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A Cloud-Based Architecture for the Internet of Spectrum Devices Over Future Wireless Networks

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ABSTRACT The dramatic increase in data rates in wireless networks has caused radio spectrum usage to be an essential and critical issue. Spectrum sharing is widely recognized as an affordable, near-term method to address this issue. This paper first characterizes the new features of spectrum sharing in future wireless networks, including heterogeneity in sharing bands, diversity in sharing patterns, crowd intelligence in sharing devices, and hyperdensification in sharing networks. Then, to harness the benefits of these unique features and promote a vision of spectrum without bounds and networks without borders, this paper introduces a new concept of the Internet of spectrum devices (IoSDs) and develops a cloud-based architecture for IoSD over future wireless networks, with the prime aim of building a bridging network among various spectrum monitoring devices and massive spectrum utilization devices, and enabling a highly efficient spectrum sharing and management paradigm for future wireless networks. Furthermore, this paper presents a systematic tutorial on the key enabling techniques of the IoSD, including big spectrum data analytics, hierarchal spectrum resource optimization, and quality of experience-oriented spectrum service evaluation. In addition, the unresolved research issues are also presented.

INDEX TERMS Internet of spectrum devices (IoSD), cognitive radio, data analytics, resource optimization, quality of experience (QoE).

I. BACKGROUND AND MOTIVATION

The dramatic increase in data rates offered by the mobile Internet and Internet of Things (IoT) is overwhelming the allocated 2G/3G/4G radio spectrum, which has caused spectrum usage to be an essential and critical issue for future wireless networks [1], [2]. Spectrum sharing has been widely recognized as an affordable, near-term method to increase radio access network capacities for 5G content delivery [3]. Notably, spectrum sharing for future wireless networks extends the previous studies on cognitive radio-based spectrum sharing [4], as it has the following new features:

- *Heterogeneity in sharing bands.* Spectrum sharing in future wireless networks will likely occur in both licensed bands (e.g., the 2.3-2.4 GHz band in Europe and the 3.55-3.65 GHz band in the USA) and unlicensed bands (e.g., ISM bands and TV white spaces).
- *Diversity in sharing patterns.* One distinguishing feature of the potential spectrum usage is the diversity, i.e., aside from the licensed exclusive access in traditional cellular networks, licensed/authorized shared access, unlicensed shared access (also known as LTE in unlicensed bands), and primary-secondary opportunistic access will coexist.

- *Crowd intelligence in sharing devices.* The exponential growth of personal wireless devices (e.g., smart phones, tablets, and vehicle wireless devices) has led to the critical spectrum deficit phenomenon for next-generation cellular networks. However, the richness of wireless sensors, the growth of storage and computing resources, and the powerful programmable capability together greatly increase the intelligence level of personal wireless devices. Consequently, the exploration and exploitation of the benefits of the crowd intelligence of the massive number of personal wireless devices will be a key aspect in the design of efficient spectrum sharing techniques in future wireless networks.
- *Hyper-densification in sharing networks.* One dominant theme of wireless evolution in future wireless networks is network densification, which is mainly realized by increasing the density of infrastructure nodes (such as base stations and relays) and the corresponding network terminals in the given geographic area. Efficient spectrum sharing techniques are urgently needed in hyper-densification wireless networks to enable the harmonious coexistence of macro cells, small cells, femtocells, device-to-device and machine-to-machine communications.

These new unique features in spectrum sharing simultaneously introduce exciting research opportunities and critical technical challenges simultaneously. To fully exploit the benefits of spectrum sharing, this tutorial article starts from the discussion of well-known research issues in the literature on optimizing the use of the radio spectrum and then presents new ideas and corresponding key enabling techniques. Specifically, introduce an emerging and largely unexplored concept of the *Internet of Spectrum Devices (IoSD)* and develops a cloud-based architecture for the IoSD over future wireless networks. This idea mainly comes from the first attempt to properly integrate of the concepts of spectrum sharing, internet of things, and cloud computing for enabling a highly efficient spectrum sharing and management paradigm. Furthermore, this article presents a systematic tutorial on the key enabling techniques of the IoSD, including big spectrum data analytics, hierarchal spectrum resource optimization, and quality of experience (QoE)-oriented spectrum service evaluation. Moreover, this article also presents the unsolved research issues ahead.

II. THE INTERNET OF SPECTRUM DEVICES (IoSD)

Spectrum devices can be grouped into two classes: spectrum-monitoring devices (SMDs) and spectrum-utilizing devices (SUDs). SMDs are responsible for monitoring or sensing the state of various spectrum bands, whereas SUDs utilize the spectrum as a medium to transmit data. In conventional 1G/2G/3G/4G mobile wireless communication systems, SMDs and SUDs are typically separated from each other, as the spectrum usage is of a fixed license and the spectrum allocation in cellular networks is often predefined.

To address the so-called 1000× mobile traffic growth challenge[1] in the next-generation cellular networks, there is an increasing worldwide interest in advocating the removal of traditional and historical restrictions on spectrum and infrastructure and a shift toward a more dynamic usage of shared resources (e.g., spectrum, base stations, and processing capabilities), which is considered as a promising vision of *spectrum without bounds and networks without borders* [7].

The realization of this vision will involve more dynamic access to the spectrum, that is, moving from static forms of spectrum access to more dynamic scenarios that redirect spectrum resources to where they are needed and that heavily leverage spectrum sharing. In response, here we introduce the following novel concept:

The IoSD is a bridging network among various SMDs and massive SUDs that enables a highly efficient spectrum sharing and management paradigm for future wireless networks via spectrum clouding technologies, including big spectrum data analytics, hierarchal spectrum resource optimization, and QoE-oriented spectrum service evaluation.

The benefits of introducing IoSD are as follows:

- By networking SMDs, spectrum information can be assembled from multiple sources, including both expert spectrum analyzers and crowd spectrum sensors (e.g., smart phones, tablets and vehicle sensors), which can be deployed in a dedicated manner or randomly called together to perform a specific spectrum-monitoring task.
- By networking SUDs, spectrum resources can be centralized and visualized trading via various spectrum markets. The resources will be sourced from traditional industry players and crowdsourced from individuals.
- By networking SMDs and SUDs, diverse spectrum services can be provided, including spectrum utilization improvement, spectrum security guarantee and spectrum usage order maintenance.

III. SPECTRUM CLOUD ARCHITECTURE

As shown in Fig. 1, a cloud-based architecture is developed to enable an IoSD over future wireless networks. At the center of the architectures, spectrum clouds serve as the bridge between SMDs and SUDs. More specifically, the spectrum clouds gather spectrum monitoring information from various SMDs (including both dedicated expert spectrum analyzers and non-dedicated personal/crowd spectrum sensors) and distribute cognitive control commands to the SUDs (i.e., spectrum scheduling and/or power control decisions). In the reverse direction, the SUDs spectrum demands and QoE are passed to the spectrum clouds for closed-loop

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[1] The term comes from a white paper [5] as follows: "Towards year 2020 and beyond, 1000× mobile traffic growth, 100 billion connected devices, and more diverse service requirements bring great challenges to the system design of 5G." In the literature, typical strategies for achieving the 5G capacity targets of 1000x mobile traffic growth mainly include network densification, spectral efficiency improvement, additional spectrum, and smart spectrum usage [6].

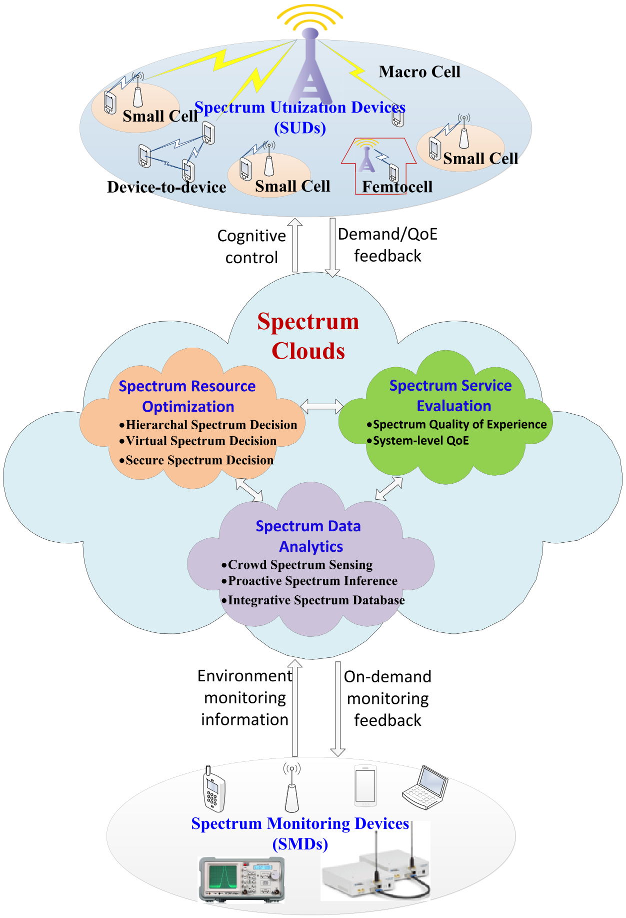

FIGURE 1. Spectrum cloud architecture for an Internet of Spectrum Devices (IoSD) over future wireless networks.

adaptive adjustment, and the spectrum clouds feedback the on-demand monitoring request to the SMDs.

Notably, there are differences among three interesting concepts: the centralized cognitive radio networks (CRNs), the decentralized/distributed CRNs, and the proposed cloud-based architecture for IoSD. Different from the centralized CRNs, the idea of virtual reality (VR) is introduced in the proposed cloud-based architecture for IoSD, i.e., there is a virtual agent in the spectrum cloud for each (remote) spectrum decision-maker entity. It is the virtual decision-makers in the spectrum cloud that make spectrum decisions (e.g., channel access and power control) in a self-organized and distributed manner, which has many valuable merits compared with the centralized decision making in the traditional centralized CRNs, especially when the number of spectrum decision-makers are massive or in a large-scale. The merits include: the feature of self-organization brings about robustness to the environment dynamics; the feature of distributed or parallel processing among the virtual spectrum decision-makers makes use of the multi-core or multi-server computing capability in the spectrum cloud environment, and thus can significantly improve the computational efficiency and reduce the processing delay.

Furthermore, different from the decentralized/distributed CRNs, the proposed cloud-based architecture for IoSD has also distinguished features. One main difference is that the proposed spectrum cloud has global information for the optimization of virtual spectrum-decisions, whereas each decision-maker in traditional decentralized/distributed CRNs only has local information. Moreover, thanks to the virtual reality technique, the information exchange between neighboring decision-makers in the algorithm iteration in the spectrum cloud are virtual, which can greatly reduce the information overhead.

Moreover, to the authors' knowledge, the concept of a "spectrum cloud" has been discussed in recent studies [8] and [9]. Specifically, in [8], cooperative spectrum sensing is implemented under a cloud network infrastructure with the aim of using the scalability and vast storage and computing capacity of the cloud. In [9], the concept of spectrum clouds is characterized as a novel session-based spectrum trading system in multi-hop networks, and a secondary service provider is proposed to facilitate the accessing of spectrum users without cognitive capabilities and to harvest the uncertain spectrum supply.

In contrast to the previous studies, the presented spectrum cloud architecture in this article has the following two key features: first, spectrum clouds serve as the bridge between SMDs and SUDs, aiming to enable a highly efficient spectrum sharing and management paradigm for future wireless networks; second, the proposed architecture is enabled by the spectrum clouding technologies, including big spectrum data analytics, hierarchal spectrum resource optimization, and QoE-oriented spectrum service evaluation.

IV. BIG SPECTRUM DATA ANALYTICS IN SPECTRUM CLOUDS

Spectrum data will be an important type of big data in future wireless networks. As shown in Fig. 2, if we treat a given geospatial area of interest as an image frame, with each spectrum data corresponding to a pixel, we can obtain a 3D spectrum video as the spectrum state evolves with time. This evolution is similar to a ubiquitous surveillance video in

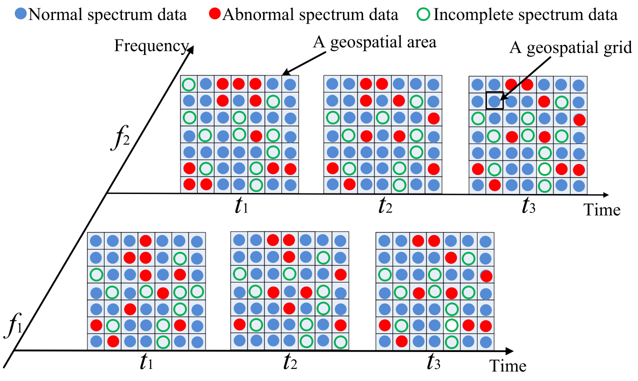

FIGURE 2. Spectrum data in the time-space-frequency multi-dimensional space.

the digital universe, which has been widely recognized as the largest type of big data [10]. More specifically, if we further use 1 byte to represent the spectrum data in a geospatial grid of 100 m × 100 m, a resolution frequency band of 100 kHz, and a time slot of 100 ms, after one week, the total data size in the frequency band ranging from 0 to 5 GHz and a geospatial area of 100 km × 100 km can be as large as:

$$\begin{aligned} &\frac{7\ \text{days}}{\text{week}} \times \frac{24\ \text{hours}}{\text{day}} \times \frac{3600\ \text{seconds}}{\text{hour}} \times \frac{1\ \text{second}}{100\ \text{ms}} \\ &\quad \times \frac{5\ \text{GHz}}{100\ \text{kHz}} \times \frac{100\ \text{km} \times 100\ \text{km}}{100\ \text{m} \times 100\ \text{m}} \times 1\ \text{Byte} \\ &= 3.024 \times 10^{17}\ \text{Byte/week} \\ &= 3.024 \times 10^{5}\ \text{Terabyte (TB)/week.} \qquad (1) \end{aligned}$$

By comparison, Facebook, one of well-known big data examples, ingests approximately 3.5×10^3 TB per week. The amount of spectrum data described above is more than 80 times that of Facebook in the same duration. Furthermore, the volume of spectrum state data grows with the time duration, frequency range, and spatial scale of interest, as well as the corresponding resolution in each dimension. Moreover, the volume of data will become considerably larger if we consider the indirect spectrum data, such as the user data, terrain data, and meteorological and hydrographic data.

With the spectrum cloud architecture for the IoSD, big spectrum data analytics allow for a more complete picture of radio spectrum usage and a deeper understanding of the hidden patterns behind spectrum state evolution and spectrum utilization. The value of big spectrum data analytics can be embodied in comprehensive spectrum modeling and flexible spectrum management and can be shared by many people. Spectrum regulators (such as the FCC and Ofcom) can use it to establish flexible spectrum policies. Mobile network operators can have more usable radio frequencies as a result of data analytics-driven dynamic spectrum sharing. Companies such as Spectrum Bridge, Inc. and Google, Inc. can provide new jobs and services in spectrum database construction and maintenance. Finally, consumers can enjoy mobile Internet, mobile social networking and wireless cyber-physical systems or or the IoT without concern over spectrum crowding.

To effectively mine the value from spectrum data, the topics of spectrum sensing, spectrum prediction, and spectrum database have been extensively studied in the literature. In the following, we will provide a brief tutorial on several emerging new issues.

A. CROWD SPECTRUM SENSING

Spectrum sensing is an effective enabling technique to collect spectrum information and identify the spectrum state [11]. In the era of IoT, there is a trend for this technique, i.e., from expert spectrum sensing to crowd spectrum sensing. To make spectrum sharing technology compatible with future wireless networks such as next generation cellular networks, one promising proposal is to employ a crowd of low-end personal devices (e.g., smartphones, tablets, and in-vehicle sensors) as spectrum sensors, other than using expensive specialized spectrum measurement equipment. However, as shown in Fig. 2, one critical challenge is the uncertainty of the quality of crowd sensing data that may be corrupted by unreliable, untrustworthy, or even malicious spectrum sensors. As the first attempt to address this challenge, our previous technical work [12] develops a data cleansing-based robust crowd sensing scheme to robustly cleanse out the nonzero abnormal data component, not the sensing data itself, from the original corrupted sensing data. Moreover, there are other unresolved challenges, such as how to motivate personal devices to participate in spectrum measurements and contribute the sensed data, how to ensure real-time spectrum sensing with randomly arriving (mobile) crowd sensors.

B. PROACTIVE SPECTRUM INFERENCE

Spectrum inference, previously known as spectrum prediction in the time domain [13], infers an unknown spectrum state from known spectrum data, by effectively exploiting the statistical correlations extracted from big spectrum data. Proactive spectrum inference can enable efficient spectrum usage by looking into the future. Similar to how Amazon has used large records of consumers' historical behaviors to successfully predict their future preferences, accurate spectrum inference is also possible because many real-world spectrum measurements have revealed that radio spectrum usage is not completely random, but that correlations exist across time slots, frequency bands, and geospatial locations [14], which motivate a trend to extend the research from one-dimensional spectrum prediction to multi-dimensional spectrum inference. So far, fundamental issues still remain unresolved: (i) the existing studies do not explicitly account for anomalies, which may incur serious performance degradation; (ii) they focus on the design of batch spectrum prediction algorithms, which limit the scalability to analyze massive spectrum data in real time; (iii) they assume the historical data is complete, which may not hold in reality.

C. INTEGRATIVE SPECTRUM DATABASE

Spectrum database is another promising technique for the IoSD via big spectrum data analytics. Fig. 3(a) shows the basic operational process. First, a mobile user with a spectrum requirement sends an enquiry (embedded with its geolocation and transmission power) to the nearby base station (BS). The BS forwards this enquiry to a remote geolocation spectrum database. The database calculates the set of vacant frequency bands at the location of that user using a combination of radio signal propagation models, terrain data, and up-to-date parameters of the working transmitters (see Fig. 3(b)), and then feeds the spectrum availability information back to that user via the BS.

As shown in Fig. 3(b), one common feature of the current spectrum database systems is tat they are *model-based* approaches in essence, as the database service is provided by using a combination of sophisticated signal

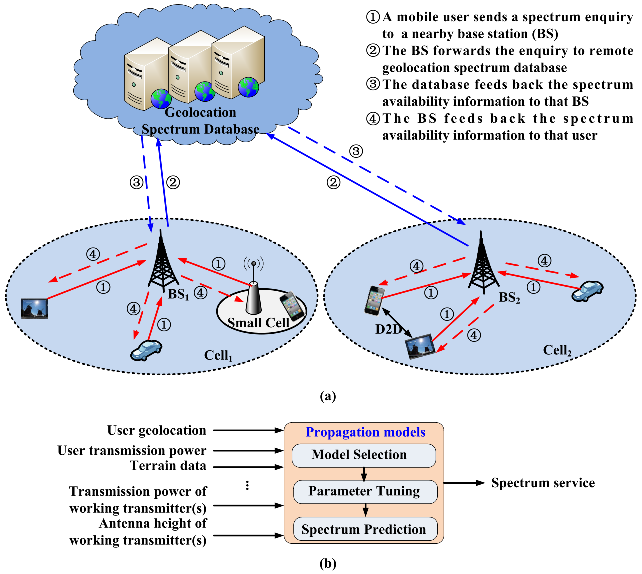

FIGURE 3. **Geolocation spectrum database-assisted dynamic spectrum sharing. (a) Basic operational process of geolocation spectrum database. (b) Key components of geolocation spectrum database.**

propagation modeling, fine terrain data, and an up-to-date parameters of the primary and secondary transmitters. One key component of the geolocation spectrum database is the selection of proper propagation models. Recent spectrum measurement campaigns (see, e.g., [17]) have demonstrated that the current propagation models are suitable for nationwide radio coverage planning but perform poorly at predicting accurate path losses even in relatively simple outdoor environments. Moreover, the suitability of a particular propagation model and the corresponding parameter setup vary greatly between different environments. Alternatively, our recent work presents a *data-driven* approach to build a database by learning the spectrum availability from big spectrum data [15]. Moreover, the standard organization IEEE 1900.6b working group is working towards to enhance the information and capabilities of spectrum databases through the use of spectrum sensing information [16].

D. UNRESOLVED ISSUES

One promising direction for future research is to combine the idea of mobile crowd spectrum sensing and proactive spectrum inference into a geolocation spectrum database, which can be further used to calibrate the propagation models and improve the accuracy of spectrum prediction. Another similar application is to develop a radio environment map, visualizing crowd spectrum data to assist in the decision making of spectrum regulators and telecommunication operators.

Notably, for a specific spectrum-related task, it is necessary to select a proper set of spectrum data for processing. To work with big data is not always the best choice, especially when the real-time processing capability is required. Specifically, for delay-tolerant applications, e.g., analyzing the long-term statistical distribution of spectrum state, more data can ensure relatively accurate results. However, for delay-sensitive applications, e.g., real-time spectrum prediction, small data processing is needed and thus excessively old data may be discarded using a finite time window. Furthermore, in parallel with the finite time window scheme, it is generally more preferable to use a forgetting factor to down-weight the old data and put more importance on recent data. Therefore, it is interesting to design online spectrum processing algorithms which update previously obtained estimates rather than re-compute all the historical data each time a new spectrum datum becomes available.

V. CLOUD-ASSISTED LARGE-SCALE SPECTRUM RESOURCE OPTIMIZATION

Fueled by the exponentially increasing demand for high-data-rate wireless services such as high-quality video streaming, social networking and online gaming, mobile operators are compelled to increase their capacity and provide a better quality of experience for end users [1]. The dense deployment of access points (APs) (e.g., small cells and Wi-Fi networks), underlain by macro base stations in 5G wireless networks, makes networks more hierarchical, heterogeneous and dynamic. However, the harmonious coexistence of conventional macro cells and various APs introduces many technical challenges in terms of spectrum allocation and interference management [18]. We now focus on spectrum resource optimization from the perspectives of hierarchical spectrum decision, distributed virtual spectrum decision and information-assisted secure spectrum decision based on the proposed IoSD framework.

A. HIERARCHICAL SPECTRUM DECISION

In future wireless systems, there will be differentiated demand and priorities of spectrum usage among massive SUDs. Taking the two-tier femtocell networks as an example, the macro users' priority are generally assumed to be higher than that of femto-users and their demand should be guaranteed first. Therefore, we need smarter multi-tier spectrum resource optimization for heterogeneous and hierarchal networks in dynamic and complex environments.

Mathematically, we can apply a hierarchal decision model (e.g., the leader-follower model characterized by the Stackelberg game) to describe the complex and coupled relationship among tiers. The hierarchal scheme is superior to non-cooperative optimization methods for single-tier networks and is naturally suitable for hierarchal networks [19]. Each SUD is a decision maker and makes decisions autonomously based on its priority, spectrum demand and network state. The SUDs in the upper tiers have a higher spectrum usage priority compared with the lower tiers. SUDs in the same tier consider the mixed information, including observed information from the upper tiers and available multi-dimensional context information (e.g., spectrum state, channel state, location, and energy,) from the information base. To capture the complex environment and network state, decision makers can utilize machine learning methods such as online learning and statistical learning in dynamic scenarios, making decisions flexible, efficient and smart.

B. DISTRIBUTED VIRTUAL SPECTRUM DECISION

In the proposed cloud-based architecture, each physical SUD connects with the cloud platform and is mapped into a specific virtual cognitive agent (i.e. a virtual spectrum device, VSD). Fig. 4 provides an illustrative diagram of the virtual hierarchal spectrum decision in two-tier small cell networks.

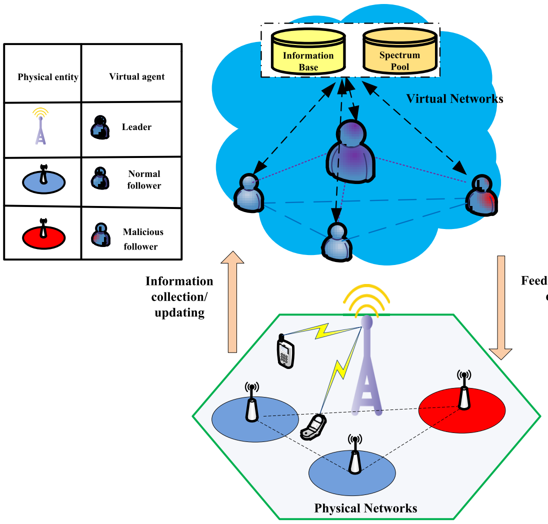

FIGURE 4. **Illustrative diagram of hierarchal resource allocation.**

Physical entities only need to carry out the feedback decision from the corresponding virtual entities. Compared with the decisions made by physical entities, the most notable difference in virtual decisions is that the use of data, information and knowledge no longer consumes communication resources, which can shorten the decision period and improve system efficiency, especially in hyper-dense network scenarios.

Accordingly, VSDs can utilize the powerful real-time process supported by spectrum clouds and obtain access to available information from the information database which includes gathered the contextual information (i.e., user type, location and demand), the network state and other data. VSDs execute decisions in a distributed manner and apply various optimization approaches to obtain the decision results. Then, the cloud disseminates the decision results to the physical SUDs.

C. INFORMATION-ASSISTED SECURE SPECTRUM DECISION

The ever-increasing intelligence level of personal wireless devices may introduce various security threats into spectrum decisions. Security mechanisms should be adopted to guarantee security, coping with malicious users remains an unresolved issue in traditional radio access networks (RANs) [20].

In the cloud-based architecture, the information database and spectrum pool in spectrum clouds can collect and update information related to the spectrum state (idle or occupied), user demand, and contextual information of SUDs in a timely manner. Benefiting from massive data, albeit containing considerable uncertainty and inaccuracy, the information bases in spectrum clouds can analyze and discovery the SUDs' behavior through data mining. This discovery can provide valuable information to classify normal and malicious SUDs, which is helpful for the spectrum manager to identify potential threat and maintain communication security.

Moreover, it is essential to build a credit framework for maintaining a comfortable wireless eco-system. Each SUD involved should follow the policies made by the spectrum managers. The spectrum cloud assigns each SUD a credit score according to its historical record of spectrum usage. Those who violate the rules will be punished and recorded in the information data base.

D. OPEN ISSUES

The underutilized spectrum band in Wi-Fi, specifically the 5G Hz band, motivates the wireless operator to integrate Wi-Fi technology into the current long-term evolution (LTE) communication system, named LTE in unlicensed band (LTE-U). One promising direction for research is to jointly consider the resource optimization in unlicensed and licensed bands and the corresponding interaction behavior among SUDs.

VI. QoE-ORIENTED SPECTRUM SERVICE EVALUATION

As mobile multimedia services are becoming increasingly popular, the QoE tends to be the most direct and sensitive performance indicator of users. QoE has also been labeled one of the main concerns in future wireless networks [3]. To analyze the spectrum service performance of the IoSD from the user perspectives, we propose a QoE-oriented spectrum service evaluation in the spectrum cloud, which includes spectrum QoE and system-level QoE.

A. SPECTRUM QoE

QoE provides a novel perspective for rethinking the current spectrum management paradigm [21]. The majority of existing works focus on maximizing users' throughput in spectrum management. However, a larger throughput does not always yields performance benefits. By considering the properties of subjective user demand, we propose the concept of spectrum QoE to characterize the relationship between the spectrum and QoE. A general form of spectrum QoE is shown in Fig. 5 (a). When the bandwidth exceeds a given upper threshold, the user can no longer perceive a better experience. When the bandwidth is smaller than a given lower threshold, the service quality is sufficiently bad that the user aborts the service. Finally, when the bandwidth is between the two thresholds, the QoE increases as the bandwidth increases following a certain growth rule. Fig. 5 (a)-(b) show three

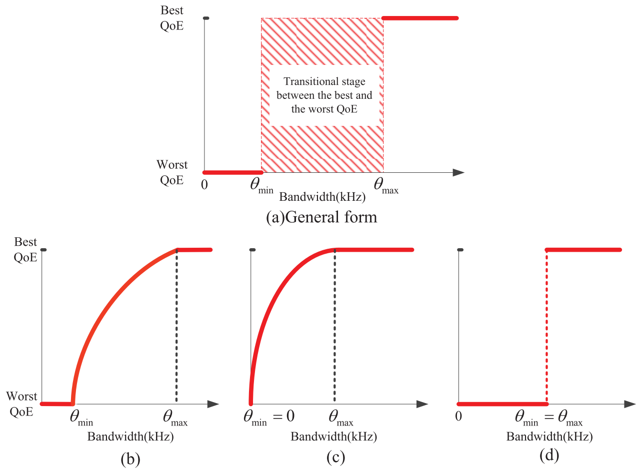

FIGURE 5. General form and three specific examples of spectrum QoE.

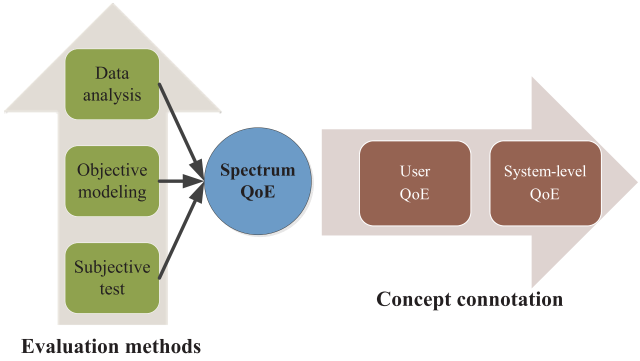

FIGURE 6. Extension of user spectrum QoE: system-level spectrum QoE.

specific examples of the relationship between the spectrum bandwidth and spectrum QoE.

The spectrum QoE perspective brings both challenges and opportunities. The challenges mainly derive from the high complexity of QoE evaluation. As the QoE depends on the devices, traffic types, user preferences, and cost, and could vary with time and location, the spectrum QoE evaluation of an individual user must be user-aware and context-aware [22]. Three types of QoE evaluation methods are currently available: a subjective QoE test (by surveying participants' perception in the experimental environment), a objective modeling (approximating the relationship between bandwidth and QoE by specific utility functions) and data analysis (treating the relationship between bandwidth and QoE as a black box, with the goal of analyzing the QoE test samples to obtain an implicit QoE model). The subjective QoE test is natural and relatively accurate, but costly. In contrast, objective modeling, is easy to implement but lacks accuracy. The data analysis method represents a new avenue by providing a tradeoff between the subjective QoE test and objective modeling, and represent a promising path in the near future.

B. SYSTEM-LEVEL QoE

Although there are numerous studies on QoE, they are limited to individual user case. For the considered spectrum management system, a system global performance metric is needed from the spectrum QoE perspective. In particular, due to the limited spectrum resource, it is commonly impossible to provide the best QoE for all users, simultaneously, so a global performance metric is imperative for balancing the system performance and fairness in spectrum planning and allocation. In response to this need, we extend the QoE of a single user to propose the concept of system-level QoE as a global performance metric, as shown in Fig. 6. The system-level QoE is not simply the sum of all users' QoEs, as the users in the system have distinct attributes and are not independent of each other; instead, they are implicitly coupled or conflicting as a result of their resource sharing property. For example, suppose that the sums of users' QoEs in two spectrum allocation strategies are equal but tha, the individual users' QoE are not the same. The global performances of these two spectrum allocation strategies could be different due to the diversity in the users' traffic types and priority levels. Several issues make the evaluation of the system-level QoE a challenging task. First, user terminals (e.g., PC, tablet PCs, smart-phones) are heterogeneous in terms of functionalities and capabilities. Second, users have different traffic types with diverse properties. Third, users are unequal in the sense that they can be differentiated by authority and priority levels. Fourth, there is a complex and conflicting relationship between individual users' QoEs. Finally, the system architecture is complex due to the layered and coexisting deployment of networks with different standards and ownerships.

Because it is difficult to define the system-level QoE explicity, we characterize it in spectrum management by the following expression:

$$QoE_{\text{system}} = f\left(\{QoE_n, d_n, r_n\}_{n \in \mathcal{N}}, \mathbf{R}, \mathbf{W}\right) - \sum_n \alpha_n c_n, \quad (2)$$

where $\mathcal{N}$ is the user set, and QoE_n, d_n and r_n are the achieved QoE, user demand and allocated spectrum resource of user $n \in \mathcal{N}$, respectively. c_n is the cost in terms of price and power, and α_n is the corresponding weights. $\mathbf{R}$ is the spectrum allocation vector of networks/subsystems, $\mathbf{W}$ is the coupling matrix of users, and $f(\cdot)$ represents the relationship between the multiple input variables and system-level QoE. $\mathbf{W}$ is an abstracted matrix reflecting the coupling relationship in the QoE, which is jointly determined by the resource competition relationship and interference relationship.

In our previous work [23], the definition of accumulative user distribution has some flavor of the system-level QoE. Specifically, the individual user's QoE is characterized by the five discrete mean opinion score (MOS) level of ''Excellent'', ''Good'', ''Fair'', ''Poor,'' and ''Bad'', and the accumulative user distribution is a vector with five elements denoting the number of users achieving QoE level no worse than each MOS level. The accumulative user distribution provides a flexible evaluation from the system perspective, e.g. the number of users with QoE better than some MOS level and could easily takes account of system fairness.

C. OPEN ISSUES

The application of big data analysis and cloud platform may contribute to the spectrum QoE evaluation. By storing and analyzing the spectrum service data on the cloud, user-aware and context-aware spectrum QoE evaluation is possible. Moreover, the system-level QoE for large-scale scenarios could be evaluated on the cloud.

VII. CONCLUSION AND DISCUSSIONS

This tutorial article introduced the concept of Internet of Spectrum Devices (IoSDs) by networking spectrum monitoring devices and spectrum utilization devices for highly-efficient spectrum sharing in future wireless networks. A cloud-based architecture is developed for the realization of IoSDs, where a spectrum cloud with three key enabling techniques including big spectrum data analytics, hierarchal spectrum resource optimization, and QoE-oriented spectrum service evaluation is systematically analyzed. This article opens a door for interdisciplinary research efforts in a fruitful direction to promote a promising vision of *spectrum without bounds, networks without borders*. A number of research open issues are still waiting for solutions.

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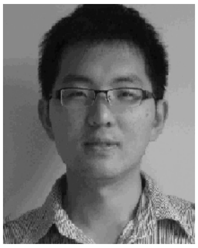

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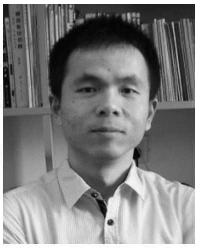

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