COST-EFFECTIVE, FOCUSED INSTRUMENTATION FOR TT&C/COMMS ENGINEERING

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ABSTRACT

The need for sophisticated tools in the expanding areas of Telemetry, Tracking and Control/Command (TT&C) and Communications (COMMS) system simulation, development, verification, analysis, maintenance, debug, and education is well understood. Emerging requirements for these toolsets include features, ease-of-use, performance, and price points that specifically address telemetry and signals work. And, while not yet as available, understood, or pervasively installed, these economical and focused tools are displacing high-cost, general-purpose Test and Measurement (T&M) equipment at an increasing rate.

KEY WORDS

TT&C Instrumentation, COMMS Instrumentation, Satellite/Aircraft/UAV/Missile Channel Simulator, Signal Emulator, Spectrum/Interference Analyzer, TT&C Testing, COMMS Testing, TT&C Engineering, COMMS Engineering

INTRODUCTION

For decades, T&M equipment manufacturers have offered sophisticated instrumentation for development, analysis, verification and troubleshooting of communications systems. General-purpose oscilloscopes, spectrum analyzers, network analyzers, signal generators, counters, power meters, and other similar instruments have long been used.

As digital data communication techniques emerged, this instrumentation set was expanded to include data generators, logic analyzers, Bit Error Rate (BER) testers, vector signal generators, demodulators, wireless test sets, and optical test instruments to name a few.

Satellite, aircraft, missile, and UAV TT&C/COMMS work is well supported by a wide variety of general-purpose test gear. Vector signal generators, for example, can create expected and worst-case signals from a simulated transmitter to test ground, airborne, or space-based receive systems. Spectrum analyzers can demodulate and characterize signals to test ground, airborne, or space-based transmitter systems.

But the sole use of general-purpose instruments in TT&C/COMMS engineering and test can lead to validation inefficiencies, increased equipment cost, and most importantly, test quality compromises. These deficiencies are neither the result of poor instrument quality nor insufficient instrument specifications.

Instead, because general-purpose instruments are targeted for broad range of applications, many are over-designed for any specific applications, and at the same time, they under-serve that same application in other ways. For example, the frequency range of a vector signal generator or spectrum analyzer is generally much wider than any particular application will utilize. Frequency coverage is a key driver on instrument design and parts costs, especially so that all instrument features and performance can be offered across the entire frequency range. Simultaneously then, many general-purpose instruments command staggering prices yet lack features important to TT&C and COMMS needs.

This paper highlights the Channel Simulator as an example of the kind of cost-effective and focused instrumentation needed to address the rigorous needs of TT&C/COMMS engineering, analysis, and verification applications. Economical and TT&C/COMMS-focused Vector Signal Generators and Spectrum Analyzers are available, and are briefly mentioned as well.

CHANNEL SIMULATOR

The Channel Simulator produces effects on signals that precisely mirror those that the signal would undergo if it were actually passing through the communications channel. For wireless communications, the channel is actually space and atmosphere, and the needed channel simulation effects include Doppler shift, Doppler shift rate, range delay, range attenuation, fading (atmospheric, multi-path, etc.), and Additive White Gaussian Noise (AWGN).

Accurate simulation of these effects is absolutely critical to verification and analysis of space-borne, airborne, and fixed or mobile ground-based receiver systems. In the lab, an accurate Channel Simulator can fully replace a flying or ground-based transmitter, and can simulate difficult-to-achieve conditions (e.g., weather extremes, satellite positions/orbits, component degradation/failures, etc.) or dangerous-to-produce scenarios (e.g., nuclear disturbance, battlefield scenarios, etc.).

The Channel Simulator can also be used to test space-borne, airborne, and fixed or mobile ground-based transmitter systems, perturbing their outputs as will occur in actual use.

Channel Simulators can play a vital role in the modeling, prediction and study of system performance related to satellites not yet launched, or to study the effects of moving satellites to new stations or orbits.

Long thought of as satellite Channel Simulators, these powerful, focused, and economical instruments are fully capable of precise channel simulation for aircraft, Unmanned Aerial Vehicles (UAVs), SATCOM-on-the-move and missile applications.

As with all T&M instruments, Channel Simulators are characterized by several key capabilities and specifications that make them suitable for their tasks. These include Doppler shift-related capabilities, range delay simulation, range attenuation modeling (including fading), and noise generation functions. Useful channel simulation requires simultaneous and dynamic application of Doppler, range delay, attenuation and noise, since signals in nature are affected not by a single effect, but by all in combination.

CHANNEL SIMULATOR: DOPPLER SHIFT

In wireless TT&C/COMMS applications where receivers and transmitters are in motion with respect to one another, Doppler shift is a significant factor in system design and validation. Receivers must remain locked to a received signal, maintaining proper BER performance, even as the received signal's frequency shifts over time due to the relative motion of the transmitter and the receiver.

Equation 1 describes Doppler shift based on the actually transmitted frequency and the relative velocity between the transmitter and the receiver.

$F_s = F_a * V/c$ (**Equation 1**.)

where F_s = Doppler shift in Hz
F_a = actually transmitted frequency in Hz
V = relative velocity between transmitter and receiver
c = speed of light (~300,000 km/s)

Figure 1 illustrates Equation 1 for a Low Earth Orbit (LEO) satellite orbiting circularly at 800 km. As its 1.5 GHz signal is encountered at the Acquisition of Signal (AOS) point, and as it moves toward a fixed receiving station, the received signal is at a higher frequency than is actually being transmitted. When the satellite is at its minimum range from the receiving station, the received signal is at the actual frequency, and as the satellite sets toward the Loss of Signal (LOS) point, the received signal is lower than its actual frequency.

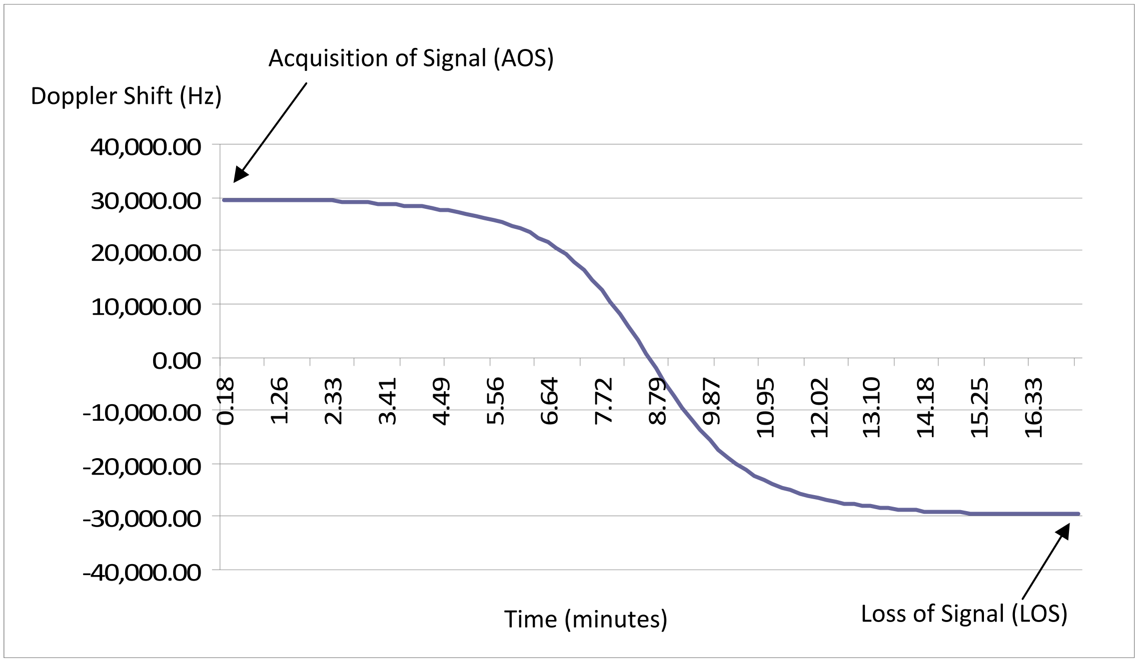

Figure 1. Doppler shift vs. time for a 1.5 GHz signal from a LEO observed at a fixed ground station.

For this satellite, the following Doppler shift ranges would be observed at a fixed ground station.

Original Frequency (F_o)	Observed Doppler (F_s)
435 MHz (UHF band)	± 8.6 KHz
1.2 GHz (L band)	± 23.7 KHz
2.4 GHz (S band)	± 47.4 KHz
5.7 GHz (C band)	± 112 KHz
10.5 GHz (X band)	± 207 KHz
24.0 GHz (Ku band)	± 474 KHz

Table 1. 800 km circular LEO Doppler shift ranges.

Similar data can be constructed for different frequencies, and for Middle Earth Orbit (MEO), High Earth Orbit (HEO), and Geostationary Earth Orbit (GEO) satellites, as well as for aircraft, UAVs, and missiles.

On a lab bench, a Channel Simulator used as in Figure 2, can apply the anticipated Doppler shift to the input signal, so that the signal into the receiver system under test is identical to what would actually be received from the transmitter.

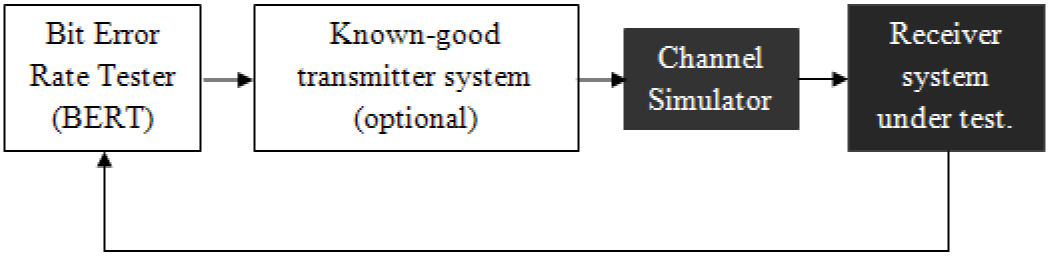

Figure 2. Channel Simulator configuration for receiver system testing.

Figure 3 shows a similar setup for transmitter system testing. In either test setup, receivers or transmitters under test may be for flying or ground-based applications. As well, up- and down-conversions as well as modems may be necessary in an actual test setup, depending on available equipment and receiver and transmitter characteristics.

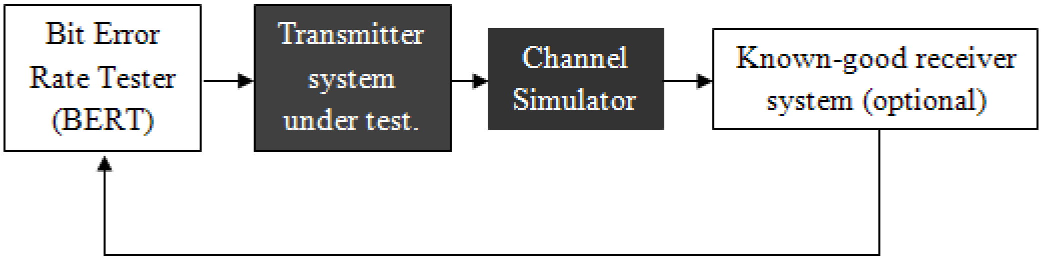

Figure 3. Channel Simulator configuration for transmitter system testing.

As Equation 1 describes, Doppler shift is frequency dependent. Since data signals have non-zero bandwidth, various portions of the signal are actually at different frequencies as can be observed with the 120 kbit/sec QPSK signal in Figure 4 below.

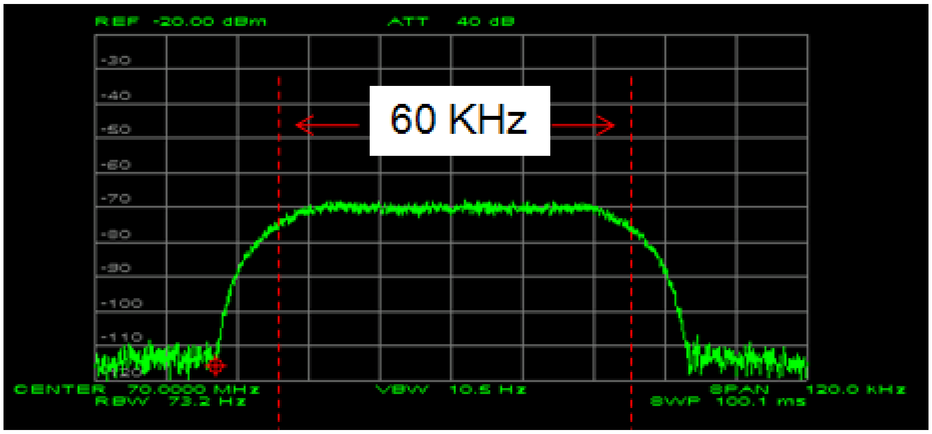

Figure 4. Typical 60 KHz bandwidth of a 120 KBit/sec (60 KSymbols/sec) QPSK signal.

For precise simulation, the Doppler shift capacity of the Channel Simulator must apply appropriate and <u>different</u> Doppler shifts across its bandwidth. In Figure 4 for example, the left side of the waveform would receive a slightly lower Doppler shift than the right side, since the left side is at a lower frequency than the right side. This is especially important at high data rates that result in wide bandwidth data signals.

CHANNEL SIMULATOR: DOPPLER SHIFT RATE

Figure 1 also shows that the Doppler shift <u>rate</u> changes throughout the pass. The flatter, more horizontal areas of the S-curve are where the Doppler shift remains relatively constant due to comparatively small changes in the closing velocity between the satellite and the ground station. As the satellite rises (the left side of the plot), its motion with respect to the ground station is mostly that which changes its altitude with respect to the ground station, not its line-of-sight range.

The steeper portion of the curve is where the satellite's range from the ground station is changing more rapidly, and as the S-curve crosses the X axis, the velocity changes sign from positive values (satellite approaching receiver) to negative values (satellite moving away from receiver).

The X axis is crossed more steeply when the mid-point of the satellite's overflight is closer to the ground station. Maximum Doppler shift rate occurs when the satellite passes directly overhead, and lower rates are observed for lower elevation angle passes.

Channel Simulators configured as in Figures 2 and 3, must apply supply Doppler shift <u>rates</u> both within and beyond the anticipated ranges for verification of appropriate receiver system margin.

CHANNEL SIMULATOR: RANGE DELAY

All communication systems have some form of inherent delay in propagation between transmitter and receiver. This is true for wire-line systems, optical systems, and wireless radio systems where propagation velocity is related to the dielectric constant of the medium through which the signal passes.

Propagation velocity is expressed as a percentage of the speed of light, and in vacuums (dielectric constant = 1) and in air (dielectric constant = 1.00054) propagation velocity can be considered to be 100% of the speed of light for most practical purposes.

Therefore, in wireless communication systems the propagation delay between a transmitter and receiver can be calculated by dividing the straight line distance between the transmitter and the receiver, by the speed of light.

For the LEO satellite discussed earlier, the range delay profile of Figure 5 can be expected. Elliptical and higher orbits produce dramatically different results.

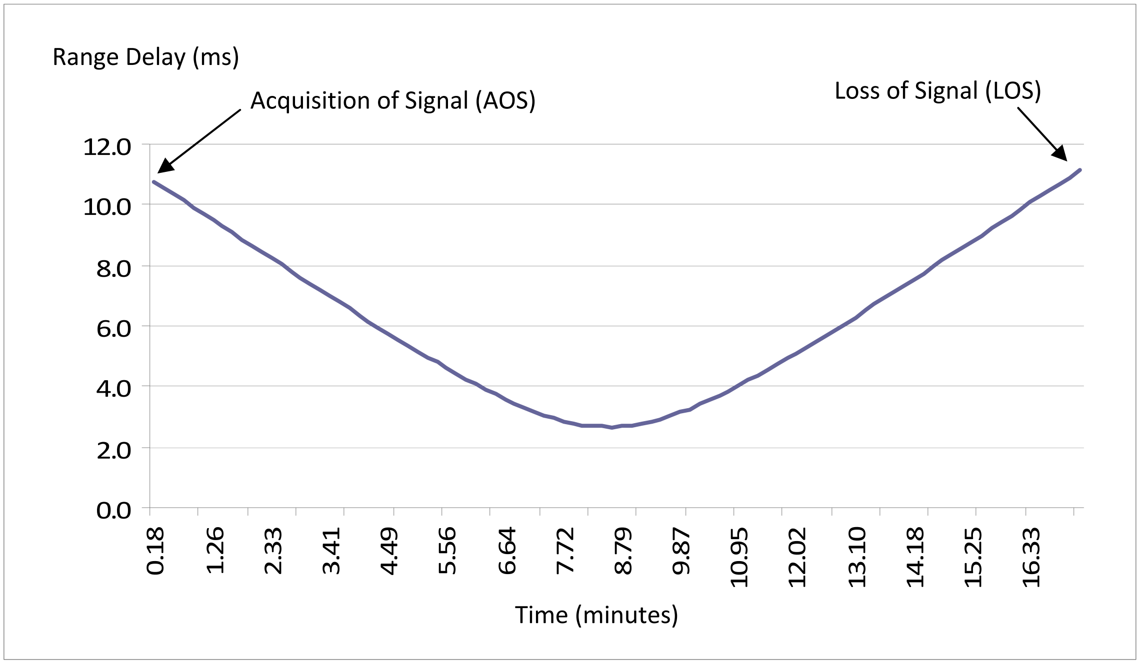

Figure 5. Range Delay vs. time for a signal from a LEO observed at a ground station.

When performing one-way tests (Figures 2 and 3), where a receiver or transmitter is being tested, the Channel Simulator must be capable of signal delay ranges dictated by both the closest and farthest separation between transmitter and receiver. Depending on orbital characteristics and ground station locations, minimum and maximum separation relates to the satellite's apogee (farthest point from the Earth) and perigee (nearest point to the Earth).

When performing complete simulations of a transmitter-satellite-receiver communications scenario as in Figure 6, the Channel Simulator must be capable of delaying for the uplink plus the downlink paths.

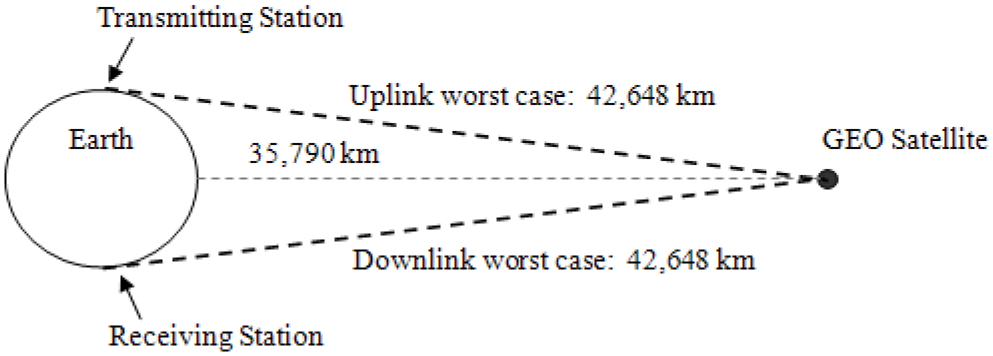

Figure 6. Maximum range for GEO satellites.

For a GEO satellite at 35,790 km above the Earth (as illustrated in Equation 2), a Channel Simulator would need a delay capacity of at least 250 ms, plus satellite transponder delay, plus margin for worst-case system analysis.

$$\begin{aligned} D_T &= (R_U + R_D) / c \qquad \textbf{(Equation 2.)} \\ &= (42{,}648 \text{ km} + 42{,}648 \text{ km}) / 300{,}000 \text{ km/s} \\ &= 0.248 \text{ s} \end{aligned}$$

where D_T = total delay in s
R_U = uplink range in km
R_D = downlink range in km
c = speed of light (~300,000 km/s)

Communications systems testing between atmospheric vehicles (aircraft, UAVs, and missiles) and between such vehicles and ground stations or satellites follow the same considerations, except that minimum and maximum delays are much smaller due to the relatively close proximity between transmitters and receivers.

CHANNEL SIMULATOR: RANGE ATTENUATION

Receiver system performance also depends on the power level of the received signal. Satellite-borne transmitters are typically low-power systems at great distances from receiver systems. Modeling dynamic signal power levels, and validating operation under worst-case conditions are key receiver system tests.

The power level of a received signal is affected by free-space path loss, which can be calculated from Equation 3.

$L = 32.4 + 20 \log F + 20 \log R$ (**Equation 3.**)

Where L = free-space path loss in dB
F = frequency in MHz
R = range in km.

For the LEO satellite discussed earlier, the path loss profile in Figure 7 could be expected.

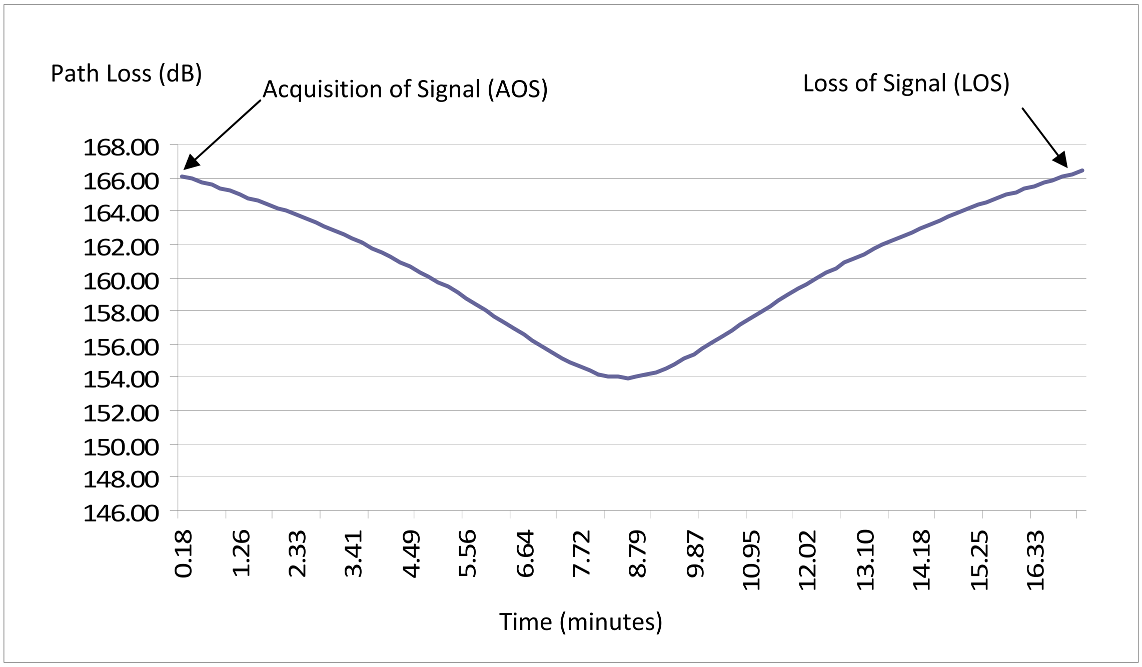

Figure 7. Path loss of a signal from a LEO observed at a ground station.

A Channel Simulator must accept a low-level input signal then further attenuate it according to the attenuation profile of the communications system being tested. To properly simulate the LEO of Figure 7, the Channel Simulator would require an attenuation capacity of at least 12 dB to13 dB.

With MEO and HEO satellites having highly elliptical orbits, or where atmospheric, Rician, Rayleigh, or Nakagami fading is to be modeled, the needed attenuation range is on the order of 50 dB.

CHANNEL SIMULATOR: NOISE

As with the Doppler, range delay, and range attenuation parameters above, all communications systems are subject to noise received by the antenna (cosmic noise and radiation from the Earth), as well as other atmospheric and man-made noise. Receiver noise itself is also an important factor.

In order that Channel Simulators be capable of creating signals truly identical to those that would be received from wireless transmitters, they must contain noise sources capable of generating expected and worst-case noise profiles.

CHANNEL SIMULATOR: PHASE CONTINUITY

Channel Simulators must perform their operations in a fully phase-continuous manner. This ensures that throughout the instrument’s capabilities, no data errors are introduced as a result of waveform discontinuities, inappropriate transitions or glitches.

The Channel Simulator must faithfully model nature in this regard, so that the instrument can be confidently substituted into the communications system for accurate and dependable results. This implies sophisticated high-resolution interpolation between commanded Doppler, delay or attenuation points.

CHANNEL SIMULATOR: ADDITIONAL SPECIFICATIONS

Channel Simulators are sophisticated instruments that provide exceptional engineering and verification value. But to maximize their true value, Channel Simulator ease of use must be strongly considered. Most users are not interested in understanding detailed orbital mechanics or propagation path dynamics in order to get the Channel Simulator to perform. Such calculations, especially those that involve multiple flying receiver/transmitter systems, or that relate to SATCOM-on-the-move, rapidly become far more complex than those included here.

For these reasons, Channel Simulators must work seamlessly with industry-standard packages that facilitate easy and powerful communications scenario development, conduct Doppler, delay and attenuation calculations, provide detailed visualization, and allow intuitive insertion of user-defined parameters such as orbits, spin and tumble models, antenna gain/coverage models, noise profiles, interference patterns, jammer systems and receiver system characteristics.

Channel Simulators must also integrate closely with user-developed software systems for simulation based on actual real-time events. Industry-standard control methods by Application Programming Interfaces (APIs) and/or Ethernet Transmission Control Protocol/Internet Protocol (TCP/IP) commands must be included for these purposes. These control methods must also result in fully phase-continuous operation.

Channel Simulator hardware should be easily connectable to other systems allowing signal taps to be easily obtained from transmitter systems, or fed to receiver systems. Industry-standard Radio Frequency (RF) upconverters and downconverters should be usable with the Channel Simulator, allowing it to be connected easily into test setups as in Figures 2 and 3, and allowing it to be designed at a lower Intermediate Frequency (IF) for cost minimization.

SPECTRUM ANALYZERS

Spectrum analyzers must be capable of demodulating detected signals, and must include sophisticated DSP engines and techniques for precise and automatic signal/modulation analysis, interference analysis, signal fingerprint matching, carrier-under-carrier detection and analysis, etc. Familiar controls, as well as frequency domain displays and constellation diagrams must be available.

These spectrum analyzers must include frequency segment monitoring, along with robust alarm generation and logging capabilities when abnormal results are observed based on frequency/time masks and metrics violations.

They must analyze and report signal quality metrics like C/N_o (Carrier-to-noise) E_b/N_o (Energy per bit to noise power spectral density), and C/I (Carrier-to-interference) ratios, as well as BER.

As with all such equipment, standard software and hardware interfaces must be provided, such that equipment can be controlled and monitored remotely.

To keep their costs low, Spectrum Analyzers can be designed at IF, utilizing industry-standard RF downconverters from received frequencies.

VECTOR SIGNAL GENERATORS

Powerful, yet easy-to-use TT&C/COMMS-focused vector signal generators are vital whenever actual signals are not available, or when signal impairments like interference, carrier-under-carrier covert/friendly signals and intentional jamming must be applied.

Such generators must easily create multiple independent signals combined at the output, each of which may be modulated differently, may be at differing data rates, and may be of diverse amplitude as illustrated in Figure 8 below. In many cases, pseudo-random data is sufficient, but in other situations, properly formatted telemetry data must be modulated onto generated signals.

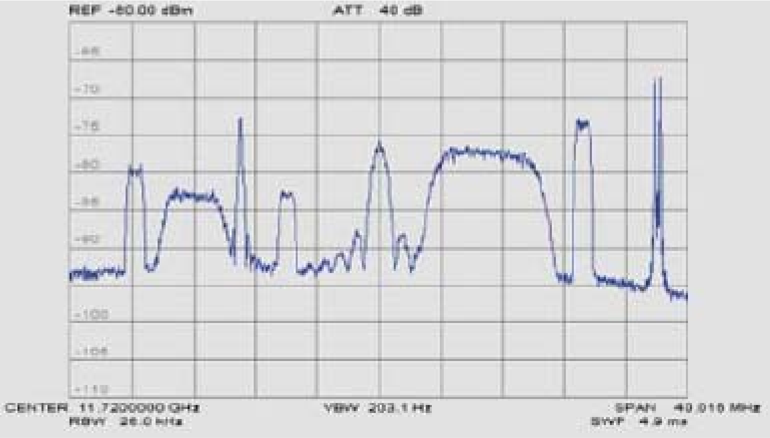

Figure 8. Vector Signal Generator capacity to generate multiple simultaneous signals.

Vector Signal Generators can also operate at IF, can be grouped together for increased channel count, and can combine their outputs with other telemetry devices.

RECONFIGURABILITY AND MODULARITY

Telemetry system instrumentation must be easily and economically reconfigurable to suit emerging and changing needs. Such design requires and benefits from the use of standard control and signal interfaces between components, both at the hardware and the software level.

Modular system architectures such as this also reduce costs by allowing the user to purchase only the portions of the system that are actually needed, yet offering the opportunity to add other modules later as shown in Figure 9.

Vector Signal Generator, Channel Simulator, and Spectrum Analyzer design at IF substantially reduces their design, component, and manufacturing costs, passing lower purchase prices to the end user.

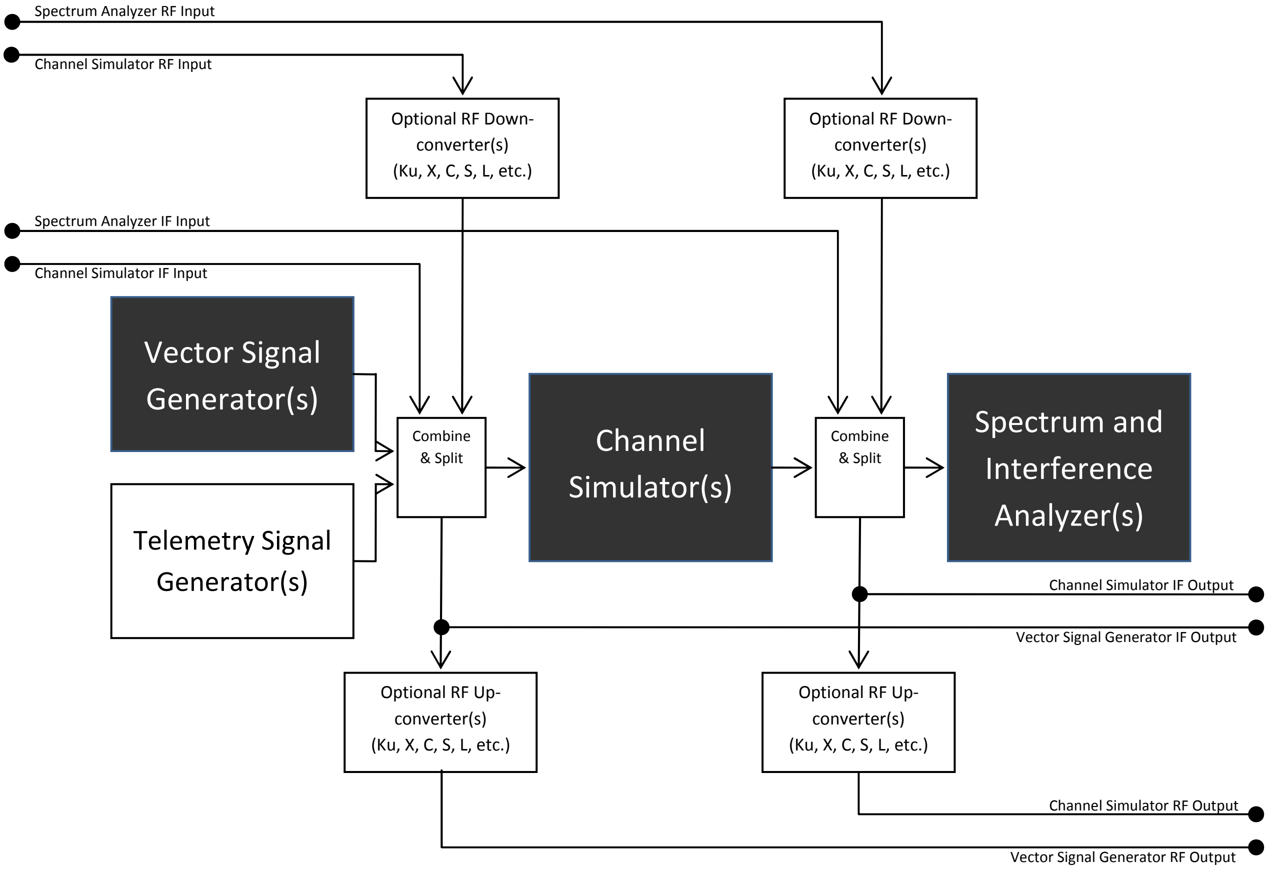

Figure 9. Modular and reconfigurable Channel Simulation and Analysis architecture.

Additional benefits of such architectures occur in the area of power consumption, heat generation, weight, and size. Further benefits in all these areas occur when software-defined instruments are utilized within the system.

A complete self-contained example system comprised of an 8-channel Vector Signal Generator, a Channel Simulator, and a Spectrum Analyzer is shown in Figure 10. This chassis contains ample room for optional RF upconverters and RF downconverters, as well as splitters, combiners, and other signal conditioning components.

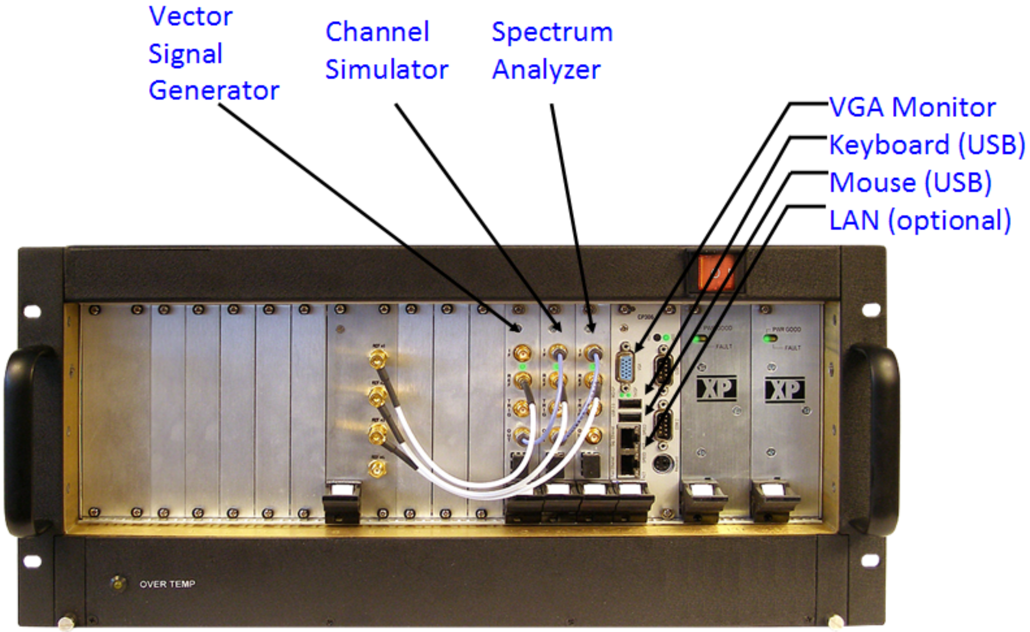

Figure 10. Modular and reconfigurable Channel Simulation and Analysis system example.

CONCLUSION

General-purpose instrumentation offers an exceptional set of features and specifications, many of which are not used however, in TT&C/COMMS applications. These features and specifications make these instruments useful for a wide variety of applications, but come at a high price for applications that do not need the capabilities. Purchase price is a major concern, but the price of necessary, but missing features for TT&C/COMMS applications, is higher yet.

Modular instruments such as Channel Simulators, RF/IF converters, application-focused Vector Signal Generators, Telemetry Signal Generators, and enhanced (but much lower cost) Spectrum Analyzers have created a new class of economical high-performance instrumentation to address TT&C/COMMS engineering and validation needs.