On-Board Test and Measurement: A Needed Enabler for Adaptive and Reconfigurable Spectrum Use

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***Abstract*—The microwave test and measurement industry has traditionally focused on test equipment for laboratory characterization. Such measurement instrumentation is often adequate to completely characterize devices designed for fixed spectrum usage. However, with the advent of adaptive and reconfigurable circuits and systems for agile spectrum usage, test and measurement capabilities must now extend to deployable, modular solutions that can be included within wireless systems. This paper discusses the motivation for these systems, and gives an example of how in-situ measurement can be used to update transmitter array calibrations in real time.**

***Keywords*—amplifier, Smith Chart, Smith Tube, optimization.**

I. Introduction

Microwave measurements have been a crucial part of wireless technology development since the first half of the twentieth century. Although Hertz used microwave frequencies in some of his early experiments to validate Maxwell's equations, microwave frequencies were not used for information transmission until the 1930s. Microwave vacuum tubes began to be constructed in the 1930s, and the first successful microwave relay link was established in 1931. In World War II, radar systems became the first practical user of microwave technology, introduced by the Allies. Following the war, microwaves began to see commercial use, including the transmission of television backhaul from production trucks to studios in the 1940s. In the 1950s and 1960s, microwave relay networks were constructed to allow telephone calls between different cities to be placed. The first microwave semiconductor devices were fabricated in the 1950s. In the 1960s, the first communications satellites were placed in orbit [1].

Throughout the development of microwave technology, microwave measurements became an inseparable partner. In the 1960s, Hewlett-Packard developed the 8407 network analyzer, which was the first network analyzer that could measure amplitude and phase across a swept frequency range. In 1967, Hewlett-Packard introduced the 8410 network analyzer, capable of swept measurements to 12 GHz, at around the same time that measurement of S-parameters began to emerge as the prevalent method for linear microwave characterization [2]. The ability to characterize fixed microwave systems accompanied the widespread construction of microwave relay networks and the launch of the first communications satellites.

As computers and microprocessors became more developed, the speed and automation of network analysis continued to improve. In the 2000s, the improvement of GaAs metal-semiconductor field-effect transistors (MESFETs) and the advent of GaN high electron mobility transistors (HEMTs) and need for first-pass design success drove the creation of large-signal and nonlinear network analyzers. In the 2010s, network and spectrum analysis tools were successfully combined in a portable measurement form, allowing these measurements to be performed in a mobile way [2].

A very significant emerging trend in wireless technology is the adaptive and reconfigurable use of the wireless spectrum. In 2017, the 3.55-3.7 GHz band formerly allocated for radar was made available for sharing with wireless communication devices known as the Citizens Broadband Radio Service (CBRS). A Spectrum Access System (SAS) approach was installed to arbitrate between users and determine access priorities [3]. This initiated a trend of installing sharing systems that has continued to the America's Broadband Initiative (AMBIT) sharing of the 3.45 – 3.55 GHz band in 2020 [4] and the sharing of the 6 GHz point-to-point microwave band through Automated Frequency Coordination (AFC) Systems in 2023 [5].

In the history of wireless technology, new technology trends have always been accompanied by microwave measurement capabilities. Presently, a trend is clearly underway for spectrum to be shared instead of owned by exclusive users. Wireless devices of the future must be adaptive and reconfigurable to operate in this paradigm. What does this mean for microwave measurements? This paper describes the evolving demands on microwave measurements that will shape the future of the industry.

II. Adaptive and Reconfigurable Wireless Devices

A movement is underway to allow wireless devices to (1) adapt to their surrounding spectral environments and (2) reconfigure in real-time to optimize performance in these dynamic environments. It is this *adaptivity* and *reconfigurability* that is the key to real-time, agile spectrum use. This flexible spectrum use will be a multiplier of available spectral resources.

Adaptive and reconfigurable wireless devices have the potential to speed wireless spectrum usage processes. Fig. 1 shows a relative timeline of various spectrum-sharing operations. Spectrum-sharing operations have a wide range of required time scales. ITU, congressional, and band-clearing processes often require months or years to complete, while radar operates on the order of nanoseconds to seconds. The goal of adaptive spectrum usage is to move all of the processes

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in Fig. 1 to the left: to make them faster, hence increasing adaptivity.

Moving a process to the left in the Fig. 1 diagram requires multidisciplinary improvements to spectrum sharing policies and technologies. Fig. 2 shows a hierarchy of enabling technologies for spectrum-use systems. Spectrum-use systems, such as radar, communications, and passive sensing systems, are included in the center of Fig. 2. These systems must improve sharing spectral resources through techniques and innovations in the areas of spectrum co-existence, algorithms, reconfigurable circuits and electronics, and propagation modeling. Policy governs the use of spectrum, and economics often appears as a significant motivation for spectrum-use decisions. Finally, security & resiliency is a topic that, in many ways, underpins the use of spectrum and upholds it. If a spectrum-use system is not secure, it is not worth using.

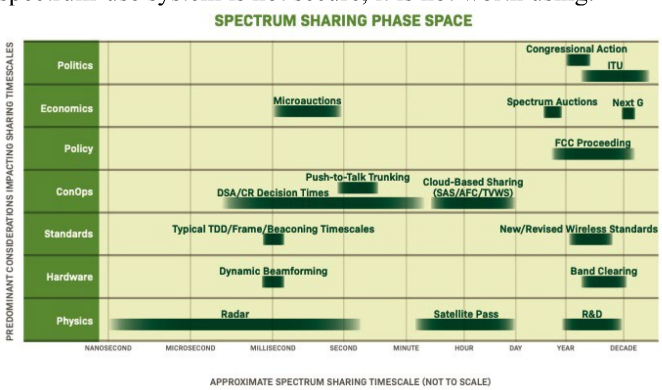

Fig. 1. Time scales of spectrum-sharing operations

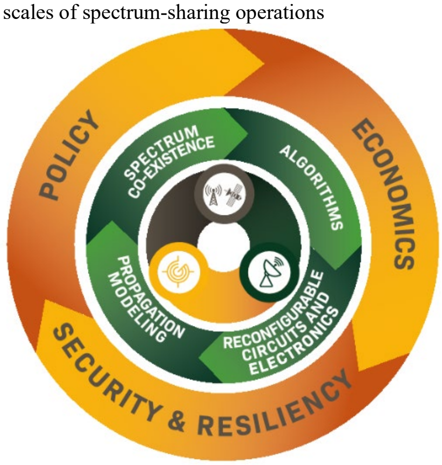

Fig. 2. Hierarchy of spectrum use systems. The types of spectrum-use systems, pictured in the center ring, utilize the technologies of spectrum co-existence approaches, algorithms, reconfigurable circuits and electronics, and propagation modeling to more efficiently share spectrum. Spectrum usage is overarched by policy and economics, which govern the use of spectrum. Further, spectrum usage is underpinned by security & resiliency, as spectru and potentially undesirable. m use must be secure and resilient, or it is useless and potentially undesirable.

To move the time scales of operations shown in Fig. 1 to the left using innovations in the areas of Fig. 2, the Fig. 2 innovations must be implemented in real-time spectrum use systems. Test and measurement systems are needed that can assess, for the purposes of real-time optimization, policy compliance, spectrum performance, security, and other features of the spectrum use system. As the system is evaluation, the evaluations of the test and measurement system can be used to reconfigure the policy, waveforms, devices, networks, and other areas of the wireless device to perform in a more desirable way. This is in stark contrast to the traditional microwave measurement approach of pre-characterization.

In a spectrum where frequencies of systems are predetermined and interference is unexpected, wireless systems and circuits may be successfully characterized before deployment in a laboratory environment. Commercially available microwave measurement tools, such as vector network analyzers, spectrum analyzers, and power sensors are all well-equipped to handle the needs of fixed-use wireless systems. However, in this new proposed spectrum environment where systems are adaptive and reconfigurable, it is expected that systems will actually change in real-time to improve their assessed performance. While pre-characterization is still useful, it has limitations, as it does not always successfully characterize the environment, mutual coupling factors, and other determining features. Further, look-up tables are space limited, and many optimum points cannot be stored (and would change even if stored). An on-board measurement system, capable of measuring in-situ (within the system) is needed. This system must characterize devices during operation following reconfigurations in such a way as to assess performance improvements or regressions following a reconfiguration, allowing a search for the optimum state to be completed.

Traditional wireless systems in a fixed spectral environment can often be viewed as open-loop systems. Open-loop systems have no feedback mechanism, and performance assessment is not implemented into performance, as shown in Fig. 3. However, in an adaptive spectrum environment, continual assessment and feedback, using a closed-loop system, is needed to evaluate and improve performance through changes in spectrum policy, networks, devices, circuits, and arrays. Such a closed-loop measurement system is shown in Fig. 4. Because this system has the capability to assess its performance through on-line measurement, it can modify circuit, device, and waveform settings in real-time to improve performance. It is the on-board, in-situ measurement system that enables this real-time performance improvement.

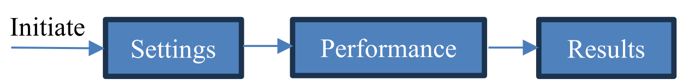

Fig. 3. Open-loop wireless spectrum-use system

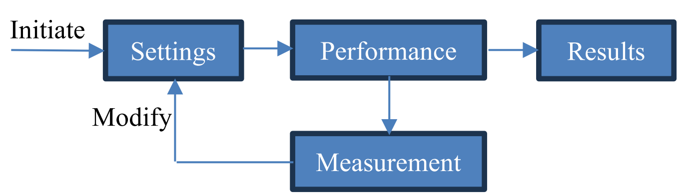

Fig. 4. Closed-loop wireless spectrum-use system

III. On-Board Measurement Assessment for Performance Improvement

How can the system settings be modified to improve performance based on in-situ measurement results? Reconfigurable circuits can use gradient-based optimizations to maximize radar transmitter output power [7]. This optimization is based on the sensed average power over a transmit spectrum that varies on a pulse-to-pulse basis to avoid interference. However, functionality of this system requires two things: (1) accurate spectrum sensing to develop understanding of interference and interference patterns and (2) on-board measurement of power. The on-board measurement of power for this algorithm is demonstrated by Egbert using a software-defined radio platform [7].

The situation gets more complicated when an array is used for transmission. Arrays rely on accurate knowledge of the magnitude and phase of each element's transmission coefficient to appropriately provide the needed antenna currents to generate the array transmission pattern. Because surface currents of the antennas, proportional to the antenna input currents, determine the transmission pattern, measurement of the antenna input current is needed. A traditional transmitter array pre-calibration involves measuring the S-parameters of each element's transmission chain. However, this simply relates the voltage traveling wave entering the antenna to the voltage traveling wave incident from the voltage source. As such, because current is the essential quantity to determine the array pattern, the S-parameter measurements are only accurate if (1) all antennas present the same impedance to the transmit chain and (2) the array transmit chain does not change its transmission properties during performance. In a frequency-dependent array, it is often desirable to change either the circuitry, the antenna configuration, or both, to maximize efficiency, range, spectral performance, and/or spatial transmission properties. These systems are expected to be seen with growing prevalence. A measurement in each array element of the antenna input current allows real-time adjustment of the input voltage excitation to compensate for non-uniformities between different element transmission properties.

In-situ measurement of antenna current is described by Baylis [6] and Goad [8]. Fig. 5 shows the block diagram of an in-situ measurement system within a phased-array element [8]. The four-port coupler serves as a reflectometer, assessing the current entering the antenna through the following equation [6]:

$$I_{ant} = \frac{V_{ant}^{+} - V_{ant}^{-}}{Z_0} \tag{1}$$

The values of V_{ant}^{+} and V_{ant}^{-} are assessed by measuring V_3^- and V_4^- [8], based on the S-parameters of the four-port network that includes the coupler and all cables and connectors between the coupler and the measurement instrument ports.

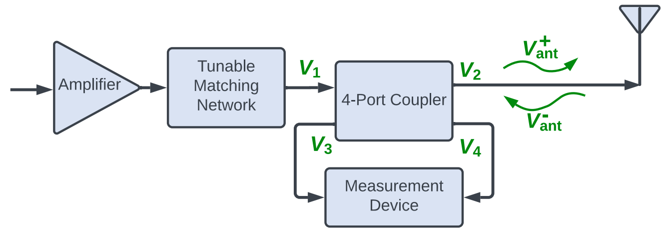

Fig. 5. Block diagram of an in-situ measurement system for phased-array voltages and currents during circuit reconfiguration. Reprinted from [8].

Goad shows that the following equations define the antenna traveling-wave voltages in terms of the total measured V_3 and V_4 from the measurement device, reprinted from [8]:

$$V_{ant}^{-} = \frac{\frac{V_3}{1+\Gamma_{L3}}\left(-\frac{S_{41}}{S_{31}} + \frac{S_{41}S_{33}}{S_{31}}\Gamma_{L3} - S_{43}\Gamma_{L3}\right)}{-\frac{S_{41}S_{32}}{S_{31}} + S_{42}} + \frac{\frac{V_4}{1+\Gamma_{L4}}\left(\frac{S_{41}S_{34}}{S_{31}}\Gamma_{L4} - S_{44}\Gamma_{L4} + 1\right)}{-\frac{S_{41}S_{32}}{S_{31}} + S_{42}}, \tag{2}$$

$$\begin{aligned} V_{ant}^{+} = {} & \frac{V_3}{1+\Gamma_{L3}}\left[\frac{\frac{-S_{21}S_{32}}{S_{31}} + S_{22}}{\frac{-S_{41}S_{32}}{S_{31}} + S_{42}}\left(-\frac{S_{41}}{S_{31}} + \frac{S_{41}S_{33}}{S_{31}}\Gamma_{L3} - S_{43}\Gamma_{L3}\right) + \frac{S_{21}}{S_{31}} - \frac{S_{21}S_{33}}{S_{31}}\Gamma_{L3} + S_{23}\Gamma_{L3}\right] \\ & + \frac{V_4}{1+\Gamma_{L4}}\left[\frac{\frac{-S_{21}S_{32}}{S_{31}} + S_{22}}{\frac{-S_{41}S_{32}}{S_{31}} + S_{42}}\left(\frac{S_{41}S_{34}}{S_{31}}\Gamma_{L4} - S_{44}\Gamma_{L4} + 1\right) + \left(-\frac{S_{21}S_{34}}{S_{31}}\Gamma_{L4} + S_{24}\Gamma_{L4}\right)\right] \end{aligned} \tag{3}$$

These quantities can be measured using a software-defined radio platform, or an RF System-on-a-Chip (RFSoC). Because these parameters measure total voltages, the total voltages V_3 and V_4 from the instrument measurements are used in equations (3) and (4) to calculate the needed quantities to solve for antenna current. Egbert demonstrates the measurement of these quantities using an SDR, a process that involves accurate calibration of the SDR using a power meter and signal generator.

This handles the "Measurement" part of the Fig. 4 diagram. In an array environment, the "Modify" operation can be performed by adjusting the input voltages from the signal source to equalize for the magnitude and phase differences caused by the reconfigurable circuit components. Haug describes an approach for equalization in which the relative voltage vector (magnitude and phase) adjustments are calculated to negate the current vector error, and demonstrates that this approach can be used with impedance tuning to optimize array performance [9].

Goad details the measurement validation of equations (2) and (3) using a benchtop setup with a two-port network analyzer used to provide excitation and measure each of the coupler output voltages V_2 and V_3 one at a time. Measurement results for the antenna input current are compared with simulation results using simulations with the measured S-parameters of the coupler and other circuit components in Fig. 6, reprinted from [8]. Fig. 6 shows that the measured current values are nearly identical to the simulated current values [8].

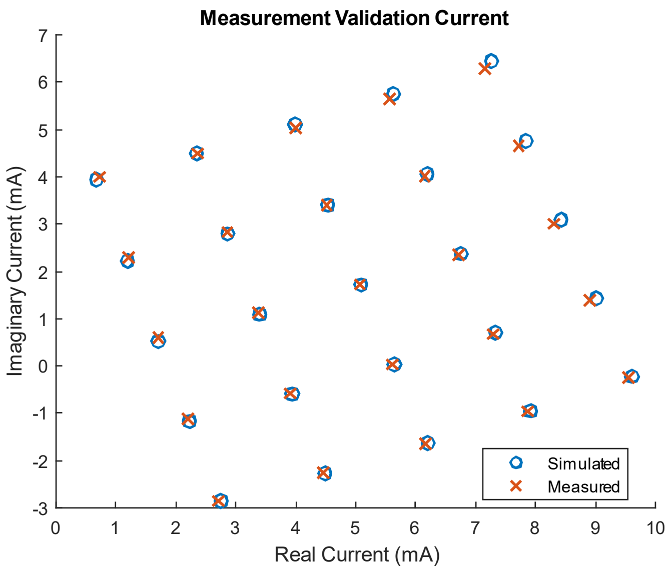

Fig. 6. Measured current using network analyzer measurements with equations (1), (2), and (3) and simulated currents using predetermined measured voltage inputs with system component S-parameters. Reprinted from [8].

IV. Building a Business Case for On-Board Measurement Capability

As spectrum-use systems become more adaptive and reconfigurable, and less rigid in their spectrum usage, pre-characterization in the laboratory will no longer be sufficient. As S-parameters and automated network analysis measurements developed the first movement of microwave measurements, it is the shift to the concept of adaptive and reconfigurable use that is expected to incite this new paradigm of microwave measurements. As test and measurement companies build business plans for accurate, repeatable, and verifiable measurements to be placed on board transmitter and receiver systems, these measurement capabilities are expected to improve in size, weight, power, and cost (SWAP-C).

The business plan allowing test and measurement companies to develop these solutions, in some sense, depends on the movement toward adaptive and reconfigurable systems. A slow movement is less likely to generate as significant of a business case for companies to develop these capabilities than a fast movement. How can companies predict the movement toward adaptive and reconfigurable measurements? There are a few key data points.

Perhaps a key data point to examine is the movement of different spectral bands toward sharing. As discussed in the introduction, bands using automated sharing systems are increasing more rapidly, from CBRS (2016) to AMBIT (2020) to AFC (2023). It is expected with the rollout of the National Spectrum Strategy, which repurposes approximately 2700 MHz of spectrum for sharing, that the allocation of bands from single-user to shared status will explode [10]. This will create a high demand for sharing systems such as the SAS and AFC, but on much faster time scales. Such systems will need on-board "certification" that their spectrum use is compliant with the sharing regulations that have been instituted for the bands of interest. This will require on-board measurements to directly ensure compliance to the users. One of the bands to be studied for sharing, not surprisingly, is the 3.1-3.45 GHz band allocated to radars in the United States. The need for Department of Defense systems to upgrade sharing capabilities will demand for new systems to have on-board measurement capabilities with minimal SWAP-C. This will quickly launch a feasible business case for the test and measurement companies.

As the first microwave measurement wave swept the world and provided enhanced wireless capabilities, it is expected that the second microwave measurement wave will provide enhanced real-time, on-board assessment to facilitate rapid spectrum usage.

Studies of this magnitude are useful in the context of a national center, where spectrum sharing technology and policy can be performed in concert with measurements. The Hub for Spectrum Management with Adaptive and Reconfigurable Technology (SMART Hub) was launched in 2023 to address significant issues surrounding real-time, adaptive and reconfigurable spectrum sharing, and to assist in the development of the adaptive and reconfigurable paradigm. It is very important that test and measurement systems be considered along with spectrum-sharing circuits, networks, systems, and policy as part of this paradigm shift.

V. Conclusions

The emerging movement from rigid spectrum usage to adaptive and reconfigurable spectrum usage places additional requirements on microwave test and measurement. In addition to traditional pre-characterization of transmitter and receiver components in the laboratory, the adaptive nature of these systems will require verifiable, repeatable, and accurate on-board measurement capabilities of feasible SWAP-C. An example of this type of system has been provided in the in-situ measurement of antenna current for beam pattern determination in phased-array transmitters. A business case can be made for microwave test and measurement companies to develop this new paradigm based on the trajectory of allocation of new bands for sharing in the last decade, in addition to the recent National Spectrum Strategy released by the United States. The development of on-board test and measurement solutions will allow spectrum sharing to be performed quickly and with minimal interference, benefiting all future wireless device users.

Acknowledgments

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