Synthetic instrumentation: An emerging technology (Part I)

Synthetic Instrumentation (SI) is an emerging technology in sync with the digital revolution. For SI paradigm to transform itself into a primetime real world solution, it will require acceptance, incremental development and support from leading test & measurement instrument manufacturers.

By Mike Granieri

A synthetic instrument (SI) synthesizes the stimulus and/or measurement functionality found in traditional instruments by using a combination of core hardware and software building blocks that are employed in a modular open architecture environment. SI is a paradigm shift that forever changes the way automatic test systems (ATS) are designed, built, fielded and supported. The concept of synthetic instrumentation goes back a number of years and was briefly explored by the military in programs such as Equate and Universal Pin Electronics in the late 1970s and early 1980s. At that time, the technology was not available to render the concept a commercial reality and the resulting implementations were primarily focused on low-frequency analog, digital and baseband, as opposed to RF/microwave applications.

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Modern-day synthetic instruments find their roots in the communications revolution of the past decade and the emergence of a concept called Software-Defined Radios (SDRs). Simply defined, an SDR (see Figure 1) consists of a digital signal processor (DSP), a transmitter, a receiver and a transmission antenna. The transmitter and receiver convert digital data to and from modulated radio waves for wireless communications purposes. The DSP provides the radio functionality, via its software component, whereby application-specific algorithms generate or process digitally represented signals for transmission or reception by the SDR. The paradigm of SDR provides design modularity and programming flexibility to rapidly accommodate emerging communications protocols/modulation schemes, functions, and user needs.

SI is based on the concept that most stimulus and measurement functions can be implemented in software with "core" SI hardware and software components. These components include frequency upconverters and downconverters, digital to analog converters

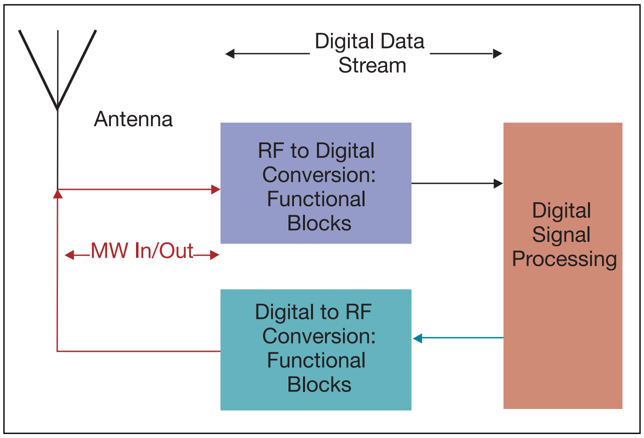

Figure 1. Software defined radio: functional block diagram.

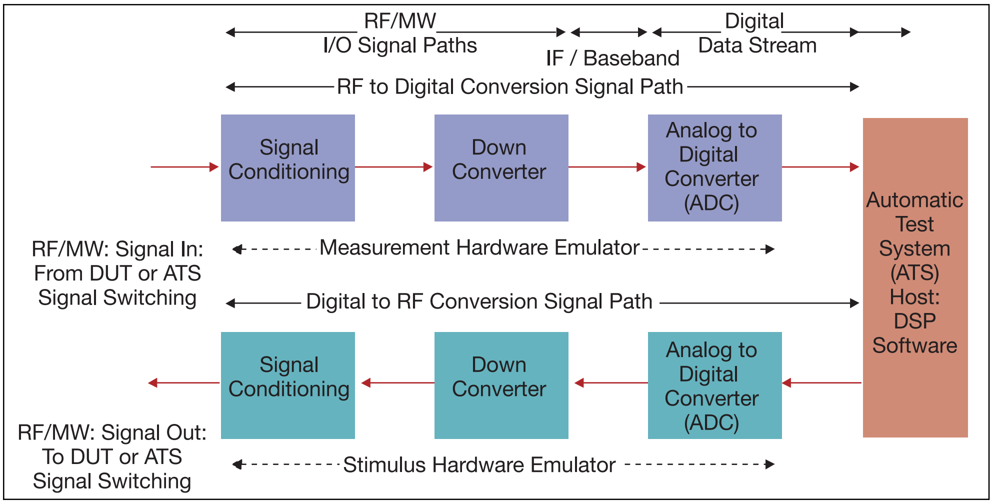

Figure 2. Synthetic instrument-based ATS: notional block diagram.

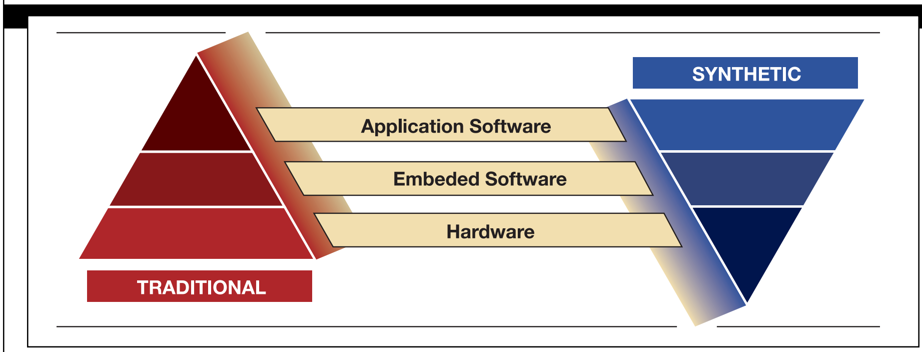

Figure 3. Instrumentation architecture: a revolutionary progression.

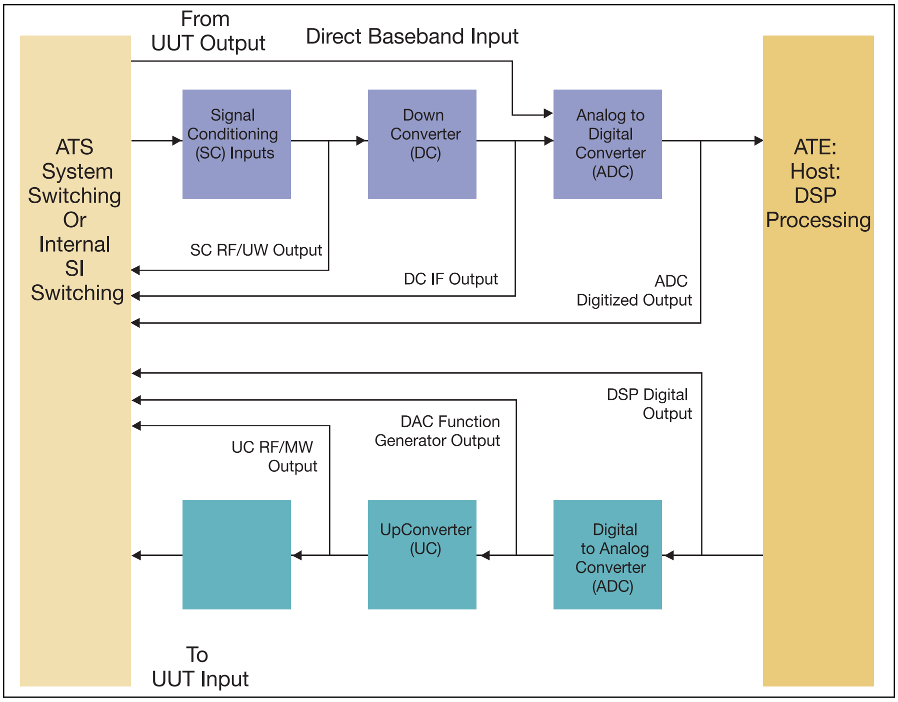

Figure 4. SI controllability/accessibility.

(DACs), analog to digital converters (ADCs) and DSP hardware and software. Depending on the user's envelope of test requirements, these components may be supplemented with commercial off-the-shelf (COTS) hardware, such as power supplies, fixturing and loads.

A high-level block diagram (see Figure 2) of a test system's test and measurement capability predicated on SI looks similar to that of an SDR. The receiving or RF-to-digital circuitry link/path comprises signal conditioning, frequency downconverter and analog to digital conversion circuitry. The signal conditioning circuitry controls the process of automatic gain control. The AGC process controls amplifiers and attenuators in the measurement signal path to scale the analog signal level to the dynamic range of the subsequent processing units.

The downconverter functional block is perhaps the most critical component in the measurement path. It must provide the frequency translation/filtering function and, via a combination of mixing and filtering, faithfully reproduce the target baseband signal that was modulated onto the microwave carrier signal. If the downconverter's conversion loss, IF filtering and associated phase characteristics are not properly specified, designed and controlled, the downconverted intermediate frequency (IF) signal being digitized and analyzed by the A/D converter and DSP software will bear erroneous results. The A/D converter in the receiving or measurement processing path is the interface between the continuous analog and sampled discrete digital domain. The operating range of the ADC is often the limiting factor in the performance of the measurement to be

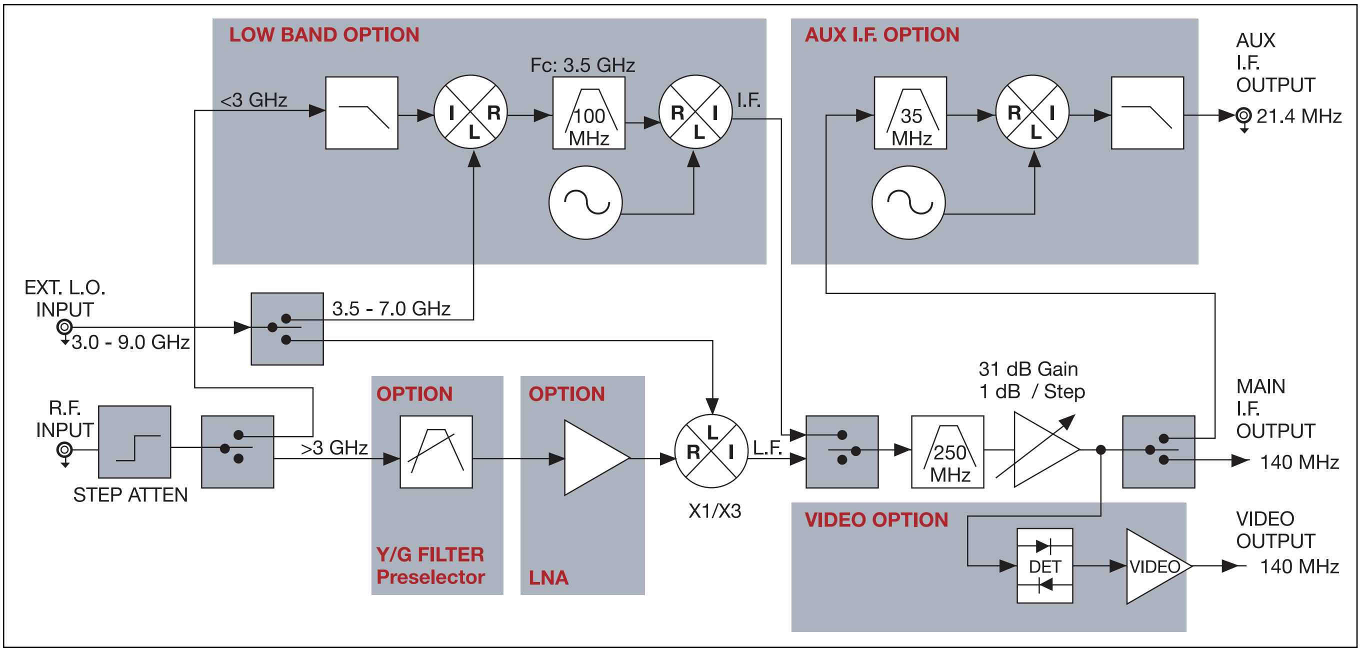

Figure 5. Critical SI technology: flexible downconverter architecture employing multiple technologies.

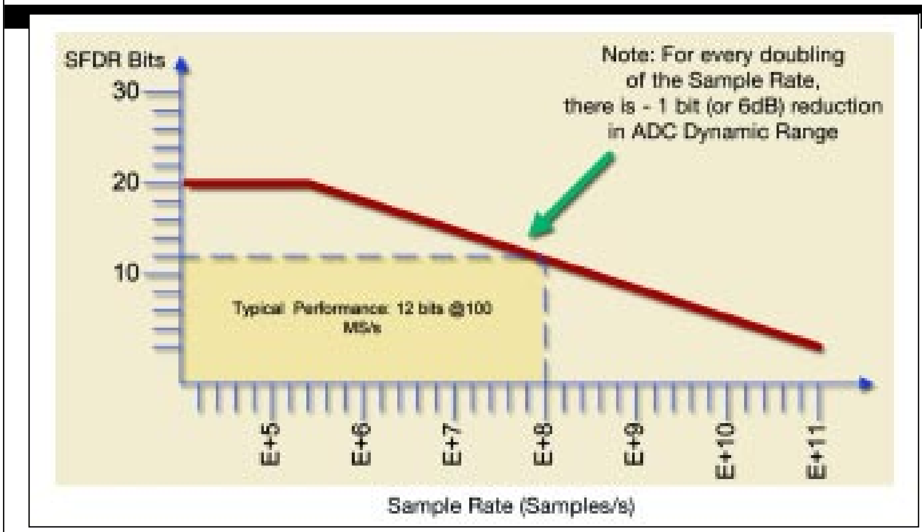

Figure 6. Typical technology curve: ADC SFDR vs. sample rate.

The test and measurement industry has undergone tremendous evolution since those early days. A wide assortment of instrument types has evolved over the past 60 years to address the test and measurement challenges faced by the commercial and military market segments.

performed, assuming the downconverter block is providing the ADC with a faithful reproduction of the target baseband signal to be measured. In the stimulus or upconverter path, the fidelity of the upconverted signal depends on the bandwidth and dynamic range of the D/A employed.

Why synthetic instruments?

It can be argued that the renaissance of electronic instrumentation began in the 1940s-1960s time frame as commercial electronic devices and military applications started to proliferate with the availability of cost-effective power generation/distribution and the emergence of the semiconductor industry. The test and measurement industry has undergone tremendous evolution since those early days. A wide assortment of instrument types has evolved over the past 60 years to address the test and measurement challenges faced by the commercial and military market segments. Traditional instruments such as digital multimeters, electronic counters, oscilloscopes, power meters, spectrum analyzers, function generators, and network analyzers (to name but a few) have emerged as markets in their own right. Each of these instrument types and classes within each class was designed using, for the most part, unique and/or somewhat different stimulus/measurement circuitry and techniques. This traditional approach primarily relied on a majority of the stimulus and/or measurement capability of an instrument to be accomplished in its proprietary hardware.

Despite the commonality found in the front end of these instruments, it is rare to find re-use of stimulus/measurement technology. On top of the hardware was a layer of embedded software (usually locked to the targeted embedded controller of the original design). Finally, on top of the embedded software was the application software that, for the most part, functioned as the graphical user interface (GUI) and/or display of the already calibrated/scaled/converted data.

An ATS predicated on the SI paradigm turns the traditional model of instruments literally upside down (see Figure 3). The synthetic hardware architecture consists of a minimal open standard hardware set (signal conditioning, upconverter, downconverter, DAC, ADC) working in conjunction with unbundled commercially available DSP software, often hosted on a PC. This reduced hardware set minimizes the need and cost for system calibration; system calibration is easily effected by the accessibility and controllability afforded by each functional block in both the SI stimulus and measurement paths (see Figure 4).

Similarly, SI obsolescence and upgrade issues are limited to a few modular hardware blocks and not to myriad instrument types and classes. In an ideal SI system, each hardware component should not use application-specific firmware—thus enabling each hardware component to be easily interchanged and upgraded with another component of the same functionality. In SI, for the

Table 1. Notional family of ADCs for synthetic instrument applications.

Bits	Sampling Rate	Range Theoretical SFDR
20	10 KHz - 100 KHz	~120 dB
16	100 KHz - 3 MHz	~96 dB
12	3 MHz - 100 MHz	~72 dB
8	100 MHz - 1 GHz	~48 dB

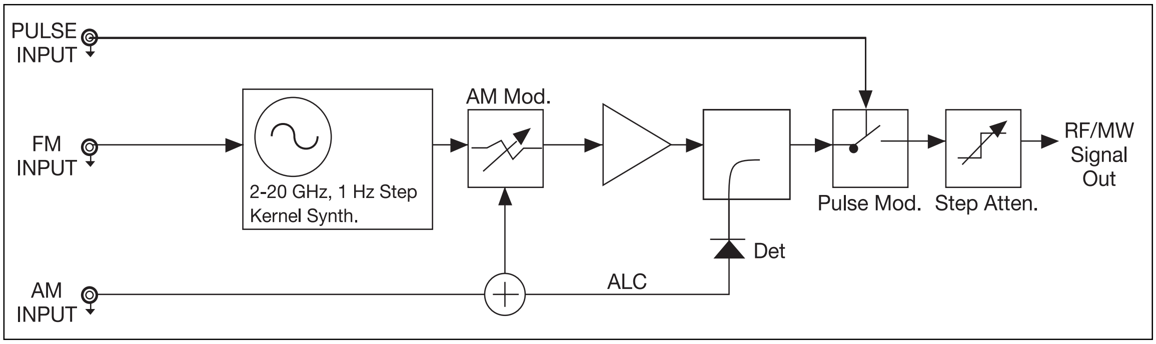

Figure 7. Legacy RF stimulus generation/modulation architecture.

Past experience and “best practices” in the RF/microwave industry have taught us that there really is no such thing as a standard downconverter. One size does not fit all.

most part, the software is the instrument. SI’s architectural simplicity, and the flexibility afforded by the stimulus and measurement software being hosted in a host/central processor enables SI-based systems to be fielded concurrently with each new weapon system. The independence and uncoupling of SI hardware from ATS stimulus and measurement software is a huge burden relief for the ATS developer and user-software-intensive ATS systems can now be freed to follow the commercial PC processor speed/performance gain curve.

Addressing critical technology issues

Based on the above discussion, the future of synthetic instrumentation certainly looks bright and promising. However as with any new innovation, there are issues of which the consumer must be aware. Summarized below are critical issues and considerations summarized from both a stimulus and measurement perspective.

Measurement issues

With respect to the SI measurement path or measurement hardware emulator (MHE), the signal conditioning unit must be carefully designed to scale the analog signal level to be measured to a dynamic range that is compatible with the functional elements (downconverter and A/D) being employed in the measurement path. Also, the signal conditioning unit must be capable of being calibrated in-situ with the other functional elements in the measurement chain. In global Department of Defense support programs, which must accommodate an array of legacy and future generation units under test (UUTs), this could be a daunting task if the global test requirements are not accurately specified and scoped properly. The same can be said of the other critical elements in the measurement path: the downconverter and the ADC.

Downconverter technology

From a measurement perspective, the downconverter is probably the most critical element in the measurement signal path. The downconverter must be capable, via a judicious combination of filtering and mixing, of faithfully reproducing the baseband signal of interest. To achieve this objective, the downconverter block must be accurately specified and designed. Some of the critical specifications that must be optimized over an array of user UUT RF/microwave test requirements are:

- Frequency range of the RF/microwave input signal.
- Dynamic range of the RF/microwave input signal: min/max level range.
- Instantaneous input bandwidth of the signal.
- Input filtering requirements (pre-selection).
- Frequency range of the local oscillator (LO)/mixer input.
- Local oscillator tuning speed (must be compatible with UUT test time requirements).
- Intermediate frequency (IF) bandwidth flexibility: must be compatible with digitizer technology to be used.
- IF output level/dynamic range: must be compatible with digitizer technology to be used.
- Noise floor: average displayed noise.
- Signal isolation (dB).
    - LO to RF.
    - LO to IF.
    - RF to IF.

In particular, the specification of a downconverter IF bandwidth is of critical importance. In some instances, such as capturing complex modulation formats, a wide IF bandwidth is required to acquire the information content in the baseband signal. The trade-off here is the time required for the A/D converter to process the signals of interest. In other applications such as AM or FM modulation, the frequency span of the signal(s) of interest are narrower and hence a narrower IF bandwidth can be used.

In many ATS applications, more than one downconverter model may have to be used to satisfy the broad range of frequency spectra applications to be processed. Past experience and “best practices” in the RF/microwave industry have taught us that there really is no such thing as a standard downconverter. One size does not fit all.

All downconverters are essentially married with other functional elements in a target system/application and have to complement and work in harmony with these elements. For this reason, application flexibility is a key feature that users should focus on when designing a downconverter, or a family of downconverters, into their target application.

This “flexibility factor” becomes most important when working in an open architecture environment where one vendor is not providing all of the technology required, or where all of the technology required may not be available from one vendor. For example, each marriage of a downconverter reference design may require some changes to its baseline characteristics to maximize system performance. As mentioned previously, this may involve modifying IF frequencies and/or bandwidths, gain, output power and video outputs.

Configuring a downconverter for a particular application could often require mixing and matching of block of circuits from a vendor's design library to satisfy the requirements of a particular application. In addition, multiple downconverter technologies often need to be employed in order to satisfy the broad-based needs often encountered in global ATS support programs. These technologies include:

* Block downconversion: frequency translation from one band to the next.

* Tuned-down conversion: employing a broadband local oscillator with a frequency resolution as low as 1-3 Hz.

* Harmonic mixing: using a fixed local oscillator and a tunable YIG filter to filter out unwanted harmonics from the RF.

* Sampling: a special form of harmonic downconversion employed in instruments such as oscilloscopes and microwave transition analyzers.

A possible and promising solution to this challenge would be to provide, using a mix of the technologies and circuit blocks described above, a small finite set or family of downconverters (or "personality modules") for a specific user's application; these modules would be matched to the unique signal measurement needs of a specific system (i.e., F18, Avenger) to be supported, or a user's unique technology needs. Figure 5 depicts an example of a downconverter employing a mix of technologies encompassing tuned downconversion and Yttrium Iron Garnet (YIG) filtering to achieve application-specific SI RF/MW "front-end" performance objectives.

A/D and D/A technology

After the downconverter, the operating range of the A/D in the signal measurement path is often the limiting factor in the performance of a synthetic instrument. The key performance measures of an A/D are its "conversion rate," which can be related to the instantaneous bandwidth of the system and its "conversion bits," which are related to its SFDR (spurious-free dynamic range). The ability to resolve signals of widely varying strength and in the presence of varying noise levels is primarily determined by the dynamic range of an instrument. The dynamic range of an ADC is the ratio between the maximum root mean squared signal level that can be sampled and the

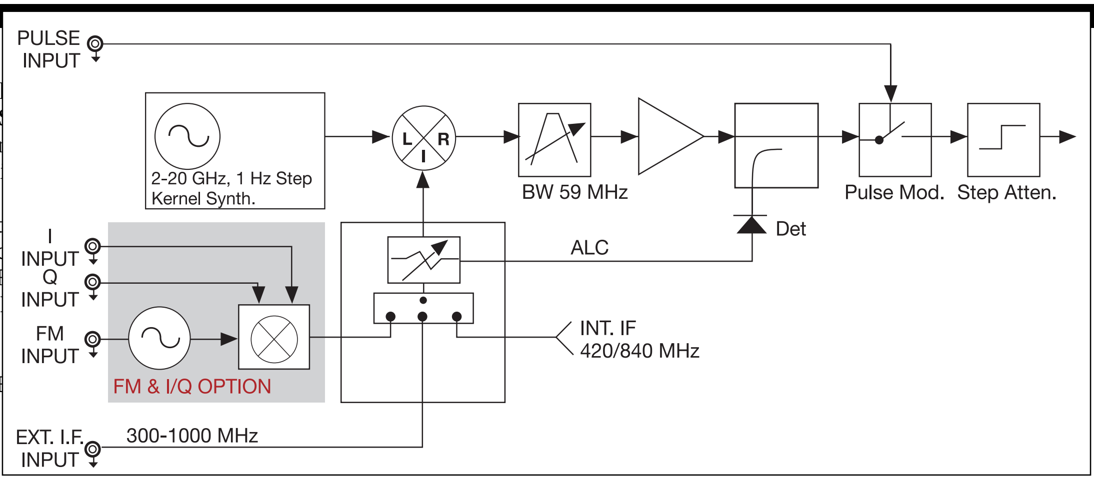

Figure 8. Flexible MW/RF stimulus generation/modulation for SI.

RMS quantizing noise level

The SFDR of an SDR or S
many variables but is primar
resolution of the A/D circu
ratio
the RMS signal amplitude t
of the peak spurious spec
The theoretical limit of SF
cuitry is approximately 6 d
be expressed as follows:

SFDR (dB) = 6.02 X (F

where (B) is the number of
tizing circuitry.

The conversion rate or instantaneous bandwidth required by an application is driven by the Nyquist criteria whereby the digital sampling rate must be at least twice the signal bandwidth of interest that the instrument needs to capture. When considering an SI instrument to measure wideband signals, care must be taken to ensure that A/D and D/A circuitry has an adequate sampling rate to capture the full signal bandwidth, as well as sufficient resolution to handle dynamic range requirements.

A key performance parameter for ADCs is the product of its maximum sample rate (Fs) in Hz and its conversion bits. This relationship may be expressed as follows:

K= B. Fs

where B is the product of 2 raised to the number of resolution bits in the A/D.

The resolution/speed metric for a given state of A/D technology defines the technological boundary (see Figure 6) of the SFDR and bandwidth space available to accommodate SI implementations.

Because of the inverse relationship between the sample rate and number of conversion bits, it is not possible for a single ADC to satisfy the dual requirements of obtaining wide dynamic range at low sample rates and, conversely, lesser dynamic range at high sample rates. To satisfy the wide range of test requirements typically serviced by modern-day automatic test systems, the ADC function used in the ATS SI signal measurement path may, in fact, require a family of ADCs from which one can select to satisfy the unique requirements for a UUT or set of UUTs (i.e., radar, IFF, etc.). Table 1 depicts a notional set of ADC performance characteristics, predicated on Figure 6, which could comprise such a family. It is envisioned as the state-of-the art in DACs/ADCs and its associated technology curve evolves over time; the family would be modified to accommodate increased bandwidth/dynamic range capabilities of ADC/DAC technology and associated products.

Stimulus Issues/considerations

A traditional legacy instrument architecture (vintage 1980) employed by prior generations of RF/MW stimulus generators and upconverters is shown in Figure 7. This class of instrument has served the T&M industry and its customer base well over the past few decades. Its functional capability consisted of an RF/MW CW signal generation and amplitude, frequency and pulse modulation capabilities. This functional capability was adequate to support the test and measurement needs of older/legacy DOD communications systems. Over the past five years, a new type of communications system has evolved employing digital modulation concepts. This new class of unit under test cannot be tested by legacy RF stimulus generators and upconverters because of their limited signal modulation capabilities.

Because of this “digital revolution” in the aerospace and defense sector, a need has emerged for a new class of RF stimulus generation architecture and capability (see Figure 8) that can accommodate legacy and emerging digital modulation formats.

The RF spectrum is a precious resource and must be shared, yet every day there are more users for that spectrum as demand for communications services increases. Digital modulation schemes have greater capacity to convey large amounts of information than classical analog modulation schemes. However, history has taught us that there is a fundamental trade-off in communications system design.

Simple hardware can be used in transmitters and receivers to communicate information. However, these simple hardware elements often use a lot of spectrum, which limits the number of users. Alternatively, more complex transmitters and receivers can be used to transmit the same information over less bandwidth. The emerging trend is that the transition to more and more spectrally efficient techniques requires more and more complex hardware that must be designed and tested.

Digital modulation is effected by employing an “I/Q” modulation capability whereby a digital stream (i.e.,”1010….) can be represented by a unique RF composite signal, or signals, that are characterized by their magnitude and phase components (or I and Q). That is, an I/Q-capable stimulus generator provides the capability to transform bits to microwave signals and provide a virtually unlimited signal generation capability. There-

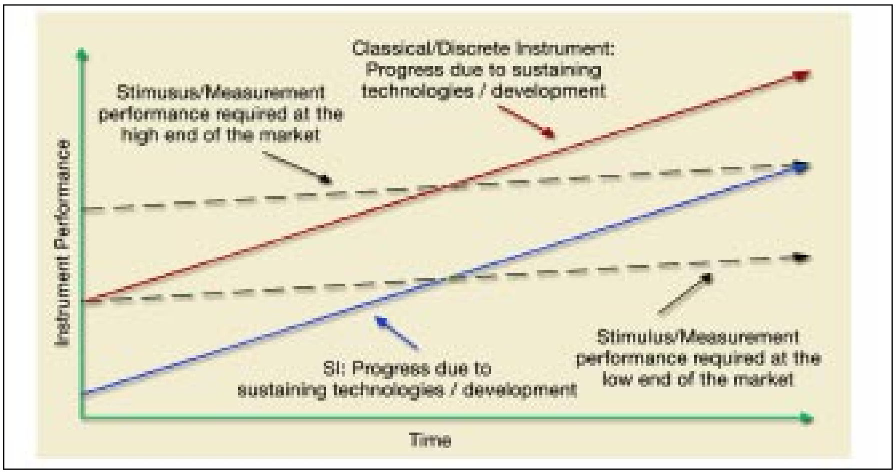

Figure 9. Synthetic instrumentation: a disruptive technology.

fore, it is imperative that modern-day ATSs incorporate a family of flexible RF stimulus upconverters/modulation capabilities that can accommodate a range of legacy analog and current digital modulation formats, as well as be upgradeable in support of emerging digital modulation formats. To do otherwise would be shortsighted.

Conclusion

SI is an emerging technology that will not go away. It is in synch with the digital revolution. We in the test and measurement industry must come to the realization that customer focus is on information, not data, and that SI is a technology enabler that satisfies this need. For the SI paradigm to transform itself from an emerging technology to "prime time" global, real-world solution will require acceptance, incremental development, and support by a supply chain of leading test and measurement manufacturers. This transformation will not be easy but will be necessary to satisfy customer need for faster, smaller, supportable, and more information-intensive instruments that are more compatible with the PC paradigm. RFD

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