RF Scene Generation for Dynamic Spectrum Testing

Jim Costabile
Syncopated Engineering Inc.
Columbia, MD, USA
jcostabile@SyncopatedEngr.com

Abstract—**The RF environment is a harsh and highly dynamic environment that includes both congested and contested spectrum. Typical testing lifecycles, include initial simulations, then laboratory testing in simulated noise environments with a few channel impairments, followed by outdoor testing in unpredictable RF environments under challenging unknown channel characteristics and unintended interference sources. The large leap from predictable laboratory testing to unpredictable Over-the-Air (OTA) testing makes it difficult to evaluate and quantify the actual performance. The use of emulated RF environments or RF scenes provides greater insight into system performance in challenging, and dynamic environments, while also enabling agile iterative performance improvements to fine tune the system. This paper describes the creation of realistic RF scenes to emulate RF environments that include a variety of narrowband and wideband signals, and random traffic patterns. We will also describe a RF learning approach that learns the spectral and temporal characteristics directly from actual RF environments, enabling the creation of RF scenes that mimic the actual RF environment enabling cost-effective repeatable test scenarios with the same complexity and rich expressiveness of actual operational RF environments. RF learning also enables the cost-effective generation of the massive RF data sets required to train, validate and test new innovative RF Machine Learning (ML) algorithms.**

Keywords—Emulated RF Scenes, RF Learning, Dynamic Spectrum Testing

I. INTRODUCTION

The RF environment is a harsh and highly dynamic environment that includes both congested and contested spectrum. Military communication and electronic warfare systems must do more than simply operate successfully in this harsh environment, they need to dominate it. Typical testing lifecycles, include initial simulations, then laboratory testing in simulated noise environments with a few channel impairments, followed by outdoor testing in unpredictable RF environments under challenging unknown channel characteristics and unintended interference sources. The large leap from predictable laboratory testing to unpredictable Over-the-Air (OTA) testing makes it difficult to evaluate and quantify the actual performance due to the unknown and rapidly changing environment and the lack of ground truth. The rapidly changing environment also makes it impossible to repeat tests under the same set of challenging conditions while refining the system to optimize performance improvements. In addition, the complexity of congested and contested environments has led to new innovative RF Machine Learning (ML) approaches to deal with the unpredictability of the dynamic RF environment. These new ML techniques typically require massive data sets to train, validate and test the algorithms to characterize and verify performance prior to operational deployment.

The use of emulated RF environments or RF scenes provides greater insight into system performance in challenging, and dynamic environments, while also enabling agile iterative performance improvements to fine tune the system through repetitive test execution against test scenarios that are both rich and complex but also easy to generate, enabling rapid Monte Carlo testing scenarios and statistical assessment of the system performance across a variety of RF scenes. The incorporation of RF learning capability, enables emulation of actual RF environments providing the ability to cost effectively execute a broad variety of testing scenarios as well as provide the massive RF data sets required of new ML applications to train, validate and test. In addition, with rugged field ready RF emulator test systems, the same system can be used in the laboratory and the field, enabling the recreation of realistic, random RF environments with known statistical characteristics even outdoors.

This paper describes the creation of realistic RF scenes to emulate RF environments that include a variety of narrowband and wideband signals, and random traffic patterns. We will also describe a RF learning approach that learns the spectral and temporal characteristics directly from actual RF environments, which then can be used to recreate these environments enabling cost-effective repeatable test scenarios, and RF data sets with the same complexity and rich expressiveness of actual operational RF environments. The ability to create realistic and statistically characterizable RF scenes enables the verification of wireless data links, electronic warfare techniques, signal detectors and demodulators, complex spectral sensing algorithms and supports the data appetite of new ML applications throughout the development cycle from design prototypes to outdoor Over-the-Air (OTA) testing.

This paper is organized as follows. Section II provides an overview of our Mockingbird RF signal and traffic emulator, which is a rugged software defined test system capable of RF scene generation and RF learning to support testing both in the lab and in the field. Section III provides our approach to RF scene generation including the ability to support a variety of waveforms and traffic patterns. Section IV presents our RF learning approach. Section V describes a new approach to RF testing that leverage emulated RF scenes and environments, and section VI extends this testing approach to congested and contested environments. Section VII describes an approach to generating massive RF data sets to enable training, validating and testing of new RF ML applications. The remaining sections include our concluding remarks and references.

II. MOCKINGBIRD RF SIGNAL AND TRAFFIC EMULATOR

Mockingbird emulates multiple RF signals ("radio personalities") and traffic patterns, enabling complicated RF scene generation replacing the need for multiple RF systems. Mockingbird includes a reconfigurable 2x2 MIMO Software Defined Radio (SDR), an embedded hardware accelerator and a simple and intuitive web application. The rugged small form factor (6x6.5x2 in, 4 lbs) enables rapid outdoor field testing in controlled but realistic RF environments with the simplicity and efficiency of a software simulation allowing RF test engineers to quickly identify RF signal challenges early in the development cycle. The built-in SDR supports a frequency range of 50 to 6000 MHz, with an instantaneous bandwidth of 40 MHz. Waveform generation includes a suite of built-in signal generators, as well as the ability to import custom baseband I/Q files from MATLAB or GNURadio, or from signal captures (using Mockingbird, or external systems). The flexible modular architecture allows rapid configuration and system extensions.

Fig. 1. Mockingbird RF Signal and Traffic Emulator

The research and development of RF scene generation and RF learning capabilities described in this paper have been implemented as software modules on Mockingbird, creating a software defined RF test system that we use for test and verification of custom wireless data links, signal detectors and demodulators, and complex spectral sensing algorithms throughout our development cycle from design prototypes to outdoor Over-the-Air (OTA) testing. We have also used Mockingbird to create complex RF Scenes for our research partners enabling field testing of dynamic spectrum sharing for cognitive radar and to emulate various jammer behaviors for training scenarios in contested wireless environments.

III. RF SCENE GENERATION

We define an RF scene as a mixture of various waveforms and traffic patterns. The typical flow is as follows:

- Create a Waveform
- Add Traffic Patterns
- Create the RF scene by adding various combinations of Waveform / Traffic Pattern Pairs

A. Waveform Generation

Waveforms can be generated via a suite of built-in signal generators, from baseband I/Q files imported from external tools like MATLAB or GNURadio or captured with the Mockingbird signal capture capability. In addition, the RF learning module provides the ability to emulate an RF signature from the learned emitter or environmental characteristics. All waveforms, regardless of source, are stored in waveform library. Waveforms transmission parameters such as transmit power and frequency are configurable. Currently, Mockingbird includes the following waveform toolkits:

- CW Test Signals: Tone, Two-Tone, Stepped Freq, Sweep
- Analog Modulation: AM, FM
- Digital Modulation:
  - FSK (MFSK, GFSK, MSK, GMSK)
  - PSK (MPSK, OQPSK, PI/4 QPSK, DPSK)
  - QAM (QAM16, QAM64)
- Frequency Hopper
- OFDM

The CW test signals provide a suite of standard RF test signals to aid characterization of the frequency response of RF systems. The Analog Modulation toolkit provides the ability to import specific audio files as the modulating message content. The Digital Modulation toolkit provides the ability to import specific bit patterns enabling protocol emulation. The OFDM toolkit provides OFDM waveforms that emulate LTE and WiFi signal characteristics.

B. Traffic Pattern Generation

Each Waveform can have multiple traffic patterns (e.g. voice traffic, data traffic). Traffic patterns are specified by defining the statistics of the transmission ON and OFF times. Various statistical distributions are available including uniform, triangular, or constant. The uniform distribution provides the most uncertainty in the realized ON and OFF times by randomly selecting a value that is equally probable between the user specified minimum and maximum times. For the triangular distribution, the user specifies a minimum and maximum time, as well as a peak time providing random traffic patterns that have more concentrated performance around the peak parameter. Constant traffic patterns enable a fixed ON or OFF time. In addition, learned distributions as a result of the RF learning process can be used, enabling traffic distributions that emulate actual traffic patterns.

Waveforms can be transmitted with or without a traffic pattern to enable test signal verification prior to prior to full RF scene test scenario creation and execution. This also provides a simple incremental testing strategy, where the wireless system under test can be tested with a continuous test signal, then add the random traffic patterns to verify operation with intermittent burst signals, prior to full complex RF test scenario generation.

C. Baseband I/Q Waveforms

The baseband I/Q process creates a waveform from a baseband I/Q snapshot providing a signal playback capability. The import process provides various amplitude scaling options, input data types (real, complex, int, float), and includes an internal resampling process allowing users to create or capture signals with the optimal sample rate of the external process or system. Waveforms created from a baseband I/Q snapshot are treated the same as any other waveform. The transmission frequency and power can be specified by the user, and various traffic patterns can be added. The primary difference is that the baseband I/Q waveforms have a finite duration, therefore waveform emulation is signal playback, not signal generation. Signal transmissions durations that are greater than the input signal duration will result in repeated samples, whereas the built-in generators create waveforms with random input bit streams that do not repeat for a long time enabling better characterization of the expected system performance over a variety of input test signals. Each transmission burst for the baseband I/Q waveforms can start at the beginning of the signal or continue from the last sample.

D. RF Scene Creation

An RF scene is a mixture of various waveform / traffic pattern pairs. The RF scene can span multiple disjoint frequency bands. The internal transmission scheduler coordinates the waveform transmissions including radio configuration (frequency and power control). Each waveform transmission burst is added to the transmission queue and transmitted according to its traffic pattern. Conflicts are managed internally, by implementing additional wait time to transmit. The wait times associated with a given RF scene can be estimated based on the statistics of the traffic patterns in the RF scene. The actual transmit times and durations are saved to a log file enabling detailed analysis of the testing results and algorithm performance. For heavy traffic loads, the waveform / traffic patterns can be distributed across multiple systems where subsets of the total RF scene are implemented on individual systems.

The RF scenes can be used as part of laboratory testing to create various time-varying spectral characteristics and interference patterns, that enable dynamic testing of RF systems including signal detectors, modulation recognition, spectral sensing and dynamic spectrum access or sharing algorithms. The figure below shows an RF scene that is comprised of multiple signals spanning disjoint frequency bands including narrowband, wideband and frequency hopping signals.

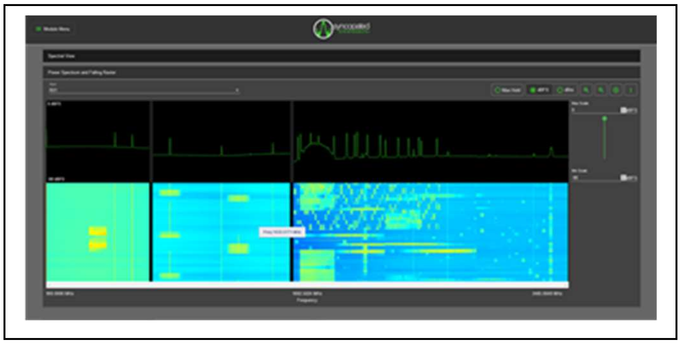

Fig. 2. RF Scene with multiple signals including a frequency hopper

IV. RF ENVIRONMENTAL LEARNING

RF learning provides the ability to learn the spectral and temporal characteristics of actual RF transmitters or the observed RF environment. RF learning isolates signals in the observed frequency spectrum, learns the Power Spectral Density (PSD) of each signal, and probability distributions of the ON and OFF times. We call the combination of these three learned results (PSD, ON and OFF time distributions) a RF signature.

Each learning session is defined over a specific frequency band and learning time duration. The longer the learning session the more accurate the learned statistics, but we have had very good success for RF learning sessions from on the order of 15 min to 1 hour. The result of the RF learning session is a signal list that includes a RF signature for each signal.

The learned RF signatures can be used to emulate the RF environment or specific RF transmitter. RF signature waveforms transmit a signal that has a PSD and transmission traffic pattern that is statistically similar to the observed RF environment or RF transmitter. The RF signature waveforms can be combined with the other waveform types described in the previous section to create sophisticated RF scenes that captures both naturally occurring RF signals learned from the actual environment along with specific signals of interest (e.g. desired signal, interfering signals, jamming signals) within a dynamic spectral environment.

V. RF SYSTEM TESTING

A. Current Workflow

The pace of new RF system development and innovative wireless communications technologies is increasing at a rate that challenges the ability to keep up from a RF testing perspective. RF testing must continue to test under specific test scenarios that include standard performance measures, and regulatory procedures, but also verify that the systems will perform in highly dynamic unpredictable operational environments. It is cost prohibitive to conduct repeated OTA testing in each actual operational environment. The RF test engineer needs the ability to characterize and refine system performance across complex and realistic RF environments with both speed and confidence to enable agile iterative performance improvements to fine tune the system prior to final system verification and deployment.

The typical RF testing setup is shown in the figure below:

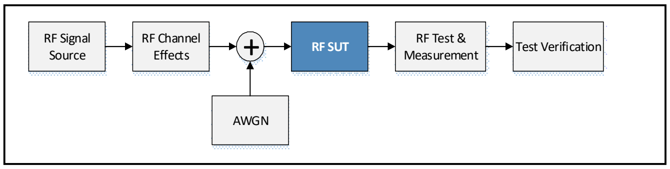

Fig. 3. Typical RF System Test Setup

The RF system developer can start with simulation, simulating the RF signal source, and testing in AWGN (Additive White Gaussian Noise). The next step is to add RF channel effects such as multipath and Doppler. Once the physical system is built, the RF test engineer tests in the lab using RF test equipment including RF signal and noise generators, RF channel emulators, and RF test and measurement equipment like spectrum analyzers, vector signal analyzers, etc. Typically, output signals are captured for additional detailed analysis using the same signal analysis tools used during simulation (e.g. MATLAB).

Once laboratory testing is completed, then the system needs to be tested OTA. Wireless OTA testing can start in anechoic chambers to remove the effects of interference from the external environment, effectively repeating the cabled laboratory testing flow with same laboratory signal generators, analyzers and capture equipment. This allows controlled testing to verify RF system performance.

To repeat the same tests outside exposes the test scenarios to the unpredictable nature of the actual RF environments including unknown channel effects, and interference and also requires rugged, weather-proof RF test equipment or covered site infrastructure to protect the expense RF laboratory equipment.

B. *New Augmented Workflow Incorporating Emulated RF Scenes*

The ability to create realistic RF scenes that capture the complexity and expressiveness of actual RF environments can be incorporated throughout the typical RF signal development and testing lifecycle including initial testing and regression testing. A new augmented workflow is shown in the figure below:

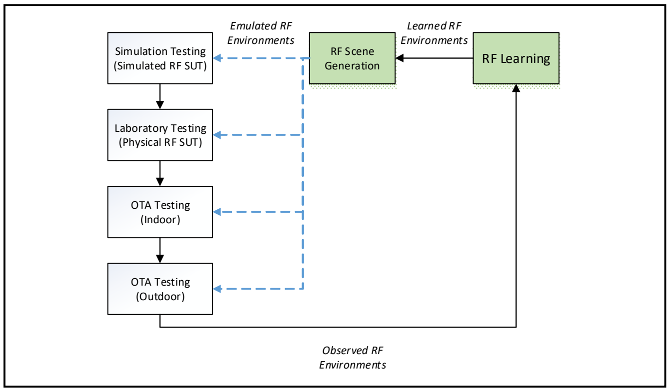

Fig. 4. New RF System Testing Workflow Incorporating Emulated RF Scenes

The revised laboratory test setup is shown in the figure below.

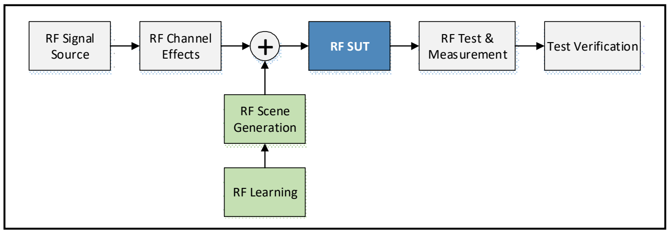

Fig. 5. New RF System Testing Workflow Incorporating Emulated RF Scenes

The revised test setup provides the ability to combine specific signal generators and the emulated RF environment through an RF coupler to enable testing in realistic environments. Test scenarios include RF scenes that represent congested or contested environments and as well as incorporation of the emulated signal of interest within the scene as either an internally generated or imported baseband I/Q file.

The OTA test setup is shown in the figure below. Our Mockingbird system is a small rugged system that supports both laboratory and field testing. Multiple Mockingbird systems can be incorporated in outdoor testing to provide emulated RF scenes as well as capture signal data for post-test RF signal analysis and system verification. This setup also supports the RF learning process. RF learning sessions could be conducted prior to the test to verify system performance in the laboratory with the learned RF environment.

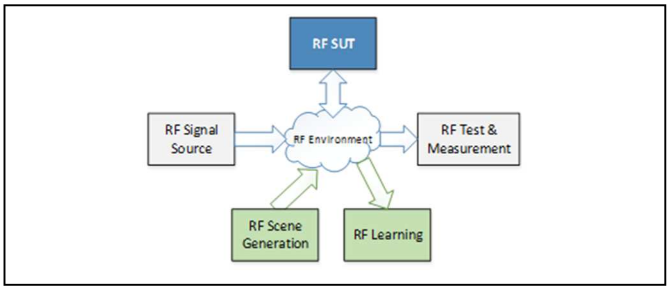

Fig. 6. OTA Test Setup Incorporating RF Scenes and RF Learning

VI. RF TESTING IN CONGESTED AND CONTESTED ENVIRONMENTS

This section uses the augmented test workflow and test setups described in the previous section to describe the process of testing in both congested (unintentional interference) and contested (intentional interference or jamming) scenarios.

A. *Congested Environments*

Wireless devices are exploding producing a very crowded RF environment. It has become critical to test RF systems in a variety of RF environments from lightly to heavily congested, with various narrow and wideband systems. The RF scene generation process described earlier can be used to create rich sophisticated RF scenes to emulate congested environments at various levels of congested and with enough variability to allow testing over a number of unique RF environments with similar statistics (e.g. levels of congestion, and temporal traffic patterns). The actual waveform transmission patterns are logged providing ground truth for each test scenario. Since the RF scenes are randomly generated instead of a simple record/playback, test scenarios can be continuously run providing long test cycles to evaluate the performance of RF systems. Testing can be refined in the lab over very long test cycles with various congestion levels, and then repeated outside in OTA testing with the same emulated RF environments plus the addition of actual RF channel effects. This allows a rigorous and planned sequential testing approach from simulated testing in noise only environments, multipath and time varying channels, and congested environments, followed by lab testing with actual RF systems using emulated channel effects and RF environments, then outdoor testing in actual RF channels but with the same emulated RF environments used in the lab.

For deployed systems that experience actual RF environments, the RF learning module can be used to learn specific RF environments and then recreate in the lab to allow refinement of the RF system performance in a cost-effective and controlled environment. These challenging RF environments can become part of the corpus of test data used to characterize RF system performance of new algorithms and capabilities. RF learned environments can also be used perform site surveys prior to deployment, to understand the RF environment and assist in evaluation of the best deployment locations for optimal performance.

B. *Contested Environments*

Contested environments add intentional interference or jammers to the unintentional interference of the congested environment described in the previous section. Jammers typically can be classified as constant jammer, random jammer, or reactive jammer. Constant jammers transmit a jamming signal continuously over a frequency band of interest. Random jammers randomly transmit burst signals that can have different frequency bands or time durations (i.e. spectral regions of support). Reactive jammers, sense the environment and jam the frequency bands with signal activity. RF systems mitigate jamming through spread spectrum waveforms (waveform resiliency) or spectrum maneuverability (jammer avoidance). For spectrum maneuverability testing, the RF system performance should be characterized in various levels of unintentional and intentional interference (both congested and contested environments). The RF scenes can be created with specific jamming waveforms including narrow band and wideband signals. The RF test signals toolkit supports tones, stepped frequency and frequency sweeps (i.e. chirp signal). The digital modulation toolkit and OFDM toolkit provides various broadband signals available as jamming signals. Jamming signals can also be created to emulate the actual communications waveform parameters to affect receiver synchronization and demodulation processes. Random traffic patterns enable the creation of various emulated jammer behavior to support additional test scenarios.

The RF learning module can learn the behavior of actual jammers and recreate that pattern with the actual learned RF spectral shape (shaped white noise jammer), as well as add the traffic pattern to an internal generated signal like the swept frequency or chirp signal.

VII. TRAINING AND TESTING RF ML APPLICATIONS

New RF ML applications are constantly evolving including Automated Modulation Recognition, RF emitter Fingerprinting, Dynamic Spectrum Access/Sharing, and RF Jammer Behavior Recognition. ML techniques learn the optional solution directly from the data, as opposed to being designed based on subject matter experts. In order for ML algorithms to perform correctly, they require very large data sets that are both representative and comprehensive covering any and all environmental conditions that are expected in the actual physical environment. These RF data sets are broken up into training, validation and testing data sets which increases the volume of data needed. Each phase requires an independent data set. Training uses labeled data sets to measure the error in the output (prediction error, classification error, etc) which is used as feedback to the system to adjust the performance. Validation uses an independent data set to test the system based during training. The optimal configuration learned during training is fixed and the validation data set is used to measure the system performance. The cycle of training and validation is repeated while adjusting the system configuration to achieve the desired level of system performance. Then a final testing data set is used that is independent of the training and validation test sets to verify system performance.

Acquiring and storing the large RF data sets required is an expensive activity. Leveraging emulated RF scenes and learned RF environments that can be recreated in the laboratory, and generated and consumed in real-time provides a constant and representative RF data corpus that can be used to enable continuous, iterative training, testing and system refinement cycles. In addition, the logging features of the actual transmitted RF scene provide the ground truth required to determine the training error used as feedback to drive the optimization algorithm. The figure below shows how emulated RF scenes and RF learning could be incorporated in the RF ML development and testing process.

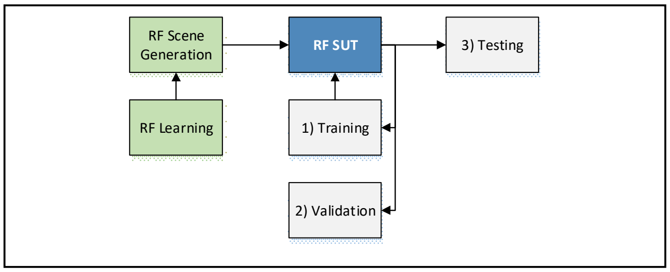

Fig. 7. RF ML Process Incorporating RF Learning and Emulated RF Scenes

Typically, RL ML data sets are created from simulations. This provides a great initial step in characterizing the ML algorithm during the algorithm development process (simulated algorithms and environments). Once the ML algorithm is implemented on an actual RF system, the integration of the physical system with the simulated environment becomes more difficult. This is another area where emulated RF environments can provide an improved testing process. The emulated environments can be used in a lab setting with other RF test instruments such as signal generators, spectrum analysis, and RF channel emulators to create a realistic environment that is more readily consumed by the physical RF system under test.

Adding learned RF environments increases the realism and variability needed to train and validate the RF ML system under test. Recorded or captured data has been leveraged in the past to add realism to the simulated data sets, but captured data is of finite duration and therefore must be randomized or shuffled to provide variability to the data set. Since the ML algorithms learn from the data, if there is not enough variability in the training data set the ML algorithm is susceptible to over-fitting. Using a contrived example, an ML image recognition algorithm is trained to classify fruit as either lime, lemon or apple but only uses red apples in the training set. If a green apple is encountered during actual operation, the ML classifier may misclassify the apple as a lime since they are both green. The use of learned RF environments to generate RF scenes provides a continuous stream of data that is statistically similar to the actual environment and provides both the realism and variability needed to optimize the ML system.

Upon completion of the training and validation process, testing could be performed both indoors and outdoors. Outdoor testing enables characterization with actual RF channel conditions but utilizes the emulated environment. Therefore, the testing is focused on evaluating the system performance primarily due to the actual RF channel providing better control over the test variables.

VIII. CONCLUSIONS

RF systems must increasingly operate in harsh and dynamic RF environments. As the complexity of the RF environment increases, so do the RF algorithms. New innovative RF ML techniques provide the ability to learn and adapt to these complex RF environments but require a vast amount of RF data to provide realistic environments with enough variability to allow the RF ML algorithm to converge to the optimal solution. Simulated environments provide a means of testing new RF algorithms in the early design and prototyping phases but are difficult to replicate all the complexity of actual RF environments and channel impairments. OTA testing provides the final system performance evaluation but is very expensive to conduct with the same expressiveness and ease of use as simulated environments. We presented an approach to bridge the gap between these two test environments using emulated RF scenes and learned RF environments. The emulated RF scenes provide a repeatable process that enables statistically similar data sets to be continuously generated providing real-time testing and evaluation. Adding the capability to learn from actual RF environments and recreate these emulated RF environments in the lab provides a very cost-effective mechanism to cost effectively bring the outdoor test environment into the laboratory. We have implemented RF scene generation and RF learning on a small, rugged, software defined RF testing instrument we call Mockingbird. Mockingbird enables agile RF testing in the lab and the field, allowing RF testing in the lab with learned RF environments, and repeated in the field using the same RF environments but now expanding to include actual RF channel conditions. Emulated RF scenes and RF environmental learning provides another tool in the RF test engineers toolbox, augmenting the tried and true sophisticated and highly accurate testing procedures used today with an agile, realistic testing methodology that enhances both laboratory and field testing.

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