Recent Advances in Radio Environment Map: A Survey

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Abstract. Electromagnetic spectrum, the main medium of wireless communication has been over-crowded. Accompanied by the arrival of big data era, the problem of the spectrum scarcity has received people's attention. The emergence of cognitive radio improves the utilization of the spectrum and provides an effective solution to break the limitations of the traditional static allocation. Radio Environmental Maps (REM) is an enabling technology of cognitive radio which can be intuitive, multi-dimensional display of spectrum information. It provides a visual basis while accessing dynamic spectrum and sharing spectrum. In this paper, the various aspects of REM are studied from the perspective of cognitive radio. Based on the concept of REM, the recent research progress of REM is summarized, and a series of challenges in the construction of spectrum pattern are also highlighted.

Keywords: Cognitive radio · Radio environment map · Spectrum trend
Spectrum dynamic access · Spectrum sharing

1 Introduction

With the rapid development of radio technology and business, the demand for radio spectrum resources is exploding. The mobile traffic is expected to increase by a factor of 1,000 over the next decade. In order to meet the huge traffic growth, the next generation mobile network is expected to achieve 1,000 times the capacity growth compared with the current wireless network deployment [1]. So the work of radio spectrum resource management is becoming complicated. National radio management departments have been fully aware of the important resources of spectrum, the economic and social development, and national defense construction. The Federal Communications Committee (FCC) established the Spectrum Task Force in 2003 and formally approved the use of dynamic spectrum access equipment in 2010. The Next Generation (XG), funded by the Defense Advanced Research Project Agency

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(DARPA), studies dynamic spectrum management through flexible spectrum policies. In addition, DARPA has introduced an advanced radio map to achieve real-time sensing of the radio spectrum in frequency, space and time [2].

At present, the existing spectrum allocation mechanism is static which is at the division of the partition. Each segment of the spectrum is fixedly assigned to different authorized users. Most of the spectrum resources have been exhausted. It is difficult for new business to provide a large section of available spectrum resources. So, the dynamic sharing of spectrum resources and promoting the integration of heterogeneous networks of cognitive wireless technology are considered to improve the spectrum utilization of promising ways [3]. The term Cognitive Radio (CR) is proposed by Dr. Joseph Mitola in 1990. In general, CR allows unauthorized sub-users to access the unoccupied spectrum of the authorized primary user [4]. The core purpose of cognitive radio is to detect the free spectrum of the radio environment and use these idle spectrums intelligently without affecting the main user system to achieve the effect of improving the spectrum utilization. Therefore, we need to build and manage the spectrum database to obtain time, space and other multi-dimensional spectrum availability information [5]. Radio Environmental Maps (REM) is a promising tool for the realization of cognitive radio network (CRN). REM is an integrated database that includes information about the radio frequency (RF) signal environment, the relevant laws and regulations, the strategy, the physical location of the equipment, the available services and relevant historical experience [6]. With REM, the primary user and the secondary user can better understand their radio environment, help secondary users access the main user free frequency band, reduce the hidden node problem, improve the overall network performance. In this paper, we summarize the recent research progress of REM, and we elaborate the various aspects of REM in detail through the whole view in order to provide a comprehensive framework for how to use REM for spectrum dynamic access and spectrum management.

As shown in Fig. 1, the structure of this paper is as follows: The second part defines REM and generalizes the application scenario of REM. The third part introduces the theory and method of spectrum trend from several key technologies of spectrum trend,

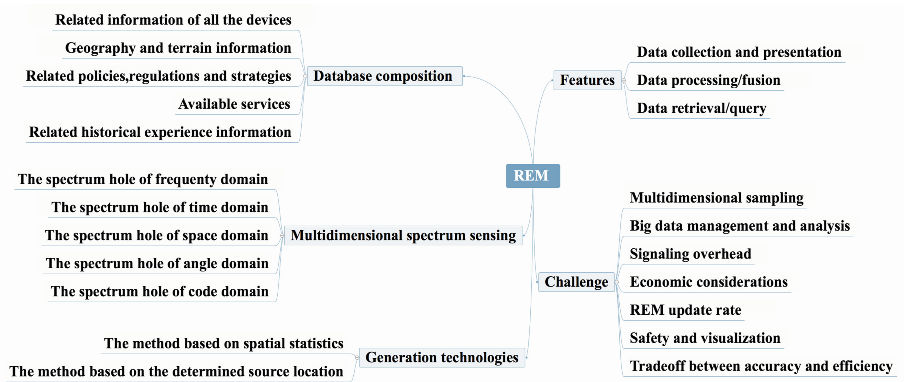

Fig. 1. Various aspects of REM

and introduces the application of spectrum potential perception, spectrum trend generation and spectrum trend respectively. Part four provides guidelines and research challenges for future work. Finally, we make a conclusion in part five.

2 Various Aspects of REM

2.1 Definition of REM

The concept and model of REM was first proposed in 2006 [7]. By using geographic location database multi-domain information, spectrum usage characteristics, geographic terrain model, propagation environment and rules, it builds a cognitive radio network integrated map. The vision is to design a cognitive radio network (CRN) that makes simple devices without advanced cognitive functions can be perceived and operated in an efficient manner by REM. The simulation results in [8] show that the utilization rate of idle spectrum can be increased by more than 50% in the case of REM support. Spectrum analysis based on radio environment map has become the main research direction of dynamic spectrum management. As shown in Fig. 2, REM is considered to be an integrated database for characterizing real-world radio scenarios.

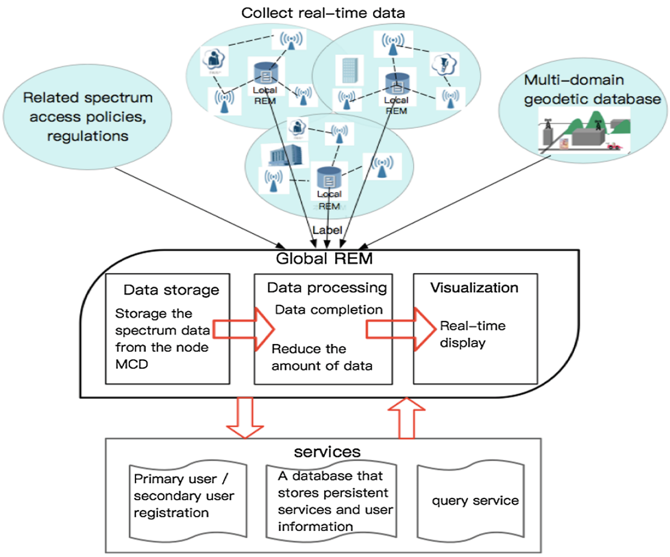

Fig. 2. REM is considered to be an integrated database for characterizing real-world radio scenarios.

In Fig. 2, REM can be divided into local REM and global REM. Global REM provides a wide range of processing capabilities, while local REM improves system responsiveness. More dynamic parameters of the radio environment will preferably be stored in the local REM, as this will facilitate REM updates. Mainly including radio propagation related information, such as propagation loss, signal strength, mobile terminal/monitoring node location information. The information stored in the global REM includes Quality of Service (QoS) metrics, information about available WiFi access networks, and so on. Local REM is synchronized with global REM, and REM synchronization is critical to the accuracy and reliability of the information provided.

It is impractical to acquire the spectrum data from the node MCD having the spectral sensing capability, since the measurement is performed at each position in the entire operation area. So the data is subjected to completion processing so as to estimate interference level at the position without measurement data, implement the data storage, processing/integration and ultimate visualization, and provide users with the radio environment information intuitively [9]. The REM database consists of three services: a primary user/secondary user registration, a database that stores persistent services and user information, and a query service. The data query service means that the secondary user obtains the best and allowed operating parameters by submitting a query to the REM manager. Because the historical data and current spectrum occupancy information are stored in the REM, the secondary user can query to obtain the current/historical state and some statistics.

2.2 REM Application Scenario

TV White Spectrum (TVWS) is a part of the UHF and VHF bands that appear after the digital shift from analog to digital. It has become an effective catalyst for the first practical application of cognitive radio networks (CRNs) [10]. As the broadcasting industry is primarily concerned with the protection of existing television services, the rules developed by regulators are too conservative, thus greatly reducing the utilization of television white space [11]. For example, the FCC developed a monitoring signal strength of −114 dBm for the primary user, which makes the primary user's channel protection threshold too conservative that is not conducive to the dynamic sharing of the spectrum and the loss of a large number of spectral resources. At present, the database-based white spectrum equipment trial operation has been taken into consideration by the United States and the relevant departments of the United Kingdom. In November 2009, the FCC issued a call for the regulatory authorities of the database. And it passed 10 companies to operate in 2010, of which four in 2013 completed the trial operation of the test. So the application of cognitive radio network in the white band of television has a very high practical significance.

The radar band is also a potential candidate band for real-time sharing of spectrum sharing. Because the radar band currently occupies a large part of the radio spectrum below 6 GHz, these bands provide better propagation conditions and reduce the cost of semiconductor devices. However, due to the wide application of radar systems, different types of radar are used in aviation, astronomy, military, weather and law enforcement and many other areas. So different radar systems require different technologies, different operating modes and different interference protection standards [12]. Therefore, a single method cannot be used to share spectrum with all the different radar systems. From the perspective of radar system spectrum sharing, the existing shared model can be divided into two categories:

1. A spatial dimension-based sharing model: Geo-restricted (GEZ) model and dynamic frequency selection (DFS) model.
2. A region-based sharing model: looking for potential sharing opportunities in space and time dimensions. There are a around the rotary radar is divided into three areas. In zone 1, the secondary user access is prohibited, because it will cause interference to the radar system. In zone 2, time sharing occurs where the secondary user can transmit each time the primary beam of the radar is pointing in the other direction. In zone 3, the secondary user is free to use the spectrum.

In [13], the radar-based radar band shared spectrum access innovation framework is introduced in detail, and the sharing details and the challenges are summarized through the actual measurement activities. In the literature [14], further proposed three different types of rotary radar system and the Internet of things to achieve the spectrum sharing framework. It can be seen that the radar band has great potential for the realization of spectrum sharing, so some countries have opened part of the S and C frequency band, contribute to the rational use of spectrum resources.

3 The Main Research Stage of Spectrum Situation

At present, the research of spectrum situation is mainly focused on three aspects: spectrum situation sensing, spectrum situation generation, and spectrum situation application.

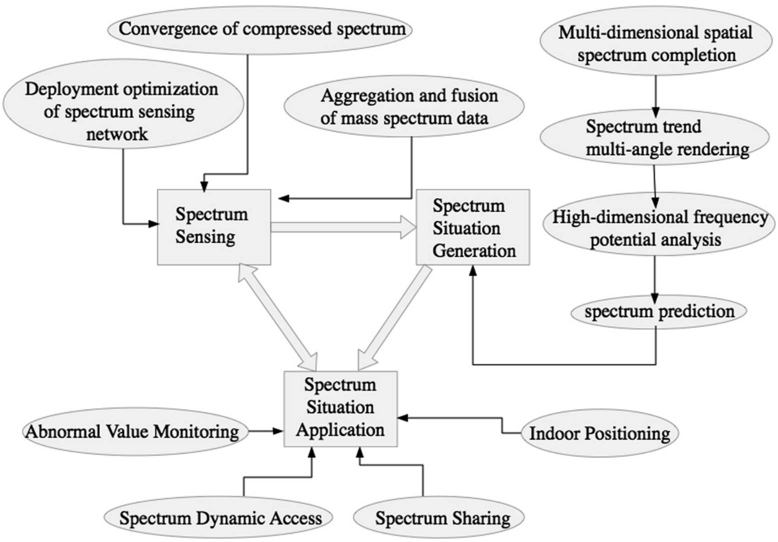

Fig. 3. The key techniques of spectrum situation

As shown in Fig. 3, spectrum sensing is the premise of spectrum situation generation and application. It is mainly responsible for obtaining the current state of spectrum space, including spectral cavity information, spectral radiated power information, spectrum modulation mode, and spectrum access protocol. Spectrum situation generation is based on the spectrum of the situation, the analysis, forecasting the comprehensive situation of the spectrum space and the future development trend. Spectrum situation application is our ultimate goal, is an important part of the spectrum of the overall situation. Through the dynamic allocation of spectrum resources, spectrum sharing, abnormal value monitoring, indoor positioning and other fields of application of the spectrum of the situation more practical significance.

3.1 Spectrum Sensing

Spectrum sensing, in which the current state of the time slot spectrum and spectrum hole can be obtained, is the essential factor to implement dynamic spectrum access. In Cognitive Radio Networks (CRN), users can be divided into two categories according to whether they have authorization: primary users (PU) and secondary users. Primary users have the priority right to use the authorized frequency band, while the secondary users need to monitor the spectrum information in the surrounding environment via spectrum sensing to share the spectrum with primary users. The spectrum cavity can be obtained in frequency domain, time domain, airspace, angle domain, code domain, etc., leading to multi-dimensional spectrum perception. As a result, multi-dimensional information is exploited to increase the efficiency of spectrum access. A detailed review of methods and challenges in cognitive radio spectrum sensing is illustrated in [15].

Wide-area spectrum situational perception includes three aspects: deployment optimization of spectrum sensing network, convergence of compressed spectrum and aggregation and fusion of mass spectrum data. Firstly, we optimize the deployment of spectrum sensing network to minimize the deployment cost of the network. Then we use the compression sensing technology to improve the robustness of spectrum sensing. Finally, we use the efficient convergence theory to converge and fuse the massive data in data center to ensure the transmission capacity and reliability, and reduce the delay of aggregation transmission. There are several types of spectrum sensing methods, such as energy detection (ED), matched filter detection, cyclic smoothing, and eigenvalue detection. Energy detection method is widely used in dynamic spectrum access, because it is easy to achieve and easy to calculate the cost [16].

3.2 Spectrum Situation Generation

Spectrum situation generation is to further analyze and predict the comprehensive situation and future development trends of spectrum based on the spectrum perception. The content includes multi-dimensional spatial spectrum completion, spectrum trend multi-angle rendering, high-dimensional frequency potential analysis, spectrum prediction and so on.

The spectral spectrum graph can collect the spectral data of the monitoring nodes in the network, collect data from the monitoring equipment regularly and make decisions based on the spectrum trend graphs to achieve reliable data fusion. However, if we want to get spectral data for each location in a cognitive radio network, it is impractical to estimate the remaining unknown nodes by known nodes. At present, the main construction method of the spectrum can be divided into two categories: based on spatial statistics and based on the determined source location.

1. The method based on spatial statistics is to characterize the characteristics of a given region by mining the spatial correlation. Using spatial statistics and spectral data at a specific location, the missing data is estimated from the function of known data. Table 1 lists the more commonly used interpolation method [17]. Recently, in the literature [18], the authors proposed a data recovery method by combining a fixed point continuation algorithm (FPCA) with a popular k-nearest neighbor (KNN) algorithm. Simulation results show that the proposed approach has a better performance in the TVWS database recovery than the traditional FPCA.

Table 1. There are several commonly used interpolation techniques.

Method	Description
1. Kriging [19]	The key to the Kriging method is the determination of the weighting factor. The method dynamically determines the value of the variable according to an optimization criterion function in the interpolation process, so that the interpolation function is in the best condition
2. Nearest neighbor [20]	This method is to find the k nearest neighbors of the unknown sample point, and obtain the attribute of the unknown sample point by assigning the weight of the attribute of these neighbors
3. Inverse distance weighted [21]	This method assumes that each input point has a local effect, and this effect is weakened as the distance increases
4. Trend surface	Trend surface uses polynomial to represent lines or surfaces, carrys out data fitting according to the least squares principle, which can be used to estimate the value of other points
5. Thin plant splines [22]	The surface of the control point is established by the sheet spline function and the slope of all points is minimized. That is, the minimum curvature surface fitting control point
6. Discrete smooth interpolation [23]	A network of interconnected networks is established between discretized data points. If the known node value on the network satisfies a certain constraint, the value on the unknown node can be obtained by solving the linear equation
7. Joint tensor completion [24]	Model the multi-dimensional spectrum data from the perspective of a spectrum tensor. Improve the low rank tensor completion algorithm, and evaluate it by comparing the improved spectrum tensor completion, the original one, and the spectrum matrix completion scheme

2. The method based on the determined source location can infer its performance by a priori information such as the location of the source, and then estimate the signal strength value for each location by applying the propagation model. Since the

method based on the location of the transmission source is based on the main user location data, the required spectral data is greatly reduced as compared with the spatial statistics-based method. In the literature [25], the existing algorithms are compared and a new method based on the determined source location is proposed. In the literature [26], the spectrum of the spectrum of the generation method were compared and summarized.

After the situation is completed, the data will be presented at multiple angles, which can be divided into the following four steps: 1. The data is unified and normalized. 2. For the time, empty dimension of the property to reduce the dimension and projection. 3. The spectral data are aggregated and depolymerized according to the time dimension, the spatial dimension and the frequency dimension. 4. Design is different from the visual model, to achieve high-dimensional trend of visual presentation. Finally, we can visually analyze the current radio environment by visualizing the spectrum trend, and through the analysis of historical data and evolution laws, we can predict the trend of complex multidimensional spectrum environment.

3.3 Spectrum Situation Application

Spectrum is widely used in the cognitive radio network. Carrying out the observation and analysis of the spectrum situation can achieve the dynamic allocation of spectrum resources, obtain the effective management of spectrum resources, improve the spectrum utilization, and guide the realization of spectrum sharing between primary users and secondary users or among various primary users [27]. As the spectral trend graph directly characterizes the mapping between the physical position and the signal energy, a signal strength database corresponding to the known position is established. Therefore, the spectrum of the map can also be applied to indoor positioning.

In addition, with the rapid development of Internet of things, the electromagnetic spectrum environment is also increasingly complex, malicious users also increased, such as: "black radio", eavesdropping, radio cheating and other illegal equipment is harmful to people's normal life, the use of spectrum, the monitoring of abnormal values, positioning, as an effective means to protect the spectrum of security. The spectrum trend has different applications in different scenarios. In [28], the application of spectrum profiles in different scenarios is described in detail.

4 Challenges

In the 5G era and the Internet of Things (IoT) environment, the intensive use of networks and the use of network heterogeneous technologies require a deeper understanding of the radio environment. REM provides a multi-dimensional, visual radio environment map, intuitive to provide users with spectrum occupancy information. In this section, we discuss a series of challenges in the construction of REM.

1. Multidimensional Sampling: It is necessary to design samples carefully on multiple dimensions, such as time, frequency, and space, to obtain the required data at the same time when measuring activity on an area with multiple devices.

2. Big data management and analysis: Multidimensional sampling challenges the real-time processing of data storage, the management and measurement of data. Big data problems and associated large computationally analyzed loads are being addressed by advances in computer technology, so it is necessary to make plans for rational storage of spectral data and data size.
3. Tradeoff between accuracy and efficiency: Increasing the resolution of any dimension will improve the accuracy of the results, but will also reduce the efficiency of the calculations. Therefore, it is necessary to dynamically balance the accuracy and efficiency based on the available computing resources.
4. Signaling overhead: In a dynamic scenario with a mobile transmission device, the data needs to be transmitted more frequently than in a fixed scene. And the local database needs to be synchronized with each other in order to keep the information in each data fresh and accurate. So in REM, signaling overhead is also a meaningful challenge.
5. Economic considerations: The number of MCDs is the main cause of high costs associated with the deployment and maintenance of REM, and is directly related to the resolution and reliability of the spatial spectrum occupancy of REM. So optimizing the MCD deployment will help reduce costs. In the literature [18], in order to determine the optimal position for sensing the main activity, an iterative clustering technique using tree structured vector quantization is used.
6. REM update rate: The REM update rate defines the granularity level of the spectrum occupancy rate in the time domain. It is necessary to frequently update the REM and the resulting spectrum occupancy change needs to be propagated to the SU with the lowest delay. This will impose a strong demand on the REM server processing speed and the MCD server interface channel quality.
7. Safety and visualization: In order to ensure the results to be accurately and successfully communicated to people who need different backgrounds of information, we need a safe, reliable and standardized database to provide users with better service. So the standardization of REM is also an important challenge.

5 Conclusion

This paper reviews various aspects of REM in the field of spectral cognition. Firstly, proposed the definition of REM and application scenarios. And then analyzed the spectrum sensing, spectrum situation generation, spectrum situation application of the various stages in detail. Finally, a series of challenges in REM construction are given, which provide a research direction for further research.

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