Software Defined Instrument Based Electromagnetic Warfare Test System

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Abstract: *Electromagnetic Warfare (EW) is a critical component to what some have called Fifth-Generation Warfare (5GW).* [1] *5GW is principally the use of Non-Kinetic Action (NKA) to manipulate the electromagnetic spectrum to enable kinetic fires, offensive NKA and Deception and Denial (D&D) through EW Tactics Techniques and Procedures (TTPs) and is an integral function of Electromagnetic Spectrum Operations (EMSO)* [2]. *EW systems designers are therefore charged with developing advanced waveforms, dynamic algorithms, multi-function/domain systems, and active operating modes to support this crucial mission space.*

To satisfy this dynamic environment, designers are turning to adaptive Software Defined Radio (SDR) technology, referred to as adaptive SDR based EW (SDR/EW). SDRs are wireless communication systems in which many of the radio functional elements, including filtering, frequency translation, and modulation demodulation, are implemented in software via Digital Signal Processing (DSP) techniques using embedded processors and Field Programmable Gate Array (FPGA) as described by Harris and Lowdermilk in 2010. [3] *This has led to the use of commercial off-the-shelf (COTS) hardware thus significantly speeding up the development process of new EW systems. Additionally, these systems can be customized with the use of application specific firmware and software.*

Consequently, the development of adaptive SDR/EW systems has outpaced the development of test and measurement instruments required to test these new systems. The challenge facing EW test system designers revolves around accelerating the transition from classical test and measurement instruments to software defined instruments (SDI) based on the same SDR concepts found in EW systems to ensure continuity between Test and Evaluation (T&E) and fielded systems (including surrogate assets).

Classical test and measurement instruments are dedicated instruments built for a specific application. As opposed to SDI that define multiple instruments (i.e., spectrum analyzer, vector signal analyzer, Radio Frequency (RF) receiver, and vector signal generator) with FPGA based DSP software and firmware. SDIs exhibit several advantages over classical test and measurement instruments, including reconfigurability and reduced development costs and time-to-market. SDIs also enjoy long life cycles since they can readily be adapted to meet future needs. SDIs employ adaptive DSP technologies to implement spectral measurement and analysis. This gives the SDI the ability to deliver increased instantaneous effective bandwidth and improved quality of measurement.

This paper will present an approach for EW test systems that leverages proven SDI technology. A comparison between a classical instrument-based test system and SDI based test system will be presented. The SDI based test system employs multiple tunable hardware receiver and stimulus channels containing FPGA based DSP resources that provide engineers with access to the electromagnetic spectrum for complex waveform analysis and generation.

Keywords— ATE, COTS, DSP, EW, FPGA, SDI, SDR

I. INTRODUCTION

The North Atlantic Treaty Organization (NATO) defines EW as: “Military action that exploits electromagnetic energy to provide situational awareness and create offensive and defensive effects.” [4] This includes EW support defined as the “division of EW involving actions taken to search for, intercept and identify electromagnetic emissions and to locate their sources for the purpose of immediate threat recognition and situational awareness.” [4]

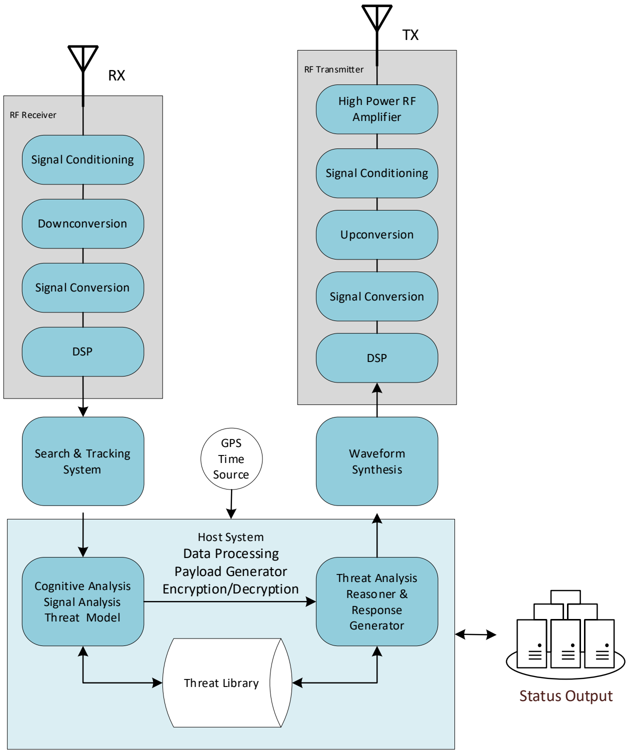

Figure 1 SDR/EW Block Diagram

Figure 1 is a simplified block diagram for an adaptive SDR/EW system. In adaptive SDR/EW systems the reaction to threats is dynamic. SDR/EW systems can observe, make decisions, dynamically react, and learn over time. This gives an advantage over less adaptable traditional EW systems. Traditional EW systems can still observe, decide, and react but the capacity to learn and apply that knowledge makes it more effective.

A typical EW application may include signal classification and or suppression of various systems leveraging the Electromagnetic Spectrum (EMS) (this action is often referred to as "Jamming"). A traditional tactic in jamming involves a priori in execution where threats are detected through observations referred to as Intelligence Surveillance and Reconnaissance (ISR) or Electromagnetic Support (ES) actions. Observations are applied to identify the threat using a threat library. The library includes mapping the threat to a predetermined jamming function. This relies entirely on the accuracy of the threat library and the corresponding response countermeasure. With SDR/EW this activity allows the jammer to adapt rapidly to continuous changes, applying posteriori knowledge thus improving threat detection, identification, and response.

SDR/EW involves identifying multiple potential threats and actively responding to the threats. The test system must be just as dynamic and measure the threat response of the SDR/EW system. This involves understanding how the SDR/EW system will respond to various threats and the impact they might have. The SDR/EW system will have the ability to simultaneously classify multiple threats and apply appropriate countermeasures.

Adaptive SDR/EW systems offer challenges when it comes to validating their functionality. The test system developer must understand the SDR/EW system to test the dynamic behavior of increasingly sophisticated and software defined threats. This goes beyond pattern recognition when validating the operation of an SDR/EW system. The test system will require increased realism in generating and reacting to dynamic threat responses. This means the test system must determine the EW system's effectiveness by not just validating pre-programmed responses. The test system must correlate test results across multiple test levels.

As with all weapons systems, system testing must be considered at all life-cycle stages. This includes design verification & validation, manufacturing & production, and sustainment & maintenance. Each of the three test stages requires its own unique test plan, methods, procedures, and techniques. Each can vary significantly in equipment, complexity, time, and expense.

For example, consider validating EW design uncertainty versus validating the manufacturing process for correct system assembly. Validating the manufacturing process requires relatively simple and repetitive test setup with little knowledge of the EW system design criteria. Whereas validating design uncertainty requires significant knowledge in the design and non-repetitive complex testing.

A. Design Verification & Validation Test

EW system design verification and validation (V&V) testing is either performed in a system integration lab, anechoic chamber, or open-air range. For V&V testing, several test cases or scenarios are defined to simulate threats and evaluate how the EW systems responds to those threats.

This works well for a legacy EW system with a static set of capabilities. The test scenarios examine the EW systems predefined responses to specific threats.

For an adaptive SDR/EW system, with adaptive response algorithms, the system behavior changes as it detects varying threat scenarios, there are an almost infinite number of test cases. The system must handle unforeseen threats, making performance assessment extremely difficult for classical test and measurement instruments.

EW system design V&V testing will check the functionality of the system against the design requirements. Functional testing is usually performed at the system or platform level. The system test could be configured in either a conducted (direct connect) or radiated test mode.

1) Conducted/Direct Connect Test

In conducted or direct connect testing, the test system transmits/receives RF signals directly through cables connected to the RF input and output ports of the EW system. This is usually performed in a laboratory environment. Several reasons for direct connect testing could be that radiating RF energy might be a safety or security concern. In addition, it might not be possible to establish the distance required for far field testing. In conducted testing the full system is not tested, i.e., the antenna elements are not tested as part of the system. Testing can be performed at both the RF transmit and receive frequency range, the intermediate frequency (IF) range, or both. As a result, direct connect allows for V&V testing of subsystems or modules of the EW system.

Conducted testing directly stimulates the RF input ports and measures the RF output ports of the system. The signals can be synthetically generated allowing for tighter control of magnitude and phase. In addition, signal impairments can be injected with more control.

Low-level functional parameter and characterizations tests can be performed. Typical characterization tests follow:

- Pulsed, Continuous Wave (CW), and Modulated
- Small Signal & Large Signal Measurements
- Gain, Insertion Loss, Conversion Gain/loss, Channel Isolation, Return Loss In/Out, Group Delay, Phase Ripple, and Attenuation Ripple
- RF Power (Peak/Average)
- Effective Radiated Power (ERP)
- Noise Figure
- Spectral Purity/Spurious Emissions
- 2nd and 3rd Order Intercept Point (IP2, IP3)
- 1dB Compression Point (P1)
- RF Timing, Rise/Fall time, On/Off Delay, Droop, Pulse Profile
- Phase Noise

2) Radiated Test

For radiated test the test system and EW system transmits/receives RF signals over the air. The EW RF signals are generated by the test system in either an anechoic chamber or open-air range. The various electromagnetic signal states are designed to simulate operational conditions for validating the EW system functions. Radiated testing allows for the full system to be tested, this would include the antenna elements. All testing is performed at the RF transmit and receive frequency range.

a) Far Field Range (FFR)

The following three conditions, defined in equations 1 through 3, must all be satisfied to be in the far field region: [5]

$$R \geq \frac{2D^2}{\lambda} \tag{1}$$

$$R \gg D \tag{2}$$

$$R \gg \lambda \tag{3}$$

Where: R = Range Length
D = Antenna aperture diameter
λ = Operating wavelength

In the far field range, there is a direct path between the system under test and the measuring antenna. Typical FR testing includes antenna testing of boresight Effective Isotropic Radiated Power (EIRP), Gain, Beamwidth, Sidelobe levels, Receiver Quadrant Balance, Gain over Temperature (G/T) and Figure of Merit (FOM). Besides antenna testing, EW support characteristics are tested. This includes threat simulation and reaction can be tested.

b) Compact Range (CR)

The compact range uses the Fresnel region as defined in equation 4. [4] This is the region between the near and far fields. In this region, the reactive fields are not dominant; the radiating fields begin to emerge. However, unlike the Far Field region, here the shape of the radiation pattern may vary appreciably with distance.

$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda} \tag{4}$$

Note that depending on the values of D and the wavelength, this field region may or may not exist.

A collimating device is used to create a nearly plane wave like the far field so that the system under test can be measured at range lengths shorter than its far field. [5] The CR can also perform the same functions as the FFR.

c) Near Field Range (NFR)

Equation 5 defines the near field region, also known as the reactive near field. In this region, the fields are predominately reactive fields, which means the E- and H-fields are out of phase by 90 degrees to each other. The boundary of this region is: [4]

$$R \leq 0.62\sqrt{\frac{D^3}{\lambda}} \tag{5}$$

The near field is measured, then using mathematical induction the physical equivalent principles of electromagnetics in the far field is computed. The NFR is used primarily to characterize the EW system antenna.

B. Manufacturing & Production Test

Manufacturing and production testing of EW systems is usually performed at room ambient and should not, if possible, require any special environmental conditioning, such as warm-up time, or temperature conditioning.

During production testing there may be multiple initial manufacturing failures that would include wiring errors, opens, shorts, improperly installed components, improperly polarized components, wrong components, bad components, and solder splashes. After the system is placed into service only one component is expected to fail at a time.

Production testing does not qualify the system design; it is used to verify that the system has been assembled correctly and that all the components are in proper working order.

The number of tests should be minimized and performed as quickly as possible to increase production rate. Statistical analyses should provide the basis for the determination of test limits to optimize the detection of faulty hardware.

Most EW system manufacturers have standard product manufacturing test plans and processes. Production tests are usually split into four categories: static, DC, peripheral, and RF tests.

Static test are DC resistance tests. These tests will find wiring errors and potentially catastrophic manufacturing faults. In-circuit testing and manufacturers defect analyzer testing falls into this category.

Peripheral tests are any test not specific to RF or DC, like serial communication or performance monitoring sensors.

DC tests are any test related to the voltage and current characteristics of the system.

RF tests are any test specific to the operation and functionality of the RF spectrum components of the system. As discussed in the previous section RF testing can be conducted or radiated testing. Sub-assemblies are tested in a conducted configuration and the final system integration and assembly would be a radiated test.

C. Sustainment & Maintenance Test

Sustainment and maintenance testing of EW systems is like manufacturing testing. It is usually performed at room ambient and should not require any special environmental conditioning.

Sustainment and maintenance testing assumes the system was once operational and fault free. Sustainment and maintenance tests are normally structured to detect single subsystem or component failures. The list of faults is not as extensive as in the production. Part orientation, wrong parts, missing parts, and solder shorts are not present at this level of test. Generally, there is only one fault on the SUT. Part degradation and component drift is possible.

If the maintenance testing is performed in the field, then the number of tests should be minimized to get the asset back into service as quickly as possible. However, if the testing is performed at the depot, then additional testing can be performed to ensure the system returns to service in a like new condition.

EW system maintenance typically employs standard test plans and processes. Maintenance tests are usually split into the same four categories as production: static, DC, peripheral, and RF tests.

II. CLASSICAL INSTRUMENT EW TEST SYSTEM

Figure 2 illustrates a classical discrete instrument EW automated test system. The system characteristically comprises of one or two 19” Electronic Industries Alliance (EIA) standard equipment racks housing a spectrum analyzer, vector network analyzer (VNA), RF power meter, digital storage oscilloscope (DSO), frequency counter, arbitrary waveform generator (ARB), and several RF signal generators.

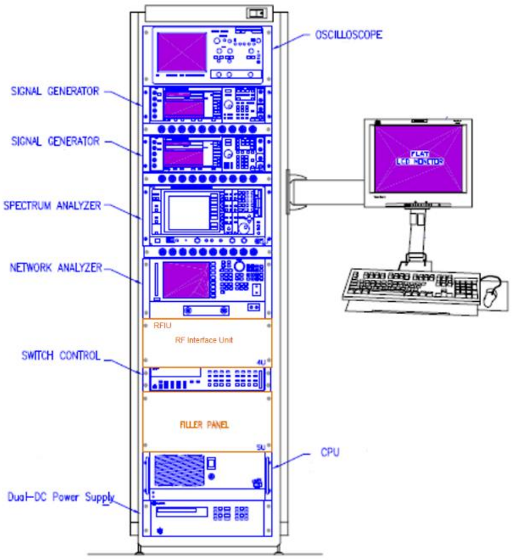

Figure 2 Classical Instrument EW Test System

These test systems operate on a wide range of EW systems: Radar, guidance systems, radio communications, jamming systems, and satellite communications to name a few. Different test strategies are necessary to validate a system's performance at each level described above.

One issue with this type of system is the obsolescence of COTS test equipment. This has threatened the life span of EW ATS. For decades test equipment obsolescence and mitigation has attracted attention from maintenance personnel as well as test equipment suppliers.

Another issue is that each instrument is a discrete piece of hardware. They must be configured and commanded in a sequential manner. Thus, making the test sequences long and complicated. As a result, RF signals are retransmitted several times so each instrument can measure and perform its specific measurement task. Additionally, this type of EW ATS cannot react dynamically to the SDR/EW systems adaptive nature.

Test and validation of EW systems usually employs black box testing focused on input and output, and not the intermediate steps within the system or module. Traditional tests are often not relevant to SDR-EW systems because of the differences in technology. For example, two-tone intermodulation distortion (IMD) tests, which indicate how receivers perform in congested bands, do not apply because the cause and effect of receiver IMD is different in the EW SDR receivers than in traditional receivers. SDR based receivers perform very well on the two-tone IMD test, therefore the results are not comparable.

III. SOFTWARE DEFINED INSTRUMENTS

As EW systems improve and become more complex with SDR technology, EW system developers, manufacturers, and end users will increasingly need more powerful test systems capable of testing adaptive SDR/EW systems. To test adaptive SDR/EW systems, the test system must be capable of testing analog and digital signals, inserting test vectors within the EW system processing threads and measuring performance. To test an adaptive SDR/EW systems, the test system itself must be reconfigurable and be capable of processing signals in real-time.

Testing and validating in real time is difficult and requires a very robust system. The optimum solution for real-time EW systems testing is through SDI technology. Primarily because the SDI foundation technology is the same as that of an SDR.

The typical SDI consists of measurement and stimulus subsystems that provide test signals to measure the responses from a SUT. The SDI will include common hardware elements combined with unique DSP based measurement science firmware and software modules that synthesize specific instrument functions. SDIs include signal conditioning, frequency translation, signal conversion, signal/data processing, instrument control, and DSP modules.

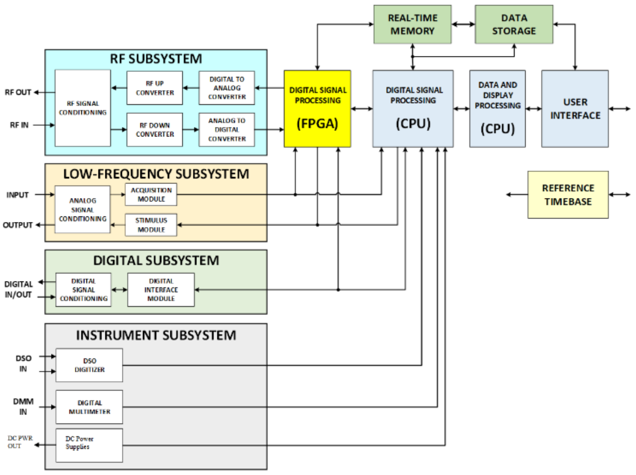

Figure 3 Typical Software Defined Instrument Architecture

Figure 3 provides a profile of typical synthesized measurement science instrumentation algorithms: Spectrum Analysis; Digital Storage Oscilloscope (DSO); Vector Signal Analyzer (VSA); Phase Noise; Noise Figure; RF Power Meter, Signal-to- Noise and Distortion ratio (SINAD) and Bit Error Rate (BER); RF Signal Generator; Vector Signal Generator (VSG); Arbitrary Function Generator (ARB or AFG); and a range of specific testing modules including Radio, SDR, Cellular Standards (4G, 5G, and 6G), Digital and Data Bus Analysis. [6] This is not an all-inclusive list of possible synthesized instruments and measurement science.

For each synthesized instrument, SDIs install the appropriate firmware and software, configure the signal paths to condition the input frequency, translate the signal through the use of an LO, and down convert the signal to an IF. Then, this analog IF is digitized using an ADC. To effect a measurement instrument, specific measurements are performed by analyzing the digitized data using DSP techniques in either an FPGA (for real-time applications) and in a multicore processor.

In response to obsolescence issues associated with fixed function or classical instruments, the Synthetic Instrument Working Group (SIWG) in 2004 initiated the development of Synthetic Instrument (SI) based test systems. [7] The SIWG defined five goals for SI and SDI, with the fundamental premise that the SI could be reconfigured based on the test requirement needed at that time to:

- Reduce the total cost of ownership of the test system.
- Reduce time to develop and field new or upgraded test systems.
- Provide greater flexibility and interoperable test systems.
- Reduce the test system logistical and physical footprint.
- Improve the quality of test.

SDIs exhibit many advantages over traditional fixed function instruments. SDIs employ common hardware with measurement science firmware and software, which leads to reduced test software development time and dramatically improved measurement speed and efficiency. Measurements using SDI technology are predicated on digitizing signals and storing the digitized data in a measurement map or database on which multiple operations may be concurrently performed to effect one or more measurement.

Because they are software defined and inherently reconfigurable, SDIs may be employed as a common component for multiple test systems. In Automated Test Systems, SDIs equipped with application specific firmware and software may be used to support a broad set of SUTs. Each test developer can tailor the SDI to meet their unique requirements by developing SUT Test Programs using C#, C/C++, or LabVIEW programming methodologies along with SUT specific interfaces.

SDIs do not suffer from the same obsolescence problems as traditional instruments, and they provide an unmatched level of TPS portability with zero or minimal recertification cost, both of which translate into significant life cycle cost savings. [8]

In addition, SDIs may be programmed to replicate the functions of obsolete test equipment. Doing so can eliminate the expense of life-time-buys required when boxed instruments go end-of-life. Modular SDIs also enable users to eliminate waste by purchasing only the hardware and software needed to support their specific test applications. With modular SDIs, incremental software and firmware functional capability may be added in the future, predicated on actual test requirements as opposed to perceived test requirements.

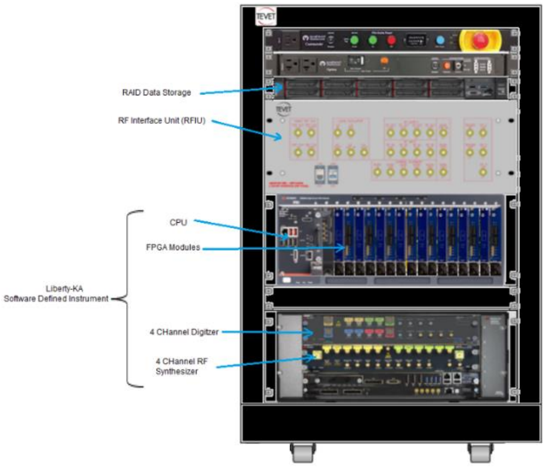

Figure 4 SDI/EW ATS

The SDI can be configured as multiple instruments at one time. Applying measurement science analysis on the same signal simultaneously. Thus, making it possible to perform multiple tests at the same time and reducing test sequence times. As a result, RF signals are transmitted once and can be evaluated with multiple instruments. Additionally, this SDI/EW ATS can react dynamically to the SDR/EW systems adaptive nature.

Figure 4 shows an example SDI based EW ATS. Each receive channel feeds to an FPGA module through a high-speed optical interface where signal processing is performed in real time. The processed data is moved over the PCIe bus to another FPGA module for analysis. The results from analysis are fed into a third FPGA for response generation. The response is sent through another high-speed optical interface to the RF synthesizer.

IV. SDR/EW TESTING WITH SDI

The operation of an SDR/EW system uses learned knowledge to apply tactical responses to an ever-changing environment. Essentially, continuously detecting threats and applying the best countermeasures until the threat is neutralized or the mission has ended.

The question is how to test whether the SDR/EW system is operating correctly. One method could be to interrogate the system with threat scenarios one at a time and ascertain if the system successfully neutralized the threats. This would provide the best test coverage, though given that there are far too many EW threats, this would take too long. Additionally, some threat scenarios may have multiple responses. This method makes it difficult to gauge dynamic performance.

A more practical test method would be to test the system against an adversarial EW system. If the system can consistently defeat the enemy, then it could be considered to have passed the test. Access to adversarial EW systems might not be possible. Known and unknown EW systems waveforms may have been stored into a library for future identification or for playback in a test scenario. SDI systems can capture, record, and playback EW waveforms. Additionally, the SDI can analyze these waveforms and determine their effectiveness against recorded threats.

SDR/EW system will need to face threats that it has never encountered. This leads to another possible test methodology.

Implement a software simulator that generates synthetic EW signals, making the SDR/EW system under test think it is fighting an adversary. Thus, analyzing the threat inputs, deciding how to react, feeding back into the test system, and controlling the simulation. It should be noted that the recorded EW signals being played back into the simulator lacks environmental impairments. This problem is solved with SDI since it can inject impairments into the data stream as the playback is being performed. EW simulation and synthetic signal generation requires significant computing and data movement. This is an ideal application for the SDI.

Consider an SDR/EW's RF receiver chain's Automatic Gain Control (AGC). It is affected by several factors: analog AGC in the RF receiver, digital AGC in the DSP, channel coding, and AGC control algorithms and software. To determine the system-level AGC performance, the test system must insert test vectors and make measurements along the RF receiver chain that allow validation of the individual AGC analog and digital modules. This requires that the test system be capable of duplicating the SDR/EW software and hardware modules and generating the various measurement functions. Given that the SDR/EW SUT is software reconfigurable, it is increasingly evident that the test system must also be software reconfigurable.

Using SDI to test SDR/EW, parameters of interest not only include the RF output transmission characteristics but also the transmitter's DAC input and output. This requires the SDI to support both analog and digital inputs. Additionally, to measure the basic performance of the SDR/EW's baseband transmitter, the SDI must provide a digital test vector to the SDR/EW transmitter, representing a pseudorandom input data stream to allow for BER testing.

Ports should be installed in the SDR/EW transmitter to facilitate access to the DSP modules within the SDR/EW processing thread. These test signals may be transported to the SDI via a digital data port that allows the SDI to evaluate the transmitter's performance at the module level. The SDI may be configured to duplicate the SDR/EW receiver at the module level. For adaptive systems, this is an important test feature because several SDR parameters may change and the performance for each module may be affected.

The complexity of SDR/EW system architectures poses a significant increase in complexity of test and measurement equipment. SDR/EWs require a test system with the ability to evaluate the functionality under a variety of ever-changing operational conditions. SDR/EWs are closed loop systems; the SDR/EW receiver provides real-time feedback to the SDR/EW transmitter enabling it to adjust its transmission characteristics. The essential characteristic for testing SDR/EWs is that the test system must emulate the SDR/EW at both the system and subsystem level.

SDR/EW testing must include characterizing and validating the SDR/EW transmitter and receiver RF front-end components and their impact on SDR/EW performance. Given the real-time, adaptable nature of SDR/EW, performance characterization and validation of the time required to switch between modes is important. Many of these functions are difficult or impossible to test using conventional instrumentation. Functions required in EW testing include the following:

- Spectrum sensing
- Spectrum monitoring and tracking
- Single Threat detection, classification, and tracking
- Multiple threat detection, classification, and tracking
- Interference cancellation
- Multipath fading and mitigation
- Transmitter and receiver synchronization
- System response time

To provide a realistic assessment of SDR/EW performance, the test system must be capable of testing the SDR/EW at both the transmitter, receiver, and digital level in the predicted signal environment. Because the SDR/EW system is changing in real-time, the test system must adapt similarly. The test system must be capable of duplicating the interoperability between SDR/EWs that exhibit different operating frequencies. The signal environment characteristics of SDR/EWs will include both time-varying spectral and temporal behavior that the test system must reproduce to test the SDR/EWs. Given that the SDI is essentially an SDR, it becomes obvious that an SDI is the ideal solution for testing SDR/EWs.

Verifying SDR/EW functionality is a nontrivial task. The RF knowledge requirement to perform these tests can be reduced through automation and by using SDIs. With SDIs, multiple methods of performing such tests allow an entry-level RF test engineer or technician to develop SDR/EW tests quickly. SDIs uniquely support dynamically performing tests based on instrumentation availability. Accordingly, SDI based testing tends to increase system versatility and reduce downtime when deployed.

A. SDI Threat Detection and Response Modeling

As a result of the physical architecture and software/firmware algorithms the SDI can synthesize various instrument types. Each instrument type exhibits the following functions:

- Acquire the signal to be measured.
- Evaluate and analyze acquired signals and all identify signal attributes.
- Scale and manipulate the signal attributes into measurement characteristics.
- Signal generation using equations or stored library signal models.
- Data presentation component that displays the signal.

1) EW Signal Attributes

For SDR/EW testing, the SDI must emulate the threat environment and scenarios in real time. This requires the ability to capture, classify, identify, and respond to threats in real time. The classification must be consistent with the SDR/EW system responses to captured signals. There are cause-and-effect relations among signals and their different attributes. The SDR/EW signals are events that can vary over time in response to detected events. The SDI must be able to detect, generate, transmit, modify, process, transduce and display signals. It is important to understand the attributes all signals possess that can be used in a threat detection and generation model. Every EW signal is composed of various identifiable attributes:

Amplitude is the steady state (static) magnitude of a signal, indexed as instantaneous or average values. Amplitude is measured in units determined by the signal of interest (e.g., volts, displacement, pressure), often expressed as relative level, i.e., in decibels.

Frequency is the rate at which a periodic signal is repeated, measured in cycles-per-second or Hertz (Hz).

Period is the time required for a periodic signal to undergo a complete cycle, measured in seconds per cycle.

Duration is the overall temporal extent of an event (e.g., stimulus interval, inter-stimulus interval, or reaction interval), measured in seconds.

Amplitude Envelope is a measure of dynamic changes in the amplitude of a signal as a function of time. Amplitude envelopes include the components of attack (onset), sustain, release, and decay (offset), usually measured in units of time, or in units of amplitude per second (i.e., as a rate of change).

Phase is the relative position of an event within a periodic cycle, or the relative difference in position existing between two periodic events, measured in radians or degrees.

Spectrum is the relative amplitudes of the various frequency components of a signal. Components may be harmonic (i.e., the frequency ratios of components are related as integers) or inharmonic.

2) *EW Measurement Characteristics*

The SDI uses the signal attributes to produce a measurement. A measurement is defined as the act of assigning numbers (or other symbols) to a combination of signal attributes. There are measurement characteristics derived from the signal attributes.

Sensitivity is the size (amplitude) of the smallest signal to which a system can respond.

Noise Floor is the amplitude response of a system when no input signal is present.

Distortion level is the amplitude of the largest signal to which a system can respond without unacceptable amplitude non-linearity.

Dynamic range is the amplitude difference (usually expressed in decibels) between noise floor and distortion level of a system.

Signal-to-Noise ratio (SNR) is the difference (usually expressed in decibels) between noise floor and any signal amplitude below the distortion level of a system.

Frequency response is the variation in sensitivity or level (usually expressed in decibels) of a system as a function of frequency; also, may include the variation in phase (usually expressed in degrees) as a function of frequency.

Transient response is the variation in sensitivity or level (usually expressed in decibels) of a system as a function of changes in amplitude or amplitude envelope.

The next four characteristics are viewed as figures of merit for all measurements. They will help determine the validity of the measurement and have a significant effect on the overall analysis.

Precision is the size of the smallest change in a signal attribute that can be measured or produced with a system; typically, a property of an instrument, but also may be a property of a procedure.

Accuracy is the validity of measurement possible with a system; influenced by the precision of a measurement system.

Repeatability is the consistency with which a measurement produces the same results at different times.

Robustness is the extent to which the results of using a measurement are immune to errors.

3) *Threat Assessment Model*

Threat assessment is a refinement of the threat detection and characterization process. The goal of threat assessment is to identify the threat to a single response action or a limited set of actions. Threat assessment may be aided by historical data to narrow the field of possible responses. The correlation of possible threats to the response can be complex.

The SDI can solve this problem with the implementation of a model-based approach. The intent is to extract the threat inference from signal attributes and measurement characteristics. This will lead to a threat response model that maps attributes and characteristics to threats.

The threat information is centralized in the model. The relationships between signal attributes, measurement characteristics and threats can be observed, and compared to threat classification. Changes in the coverage of a threat class with respect to attributes and characteristics are reflected as in the model describing that threat. Additions of new threats are implemented as additional model locations.

The model is composed of three sets of data; the j set of signal attributes, A_j, k set of measurement characteristics, M_k, and n set of threats, T_n. Each threat is defined by the subset of attributes and measurements that will indicate the threat is present.

The model can be imagined to be a three-dimensional array with threats as the X-axis, signal attributes as the Y-axis, and measurements as the Z-axis. The combination of all three together would indicate the presence of the threat. A combination of attributes maps to measurements and in turn to threats.

There are certain approximations which go into a treatment of this problem. It is difficult to determine what threats are thoroughly detected. In the general case, it would be best to rate the coverage with some form of probability. This would add a further dimension to the model. The addition of probability of threat and historical trend data would improve the accuracy of threat classification and response action. The following is required for the development of such a system:

- Generalized modeling approach.
- Inference algorithm
- Analysis of multiple or concurrent threats
- Ability to scale more complex threat scenarios.
- Inclusion of historical threat/response data.
- Use of threat probability data.

The model could be augmented with failure information. In addition to modeling signal attributes, measurement characteristics, and threats, design, manufacturing, and maintenance faults could be modeled. This would allow for an additional capability for fault diagnosis.

The inference algorithm would be agnostic of SDR/EW system. Testing would be driven by the model not by specific hardware or system design constraints. This information would be captured in the model. Thus, allowing the SDI to perform analysis no matter what EW system is being tested.

V. CONCLUSION

This paper presented an approach for EW test systems that leverages proven SDI technology. A comparison between a classical instrument-based test system and SDI based test system was offered. It showed that the shortfalls of traditional discrete instruments can be overcome through the application of SDI. This is because the SDI based test system employs multiple tunable hardware receiver and stimulus channels containing FPGA based DSP resources that provide engineers with access to the electromagnetic spectrum for complex waveform analysis and generation.

SDI based ATS consists of multiple instruments in one instrument. SDIs exhibit advantages over classical test and measurement instruments, including reconfigurability and reduced development costs and time-to-market. SDIs also enjoy long life cycles since they can readily be adapted to meet future needs.

The SDI can be configured as multiple instruments at one time. Applying measurement science analysis on the same signal simultaneously. Thus, making it possible to perform multiple tests at the same time and reducing test sequence times. As a result, RF signals are transmitted once and can be evaluated with multiple instruments. Additionally, this SDI/EW ATS can react dynamically to the SDR/EW systems adaptive nature. SDIs are the ideal instruments for SDR/EW system test, with RF signal generation and measurement combined with real-time analysis, using FPGA for digital signal processing.

SDR/EW system testing will require an increased level of testing using threat signal simulation and threat scenario modeling, rather than solely relying on captured threat waveforms. EW test scenarios can be verified in simulation and hardware integration lab before reaching the test range. Thus, yielding greater test coverage earlier in the process and reducing cost.

A thorough test requirements document and test strategy must be defined up front. This will establish guidelines for SDR/EW test that determine what scenarios can be simulated, require hardware integration lab testing, or range testing.

Another element to evaluate when developing an SDR/EW test strategy is in identifying components or functions of the SDR/EW system specific tests are evaluating. For example, a test that evaluates the system's ability to perform jamming will require models, equations, or recordings of threats to detect, classify, and jam. Another example would be testing the ability of the system to locate the position, range, and direction of a threat. This might require a moveable threat generator or additional complex modeling. A final example would be testing the SDR/EW systems ability to decide in real time on threat determination and response.

SDR/EW systems are an application of adaptive Software Defined Radio technology. Software Defined Instrumentation is another application of SDR technology. This paper indicated that the development of adaptive SDR/EW systems has outpaced the development of test and measurement instruments required to test these new systems. Additionally, it identified that the challenge facing EW test system designers is how to accelerate the transition from classical test and measurement instruments to SDI based on the same SDR concepts found in EW systems.

VI. AUTHORS

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VII. REFERENCES

[1] D. Abbott, The Handbook of Fifth-Generation Warfare, Nimble Books, 2010.

[2] Joint Chiefs of Staff of the Department of Defense for the United States, "Joint Electromagnetic Spectrum Operations; Joint Publication 3-85," Department of Defense, Washington, DC, 2020.

[3] F. Harris and R. W. Lowdermilk, "Software defined radio: Part 22 in a series of tutorials on instrumentation and measurement,”," *IEEE Instrum. Meas. Mag., vol. 13, no. 1*, p. 23–32, February 2010.

[4] N. S. OFFICE, "AAP-06(2021) Glossary of Terms and Definitions (English and French),," NATO, Brussels, Belgium, 2021.

[5] C. Balanis, Antenna Theory 3rd Edition, Hoboken, NJ: Wiley, 2005.

[6] D. R. Carey and R. W. Lowdermilk, "Testing Software Defined and Cognitive Radios using Software Defined Synthetic Instruments," *IEEE Instrumentation & Measurement Magazine*, vol. 18, no. 2, pp. 19-24, 2015.

[7] U.S. Department of Defense, *Synthetic Instrument Working Group, Meeting #2 Statements and Definitions*, U.S. Department of Defense, 2004.

[8] R. W. Lowdermilk and D. R. Carey, "Synthetic instrumentation eases ATE obsolescence woes," *COTS Journal*, vol. 16, no. 4, pp. 30-36, 2014.