Measurement-Based Spectrum Database for Flexible Spectrum Management

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SUMMARY In this paper, we propose the novel concept of a spectrum database for improving the efficiency of spectrum utilization. In the current design of TV white space spectrum databases, a propagation model is utilized to determine the spectrum availability. However, this propagation model has poor accuracy for radio environment estimation because it requires a large interference margin for the PU coverage area to ensure protection of primary users (PUs); thus, it decreases the spectrum sharing efficiency. The proposed spectrum database consists of radio environment measurement results from sensors on mobile terminals such as vehicles and smartphones. In the proposed database, actual measurements of radio signals are used to estimate radio information regarding PUs. Because the sensors on mobile terminals can gather a large amount of data, accurate propagation information can be obtained, including information regarding propagation loss and shadowing. In this paper, we first introduce the architecture of the proposed spectrum database. Then, we present experimental results for the database construction using actual TV broadcast signals. Additionally, from the evaluation results, we discuss the extent to which the proposed database can mitigate the excess interference margin.

key words: dynamic spectrum access, cognitive radio, spectrum database, TVWS

1. Introduction

Because of the growth in demand for mobile communications systems, data traffic has significantly increased during the last decade. Reference [1] predicts an exponential increase in data traffic that corresponds to a 10-fold increase in traffic between 2013 and 2019. Similarly, many industries forecast a 1,000-fold increase between 2010 and 2020. Because this exponential growth consumes finite spectrum resources, traditional spectrum utilization policies with exclusive resource allocation must be changed in future wireless communication systems. For this reason, many researchers have shown an interest in spectrum sharing with dynamic spectrum access (DSA), which is an innovative spectrum utilization method [2], [3].

Cognitive radio (CR) is a DSA tool that can solve the shortage of spectrum resources. Using CR, secondary users (SUs) can utilize spectrum bands that are licensed to primary users (PUs) under interference constraints for PUs. In the spectrum sharing environment, SUs must not interfere with primary communications. Because SUs are required to set parameters by taking into consideration the worst value of the radio environment estimation error, low-accuracy estimations reduce the spectrum sharing efficiency. Therefore, it is important to have accurate knowledge of the radio environment [5], [6].

Today, spectrum cognition techniques can be categorized into two methods: spectrum sensing and spectrum database use. Spectrum sensing uses the detection of PU signals to characterize radio environments [7]. To provide good protection, signal detection must be performed under the (strict) condition that the PU signal strength be below the noise floor, even under low signal-to-noise ratios (SNRs) and fading conditions. Fluctuations make it difficult for the SUs to achieve stable detection; thus, although this technique can model the radio environment in real time, it is very challenging to implement. The second method is based on storing information about spectrum availabilities of each location in spectrum databases [8]. In this method, SUs should query the database before they utilize the spectrum. Then, the database provides spectrum information to the SUs. The spectrum database is especially useful for fixed broadcasting PUs because the spatial distribution of the average signal power does not change. The television (TV) band is a suitable spectrum for database-aided spectrum sharing; its standardization has been discussed in many countries including the US [9], the UK [10], and Singapore [11].

In the US, rules for spectrum database utilization for TV white space (TVWS) are defined by the Federal Communications Commission (FCC). On the basis of that regulation, some service providers have already launched spectrum databases [12], [13]. The Office of Communications (Ofcom) in the UK started a TVWS pilot program for database-aided TVWS utilization in July, 2014 [10], [14]. For the TVWS pilot, some industries, e.g. Spectrum Bridge, Google, Microsoft, and NICT, have been permitted by the Ofcom to launch databases.

Current databases usually evaluate white space based on empirical propagation models. F-Curve, a propagation model that is utilized in the FCC-defined database, estimates the propagation loss based on the percentage of locations, the percentage of time, frequency, and transmitting antenna heights [15]. The Ofcom-defined database
uses a SEAMCAT extended Hata propagation model [16]. This model considers antenna heights of transmitter and receiver, frequency, and terrain information. However, it is well known that empirical propagation models cannot take into account all of the indeterminacies of radio environments, such as shadowing effects and differences of location. Figure 1 shows several simplified path-loss models [17]. These curves follow a path-loss equation $L(d) = -20 \log \frac{d}{d_0} + 10 \gamma \log \frac{d}{d_0} + 20 \text{[dB]}$, where $\lambda$ is the wavelength [m], $d_0$ is the reference distance [m], $d$ is the distance from a transmitter [m], and $\gamma$ is the path-loss index. For example, at $d = 1,000$ [m], there is a difference of 20 [dB] between $\gamma = 2$ and $\gamma = 3$ and also between $\gamma = 3$ and $\gamma = 4$. Because SUs must not interfere with PUs, their communication parameters are determined based on the worst case scenario. For this reason, the conventional approach requires the system to set large margins to ensure no interference with PUs [15]. We have proposed a pathloss model-tuning method [18] to improve the estimation accuracy. The method estimates suitable pathloss parameters, transmission power, and pathloss-index based on measurement datasets using a maximum likelihood method. However, the method has reduced accuracy under shadowing effects.

The error characteristics of propagation models have been presented in [19], [20]. In [19], the authors measured the field strength of radio waves over TV bands using a highly accurate spectrum analyzer. The statistical results showed that many propagation models perform biased estimation with wide error variances. Phillips et al. [20] analyzed the efficacy of basic path-loss models when predicting median path losses in urban environments. By comparing results to those of many other path-loss models, the authors identified the danger of using basic a priori models to predict the vagaries of the radio environment. It has also been claimed that complex models that consider a larger number of variables (i.e., terrain models) do not necessarily make better predictions. To fit propagation models to the regional radio environment, complex models often require a great deal of information about the radio environment, e.g., terrain, antenna height, antenna pattern, and some measurement data. The fitted curve can achieve near-unbiased estimation over a wide area. However, the information increases the calculation complexities, but cannot improve local accuracy due to shadowing effects. For these reasons, we examined early studies of measurement-based database construction [21], [22].

In this paper, we propose the novel concept of using a spectrum database that consists of measurement information reported by mobile SUs. Figure 2 shows the concept of the proposed spectrum database. The proposed database is a hybrid system, combining spectrum sensing and a spectrum database. The spectrum database consists of radio environment information that is measured by mobile SUs (e.g., vehicles and smartphones). The SUs measure the received signals from the PUs while the SUs move (without transmitting signals). The collected dataset is related to the measurement location, and is reported to the database. After enough data are gathered, the database estimates the radio environment characteristics of the PUs by statistical processing with the large created dataset. Because the data include actual propagation losses and shadowing effects, accurate channel statuses can be determined. SUs can connect the database to a wireless access point such as a cellular network to estimate the radio environment around the SUs, and adjust their own communication parameters, which causes no harmful interference to PUs. Today, there are very many vehicles and smart phones around the world. Because these mobile terminals have high mobility, we consider them particularly suitable for use as probing sensors. These features of mobile terminals enable the spectrum database to gather measurement data rapidly and over a wide range. Thus, the radio environment can be estimated accurately. In addition, using the accurate knowledge of the received PU signal power, spectrum sharing based on PU signal quality metrics such as the signal-to-interference-plus-noise ratio (SINR) can be implemented.

The remainder of this paper is organized as follows. Section 2 describes our proposed hierarchical spectrum
database architecture, which enables flexible configuration of spectrum utilization policies. In Sect. 3, we explain how to process the large measurement dataset. Section 4 describes measurement configurations for a field test of the spectrum database construction method; the field test results are presented in Sect. 5. We describe future tasks in Sect. 6. Section 7 concludes this paper.

2. Hierarchical Database Architecture

Figure 3 summarizes the two spectrum database utilization methods: propagation model-based spectrum databases and proposed databases. For the databases populated using propagation modeling, spectrum availability is determined in two steps. First, the service area of a PU is estimated using the propagation model. Second, the expected service area is extended by an additional margin to guarantee interference-free operation for the PUs located at the boundary of the primary coverage area. Because the margin is added without any regard for the actual propagation conditions, the SU transmission power and the SU coverage area are unnecessarily reduced. As a result, the total spectrum sharing performance is degraded. On the other hand, the proposed database can provide accurate propagation information regarding the PU signals to the SUs. Therefore, if the location of the PU receiver is known, aggressive spectrum sharing while controlling the SU transmission power can be realized. This flexible and sophisticated transmission power control method can obtain highly efficient spectrum sharing performance between PUs and SUs because the spectrum database can help to accurately determine the received power of PU signals at any location and any frequency if a perfect spectrum database can be generated.

The proposed spectrum database can realize highly efficient spectrum utilization with strict interference management by employing measurement datasets. However, if all of the measurement data are uploaded to the database covering a large area, a large amount of data must be processed to estimate the primary coverage, which makes it difficult to provide spectrum usage information to SUs. Therefore, we consider a hierarchical database structure that supports storing data particles of flexible size in each layer, as shown in Fig. 4. In the hierarchical architecture, the size of an area supported by the databases at each layer is different. The databases at the lowest layers operate with high-resolution raw data, but they can only support small areas. Higher layers, with information of lower resolution, are statistically calculated from the lower-layer data. Because of the reduced size of the stored information, the databases on higher layers can support wider areas.

As shown in Fig. 4, the lowest-layer database is located at each SU. SUs probe the radio environment during displacement and store the most recent measurement results in these databases at high resolution. However, because an individual local database cannot cover a sufficiently large area, any comprehensive view of the primary signal propagation must be derived from the locally collected data. Hence, a second-layer database is used to store the stochastic information gathered from surrounding SUs. This layer consists of many databases supporting small areas of a few square kilometers in size. SUs upload measurement datasets when the second-layer database requires updates to its own statistical information. After enough data are gathered, SUs can utilize the statistical information provided by the second-layer database. We consider the second-layer database to be fixed and to be managed by industry, which is permitted to manage the database by governments. If there is an immediate demand for white-space utilization, the second-layer database with mobility can be added for the required area. Because it is difficult to store all of the measurement data, stochastic information with lower resolutions is stored according to the location coordinates based on a grid structure. A database of this size can gather information on signal power from surrounding SUs and can store the average power for each frequency and location. This database can support SU interference management so as to achieve strict transmit power control without degradation of PU reception quality. The database at the highest layer implements a spectrum utilization policy provided by the regulatory organiza-
tion in charge of a region, such as the FCC in the US, Ofcom in the UK, or the Ministry of Internal Affairs and Communications (MIC) in Japan. As a result, metrological spectrum management can be realized with highly efficient spectrum sharing.

The proposed architecture can be used for various primary systems. Here, various parameters of the database are constructed according to the spectrum characteristics of the primary system. We assume that the frequency of data upload and the spectrum allocation period are the main parameters used for database construction, and that the database must adjust these parameters based on the spectrum characteristics. In this paper, we specifically consider the compatibility with the current TVWS spectrum database design. According to the current rules of TVWS utilization, SUs must access the database at intervals of several hours: two hours in the UK and 24 hours in the US. We follow these time frames for the spectrum allocation periods. Because broadcast TV transmitters are fixed, their spectrum occupancies are static in the time domain. Therefore, in terms of TV protection, the importance SUs need to know is the spatial distribution of the average received signal power. Because the variation of the distribution is gradual in the time domain, the frequency of the dataset upload by each measurement terminal is expected to be low. From the practical standpoint of database access cost, frequent dataset uploading is undesirable. Dataset upload should be conducted only when the node can access the wireless networks with sufficient capacity, such as public wireless LAN (WLAN), home WLAN, and cellular networks.

Of course the measurement-based database design can be applied to other networks with frequent changes of spectrum usage: unlicensed bands, cellular systems, radar bands, and so on. However, spectrum occupancies of these systems fluctuate drastically in the time domain; thus, other characteristics of white-spaces, e.g., variance, duty cycle, and transition ratio, are required. We speculate that the requirements increase the complexity of measurement systems and increase the upload cost. Generalization of such complexities and the database design should be studied further.

3. Low-Layer Configuration in TVWS

This section explains the low-layer configuration in TVWS. As already mentioned, the most important spectrum characteristic in TVWS is the average received signal power. To estimate the spatial distribution effectively, we assume that measurement nodes probe signals with short-term averaging. In addition, the second-layer databases collect the datasets and average the data per short-size grid.

3.1 Lowest Layer: Local Database at Node

A layer is implemented at each measurement node. Each node probes signals during displacement and stores the signal data in its own database. Because each node moves with the user, the explicit spatial border of this layer is not determined. To remove signal variations due to small-scale fading, each node periodically measures signals (with short-term averaging), as shown in Eq. (1).

\[ P_i = \frac{1}{M} \sum_{t=0}^{M-1} |h_i[t]s[t] + w_i[t]|, \]  

where \( h_i[t] \) represents the channel coefficient at the \( i \)-th node location, which includes propagation loss, shadowing, and small-scale fading. \( s[t] \) is the signal from the primary user. \( w_i[t] \) is additive white Gaussian noise (AWGN). \( M \) is the number of averaged samples of each sensor. The mobile terminal equipped with a GPS device stores the value \( P_i \) and the current location, time, and observed TV channel in the local database of the node. These values are uploaded to second-layer databases via wireless access networks. After upload, the node can erase the dataset from its own database.

3.2 Second Layer: Local Database

The second layer typically consists of fixed multi-databases managed by industries which are allowed to utilize it by governments. Each database supports a small area of a few kilometers, which matches the typical coverage of TV transmitters. Higher-layer databases divide datasets from mobile nodes into corresponding second-layer databases, based on measurement location and the supported area of the second-layer databases. After the data has been gathered, the spatial distribution of the average received signals can be estimated. In addition to the difficulty of storing a large number of measurements in a single database, another important problem to overcome is the limited accuracy of localization systems in the mobile terminals. A typical GPS device experiences errors on the order of several meters (up to more than 10 meters). For these reasons, we use a grid structure for location indexing, as shown Fig. 5. We divide each area of a few square kilometers (which is assigned to a database on the layer immediately above the local databases on the mobile terminals) into a square grid with a side length of \( l \) [m]. Each square cell in the grid in the second-layer databases is represented by the average received signal power of all measurement data that was collected from the cell described with coordinates \( x \) and \( y \) that satisfy the condition
\[
\sqrt{(x - x_c)^2 + (y - y_c)^2} \leq \frac{1}{\sqrt{2}},
\]

where \(x_c\) and \(y_c\) represent the coordinates of the grid field’s center. In other words, the PU power in a given grid field is estimated as the mean \(\mu\),

\[
\mu = \frac{1}{N} \sum_{i=1}^{N} P_i,
\]

where \(N\) is the number of observations that satisfy Eq. (2).

Note that there are borders of the estimation areas between the databases. Thus, white-space determination methods taking into account the information of databases, which are located on the both ends of the boundary, are required. For example, average of two values which are stored in the both ends of databases is a simple connection method.

4. Measurement Campaign over TV Bands

We conducted a large-scale measurement campaign to evaluate the radio environment estimation performance of the proposed spectrum database [23], [24]. We used five vehicles with spectrum sensors. A TV transmitter was treated as the primary system, and measured the signal power from the transmitter. Two one-week measurement campaigns were conducted, in October 2013 and in February 2014. The prior measurement datasets were stored in the spectrum database. On the other hand, the posterior measurement datasets were treated as instantaneous measurement data and were used for strict evaluation of the statistical estimation error characteristics.

4.1 Measurement Object and Measurement Area

Figure 6 shows the measurement area and the object of measurement. This figure describes a 40 [km] \(\times\) 45 [km] square area. In this experiment, Kumagaya relay station was treated as the PU transmitter. This station is located in Kumagaya city, Saitama, Japan, which is a suburban area near metropolitan Tokyo. We mainly measured the signal of 13CH (center frequency of 473.14 MHz and bandwidth of 6 MHz). The signal is a vertical polarized signal with an EIRP at 31 W.

4.2 Experimental Structure

Figure 7 shows the sensing equipment used. The spectrum sensing function was implemented on a software-defined radio platform, Universal Software Radio Peripheral (USRP) N210, using GNU Radio software, and run on a laptop computer. The TV signal was sampled using a fast Fourier transform (FFT) with a 200-kHz sampling rate; the number of samples \(M\) was set to 2,048. Five vehicles measured the signal while driving on roads. The observation results were stored on the laptop, together with location information collected using a Garmin GPS18xUSB GPS unit. To allow data collection in a short time, we had two sensing devices in each vehicle, as shown in Fig. 8. We used five vehicles in total; thus, ten measurement units were utilized. Each USRP has individual (linear) differences in measurement values. Therefore, we had to offset the difference by employing tone signals in the TV band, provided by a signal generator (Rohde-Schwarz, SMU200A).

Here, the measurement parameters dictate that the mea-
Fig. 9 Calibration equipment for investigating the difference between the band-limited measurement power and the full band signal power.

Fig. 10 Measurement power of USRP N210: Measurement of 6-MHz ISDB-T signal using FFT with 200-kHz sampling rate.

Fig. 11 Generated radio environment map at 473.14 MHz.

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4.3 Spectrum Database Construction

For statistical processing of the measurement dataset, we prepared a MySQL database server at our university. The database server has two tables: a raw data table and a statistical data table. The raw data table stores the large measurement dataset with no changes. Each measurement datum is associated with measurement parameters: location, frequency, power, and so on. The statistical data table has the average received signal power for each spatial grid cell containing raw data. In addition, the database uses statistical processing functions that generate the statistical data table from the raw data table. These functions produce spatially-distributed average received signal information when the appropriate queries are made.

After the field test, all measurement data were recorded on the MySQL database server. To estimate the spatially-distributed average received signal information, the prior measurement datasets were averaged over spatial grids with a 10-m side length.

5. Measurement Results

Figure 11 shows an average received signal map at 473.14 MHz. This map consists of datasets measured in a prior measurement campaign and stored in the MySQL database server. The strong trend of path loss increasing with increased distance from the transmitter is clearly visible. The map also indicates that some regions have a received power value significantly different from the received power value measured in adjacent cells. Because of time variation factors, which include AWGN, are averaged out using long-term measurement, these variations are attributed to shadowing effects.

In this section, we evaluate the estimation error performance of the constructed spectrum database. The generated map is an instance of the proposed spectrum database. The dataset that is measured a posteriori is used to obtain the most probable value and is compared with both the map and a propagation model.

5.1 Comparison with a Propagation Model

To clarify the probabilistic error performances, we evaluated the cumulative distribution function (CDF) of the radio environment estimation error. As a comparison method, we used...
Notice 640, which is a propagation model for Japanese TV broadcast systems. This propagation model is defined by the Japanese spectrum regulator, MIC; it is virtually identical to the propagation model defined by the FCC. Japanese TV broadcast operators often use this model to estimate the communication areas of TV transmitters because MIC licenses the use of TV spectrums based on the estimation results for Notice 640. According to MIC, the propagation curve considers multipathing and diffraction due to terrain; however, the theoretical rationale is unclear. To estimate the radio environment based on Notice 640, we used a radio propagation simulator called area kakube [25]. This software was made for Japanese TV broadcast operators. Notice 640 based electrical field strength can be calculated using stored Japanese terrain information. Note that the measurement signal power is attenuated because of the band limit on the measurement, as discussed in Chapter 4. Therefore, we subtracted 14.7 dB from the calculation results taken from area kakube.

Figure 12 shows a statistical comparison of residual-error performance. The first curve indicates the CDF of differences between average values in the constructed radio environment map and the dataset of instantaneous received signals, which are collected in the second measurement campaign. The second curve shows the residual error performance of Notice 640. This figure confirms that the curve of the proposed database rises rapidly from −10 dB. On the other hand, the curve of Notice 640 rises slowly from −80 dB to +80 dB.

Here, we show the CDF of the absolute error to confirm the residual error level, as shown in Fig. 13. In the 90th percentile, the proposed database has a residual error of roughly 7.0 dB, and the propagation model has a residual error of roughly 37.0 dB. This figure shows the poor accuracy of the propagation model. On the other hand, the proposed database is shown to achieve high estimation accuracy.

5.2 Impact of the Proposed Spectrum Database on Reduction of the Excess Interference Margin

When SUs share a spectrum, they must set an interference margin after due consideration of the probabilistic error performances based on the radio environment estimation. If SUs estimate the radio environment with a low-precision method, SUs need to set exceed margin. This means that SUs lose opportunities for spectrum sharing so as to protect primary communications. Thus, the estimation error in cumulative probability indicates the extent to which SUs determine the interference margin directly. This section evaluates the extent to which the proposed spectrum database can improve the error performance in terms of cumulative probability. Figure 14 presents the upside cumulative probability performance and downside cumulative probability performance; the former shows underestimation characteristics, and the latter shows overestimation characteristics. Each value is plotted with reference to Fig. 12. In the evaluation results, the proposed database achieves more than 20 dB performance improvement, for both the upside performance and the downside performance. The improvement in
the estimation error is shown in Fig. 15; this figure shows the difference between the proposed spectrum database and Notice 640. This figure clarifies that the proposed spectrum database can mitigate the excess interference margin by more than 20 dB.

6. Future Tasks

We have confirmed that the proposed database can achieve highly-accurate radio environment estimation. It is expected that the proposed architecture will improve spectrum utilization efficiency in the future. However, some unsolved issues remain. At the end of the paper, we describe the major tasks that we have identified during this study that remain to be completed.

If the compatibility with the current TVWS database is considered, the most spectrum use policies in the high-layer is roughly equivalent to the current policies. On the other hand, to achieve highly efficient spectrum sharing, the database should modify several parameters for white-space estimation: interference margin is a main parameter. The parameters depend on estimation results and estimation error; the facts should be discussed carefully. This section mainly focuses on measurement indeterminacies due to collecting data from mobile terminals of citizens. In the measurement campaign, an identical experimental system was structured. We confirmed highly accurate estimation under these ideal measurements. However, it is difficult to construct the system in realistic situations. The indeterminacies degrade the estimation accuracy, thus, we should try to solve the issues.

6.1 Accuracy of Measurement Results due to Different Devices in Various Installation

We mounted antennas on the roof of each vehicle during the measurement campaign. Although the installation location affects the measurement results, it is difficult for all measurement nodes to be suitably located. For example, many users want to avoid mounting the antenna on the roof of their vehicles because of design limitations. Smartphone users will likely observe that the signal is changed based on where the phone is located: in a hand, in a pocket, etc. Because these differences increase the individual differences between measurement data, calibration techniques will be a key technology.

6.2 Reliable Estimation under Few Datasets

We have confirmed highly accurate received power estimation using the proposed method for a sufficient number of datasets. In realistic situations, because database construction depends on the number and mobility of SUs, there might be some areas through which only a small number of SUs pass (and therefore, can measure). When the number of measurement samples is small, the accuracy of the average received power estimation decreases, causing harmful interference to PUs in the area because of poor secondary communication parameter settings. This issue is specific to the proposed database; it is caused by using mobile terminals as the measurement sensors. However, SUs must protect primary communications, even if there are only a few samples. We have already begun the initial examination of a possible solution [26].

6.3 Upload Timing of Datasets

It is clear that frequent dataset gathering increases the estimation accuracy. However, because of the practical issue of database access cost, frequent uploading is undesirable, as we explained in Sect. 2. On the other hand, keeping the datasets over a long period of time in the local database at the node requires high-capacity storage. Therefore, we should develop data exchange algorithms that consider this trade-off.

7. Conclusion

In this paper, we proposed the novel concept of a measurement-based spectrum database. The spectrum database consists of a large number of measurement results for the radio environment reported from mobile terminals such as vehicles and smart phones. To meet regional spectrum use policies, the proposed spectrum database has a hierarchical architecture. The low layer gathers the large measurement dataset. The high layer stores the spectrum use policies and dictates how the dataset in the low layer utilizes the spectrum. This paper focused specifically on low-layer database construction. To evaluate the estimation error characteristics of the proposed spectrum database, a field experiment for radio environment probing was conducted over TV bands. From the spectrum database construction results, we confirmed that the proposed database dramatically reduces the estimation error of the radio environment information. In addition, we showed that the proposed database can reduce the interference margin.
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References


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