Performance of RF Mapping Using Opportunistic Distributed Devices

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Abstract—**The DARPA RadioMap program focuses on large-area near-real-time spectrum situational awareness. The program seeks to make this capability affordable through using opportunistic distributed devices as the sensor network; that is, through adding spectrum measurement functions to devices such as tactical radios and jammers already deployed for other purposes. This paper provides an overview of the approach and the envisioned uses for the RadioMap capability. We present the evaluation methodology developed for the program, which could apply to any distributed Radio Frequency (RF) Mapping system. We report performance observed in the RadioMap phase 2 field trials that occurred September 2014 in Arlington, Virginia.**

Keywords—Spectrum monitoring; radio frequency mapping; distributed systems; field trials; performance measurement; experimental methodology.

I. Introduction

Spectrum situational awareness is an increasingly vital military capability. Its importance continues to grow as individuals, platforms and devices come to rely on radio frequency (RF) communications more deeply and continuously.

In this environment, being able to "see" into the spectrum offers high value for military operations. A ground combat unit can use RF spectrum information to rapidly differentiate friend from foe; to receive warning when a military device activates in the middle of a dense civilian area; or to determine whether there is movement under dense foliage on the far side of a valley. An Electromagnetic Spectrum Operations (EMSO) specialist provided with a broad-area near-real-time spectrum usage map can improve their performance at Electronic Warfare missions, through better targeting, device selection, and battle damage assessment. A military spectrum manager can rapidly correct errors in their spectrum assignment database, determine which channels are unused when making new assignments, and more rapidly resolve the cause of interference problems in order to recommend mitigation actions. Future Dynamic Spectrum Access systems can use the information to automatically share spectrum without causing interference, increasing the number of devices and the amount of communications that can be supported in limited spectrum.

The benefits of spectrum situational awareness just listed are well known and not controversial. The challenge is to make broad-area spectrum situational awareness affordable and readily accessible. Deploying a dedicated network of spectrum monitors has proven unaffordable even with the availability of mature commercial off-the-shelf devices and the high level of automation in current systems.

The DARPA RadioMap program seeks to develop technology that turns devices already deployed for other purposes, particularly tactical radios and Counter Remote-Controlled Improvised Electronic Device Electronic Warfare (CREW) jammers, into the sensor network needed for spectrum situational awareness. RadioMap leverages the underlying technology trends toward Software Defined Radio and reactive jamming that enable the current generation of military radios and CREW jammers to provide this function.

RadioMap has completed Phases 1 and 2 (2 years) of a 4 year program. At the end of Phase 2 in September 2014, the program conducted a large-scale field trial in Arlington, Virginia. This paper draws on our experience with that field trial to make contributions in two areas: methodology and performance results. We describe the performance evaluation methodology developed for RadioMap, which we believe should generalize to any spectrum situational awareness system. If a compatible evaluation methodology is used for future experiments by other programs, the community will be better able to compare approaches and products. Using this methodology, we present the performance achieved in the field trial. While the RadioMap performers continue to improve system performance in the ongoing Phase 3 of the program, the results presented here are a valuable data point that the community can use to understand the spectrum monitoring performance possible in a distributed system of low cost sensors.

II. Background

A. Operational Scenario

The RadioMap program focuses on ground tactical units, particularly those operating in dense RF environments with complex propagation such as urban areas. We assume there is a moderately dense deployment of blue-force ground tactical RF devices, several per square kilometer, covering the operational area of interest. For a device to participate in the RadioMap sensor network, it must have an RF receiver and a data network connection enabling communication with the task manager and fusion engine for the sensor network. In the case of tactical radios, one RF receiver supports both spectrum sensing and data communications.

The task manager and fusion engine software runs on any available computational platform. In the case of small squads,

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it may run in one of the tactical radios or on a squad leader's C2 device. For larger units, it may run on a preexisting or a dedicated server in a command tent.

Once created, the RF RadioMaps are distributed to a variety of users. The data is displayed to each user in ways appropriate to that user's mission, normally by feeding the data into their existing workstation or decision support software. Users also have the ability to query a historical database of all measurements in a given area and to task the RadioMap system to gather desired information. These capabilities will be available only to some users and via some workstations.

B. *RF Mapping goals*

RF Mapping provides information about how the spectrum is being used. That is, it provides a map of what a receiver would hear at any location in the area of interest.

The map provides information about the externals of observed transmissions. Externals include power level, center frequency, bandwidth, duty cycle, and modulation type.

The map does not provide information about the internals of observed transmissions, such as voice or data content. If a signal of interest is observed in the RadioMap, a properly authorized signal intelligence (SIGINT) system with the necessary technical capability should be cued to capture the content of that transmission.

The map provides only limited information about the location of transmitters. Location estimates are coarse because they represent a mathematical best fit to a sparse set of observations. If a precise geolocation is required, a specialized system with hardware designed to provide high location accuracy should be cued.

C. *Technical Challenges*

The basic approach for RF mapping with low-cost or opportunistic sensors is to measure the power of each transmission using multiple devices at different locations. When combined with varied propagation in the environment, due to buildings or terrain, the multiple measurements enable determining the approximate location and power level of each transmission. From this information, the rest of the RF map can be derived.

RF mapping faces inherent challenges in dense RF environments with complex propagation, such as urban areas. Currently, models that accurately predict RF propagation in these environments are too computationally costly to deploy as a real-time tactical capability. However, a poor propagation model will result in significant mapping errors. Thus the selection, optimization, and parameterization of an approximate propagation model is a critical technical challenge. Furthermore, it is vital to correctly correlate measurements across sensors. If two transmissions are erroneously treated as one during data fusion, or vice versa, there will be significant mapping errors. Normally, the measurements are sparse in space and time, so there is a significant interpolation challenge in both dimensions.

RF mapping using opportunistic devices faces further challenges. The tasking and fusion engine cannot control the location or duty cycle of the sensors; it must "make do" with whatever information is available to it. Thus the software needs to estimate the confidence level (error bars) of the results it provides, based on the location and frequency of available measurements and the operating environment, so users can determine whether the information is accurate enough for their particular mission decision.

D. *Phase 2 Field Trial*

The results reported below used COTS sensors, not military tactical devices. The sensor nodes ranged in price from $1000-$4000. The sensors ran at 100% duty cycle. Performance can be expected to degrade in situations where opportunistic sensors are highly loaded with other tasks so there is only limited time available for spectrum monitoring. Sensor data was transmitted to the fusion engine via the local cellular network. Performance can be expected to degrade in highly loaded tactical networks where capacity available for RF mapping is limited and connectivity is intermittent. Both of these effects will be studied in detail in RadioMap Phase 3.

Final reports from Phase 2, which provide the details on the sensors and the RF mapping algorithms that are necessary to fully evaluate the data presented in this paper, are available on request. These reports are ITAR restricted.

III. Evaluation Approach

A. *Ground Truth Measurements*

The Radiomap Program evaluation approach employs a blind test in which a set of Government team spectrum sensors are deployed according to a schedule to undisclosed locations within an area of interest. The Government team selected locations that were not occupied by performer team sensors, and over the period of a day long schedule varied the position of the Government sensors relative to performer sensors including minimum separation and closure (see Fig. 1).

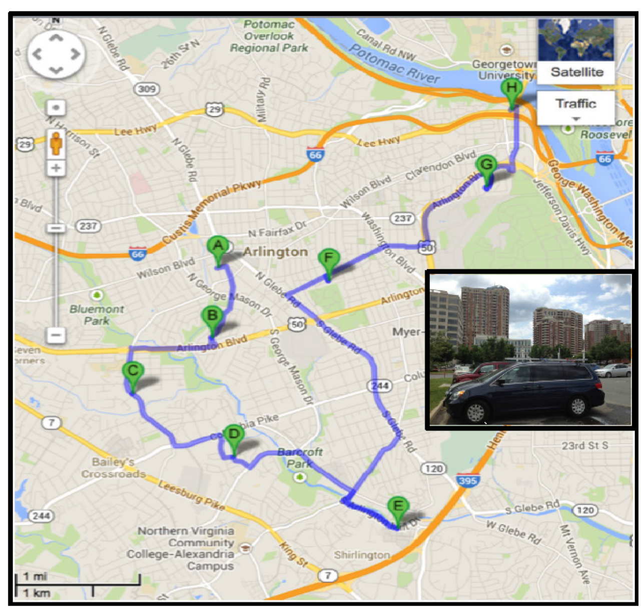

Fig. 1. Typical Government Ground Truth Measurement Location Map

Government ground truth sensors were composed of a grouping of three independent Agilent N6841A spectrum sensors, employing three independent antennas. The antennas were omni-directional discone antennas mounted on the roof of a stationary van at about 6 feet in height. The purpose of the three senors was to generally mitigate the presence of nulls or blind zones that may have been produced by multipath from ambient emitters. The sensors were configured to scan over the range of 470 to 928 MHz. The sensors processed Fast Fouriour Transforms (FFTs) onboard and delivered the results to a single controlling computer. The Government team FFT resolution bandwidth was 1.7 kHz, and was later converted to 10 kHz resolution for comparison to the performer results. The sensor was configured to make 5000 sweeps over the frequency range with 100 measurements averaged together prior to downloading to the computer. This represented a 10-minute measurement period. The 5000 sweeps from all three sensors were averaged together (in absolute units) to provide a Power Spectral Density (PSD) representative of the 5-minute period. This PSD was then converted to a spectral flux density.

After completion of the day-long measurement schedule, the performer teams were informed of the Government team's ground truth measurement schedule and locations. The performers were asked to generate the PSD averaged over the corresponding 5-minute period. The Government Team ground truth measurements could then be compared to the performer estimates. Fig. 2 shows the ground truth sensor system within context of the overall performance evaluation process.

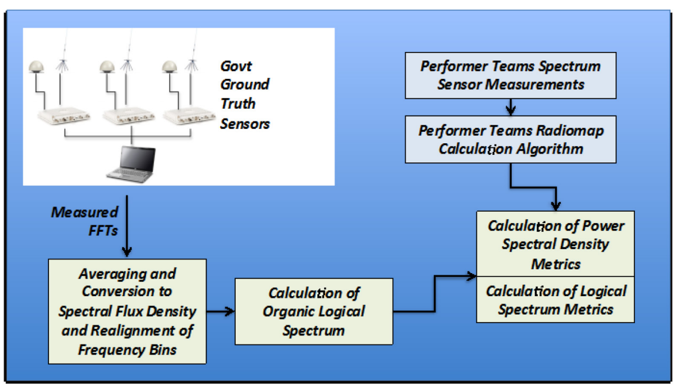

Fig. 2. RadioMap Generation and Scoring Process

B. *Logical Spectrum Definition*

The Ground Truth physical spectrum measurements were transformed into the Logical Spectrum domain. The primary building block of Logical Spectrum is called a Signal Group. A Signal Group consists of a channelized RF emitter that is described by parameters of relevance to the RadioMap program. These parameters fall into two general classes,: (1) Identification (i.e., signal type, center frequency and bandwidth) and (2) characterization (i.e., average / peak power and spectrum occupancy).

Signal Group Identification parameters are typically expected to remain constant over timespans on the order of weeks to months. For example, licensed wireless emitters typically operate at center frequencies and bandwidths that are stable over the license time frame. The System Type associated with the license is also typically stable.

Signal Group Characterization parameters are typically expected to vary over timespans on the order of minutes to hours. For example, received (average and peak) power can vary significantly due to fading caused by environmental effects such as transmitter and/or receiver movement and building and vegetation variation, among others. However, there will be cases in which variation on these timespans will not occur. For example, with regard to occupancy, whereas cellular mobile stations transmit occasionally, the associated base stations typically transmit continuously. Mobile station transmissions also tend to be more likely in "busy hour" times (e.g., during commute times) than they are in "off hours" (e.g., middle of the night).

A Spectrum Hole is a special case of a Signal Group in which a contiguous frequency band is declared to be unoccupied by any emitter. Spectrum Hole identification is important due to the desire for opportunistic spectrum utilization. That is, a RadioMap needs to reliably identify spectrum that is occupied by an emitter as well as that which is unoccupied, and thus is a candidate for opportunistic use.

The reverse of a Spectrum Hole is a False Signal Group, for which the performer predicts the existence of an active emitter where the ground truth measurements show a Spectrum Hole. Poor performance here implies a loss in opportunistic spectrum utilization.

The concept of anomalies is also important to Logical Spectrum. The RadioMap program defined two types of anomalous signals.

Type 1 is an unexpected Signal Type as determined by its center frequency and bandwidth from a database of expected Signal Types. In other words this is a rogue emitter.

Type 2 is a known Signal Type that is not consistent with an expected frequency assignment. That is, the measured parameters of the detected signal are consistent with Signal Type(s) that have been approved for operation in the band. However, the detected signal is occupying a specific channel in the band for which there is not a valid assignment.

C. *Logical Spectrum Evaluation Process and Metrics*

The Government team evaluated Performer predictions on a representative subset of Signal Groups over the RadioMap frequency range. Prior to evaluation the Performers did not know this Signal Group subset. Therefore, they had to collect data sufficient to generate Signal Group prediction across the entire RadioMap frequency range. A high level overview of the evaluation process is shown in Fig. 3.

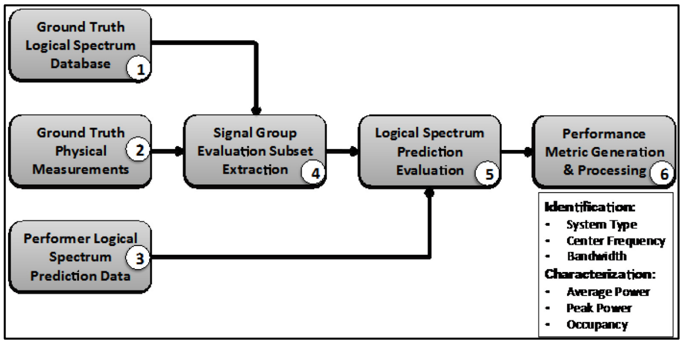

Fig. 3. Logical Spectrum Evaluation Process Overview

Prior to the Performer tests, the Government team conducted detailed physical and logical (e.g., FCC license assignments) surveys of the test area in order to generate a comprehensive Ground Truth Logical Spectrum Database (1).

During the Performer trials, the Government team conducted ground truth physical measurements at numerous locations throughout the test area (2). The Performers did not know these ground truth locations during the trial period. The Performers measured the spectral environment using sparse sets of static and mobile sensors throughout the test area. After the test period, the Government team provided the ground truth locations to the Performers. The Performers then generated Logical Spectrum predictions (3) based on their sensor measurements and associated data and analysis systems.

The Government Team generated a set of Signal Groups (4) against which the Performer predictions were evaluated (5) that were based on the Government team's physical measurements and spectrum databases. Finally, the raw prediction evaluation data was processed (6) to generate composite identification and characterization performance results across the ground truth locations.

Performance evaluation metrics were developed for both identification and characterization dimensions of Signal Group prediction. For identification, the Performer had to correctly predict all three components (i.e., system type, center frequency and bandwidth) to within specified tolerances in order to be credited with a success.

For characterization, prediction error tolerance regions were created with associated scoring values. For example, power estimates (average and peak) within ±10 dB of the ground truth value were given double credit and within ±20 dB single credit. Estimates with errors beyond ±20 dB received no credit. A similar metric was defined for occupancy performance evaluation.

This data has been evaluated across numerous dimensions, including both contractual and specialized metrics. The following section provides a small sample.

IV. Performance Of RadioMap In The Phase 2 Trial

A. Signal Group Identification

Fig. 4 shows the likelihood of a successful Signal Group identification as a function of ground truth location, expressed as a percentage. The mean success rate is approximately 86%. There is a relatively tight variation around this mean, with a Standard Deviation of less than 4%.

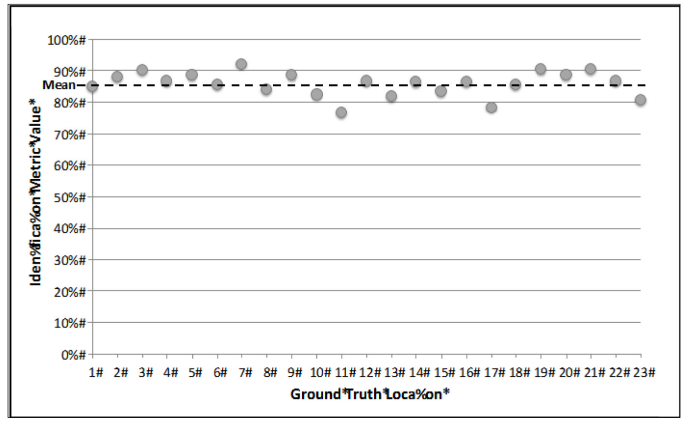

Fig. 4. Signal Group Identification Performance

The Government Team conducted numerous root cause analyses to assist the performer's technology enhancement efforts. Fig. 5 shows the results of an identification failure mode analysis. Along the horizontal axis are found the seven possible failure modes (left to right, from all three components failed, to three combinations of two component failures to three single component failures).

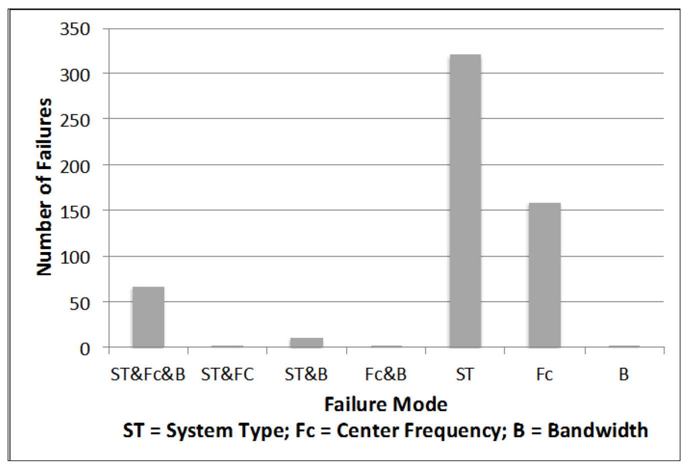

Fig. 5. Consolidated Identification Failure Profile

Note that approximately two-thirds of identification failures are due to the System Type component in isolation. Thus, this is an area to focus future research.

B. Signal Group Characterization

Fig. 6 shows performance evaluation results as a function of ground truth location for both average and peak power estimation. A "perfect" score of 1 can only be obtained if the estimated power for every Signal Group evaluated at a ground truth location is within ±10 dB of the measured value.

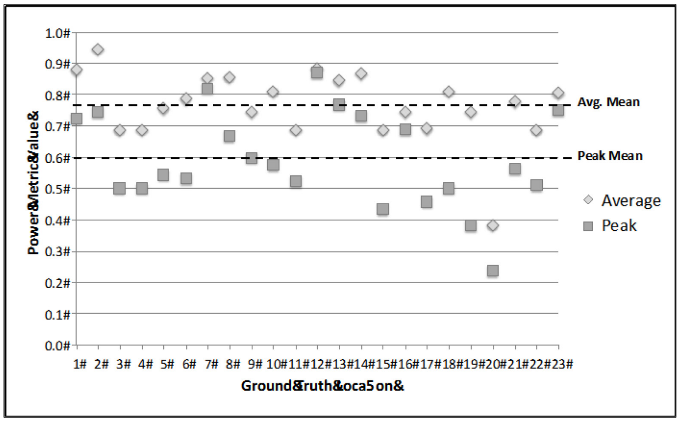

Fig. 6. Signal Group Average / Peak Power Characterization Performance

The mean metric values for average and peak power estimation are approximately 0.77 and 0.59, respectively. The standard deviations for average and peak power are approximately 0.11 and 0.15, respectively.

Plotting as a function of ground truth location provides clues for performance improvement. For example, location number 20 appears to be an outlier for both average and peak power estimation error. Further study of the RF environment and/or Performer sensor distribution (or other factors) for this instance may provide insight into power estimation error root causes, thus supporting performance improvement.

Spectrum occupancy is a central concept to RadioMap, as it provides the means by which to distinguish between spectral regions containing intentional as opposed to natural sources of energy content. Occupancy is defined using a spectrum energy threshold[1],[2] that has been commonly defined between the Government and Performers, and, that has been calibrated to ensure uniformity of application between the various sensor systems utilized.

Over a given measurement window time, a Spectrum Hole is a spectral region with zero occupancy. Although average occupancy is an important parameter, there is a wealth of information that can be inferred about specific emitters and general spectrum use by study of occupancy patterns over time and space.

Fig. 7 shows performance evaluation results as a function of ground truth location for occupancy estimation. The mean and standard deviation values are approximately 0.82 and 0.1, respectively.

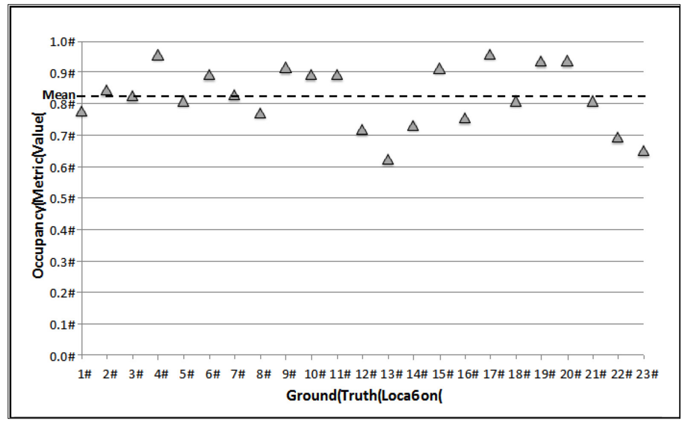

Fig. 7. Signal Group Occupancy Characterization Performance

Fig. 8 shows measured ground truth occupancy as a function of time for three specific System Types (i.e., Land Mobile Radio Base Station and Mobile Handset and GSM Base Station). These distinctive patterns can be used, for example, as a means of classifying unknown emitters.

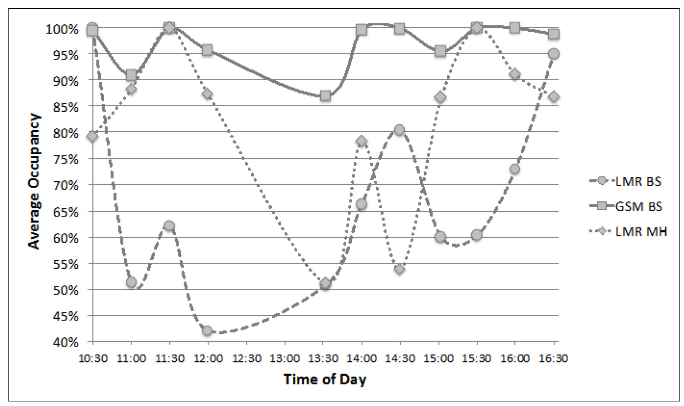

Fig. 8. Ground Truth Occupancy vs. Time for Three System Types

The RadioMap Government team has conducted extensive analysis of the available data across numerous dimensions. Some of these analysis areas are:

- Spectrum Hole and False Signal Group detection
- Anomalous signal detection
- Occupancy as a function of sensor noise floor
- Power and occupancy behavior conditioned on power level and system type
- Emitter power as a function of location
- Correlation of time-coincident measurements at different locations
- Emitter identification error modes
- Occupancy over spectrum bands
- Emitter classification and visualization techniques
- Physical spectrum estimation performance.

The data generated by the Government team and the Performers in RadioMap Phase 2 is a valuable resource both for understanding spectrum use in general and the RadioMap capability / potential in particular. The data will be made available to the community via a data distribution site at Johns Hopkins University.

V. Next Step: RadioMap Phase 3

Ongoing work in the RadioMap program seeks to improve the capabilities demonstrated in Phase 2 in four areas.

- Maximization of RF mapping performance under conditions of randomly changing network link and sensor availability.
- Detection, geolocation, and efficient implementation of queries for real-time and historical instances of, signals of interest within the sensor field.
- Capability to perform RF mapping at reduced accuracy in situations where prior RF measurements of the environment are lacking, or building data are lacking, or both. Capability to improve RF mapping accuracy over time by employing measurements gathered during operation.
- Use of a database capable of scaling to large amounts of stored spectrum information to support historical queries and streaming playback simultaneously with ingestion of new spectrum information.

In addition to work on the underlying technology, the program is re-implementing the software on top of a distributed middleware called WALDO that will enable rapid extensibility to new application capabilities and rapid incorporation of new devices often with improved technical characteristics into the sensor network. The RadioMap capability is being integrated into a larger Service Oriented Architecture (SOA) called the Electronic Warfare Services Architecture (EWSA).

The RF mapping application and WALDO middleware will be ported onto multiple tactical RF devices and evaluated in US Marine Corps electronic warfare (EW) and ground combat exercises in 2016 and 2017.

VI. Conclusions

The RF Mapping evaluation methodology described in this paper should provide a useful model for future evaluations carried out by other programs.

The performance achieved in the RadioMap program phase 2 field trial in the dense, complex RF environment of Arlington, Virginia, shows promise that this capability will be useful in future ground tactical operations.

Acknowledgment

The authors thank the other members of the RadioMap program team, and especially the hard work by the performers at Leidos and Argon ST who developed the RadioMap technology measured in this paper.

References

[1] International Telecommunication Union, Recommendation ITU-R SM.1880, "Spectrum occupancy measurement," February 2011.

[2] International Telecommunication Union, Recommendation ITU-R SM.2256, "Spectrum occupancy measurements and evaluation," September 2012.