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An Overview of the NTIA/NIST Spectrum Monitoring Pilot Program

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Abstract—**This paper provides an overview of a Spectrum Monitoring Pilot Program within the U.S. Department of Commerce. It provides background, motivation, goals, accomplishments, and plans for future work. We describe the development of a federated Measured Spectrum Occupancy Database (MSOD) architecture that allows organizations to host MSOD instances and contribute data to the overall program. We also describe progress in RF sensor R&D and deployment.**

I. INTRODUCTION

Exploding demand for wireless broadband access [1] has prompted U.S. government initiatives [2] to make more frequencies available for commercial broadband applications. Desirable radio spectrum has been mostly allocated in the U.S., as can be seen on the National Telecommunications and Information Administration's (NTIA's) radio allocation chart [3]. There are two basic ways to make more spectrum available: (1) open frequency bands to shared use or (2) relocate incumbent users to other bands. In both cases, the density of systems in space, frequency, and time will increase. Without adequate planning and precaution, this creates a higher probability of interference events, increased risk for incumbents and investors, and a reduction in spectrum value.

Measured spectrum occupancy is useful information for planning, engineering, and enforcing new spectrum sharing and relocation scenarios. With some standardization and the development of best practices to ensure data quality, measured spectrum data could be made available alongside license and assignment data [4] to improve the quality and quantity of information available for planning by policy makers, spectrum managers, and investors. In the engineering phase of a transition process, real-time and historical measured spectrum data could be used to check assumptions, validate propagation and usage models, and field test dynamic coordination schemes and technologies. After a sharing or relocation authorization, open and transparent use of relevant spectrum data can play a critical role in interference resolution and enforcement in the increasingly dynamic and complex interference environment.

Long-term and continuous acquisition of spectrum data, i.e., spectrum monitoring, is currently being performed by industry, academia, and government for a variety of purposes [5]. There has been little effort, however, to collect, extend, and curate this information for the benefit of all. The organizations acquiring spectrum data employ a wide variety of data types to suit their purposes. The means of acquiring the data also varies and there is no one-size-fits-all approach. With all these disparate sources, types, and methods, there is a need for infrastructure and standardization to aggregate and achieve full collective value of the data.

Pursuant to the 2013 Presidential Memorandum [6], NTIA and the National Institute of Standards and Technology (NIST), sister agencies under the U.S. Department of Commerce, have invested in the development of a spectrum monitoring capability for the recently announced Center for Advanced Communications (CAC) [7]. The goals of our pilot program are to (1) develop an infrastructure to acquire and amass spectrum monitoring data and make it available to the spectrum community in near real time via the Internet [8], and (2) establish best practices for the acquisition of spectrum data.

Toward that end, we are developing a distributed Measured Spectrum Occupancy Database (MSOD) architecture. MSOD will enable industry, academia, and government agencies to host MSOD instances and contribute spectrum data to the overall program. Users will be able to query MSOD via a web service or view and download data with a browser-based data visualization application. In the visualization tool, band occupancy statistics over long time intervals will be available to inform policy discussions. Also, near-real-time amplitude versus frequency data will be available for spectrum coordination and enforcement purposes.

We are also pursuing RF sensor development and deployment. Sensor hardware and software are being designed to detect well-defined system transmissions in specified frequency bands, e.g., LTE at 0.7 GHz and 1.7 GHz [9] and pulse radar at 3.0 GHz and 3.5 GHz [10]. Novel aspects of the sensor designs include: (1) local calibrations to indicate health of sensors in the field and to measure system noise level; (2) a standard format for the transfer of calibrated measurements from the sensor to the repository; and (3) benchmark tests on commercial-off-the-shelf (COTS) sensors and software defined radios (SDRs) to assess capabilities and limitations.

This overview paper provides high-level descriptions of the NTIA/NIST Spectrum Monitoring Pilot program. We describe design requirements and strategies, fiscal year 2014 (FY14) accomplishments and challenges, and areas of future work including sensor deployment plans.

II. MSOD DEVELOPMENT

The MSOD design supports a distributed deployment of multiple databases and servers spanning multiple sites and organizations (Fig. 1). Each organization can maintain its own database and web server (i.e., MSOD instance or node), which exports a secure hyper-text transfer protocol (https) web interface. Data is not replicated across all databases. Rather, an organization advertises its public meta data selectively to other organizations with which it chooses to federate. When a user queries data that is not physically stored on the attached host database but is stored on a federated database, the web browser transparently fetches data from the appropriate server to display it (dashed arrows in Fig. 1). In this way, a web browser may communicate directly with multiple web servers to display the data in a unified fashion in a single web application.

To enable distributed storage and access, each web server maintains a soft-state[1] connection with its federated peers. Periodic soft-state messages send high level information about the sensors supported by a given MSOD node. Using the soft-state messages it receives from other nodes, each web server populates and maintains a directory indicating where data corresponding to a given sensor is located. If an MSOD node disconnects from the system, the soft-state message registered by that web server is discarded by its federated peers. This architecture allows for non-centralized, autonomous management. However, it relies on adherence to a common specification for the interaction between the web server and browser.

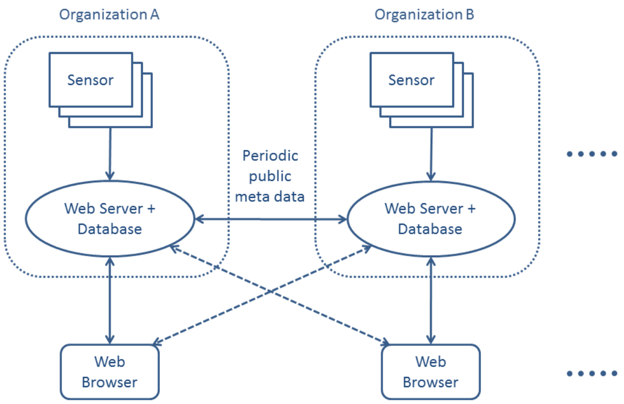


Fig. 1. Distributed MSOD architecture

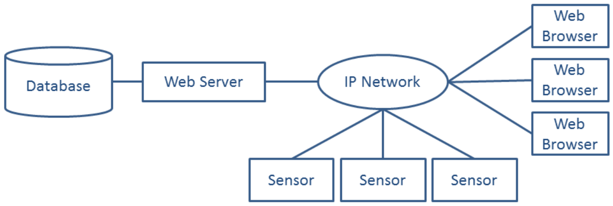


Fig. 2. Architecture of an organization's MSOD infrastructure

A. *An Organization's Database*

An organization's MSOD serves as a repository for the spectrum data acquired by the organization's sensors. The enabling components are a database and an https web server that provides access to the database via web-based services (Fig. 2).

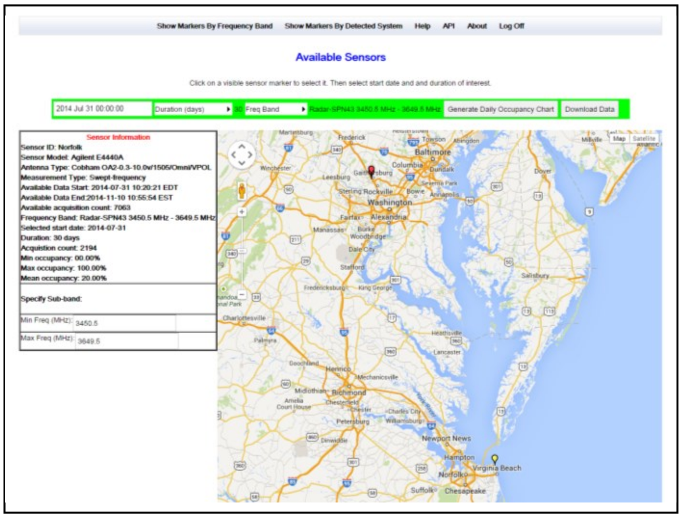
The database is document-oriented and stores all data in JavaScript Object Notation (JSON) documents. As such, it is well suited to directly ingest JSON messages from the sensors, storing them as documents. It supports indexing of document attributes, such as the time of a data acquisition, for subsequent queries. A typical query in support of data visualization is all measurements of a particular sensor in a given frequency band and over a given date range.

MSOD receives sensor measurements in one of two modes. In acquisition mode, the sensor posts a finite set of measurements collected over an interval of time. It posts acquisitions intermittently, typically with a fixed periodicity, using an https post request. In streaming mode, the sensor continuously transmits measurements over a persistent TCP/IP socket connection.

B. *Data Presentation*

Visualization of occupancy data is provided through a web browser application. The application can be configured to require users to enter a user name and password in order to see the data. Password protection allows the system to host potentially sensitive measurements. After login (if required), the user is presented with a map of sensors that he/she is authorized to view (Fig. 3). The user can filter the sensors displayed on the map by frequency band or target system. The user can also zoom the map to the desired geographic area.

Upon selecting a sensor, the user is shown specific details, including characteristics of the sensor and the range(s) of frequencies and dates over which data from that sensor are available. The user can then specify the desired date range and frequency range and click to generate a plot of band occupancy versus time in 24-hour increments (Fig. 4).



Available Sensors

Click on a visible sensor marker to select it. Then select start date and and duration of interest.

2014 Jul 31 00:00:00 | Duration (days) 30 | Freq Band Radar-SPN43 3450.5 MHz - 3649.5 MHz

Sensor Information
Sensor ID: Norfolk
Sensor Model: Agilent E4440A
Antenna Type: Cobham OA2-0.3-10.0v/1506/Omni/VPOL
Measurement Type: Swept-frequency
Available Data Start: 2014-07-31 10:20:21 EDT
Available Data End:2014-11-10 10:55:54 EST
Available acquisition count: 7063
Frequency Band: Radar-SPN43 3450.5 MHz - 3649.5 MHz
Selected start date: 2014-07-31
Duration: 30 days
Acquistion count: 2194
Min occupancy: 00.00%
Max occupancy: 100.00%
Mean occupancy: 20.00%

Specify Sub-band:
Min Freq (MHz): 3450.5
Max Freq (MHz): 3649.5

Fig. 3. Sensor selection screen (Map data ©2014 Google)

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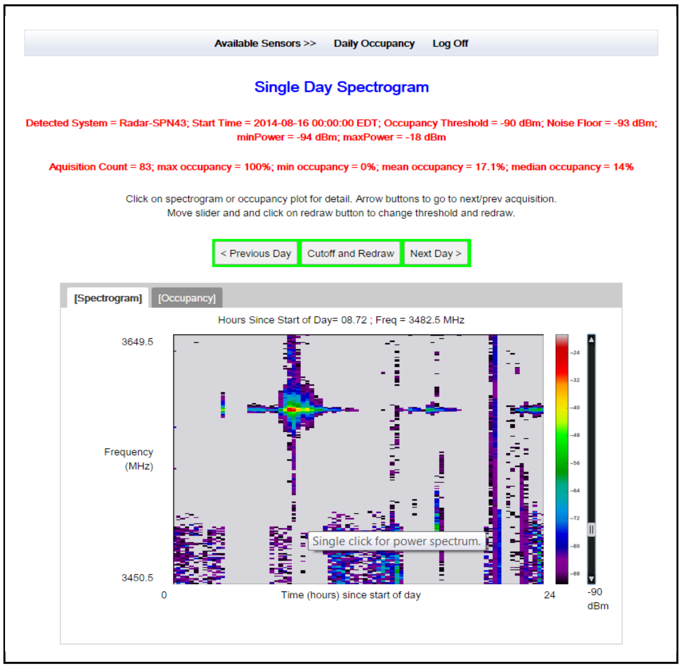
[1] Soft-state means that a server does not keep a permanent record of information it receives from a peer server (hence the term "soft"); rather, it periodically retrieves the information and refreshes it. Thus, if a sensor's location information is changed, for example, the peer fetching that information will update its copy after a refresh interval.

Band occupancy is defined as the percentage of frequencies or channels in the band with a detected signal level that exceeds a default or user-defined threshold [11]. A default threshold is defined according to measurement range requirements and the specified detection scheme, which subsequently sets sensor sensitivity requirements. The daily band occupancy chart displays the minimum, maximum, average, and median for each day. This is an active chart; clicking a data point shows the data for that particular day.

The nature of the subsequent chart depends on the sensor's detection scheme. In the case of a radar sensor (Section III.C.1), a spectrogram of frequency-swept data is displayed, where each vertical line corresponds to a sweep of the channels in the selected frequency range (Fig. 5).

Start Date= 2014-07-31 00:00:00 EDT;Detected System = Radar-SPN43; minFreq = 3450.5 MHz; maxFreq = 3649.5 MHz; channelCount = 200; Occupancy Threshold = -90 dBm

Fig. 4. Daily band occupancy chart



Detected System = Radar-SPN43; Start Time = 2014-08-16 00:00:00 EDT; Occupancy Threshold = -90 dBm; Noise Floor = -93 dBm; minPower = -94 dBm; maxPower = -18 dBm

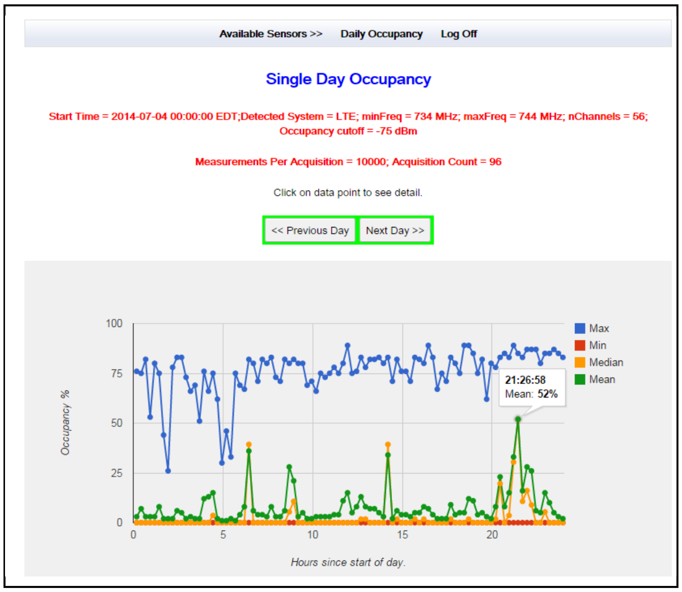
Aquisition Count = 83; max occupancy = 100%; min occupancy = 0%; mean occupancy = 17.1%; median occupancy = 14%

Click on spectrogram or occupancy plot for detail. Arrow buttons to go to next/prev acquisition.
Move slider and and click on redraw button to change threshold and redraw.

Fig. 5. Frequency-swept data for the 3.5 GHz maritime radar band

In the case of a communications (comm) sensor (Section III.C.2), a second occupancy chart is displayed for that 24-hour period, where each data point corresponds to the band occupancy of a single acquisition (Fig. 6). Clicking on a data point in this occupancy chart displays a spectrogram for that acquisition which can be more closely inspected (Fig. 7). Thus, comm sensor data has an extra layer of visualization.

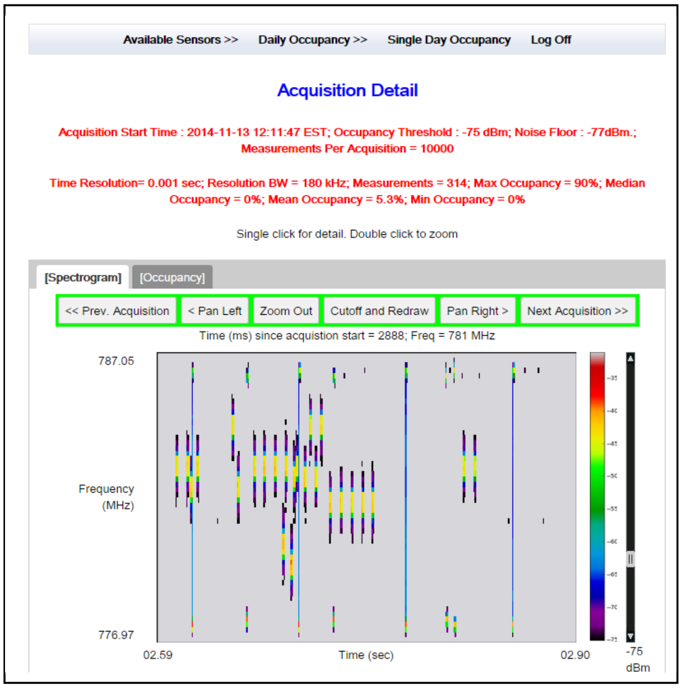
In addition to viewing historical data stored in the database, the user has the option to view live streaming data from sensors that support it. Selecting this option displays a running spectrogram of the received measurements in the top half of the screen and the evolving band occupancy time series in the bottom half (Fig. 8). Clicking on a data point generates a power spectrum (power vs. frequency) plot at that point in time.



Start Time = 2014-07-04 00:00:00 EDT;Detected System = LTE; minFreq = 734 MHz; maxFreq = 744 MHz; nChannels = 56; Occupancy cutoff = -75 dBm

Measurements Per Acquisition = 10000; Acquisition Count = 96

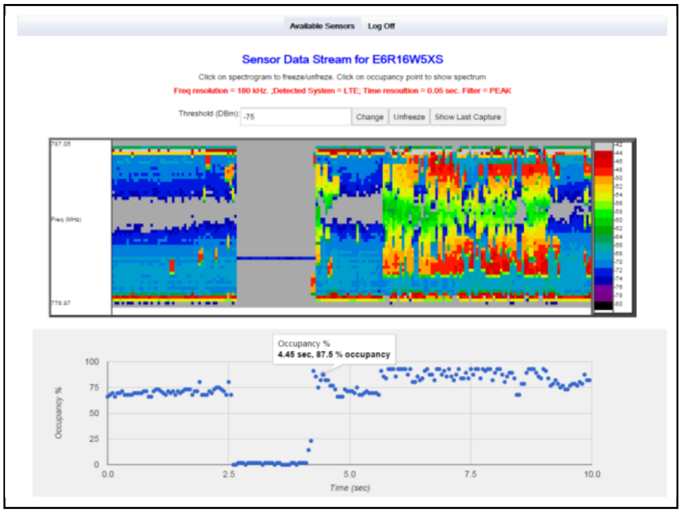
Fig. 6. Comm sensor occupancy chart



Acquisition Start Time : 2014-11-13 12:11:47 EST; Occupancy Threshold : -75 dBm; Noise Floor : -77dBm.; Measurements Per Acquisition = 10000

Time Resolution= 0.001 sec; Resolution BW = 180 kHz; Measurements = 314; Max Occupancy = 90%; Median Occupancy = 0%; Mean Occupancy = 5.3%; Min Occupancy = 0%

Fig. 7. Spectrogram of comm sensor data



Sensor Data Stream for E6R16W5XS

Click on spectrogram to freeze/unfreeze. Click on occupancy point to show spectrum

Freq resolution = 180 kHz. ;Detected System = LTE; Time resoultion = 0.05 sec. Filter = PEAK

Threshold (DBm): -75

Occupancy %
4.45 sec, 87.5 % occupancy

Fig. 8. Live streaming data

C. *Implementation*

MSOD software was constructed using well-tested and widely-used open source technologies to reduce cost and enable participation from the overall community. We used the Python flask web services container to construct the web application, SciPy for the data visualization components on the web server, and MongoDB for the database.[2] We used Google Web Toolkit to generate the JavaScript for the client web browser. These technologies worked well with the choice of JSON for the messaging format and reduced our development time significantly.

Hardware design and configuration are determined by the priorities of the host organization. Security requirements, for example, will influence an organization's implementation. Data storage, throughput, and retention requirements will depend on the data purpose, type, and method of acquisition.

The current MSOD implementation, for example, is well-suited for informing non-technical spectrum policy circles. Data reduction is performed mostly at the sensor via detection schemes based on a priori knowledge of the transmissions to be measured. Relatively low bandwidth amplitude-versus-frequency data are sent from sensors to MSOD for the purpose of computing occupancy statistics every 10 or 15 minutes for relatively long time intervals (e.g., weeks or months). Data will be retained for years in this scenario.

In contrast, an MSOD implementation to support technical spectrum enforcement teams might record relatively high-bandwidth amplitude and phase data for the purpose of post processing to identify transmissions that are not operating as intended. Data might only be retained for hours in this scenario before it is reduced for long-term storage.

III. SENSOR RESEARCH AND DEVELOPMENT

This section describes the general RF sensor architecture, related research, and prototype development. Sensor designs are band specific and follow RF and digital signal processing best practices.

A. *General Architecture and Requirements*

The general sensor architecture is comprised of an antenna, preselector (PS), COTS sensor, and measurement controller (Fig. 9). General site requirements include: AC power; shelter to protect subsystems from the elements; cable entry for routing cables; and a structure for mounting the antenna and preselector. Field-of-view requirements depend on the service to be measured. Antenna parameters (e.g., frequency range, polarization, radiation pattern) must also be appropriate for the band/service to be measured.

1) Preselection and Calibration

The PS attenuates unwanted out-of-band signals, sets the dynamic range of the system, and enables local calibrations. Local calibrations are required to give assurance that sensors at remote locations are operating as expected and to measure the system noise level. This is achieved by switching to a known signal source. The PS is ruggedized and weatherproof to accommodate outdoor operation. Well-designed PSs are essential to ensuring the integrity of the measured spectrum but are inherently costly. A design goal is to reduce the cost of the PS commensurate with the reduction in cost of the accompanying COTS sensor (see Section III.B).

2) Detection, Formatting, and Backhaul

Onboard processing applies the appropriate band-specific detection scheme (that produces a desired statistic versus frequency), formats the data according to a predefined MSOD data transfer specification, saves data on a local hard drive, and pushes it to an MSOD instance when the IP network (cellular or Internet) is available. Data reduction and formatting can be performed onboard or external to the COTS sensor. The measurement controller houses power management hardware and a miniaturized computer (if needed).

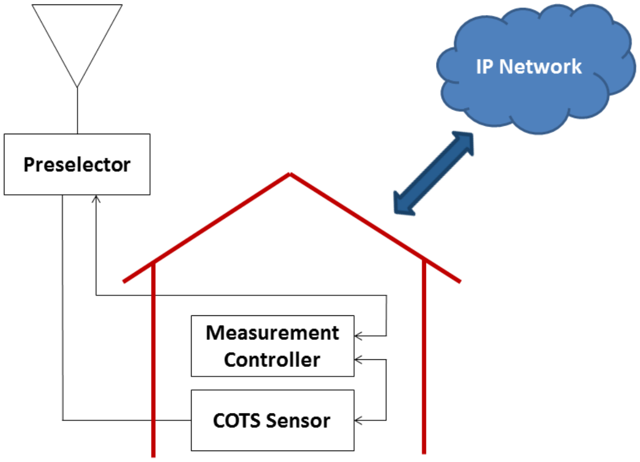


Fig. 9. General sensor architecture

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[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST or NTIA, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

```
{
    "Ver": "1.0.12",
    "Type": "Loc",
    "SensorID": "101010101",
    "SensorKey": 846859034,
    "t": 987654321,
    "Mobility": "Stationary",
    "Lat": 40.0,
    "Lon": -105.26,
    "Alt": 1655,
    "TimeZone": "America\Denver"
}
```

Fig. 10. Sample sensor location message

3) MSOD Transfer Specification

Three message types — system, location, and data — are defined for the communication from a sensor to the server. All messages are JSON formatted and consist of attribute-value pairs. Fig. 10 shows an example location message.

A *system* message lists the critical hardware components with relevant RF specifications. It can also contain calibration data. System messages are sent when the sensor registers with the database, at the start of a sequence of acquisitions, and/or at a specified calibration interval (e.g., hourly, daily).

A *location* message specifies the geolocation of the sensor. A sensor sends a location message when it initiates a sequence of acquisitions. If mobile, a sensor can also send a location message whenever its location changes.

A *data* message consists of a header specifying the data characteristics of the ensuing measurements followed by a block or stream of data. Data is formatted as a sequence of power vectors, where each vector is a sequence of scalar powers, one for each frequency or channel in the band. In acquisition mode, the sensor sends a data message (header plus data block) for each acquisition. In streaming mode, the sensor sends a single header followed by a continuous stream of power vectors.

B. COTS Sensor Evaluation

Historically, NTIA's Institute for Telecommunication Sciences has used a spectrum analyzer (SA) as the centerpiece of systems designed to measure short-term spectrum usage one location at a time, e.g., [11]. Since the intent of this program is to deploy many sensors and acquire continuous long-term data, the relatively high-cost SA is not practical. In fact, the primary sensor-design task is to replace the SA functionality with an appropriate COTS sensor (based on requirements set by the band/service to be measured). Toward this end, NTIA has an ongoing effort to assess the functionality and programmability of various COTS sensors and SDRs available on the market and produce a corresponding cost/capability matrix.

Investigations have identified four tiers of COTS sensors aligned with high-, mid-, low-, and ultra-low cost. Benchmark tests to compare the RF performance of these boxes have been developed. RF performance metrics to be measured include noise figure, dynamic range, spurious responses, intermodulation distortion, adjacent signal overload, alias rejection, frequency and amplitude stability and accuracy, amplitude flatness, phase noise, discrete Fourier transform window characterization, and data throughput.

Sensor evaluation requires development of signal processing algorithms that are typically built into an SA. This can be a significant development effort. Once basic detection routines are developed and validated, more advanced detection schemes will be pursued.

C. Band/Service- Specific Sensor Development

RF sensors are being designed to meet band/service-specific requirements with a goal of minimizing cost and form factor. We have developed a radar sensor prototype to measure pulsed radar signals and a comm sensor proof-of-concept to measure common comm signals (e.g., LTE).

1) Radar Sensor

The radar sensor design is based on that described in [11], except a slant polarization omni-directional antenna replaces the vertical linear omni, the PS is closer to the antenna to improve sensitivity, and data is formatted according to the MSOD data transfer specification.

Pulsed radar signals are typically high power, which drives a large spurious-free dynamic range requirement (60 dB). We are attempting to meet this requirement with a mid-tier COTS sensor. The cost of a single radar sensor with this configuration is approximately $50,000.

The radar sensor prototype was tested in the lab and deployed at Virginia Beach in August 2014 to monitor the 3.5 GHz maritime radar band. A spectrum analyzer was used instead of a COTS sensor for this install. Once the necessary functionality of a mid-tier COTS sensor has been fully developed and tested, it will replace the SA.

2) Comm Sensor

The comm sensor design is based on low-cost, software-controlled RF hardware paired with a general purpose or embedded processor that performs digital signal processing. In its current instantiation, the RF front end can be tuned from 400 MHz to 4400 MHz and has been used to monitor bandwidths up to 20 MHz. A typical usage scenario for this sensor is monitoring 700 MHz LTE.

A key design goal of the sensor was to provide real-time spectrum occupancy information to the MSOD. The motivation for real-time information is the support of dynamic spectrum coordination among multiple systems sharing a band. The data rate of the streamed measurements depends on the width of the band, the time and frequency resolution with which it is measured, and the data type of each measurement. For example, continuous monitoring of a 10 MHz LTE link with 180 kHz frequency resolution, 1 ms time resolution (i.e., the time-frequency resolution of the LTE resource block), and 8 bit signed integers generates a data flow of just under 0.5 Mb/s from the sensor to the MSOD.

The comm sensor is at a proof-of-concept stage and costs approximately $6,000. Further testing and development are needed before it is field-ready.

IV. FUTURE WORK

MSOD software is under development and will continue to evolve even after production servers are deployed. NTIA is purchasing the IT equipment to provide a high-availability, web-accessible MSOD with a production environment for system users and a quality assurance environment for testing. NTIA will establish security controls to meet Government-mandated security requirements. Since NTIA is the Federal spectrum regulator, the NTIA MSOD will primarily serve policy circles and agencies. Informing policy and enforcement will be the key application areas. In general, the data will be only available to authorized users, i.e., it will not be accessible to the general public.

In addition, NIST's Communications Technology Laboratory plans to set up an MSOD instance logging non-sensitive measurements which will be accessible to the general public. The primary focus of research with the NIST MSOD will be dynamic spectrum coordination, using real-time sensor measurements to inform the allocation of resources in a shared spectrum scenario with tiered access (i.e., a priority incumbent system sharing spectrum with one or more secondary systems).

In terms of sensor research and development, we will continue evaluating different sensors available on the market and expanding the sensor cost-capability matrix. In addition to measuring RF engineering performance metrics, we plan to pursue a detection standardization test-bed where common signal types are parameterized, emulated, and injected into a detection device. We typically measure to gain an estimate of the signal parameters (e.g., peak detection to obtain a pulse amplitude estimate). A detection standardization test-bed will provide a tool for detection scheme validation, optimization, and uncertainty analysis. It will also enable signal identification and demodulation advancements when appropriate. Further, we will continue developing and testing firmware for different COTS sensors to diversify our options. We will to strive toward smaller and less-expensive devices, while maintaining the appropriate functional specifications to meet the requirements defined by the measurement at hand.

Regarding sensor builds and deployments, we will adapt yearly project plans to monitor scenarios identified in policy circles, e.g., the Commerce Spectrum Management Advisory Committee, Policy and Plans Steering Group, and the International Telecommunications Union (ITU). We will continue to consult with Federal agencies to determine technical parameters, sensitivity of data, and agency needs.

In FY15, we plan to build and deploy five 3.5 GHz sensors at Cape Cod, Key West, San Diego, San Francisco, and Astoria (in addition to the one already installed at Virginia Beach). In addition to monitoring the 3.5 GHz band, these installations will be used to monitor the 2.9 GHz to 3.1 GHz Radionavigation band. NTIA's Office of Spectrum Management is tasked with a quantitative assessment of spectrum usage of these bands [10]. Also in FY15, we plan to build a field-ready comm sensor prototype and acquire the components to build a number of replicas. Possible application areas for the comm sensor in FY16 include the 1695 MHz to 1710 MHz meteorological satellite band that will soon be shared with LTE uplinks [9], the spectrum test city [12], and/or the 700 MHz public safety space which is in transition.

An on-going effort will be made to benchmark and document available criteria, requirements, parameters, designs, interfaces, software, data sets, and other information in each phase of the project. Subsequent papers and reports will cover specific sub-topics in greater detail. A project website or portal will be developed to manage and make accessible the latest material and resources. Once the software reaches a mature state, we will make the MSOD source code publicly accessible on the GitHub repository to enable other entities to add their own MSOD instance.

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