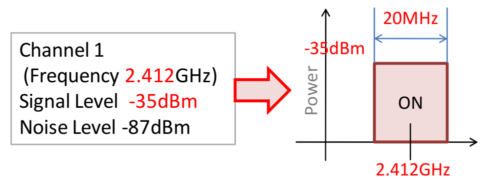

Fig. 16. Measurement using a WLAN module

via an Ethernet connection. We implemented the Device Controller using C and a library named RsSpecAn provided by R&S [39]. In RsSpecAn, the sweep start and sweep end are set via the `ConfigureFrequencyStartStop` function. The bandwidth of the band-pass filter is set via the `ConfigureSweepCoupling` function with the `COUPLING_RBW` flag on. The time for a single sweep is set via the `ConfigureSweepCoupling` function with the `COUPLING_SWEEP_TIME` flag on. ΔF_{LO} can not be directly set; instead, we set the number of measurement points that is determined by (`FREQ_LOWER` − `FREQ_UPPER`)/`RBW` via the `ConfigureSweepPoints` function.

WLAN module Intel 5300 : The WLAN module embedded on the laptop measures channel quality factors such as RSSI. For example, the `iwlist` command available in Linux provides the signal strength and noise level of all channels. We can obtain the occupancy of the spectrum based on the availability of such channel quality information.

IEEE 802.11 defines each channel to have a 20 MHz bandwidth and a 5 MHz interval. For example, if a WLAN module detects a channel that has a -35 dBm signal strength at 1ch (2.412 GHz) as shown in Fig.16, the Device Driver determines the occupation of the 20 MHz bandwidth centered at 2.412 GHz which spreads from 2.402 GHz to 2.422 GHz.

`FREQ_LOWER` and `FREQ_UPPER` determine the measurement channel. `RBW` is fixed to 5 MHz which is the channel interval defined in IEEE802.11. `TIME_RESOLUTION` is defined as the measurement interval.

We implemented the Device Controller for the WLAN module in C using iwlib. iwlib is provided by Wireless Extension [40], the typical WLAN device driver API, and used in the `iwlist` command.

SDR front-end USRP2 : Although it is possible to determine the spectrum occupancy based only on IQ signals acquired from USRP2, we embedded FFT in the Device Driver in order to improve the frequency resolution. Because the bandwidth of the spectrum is limited by the sampling frequency F_{S}, the Device Controller periodically sweep the center frequency F_{C} and calculate the FFT as shown in Fig. 17(a). The Device Driver can judge the spectrum occupancy based on the signal strength of each FFT bin.

`FREQ_LOWER`(F_{L}) and `FREQ_UPPER`(F_{U}) determine F_{CL} and F_{CU} which are the lower and the upper bounds of the sweep, respectively, as expressed in the following formulas.

$$\begin{aligned} F_{\mathrm{CL}} &= F_{\mathrm{L}} + \frac{F_{\mathrm{S}}}{2} \\ F_{\mathrm{CU}} &= \left\lceil \frac{F_{\mathrm{U}} - F_{\mathrm{L}}}{F_{\mathrm{S}}} \right\rceil \cdot F_{\mathrm{S}} - \frac{F_{\mathrm{S}}}{2} + F_{\mathrm{L}} \end{aligned}$$

`RBW` affects the number of FFT points as $F_{\mathrm{S}}/\mathtt{RBW}$. `TIME_RESOLUTION` determines T_{seg} which is the measurement time per spectrum segment as follows.

$$T_{seg} = \frac{\mathtt{TIME\_RESOLUTION}}{\lceil (F_{\mathrm{U}} - F_{\mathrm{L}})/F_S \rceil}$$

To generate the binary information, we utilize the energy detector which compares a predetermined threshold and the maximum power of each spectrum bin per unit time.

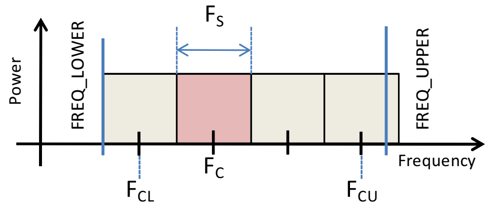

Fig. 17. Measurement using the SDR front-end

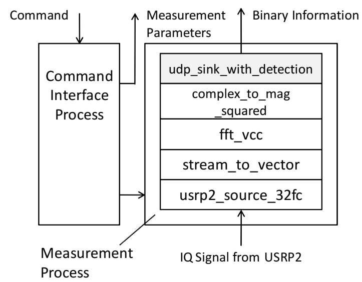

Fig. 18. Process and GNU Radio signal processing block diagram

We used Python and GNU Radio [41], which is an SDR development environment. Figure 18 shows the implemented processes and the signal processing blocks using GNU Radio. `udp_sink_with_detection` is a newly implemented original signal processing block.

To sweep the center frequency, the Device Controller sets the center frequency of USRP2 through the `set_center_freq` function of the signal processing block `usrp2_source_32fc` every T_{seg} sec. The number of FFT points is set as an initialization parameter in the signal processing block `fft_vcc`. The threshold for spectrum occupancy judgment is set through `udp_sink_with_detection` as an initialization parameter.

F. Development cost of new Device Controller

The Web Interface and Data Manager are independent of the type of wireless devices or measurement equipment. Thus, when implementing a sensing node with a different configuration, only the Device Controller needs to be newly implemented. Table III shows the program size of the implemented software components. The Web Interface, Data Manager, and Device Controller have roughly the same size. This means that our architecture reduced the development cost for supporting new hardware to 1/3 of the value for a vertically integrated architecture.

V. Evaluation

A. Performance of Tiny Spectrum Format

In order to confirm the effectiveness of the TSF, we compared the file size with that of other formats using real data acquired using the spectrum analyzer R&S FSL 6. The time resolution was 1 sec, the measurement time was 2 min, the frequency range was 100 MHz – 2.0 GHz, and the frequency resolution was 300 kHz. We wrote the real data in TSF, Binary, CSV, and XML formats, and then compressed them using bzip2.

Figure 19 shows the file sizes for each format as the number of samples increases. All formats, including Compressed XML, Compressed CSV, Compressed Binary, and Compressed TSF linearly increase in file size as the number of samples increases, but Compressed TSF has the smallest file size.

If we denotes the number of samples ($\times 10000$) as N, the file sizes can be approximated as $\text{Size}_{\text{TSF}}(N) = 0.193N + 0.726$ [kByte] and $\text{Size}_{\text{Binary}}(N) = 0.293N + 1.320$ [kByte].

If we assume that the number of samples is sufficiently large, the ratio of the file sizes of Compressed TSF and Compressed Binary is

$$\lim_{N\to\infty} \frac{\text{Size}_{\text{TSF}}(N)}{\text{Size}_{\text{Binary}}(N)} = \frac{0.193}{0.293} = 0.659$$

Thus, Compressed TSF achieves a file size approximately 66% that of Compressed Binary.

In addition to the real data, we also made a file size comparison using random data. Comparison using random data represents the worst case scenario because TSF is not effective anymore. Figure 20 shows the file sizes for each format. The file sizes for TSF are the same as those for Compressed XML and Compressed CSV. Compressed TSF shows larger file sizes than those of compressed Binary. The approximations of the file size are $\text{Size}_{\text{TSF}}(N) = 1.601N + 0.1228$ [kByte] and $\text{Size}_{\text{Binary}}(N) = 1.255N + 0.406$ [kByte].

If we assume that the number of samples is sufficiently large, the ratio of the file sizes for Compressed TSF and Compressed Binary is

$$\lim_{N\to\infty} \frac{\text{Size}_{\text{TSF}}(N)}{\text{Size}_{\text{Binary}}(N)} = \frac{1.601}{1.255} = 1.28$$

Even in the worse case, the file size of Compressed TSF is only 1.28 times that of Compressed Binary.

B. Measurement using heterogeneous sensing nodes

In order to verify the ability to measure the spectrum utilization using heterogeneous wireless devices and measurement equipment, we measured the spectrum utilization of the 2.4 GHz band in laboratory environment using the 3 types of sensing nodes.

TABLE III
Program Size

Component	Language	Lines
Web Interface	PHP 5	1399
Data Manager	C	1699
Device Controller		
- Spectrum Analyzer R&S FSL 6	C	958
- WLAN module Intel 5300	C	1212
- SDR front-end USRP2	C++	730
	Python	559
Server Software	HTML/CSS	266
	JavaScript	205
	PHP 5	1170

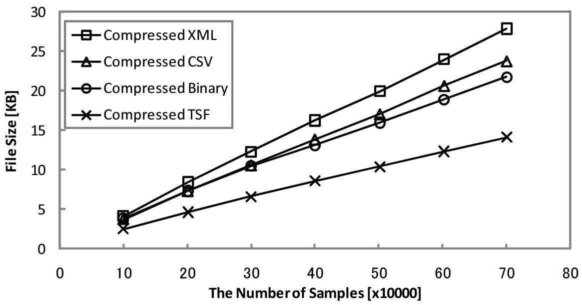

Fig. 19. Comparison of file sizes for real data

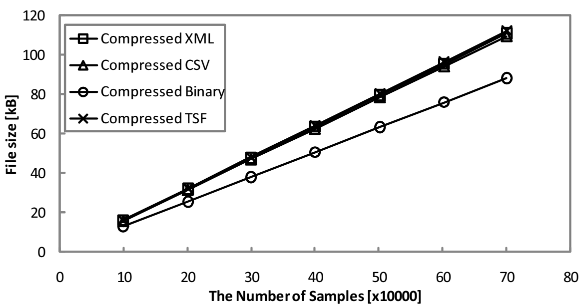

Fig. 20. Comparison of file sizes for random data

One-minute snapshots captured by the spectrum analyzer, WLAN module, and SDR front-end are shown in Fig. 21, Fig. 22, and Fig. 23, respectively. Heavy utilization of 1ch (2.402 GHz – 2.422 GHz) and 11ch (2.452 GHz – 2.472 GHz) is observed in all the snapshots. As for other channels, while the snapshots of the WLAN module shows the utilization of 7ch (2.432 GHz – 2.452 GHz) only between 4 and 10 sec, the snapshots of the spectrum analyzer and the SDR front-end shows scattered utilization of 7ch during the whole time period.

From these results, the spectrum utilization ratio is calculated as 31.2 % for the spectrum analyzer, 49.4 % for the WLAN module, and 32.6% for the SDR front-end.

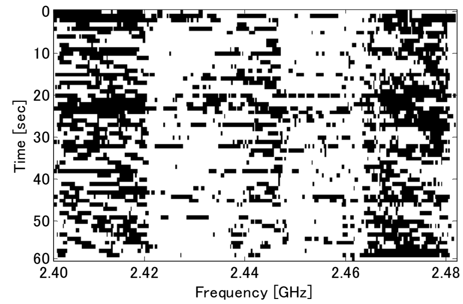

Fig. 21. Measurement results for the spectrum analyzer

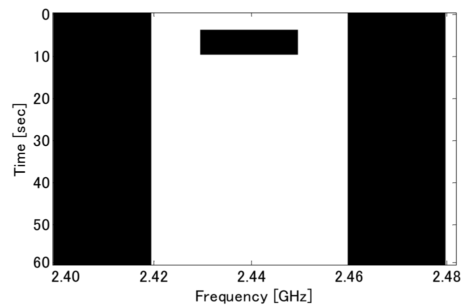

Fig. 22. Measurement results for the WLAN module

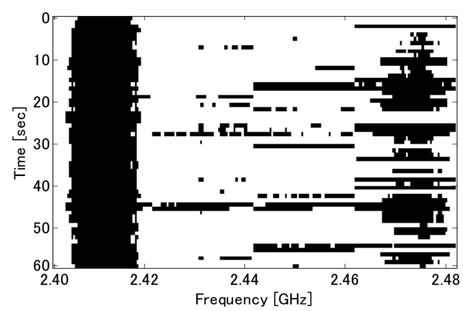

Fig. 23. Measurement results for the SDR front-end

C. Multi-site measurement

In order to verify the ability to collect measurement data from multiple locations, we conducted multi-site measurements using the USRP2 sensing nodes at 4 locations in Tokyo. The measurement sites were 1. University of Tokyo (Komaba), 2. University of Tokyo (Hongo), 3. Tokyo Institute of Technology, and 4. Residential area (Soshigaya). Figure 24 shows a map of the measurement sites. The measurement time period was 24 hours from 16:00 Oct. 4, 2010 – 16:00 Oct. 5, 2010. The frequency range was from 100 MHz – 2.0 GHz, and the frequency resolution was 390 kHz. The time resolution was 20 sec.

Figure 25 shows the average spectrum utilization ratio over the 24 hour period. Heavy usage is seen for 100 MHz, 200 MHz, 500 MHz, which are used for TV broadcasting, and 800 MHz ,which is used for mobile phones. Frequencies above 900 MHz are somewhat less utilized than those below 900 MHz. Because all of the 4 locations are in the urban area of Tokyo, the overall trend is similar at every location. However, some differences exist in spectrum utilization between the sites, such as the distinct utilization of the 900 MHz band at University of Tokyo (Komaba).

D. Route measurement

In order to verify the ability to measure spectrum utilization using a mobile sensing node, we conducted measurements along a route using a WLAN module embedded on a Lenovo X200. Figure 26 shows the measurement route. The route is 7.8 km long and runs partly beside a railway line through a residential area in the western part of Tokyo. The frequency range was from 2.402 GHz to 2.478 GHz which the WLAN module is able to measure.

Figure 27 shows the spectrum utilization observed along

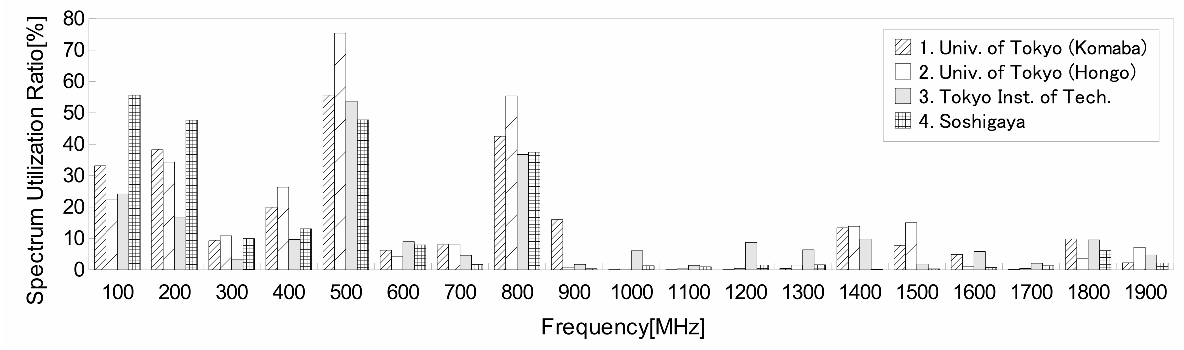

Fig. 25. Spectrum utilization ratio at 4 locations

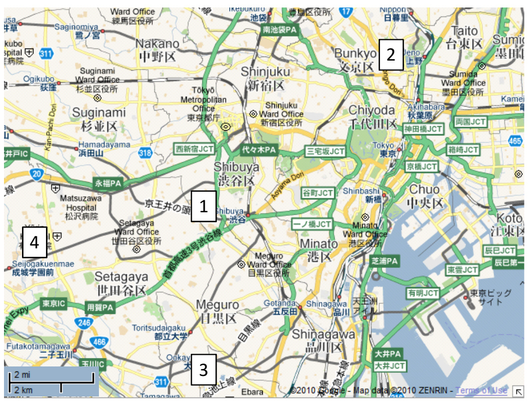

Fig. 24. Locations of sensing nodes

Fig. 26. Measurement route

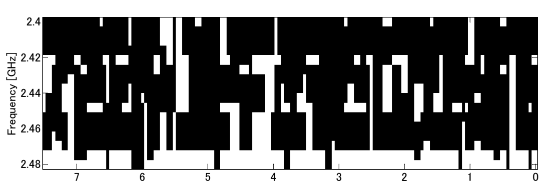

Fig. 27. Spectrum utilization along a route

the route. 1ch (2.402GHz – 2.422GHz), 6ch (2.427 GHz – 2.447), 11ch (2.452 GHz – 2.472 GHz) are heavily utilized so as to avoid interference due to channel overlap. The overall spectrum utilization is calculated to be 73.6%. This utilization may correspond to home networks because the measurement route is in a residential area.

VI. Conclusion and Future Work

In this paper, we described the design, implementation and evaluation of a distributed spectrum sensing system which continually measures the spectrum utilization in the spatial domain. The system is aimed at speeding up the decision making process of the government concerning spectrum policy to allow the more efficient use of the spectrum. The proposed architecture can utilize heterogeneous wireless devices and measurement equipment as sensing nodes in order to rapidly extend the measurement coverage. To verify the architecture, we implemented 3 types of sensing nodes using a spectrum analyzer, a WLAN module, and a SDR front-end. We evaluated the system through measurements using heterogeneous sensing nodes, multi-site measurements, and mobile measurements.

There are three possible approaches to further research. First, we can extend the server-side architecture to achieve the scalability to accommodate more sensing nodes. A distributed server architecture might be a candidate in which each server manages its own regional division. Second, we can extend our system to guarantee the accuracy of collected data. Authentication mechanism of sensing node owners might be helpful to distinguish the data coming from reliable owners such as research organizations from anonymous data. Finally, we should investigate a framework for administration and operation. Studies in voluntary computing such as SETI@home [42] and also Participatory Sensing [43] or People-Centric Sensing [44], in which numerous mobile smartphones are utilized as sensor nodes, might be used as references.

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