A Cloud-Based Approach to Spectrum Monitoring

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Thousands of wireless communication systems have been fielded, with hundreds more under development. The RF spectrum has growing economic value to consumers, businesses, and governments worldwide. This has generated such a demand for wireless bandwidth that spectrum allocation, the existing primary method of spectrum management, is becoming increasingly inadequate. In this paper, we briefly summarize the response to the U.S. National Telecommunications and Information Agency's Notice of Inquiry concerning a Spectrum Monitoring Pilot Program and present a cloud-based system-of-systems for spectrum monitoring based on the response to the Inquiry. We describe the interface to the cloud as an important enabler and propose a solution that allows ontology descriptions to be used for both spectrum management and monitoring. These ontology descriptions support the use of semantic techniques such as queries, responses, and reasoning.

Introduction

The RF spectrum has three dimensions: time, frequency, and location. While current spectrum management has utilized nearly the entire frequency dimension, there is significant unexploited potential along the other dimensions. Spectrum surveys have consistently shown that much of the licensed spectrum is idle at any given time [1]–[3]. Consequently, responses to requests for additional bandwidth will increasingly involve sharing rather than exclusive allocation. The concept of spectrum sharing is simple: If one system does not require bandwidth at specific times, that bandwidth can be used by secondary systems during those times, provided that the secondary systems do not cause unacceptable interference. While spectrum sharing is very desirable, it will produce a variety of interference scenarios and require accurate real-time spectrum usage data. Therefore, it is necessary to integrate spectrum management and monitoring on a large scale, but such a system does not currently exist.

To date, spectrum monitoring attempts have primarily been limited to one-time surveys conducted in many locations around the world [1]–[3]. These surveys each lasted for a relatively short time, typically used a single spectrum analyzer connected to a laptop computer, and were performed at one site or at a single site at a time. One attempt to overcome some of these shortcomings is reported in [4], but the system is still based on spectrum analyzers. Spectrum analyzers are powerful pieces of lab equipment with a human operator interpreting signals in real time [5], [6]. It would be inefficient to build a large-scale spectrum monitoring systems merely by extending these isolated surveys, because at present, it is not possible to integrate data from different spectrum sensors (which measure different RF frequencies and have different resolutions, bandwidths, etc.).

In 2013, in light of the increased need for a permanent large-scale spectrum monitoring solution, the President of the United States directed the National Telecommunications and Information Agency (NTIA) to design and conduct a pilot program to monitor spectrum usage in real time in select communities around the country [7]. (The NTIA is responsible for managing the wireless spectrum used by federal agencies and ensuring that federal communication systems do not interfere with each other.) One purpose of the monitoring is to confirm that known communication systems operate as authorized or provide evidence that they do not. Furthermore, monitoring is required to detect interference between wireless systems and identify unlicensed transmitters. Another purpose of spectrum monitoring is to help determine how much these systems are using the spectrum that they have been given and identify opportunities for spectrum sharing among not only federal agencies, but also civilian users. To achieve all of these goals, monitoring has to be permanent; one-time, single-site surveys are no longer adequate. The expectation is that after the NTIA's pilot program, there will be a permanent spectrum monitoring system. In view of these objectives, the NTIA asked the public to comment on the proper parameters of such a system, including monitored frequency band(s), resolution bandwidth, sampling rate, dwell time, antennas, geographic locations, etc. [8].

Design Constraints

The industry's response [9] to the NTIA's Notice of Inquiry reveals emerging consensus regarding several aspects of

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spectrum monitoring. All stakeholders generally agree that spectrum monitoring between 30 MHz and at least 3, preferably 6 GHz, is needed. In the future monitoring may be extended to other frequency bands. The industry generally believes that spectrum monitoring should capture and store in-phase and quadrature (IQ) components at baseband or IF output. (Most systems today use quadrature A/D conversion.) The IQ data should then be processed using FFTs to obtain power spectral density. Other specialized analysis can also be performed on the IQ samples. To monitor signals up to 6 GHz, it has been proposed in [8] that the dynamic range of the monitoring system (the power difference between the strongest and weakest signals to be analyzed) be at least 60 to 75 dB. Another aspect where consensus is emerging is that monitoring should start with *a priori* information provided by an accurate database of systems that are known to be operational. This database must include the technical parameters that are relevant for their term of authorization, such as frequency bands, effective radiated power, etc.

However, it is not possible to determine a single set of parameters since the spectrum environment is far too complex. Between 30 MHz and 6 GHz, there are numerous wireless systems with different bandwidths, modulation formats, multiple-access techniques, output power levels, etc. There are certain bands that require real-time or near real-time performance (e.g., bands used by public-safety operations). Spectrum use varies widely with location. Urban, suburban, rural, and remote areas need different monitoring systems.

Consequently, the monitoring system should *not* have a few large and expensive monitoring stations such as spectrum analyzers but should involve a large number of simpler and more inexpensive spectrum sensors. Several of the companies that responded to the NTIA's Notice of Inquiry offer proprietary equipment that is lower-cost and network-enabled. However, there is no interoperability among these different devices. Interoperability, while supported by some, has not been established clearly as an objective [9], and it is even less clear how to achieve it. Understandably, in their responses, companies touted more the characteristics of their proprietary technologies [9].

Several conclusions can be made. The monitoring system will use spectrum sensors with different characteristics and from different companies. To make the spectrum monitoring system sustainable and permanent, yet able to evolve over time, it must be considered a system-of-systems, where the entire system has an indefinite lifetime, while the individual elements that comprise it have finite lifetimes. Therefore, regulatory agencies such as the NTIA should be concerned less about specific spectrum monitoring parameters and more about the architecture of this system-of-systems.

Cloud-Based System-of-Systems

The area of cloud computing has recently experienced very significant commercial growth. In cloud computing, a program does not run on a local computing device (thin client) but on one or more remote servers. These servers provide services to the client. There have been attempts to transfer the cloud concept to wireless systems, e.g., [10]. A related major trend that has emerged recently is Big Data, which is associated with the creation, storage, and processing of exceptionally large volumes of data. Cloud computing and Big Data principles are beginning to be used in instrumentation and measurement systems. For example, it is possible to process the data obtained from thousands of sensors in a cloud [11]. It is also possible to control distributed instruments remotely by cloud applications [12]. In this paper, we propose spectrum monitoring to be done in a cloud as in the illustration in Fig.1.

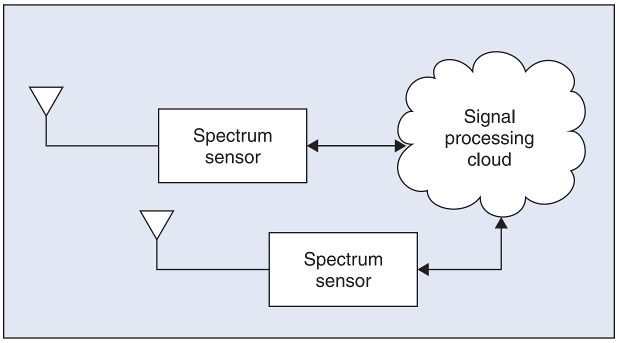

Fig. 1. Spectrum monitoring client connected to a cloud.

There are some very important differences between the proposed cloud architecture in Fig. 1 and computing clouds and previously known clouds in instrumentation and measurement [11], [12]. One difference is the interface between the thin client and the cloud. In computing clouds, this interface is a trivial issue. For spectrum sensors, the interface is not a trivial issue. The reason is that spectrum sensors must include analog as well as digital hardware, and the cloud interface becomes an important architectural problem. Another difference is that thin clients usually do not offer any services to the cloud. In a spectrum monitoring cloud, the sensors offer at least a sensing service. Other services can be provided, e.g., modulation identification and complete demodulation of the signal in some cases. Since the cloud also offers services to the thin clients or to third parties, the client-server distinction is blurred.

The cloud can offer digital hardware using the infrastructure as a service (IaaS) model. For example, the cloud can use software-defined radio technology to perform many base transceiver station operations [13]. Higher levels of service can also be offered, such as *platform as a service* (PaaS), where the cloud offers system-level software in addition to digital hardware, and *spectrum monitoring software as a service*, where the entire hardware and software solution that implements spectrum monitoring is offered as a service. The monitoring software can be implemented as a collection of interacting entities each fulfilling a specific role.

While the use of Big Data recently in instrumentation and measurement techniques appeared in, e.g., [14], the amount of data produced by spectrum monitoring, as proposed here, dwarfs any other Big Data. The amount of data B produced is

$$B = F_s \times N_b \times T \text{ bits}$$

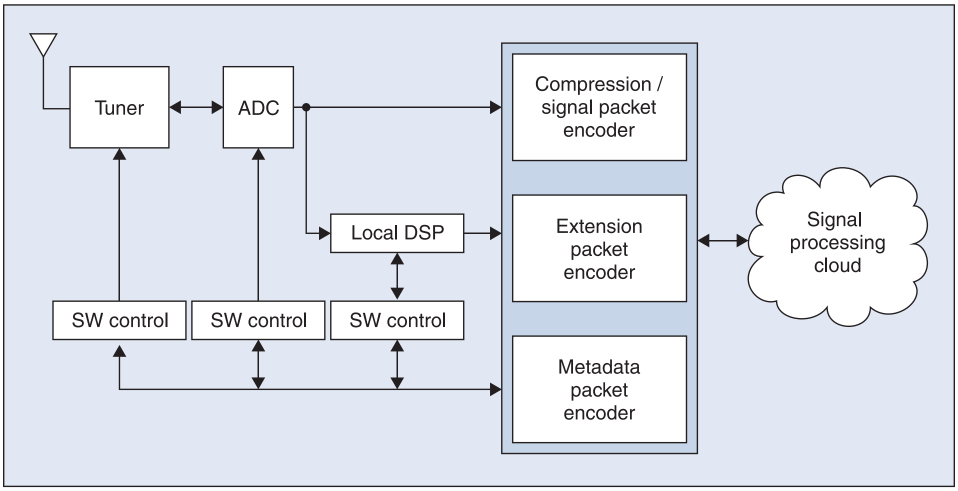

Fig. 2. Architecture of a spectrum monitoring client and cloud interface.

where F_s is the sampling frequency, N_b is the number of bits per IQ sample (typically 32, assuming 16 bits for the I and Q components), and T is the recording time. For example, to continuously monitor the band 30 MHz to 6 GHz at once, assuming a practical sampling frequency of 15 GHz or 7.5 GHz in quadrature (ignoring the enormous required dynamic range), over 2500 Terabytes per day would be generated by just a single spectrum sensor. (For comparison, Facebook, one of the biggest Big Data examples, ingests about 500 Terabytes per day.) Practical systems do not monitor the entire band continuously, reduce the IQ data to only certain time intervals in a 24-hr period, and generate much less, on the order of several GB/hour [9].

The cloud-based architecture has several important advantages. It allows the results to be made available to stakeholders in industry and academia to perform their own analysis. Once the cloud is operational, it becomes very easy to add another thin client to the cloud. In this way, improvements can be made over time. The cloud also allows distributed databases to be used to complement the central one. Distributed databases can contain detailed information for smaller geographic areas and can be updated quicker to support spectrum sharing.

Interface to the Cloud

The interface to the cloud is the key to building a system-of-systems where only a portion of the spectrum sensors can be replaced at any one time. This interface requires abstract descriptions of the technical parameters of the sensors. There are interfaces for cloud radio access networks (C-RAN) [15], [16]. These standards are not appropriate abstractions, because they are only for LTE signals. The International Telecommunication Union (ITU) defines Radio Monitoring Transfer Protocol (RMTP) [17], which merely allows control of multiple monitoring stations from different manufacturers, but is also not an abstraction. It is much more appropriate to use the ANSI/VITA 49 – 2009 standard [18] because it is an abstraction of RF front-ends [19]. This standard defines two main types of packets: data (IQ samples) and metadata (data about data, or context data). Note that this interface is independent of the specific technique to carry these packets. The actual interface to the cloud may be Ethernet or wireless. A metadata packet includes the RF center frequency, bandwidth, sample rate, timestamp, location, calibration information, etc., and it is generated every time one or more of these parameters changes. The timestamp reflects all delays prior to digitization. Each data packet stream is paired with its corresponding metadata packet stream using a common stream identifier. Ultimately, the metadata is an abstract description of the spectrum sensor, and it allows the signal impinging on the antenna to be described exactly and later reconstructed, if necessary. Furthermore, Time Difference of Arrival (TDOA) localization is possible using the packet streams from multiple sensors. Simply connecting monitoring clients to a cloud without such a metadata description, as done in current sensing products, cannot achieve any of these advantages.

When used for spectrum sensing, the VITA 49 standard [18] is incomplete in two respects. Since monitoring generates enormous amount of IQ data, we propose to extend the VITA 49 standard to include compression on the IQ samples. Recently, data compression of IQ samples has been studied for LTE baseband signals that are subsequently demodulated [20]. Lossless compression ratios of about 1.5 and lossy compression ratios of up to 4 lead to a small increase on the bit error rate; furthermore, the performance degradation is gradual [20]. Monitoring typically does not involve demodulation of the wireless signals, and therefore, compression ratios can be much higher. Fig. 2 illustrates a spectrum sensor that compresses the IQ samples before transmitting a data packet to the cloud. If the sensors perform more computationally intensive steps such as FFTs, fast feature identification, etc., the results can be transmitted as extension packets (Fig. 2). Another area where the VITA 49 standard needs to be extended is to allow a spectrum sensor to be controlled by a metadata packet to control its parameters such as RF frequency, resolution, bandwidth, etc. Therefore, while the IQ data is transmitted only in one direction, metadata transmission must be in both directions (Fig. 2).

Ontologies and Semantic Networks

Ontology is a general mechanism to describe objects in a certain domain and the relationships among these objects. One example is the Web Ontology Language (OWL) 2 Direct

Semantics [21], which is the *de facto* standard for the Semantic Web. This ontology language can be used to represent the metadata produced by every spectrum sensor. For example:

SpectrumSensor **and** RFFrequency **some** MHz [>=30, <=6000] **and** Resolution **some** KHz [>=10, <=1000]

Service providers (both in the cloud and in thin clients) can advertise in a service registry the descriptions of their capabilities. Clients can search using an ontology query language, interpret these descriptions, and select appropriate services. With declarative APIs, the ontology will support the automatic execution of these services. Furthermore, describing not only the metadata but also the database with licensed systems of the regulatory body is possible using the ontology. For example:

Band1 SubClassOf Band **and** Unlicensed **and** (bandwidth some MHz [>=900, <=928]) **and** (maxPower some mW [<=1000]).

Coupling spectrum monitoring and spectrum management leads to an integrated system where an OWL reasoner can determine if the sensing results contradict existing over-the-air policies, automatically identify spectrum-sharing opportunities, and evaluate the efficiency of actual spectrum usage.

Conclusions

In response to the NTIA's Notice of Inquiry, we suggest that the spectrum monitoring network be viewed as a system-of-systems. An abstraction is required to properly interpret the results produced by each platform. We advance a cloud-based system that collects and stores compressed I/Q data, enabled by a packet-based interface to the cloud. New measurement devices can be incorporated (for example to cover new frequency bands, etc.) without hardware/software upgrades elsewhere. Furthermore, we propose that both the metadata and the database with authorized systems be described as knowledge bases over the same ontology, which couples spectrum management to spectrum monitoring and allows reasoning to be used. Ultimately, the approach allows spectrum monitoring to move from machine-to-human to machine-to-machine interactions.

References

[1] J. Xue, Z. Feng, and K. Chen, "Beijing spectrum survey for cognitive radio applications," in *Proc.2013 IEEE Vehicular Technology Conference (VTC Fall)*, pp. 1-5, Sep. 2013.

[2] V. Valenta, R. Maršáek, G. Baudoin, M. Villegas, M. Suarez, and F. Robert, "Survey on spectrum utilization in Europe: Measurements, analyses and observations," in *Proc. International Conference on Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM)*, pp. 1-5, Jun. 2010.

[3] K. Patil, R. Prasad, and K. Skouby, "A survey of worldwide spectrum occupancy measurement campaigns for cognitive radio," in *International. Conference on Devices and Communications (ICDeCom)*, pp. 1-5, Feb. 2011.

[4] A. Iyer, K. Chintalapudi, V. Navda, R. Ramjee, V. N. Padmanabhan, and C. R. Murthy, "Specnet: Spectrum sensing sans frontieres," in *8th USENIX Symp. Networked Systems Design and Implementation (NSDI)*, Apr. 2011.

[5] A. Adnani, J. Duplicy, and L. Philips, "Spectrum analyzers today and tomorrow: part 1 towards filterbanks-enabled real-time spectrum analysis," *IEEE Instrum. Meas. Mag.*, vol. 16, no. 5, pp. 6–11, Oct. 2013.

[6] P. Bilski and W. Winiecki, "A low-cost real-time virtual spectrum analyzer," *IEEE Trans. Instrum. Meas.*, vol. 56, no. 6, pp. 2169–2174, Dec. 2007.

[7] Expanding America's Leadership in Wireless Innovation, Executive Memorandum, Federal Register, 78, 119, 2013. [Online]. Available: http://www.gpo.gov/fdsys/pkg/FR-2013-06-20/html/2013-14971.htm.

[8] National Telecommunications and Information Administration, U.S. Dept. of Commerce. (2003, Aug. 16). Spectrum Monitoring Pilot Program, Notice of Inquiry. [Online]. Available: http://www.ntia.doc.gov/federal-register-notice/2013/spectrum-monitoring-pilot-program.

[9] National Telecommunications and Information Administration, U.S. Dept. of Commerce. (2003, Oct. 17). Comments on Spectrum Monitoring Pilot Program. [Online]. Available: http://www.ntia.doc.gov/federal-register-notice/2013/comments-spectrum-monitoring-pilot-program-0.

[10] H. Harada, "Cognitive wireless cloud: A network concept to handle heterogeneous and spectrum sharing type radio access networks," in *Proc. IEEE Int. Symp. Personal, Indoor, and Mobile Radio Communications,* Sept. 2009.

[11] P. Chen, C. Chen, Y. Chen, J. Wang, T. Liao, and C. Hwang, "Universal environmental surveillance system with instrument cloud technology," in *Proc. IEEE International Instrumentation and Measurement Technology Conference., (I^{2}MTC) 2013*, May 2013, pp. 845–849.

[12] A. de Lima Ribeiro and A. Da Silva, "Architecture for publication and universal access to smart transducers," in *IEEE International Instrumentation and Measurement Technology Conference (I2MTC),* May 2012, pp. 2361–2364.

[13] I. Gomez-Miguelez, V. Marojevic, and A. Gelonch, "Deployment and management of SDR cloud computing resources: problem definition and fundamental limits," *EURASIP J. Wireless Comm. and Networking*, vol. 2013, no. 59, Mar. 2013.

[14] M. Courtney, "Data on demand," *Eng. & Technol. Mag.*, vol. 9, no. 1, pp. 64–67, Feb. 2014.

[15] Common Public Radio Interface, CPRI. [Online]. Available: http://www.cpri.info.

[16] Open Base Station Architecture Initiative, OBSAI. [Online]. Available: http://www.obsai.com.

[17] Spectrum Monitoring Handbook, International Telecommunication Union, 2011. [Online]. Available: http://www.itu.int/pub/R-HDB-23.

[18] VITA Standards Organization. (2009, May 26). VITA Radio Transport (VRT) Standard, ANSI/VITA 49.0-2009. [Online]. Available: http://www.vita.com/.

[19] T. Cooklev, R. Normoyle, and D. Clendenen, "The VITA 49 RF-digital interface," *IEEE Circuits Syst. Mag.*, vol. 12, no. 4, pp. 21–32, Nov.–Dec. 2012.

[20] A. Vosoughi, M. Wu, and J. Cavallaro, "Baseband signal compression in wireless base stations," in *Proc. IEEE Global Communications Conference (GLOBECOM)*, pp. 4505–4511, Dec. 2012.

[21] OWL2 Web Ontology Language W3C Recommendation. (11, Dec. 2012). [Online]. Available: http://www.w3.org/TR/owl2-overview/.

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