Broadband channel simulator for robust satellite link designs

Impairments in broadband satellite communications signals occur, but by simulating these impairments in a real-time environment, a broadband communications system design can be proven and optimized prior to production.

By Jack Anderson

In the real estate market, there are three priorities: location, location and location. In the broadband satellite communications arena, the top three priorities would be data, data and data. In mainstream, down-to-earth communications systems such as DSL, cable modems, WiFi and even cellular, high-speed access to information is fast becoming a must-have and is highly addictive. Anyone who has worked from a dial-up modem connection after getting accustomed to broadband knows what this means.

Data rates in satellites are an element of the overall capacity of the satellite. Multiple transponders, transponder bandwidths, carrier frequency, transponder receive sensitivity, transponder transmit power, communication signaling schemes, and communication data structures all contribute to the capacity equation. A recent industry study indicates that from 1990 to 2002, the average number of equivalent 36 MHz transponders on geosynchronous satellites increased from 26 to 48 transponders per satellite launched. This same study showed that the average power levels for these satellites increased by 350%, the design life increased from 10 years to almost 14 years, and the satellite size and complexity increased by factors of 2 to 5 times[1]. Shin Satellites' iPSTAR, a new generation of Internet Protocol (IP) satellites, boasts a total capacity of 40 Gbps, which they claim is a 40 times increase over current satellite capability.[2] Hughes Network Systems' SPACEWAY has a 800 Mbps downlink data rate per spot beam[3] and includes sophisticated on-board processing, dynamically switched spot beams, bandwidth-on-demand allocation and TDMA formatting. SPACEWAY will set the bar for fielded commercial satellite technology when launched this summer.

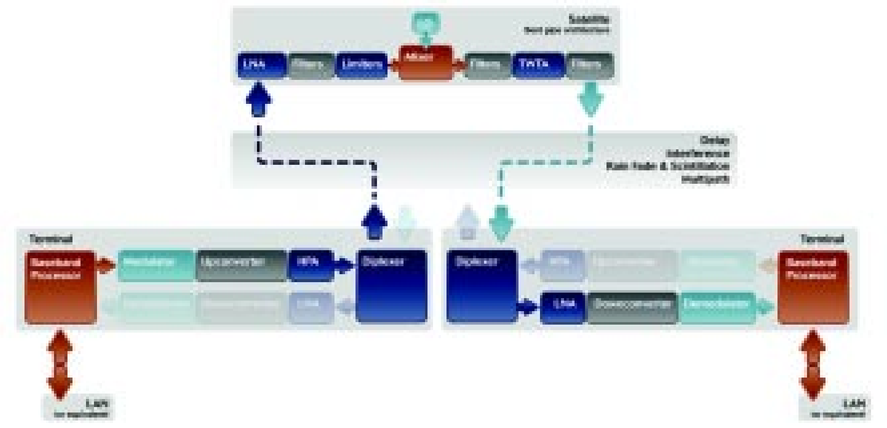
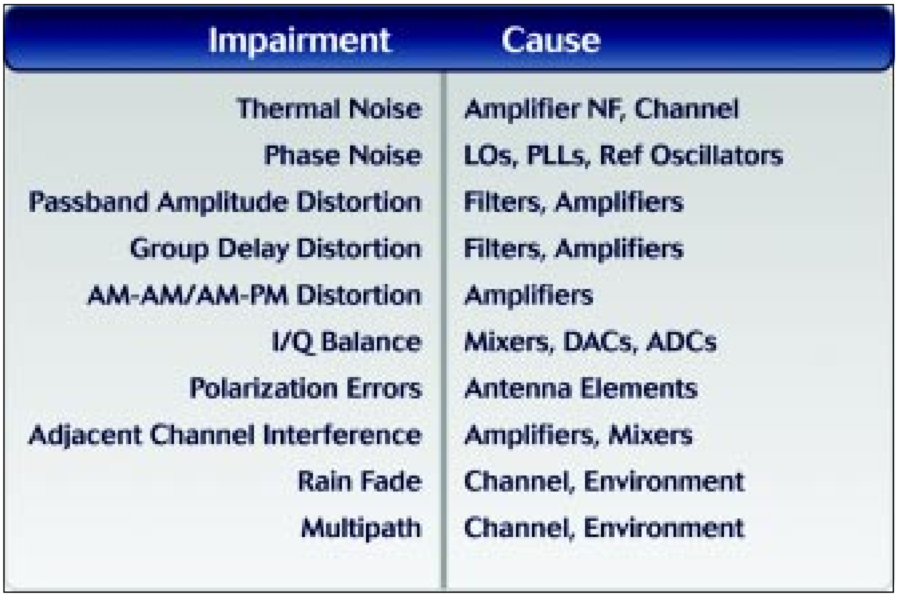


Figure 1. Notional diagram of satellite communication link.



Impairment	Cause
Thermal Noise	Amplifier NF, Channel
Phase Noise	LOs, PLLs, Ref Oscillators
Passband Amplitude Distortion	Filters, Amplifiers
Group Delay Distortion	Filters, Amplifiers
AM-AM/AM-PM Distortion	Amplifiers
I/Q Balance	Mixers, DACs, ADCs
Polarization Errors	Antenna Elements
Adjacent Channel Interference	Amplifiers, Mixers
Rain Fade	Channel, Environment
Multipath	Channel, Environment

Table 1. Channel impairments and associated causes.

The advanced broadband communications satellites being developed today are costly to design, manufacture and deploy. Most will be placed in geosynchronous (GEO) orbits. They require a significant initial capital outlay years before they are placed into service and start to see revenue returns. To this extent, the satellite designers try to maximize payload capacity, so that once in service, the satellite operator will achieve the greatest revenue stream. It is part of the fundamental return-on-investment (ROI) business calculation—the more capacity, the more potential sales.

In an ideal world, all design parameters would be maximized to obtain the highest possible capacity and performance. In the real world, real trade offs in these parameters

Figure 2. Celerity CS80072 broadband channel simulator.

must be carefully considered and modeled to ensure design goals are achieved. For example, as the carrier frequencies go up, the available bandwidth increases, but available technology to generate the downlink power decreases. And while higher bandwidths will support faster data rates, the lower power decreases the signal-to-noise ratio (SNR) at the receiver, which will limit the effective data rate achievable through the system. The trend in downlinks moving from L band (2.4 GHz) and C band (6 GHz) to Ku band (14 GHz) and Ka band (30 GHz) also bring with it the challenges of increased atmospheric attenuation, pronounced rain fade and scintillation.

Accurate results may require hours of computing time, even on the fastest processors, leading to a limitation in the number of cases simulated and the combination of impairments tried.

In addition to the move to Ku and Ka bands, other trends in the industry include:

- Increased transponder bandwidths from standard 36 MHz to 72 MHz and beyond.
- Changes in signal modulations from standard BPSK and QPSK to 8PSK, QAM, concentric PSK or Star QAM, and even OFDM[4].
- Frequency-hopped carriers.
- More robust coding, including turbocodes.

So what does this mean to the satellite design engineer?

As advanced communications satellite designs push the envelope to maximize data rates and capacities, they can leave little margin for error. Any parameter or real-world effect not analyzed or accounted for could offer surprises that lead to degraded performance and corresponding loss of revenue. The converse is that the system may be overdesigned, putting too much margin in each parameter due to unknowns or worst-case estimates, adding unnecessary cost in price, components, weight, and complexity. Many parameters and variables need to be considered, and the entire communications channel must be analyzed—both satellite and ground terminals. Figure 1 is a notional diagram of a complete satellite link for a traditional "bent pipe" configuration, showing the major components. The satellite portion shows only one transponder slice. In reality, from 30 to 50 transponders could be on the satellite.

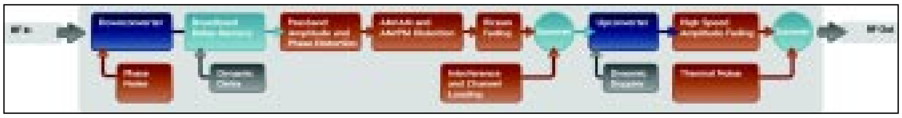


Figure 3. Major functions of an ideal broadband channel simulator.

Each component has its non-ideal performance, which can lead to an overall degradation in the system. A representative list of degradations, also called impairments, along with the component causing the impairment is shown in Table 1. The first and most basic impairment is thermal noise. With the carrier power it sets the carrier-to-noise ratio (CNR) or SNR in a channel. When SNR and bandwidth are specified, Shannon's law defines the maximum channel capacity in bits per second, a limit that is never achieved. Many papers have been written on this subject, and exhaustive theoretical studies have been performed to predict the raw bit error rate (BER) of the communications system as a function of modulation, coding and SNR.

Not as well understood but important to the overall system performance and capacity are the other impairments listed in Table 1. As the broadband system designs extend the bandwidths up to hundreds of megahertz, move to higher-order modulations, and apply powerful error correction schemes, they push the performance close to the digital boundary between low error rates and unacceptably high error rates, making it critical to accurately simulate all impairments realistically in the channel to ensure an optimal design.

Design simulation and test tools

Several approaches are available to the satellite system designers to aid in the design process. Computer modeling and simulation tools provide the designers insights into overall performance, with models that take into account a number of channel impairments. These are used to develop the basic designs and to estimate performance. This software runs on desktop computers and advanced workstations. Accurate results may require hours of computing time, even on the fastest processors, leading to a limitation in the number of cases simulated and the combination of impairments tried. There is also the chance that the models do not accurately reflect the real world.

At the other extreme, experimental satellites have been built and launched to test new communications technology and concepts in the real world using real hardware and software. These satellites include ACT, Artemis, Kopernikus, N-Star, Superbird, and Italsat F1. Satellites are costly to produce, but have been valuable test beds in refining technology and defining techniques for the broadband satellites designs of today. While satellites are the pinnacles of real-world test beds, their performance is fixed by design, leaving little flexibility to change any specification on demand. As such, impairments cannot easily be modified to test the effects on overall system performance.

Satellite channel simulators combine the best of both worlds in test and simulation, offering the advantages of accuracy and real time. One example is the Celerity CS80000 Broadband Channel Simulator (BCS) family from Aeroflex, shown in Figure 2. These simulators are laboratory instruments that create real-world channels with impairments in a controlled, accurate and repeatable manner. Because these are real-time systems with broadband RF inputs and outputs, actual hardware terminals can be used during testing. This real-time testing allows a much larger number of test cases to be run than with the software models, so that more exhaustive testing is achieved. The features are:

- Stable, repeatable simulation with defined controllable impairments.
- Real-time and full-bandwidth channels that support real hardware and fast test times.
- Worst-case scenario simulations with any combination of impairments.
- Lab instrument that minimizes costly drive testing or real satellite test times.

Other development test tools include Broadband Signal Generators (BSG) and Broadband Signal Analyzers (BSA). While not channel simulators, these instruments generate realistic satellite signals and environments with impairments as well as record and analyze signal channel performance.

Broadband channel simulators: The basics

Figure 3 shows the major functions of an ideal broadband channel simulator. These functions closely emulate the actual channel

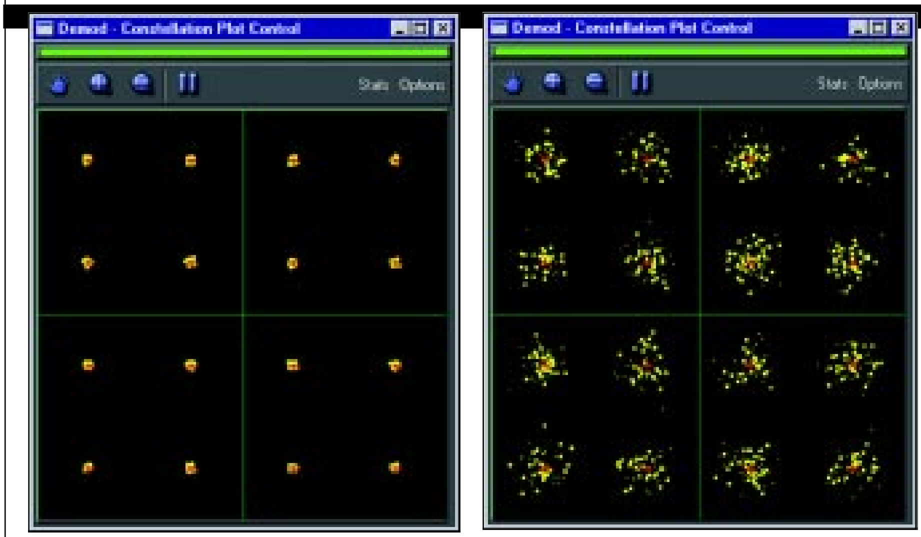


Figure 4. Constellation of 16 QAM signal with 50 dB SNR and with 20 dB SNR.

and impairments, plus offer the speed, accuracy, and flexibility to quickly try many combinations of settings.

Testing with Aeroflex channel simulators have shown that modulations up to 64 QAM can be successfully used with 40 dB dynamic ranges with minimal degradation.

Channel simulators must have *sufficient bandwidth and dynamic range* to meet the channel requirement. Without intentionally added impairments, they should faithfully pass the signals with minimum degradation. For many satellite systems, the minimum dynamic range for the simulator would be about 40 dB. For satellite communications systems that use advanced modulations, higher dynamic ranges may be required. Testing with Aeroflex channel simulators have shown that modulations up to 64 QAM can be successfully used with 40 dB dynamic ranges with minimal degradation.

Channel delay is also important. Long delays are a key part of the satellite channel. For geosynchronous satellites, the 22,300-mile average distance between the earth terminal and the satellite causes a 120-millisecond delay in uplink or downlink signals. If one hop (up and back) or two hop links are to be modeled, delays up to 600 milliseconds are needed. This is important when testing IP schemes to ensure that they work with the long satellite delays, especially in bent pipe configurations. Standard terrestrial IPs that use carrier sense multiple-access/collision detection (CSMA/CD) will not work if the delays are too long to resolve collisions, and must be modified and tested for GEO satellite use.

Dynamic delay and dynamic Doppler are required to simulate satellite or ground motion. Geosynchronous satellites are not stationary but are positioned with a slight offset from the equatorial plane (inclination), so their relative motion as viewed from the earth is a long figure eight moving mostly north and south over a 24-hour period. This motion causes delay and Doppler shifts in the signal. The delay change can be as much as 1 millisecond for a 2° inclination. The Doppler frequency shift depends on the carrier frequency, but is approximately 1 kHz with a Ku-band carrier for a 2° inclination. Low earth orbit (LEO) and medium earth orbit (MEO) satellites exhibit far greater dynamic delay and Doppler, as they move across the sky from horizon to horizon with each pass.

Iridium LEO satellites operate at altitudes of about 485 miles, orbiting the earth every 100 minutes. Delay changes of 2 milliseconds to more than 5 milliseconds occur when in view, with corresponding high Doppler frequency shifts. Dynamic delay is important in a channel simulator because the delay change actually shifts the symbol timing of digital signals, forcing the terrestrial terminal's receiver-demodulator to buffer signals in memory to operate with a fixed bit rate output network. Too much delay change can cause these buffers to overflow or underflow, with a resultant dropping of data. A key requirement in a channel simulator is the ability to change delay dynamically without glitching the phase of the signal. Tools for creating and controlling the delay and

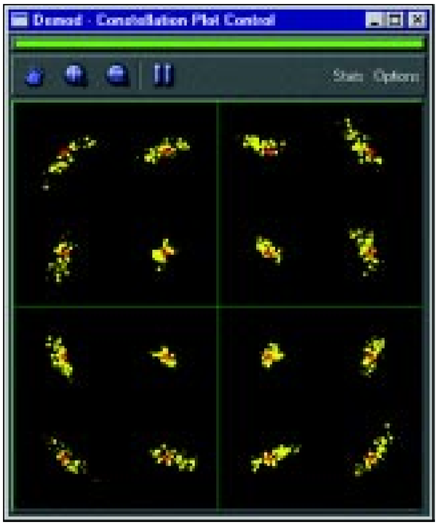


Figure 5. Phase noise effects.

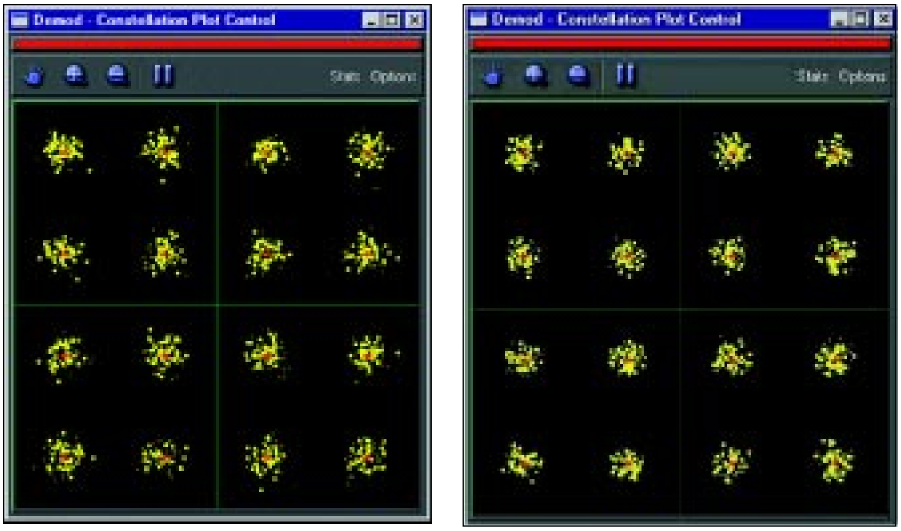


Figure 6. Passband amplitude and phase variation effects on 16QAM signal (without equalization).

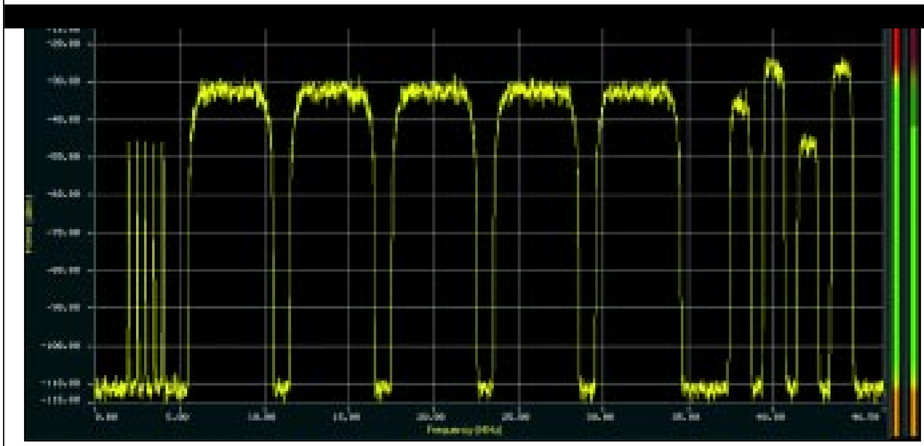


Figure 7. Realistic channel loading and interference simulation using CS25040 BSG.

Doppler scenario files over a 24-hour period are also important.

Two synchronous channels should be available in the channel simulator, with independent dynamic delay and Doppler controls. Many communications links operate in duplex mode, where the two terminals are interacting. Two simulator channels allow the flow of data in both directions to support this mode.

Simulators need to have statistically accurate additive white Gaussian noise (AWGN) generators that cover the channel bandwidth with precise control of noise power densities.

Broadband channel simulators: Advanced capabilities with realistic impairments

Now that the simulator basics are covered, the number of impairments available and the realism and control of the impairments prove the simulator's real value to the developer. The ideal simulator should simulate as many of the impairments shown in Table 1 as possible. Thermal noise is a good starting point, as its effects on system performance are well understood. But other factors such as I/Q imbalance, phase noise, phase and amplitude distortion, gain linearity, channel loading, multipath, and interference further degrade the real-world system performance, and must be considered to optimize designs and avoid performance pitfalls.

Thermal noise has already been discussed as to the impact it has in a communications channel. Simulators need to have statistically accurate additive white Gaussian noise (AWGN) generators that cover the channel bandwidth with precise control of noise power densities. This is summed into the channel, and allows accurate SNRs to be created and BERs to be measured. Figure 4 shows a constellation plot for an ideal 16 QAM signal operating at 50 Msymbols per second and 50 dB SNR, plus a constellation with the same signal with a 20 dB SNR. The noise causes the tight cluster of points designating a symbol to spread out, increasing the probability that a decision error will be made.

Phase noise, like thermal noise, is unavoidable in communications systems and occurs whenever frequency devices are used. Phase noise is seen as sidebands around a carrier and is often measured in 1 Hz to 1 MHz offsets. The higher RF carriers, faster time bases, and wider loop bandwidths used for the broadband systems generate higher phase noise with continuous and spurious phase noise distributions. Figure 5 shows the constellation plot of the16 QAM with phase noise starting at -40 dBc/Hz 100 Hz from carrier and tailing off to -90 dBc/Hz 1 MHz from carrier. Simulators, such as the CS80072, with precision control of phase noise distributions allow communications links to have the communication channel's phase noise specification tested and validated.

With broadband RF components, it is difficult to maintain passband amplitude flatness and phase linearity over the signal bandwidth. *Deviations in flatness and phase linearity* (also represented as group delay distortion) will degrade the complex broadband signals. Equalization is almost always applied as part of the demodulation process to minimize these effects. The equalizer designs of broadband systems can be confirmed using the channel simulator. Figure 6 shows the effects of 2 dB of passband ripple on the constellation of the 16 QAM signal, and the effects of 10° of passband phase deviation on the constellation.

Broadband satellites support multiple broadband signals in the channel, separated either in time (TDM), frequency (FDM), or both. *Gain transfer distortions* that include AM/AM and AM/PM distortion can degrade the system performance by causing multiple-carrier intermodulation and signal distortion. Traveling wave tube amplifiers (TWTA), a common choice for the high-power downlink transmit amplifier in satellites, can have significant gain transfer distortion even with linearizers. This distortion is the main reason why traditional satellite modulations are limited to QPSK or OQPSK. Channel simulators that simulate AM/AM and AM/PM would allow development and testing of new modulation techniques in advanced communications channels.

Simulators that inject *broadband channel loading and interference*, such as that shown in Figure 7, can uncover intermodulation problems as well as test for receiver selectivity and adjacent channel interference.

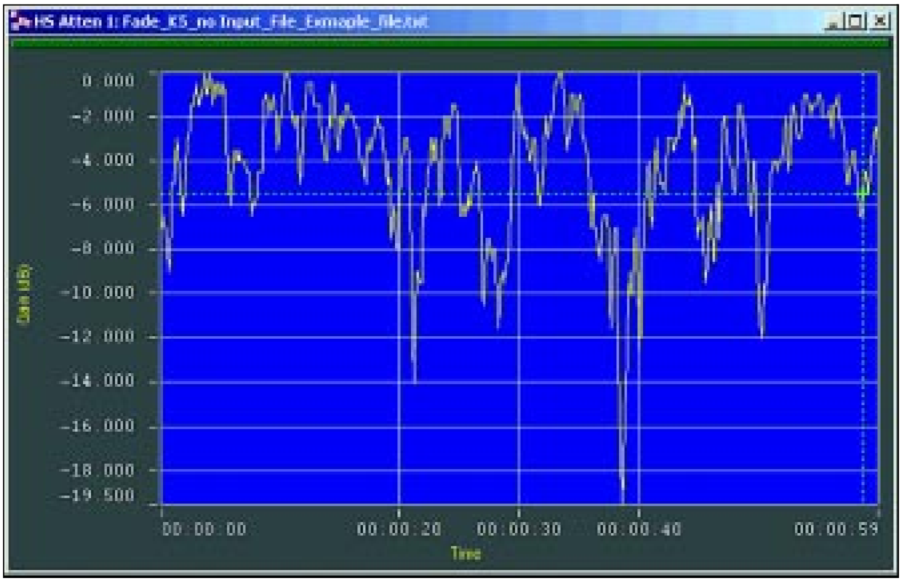


Figure 8. Received power over 60 seconds with a Ricean simulator module.

Simulators can also add co-channel interference that falls on top of the signal of interest to simulate cross polarization leakage. The multiple signal environment used for channel loading shown in Figure 7 was created using Aeroflex's CS25040 Broadband Signal and Environment Generator, which can generate up to 160 MHz bandwidth environments.

Ricean multipath effects result when the direct signal path and a number of reflected paths, with the proper simulated signal impairments, are combined at the receiver. This causes fluctuations in the received signal power (and phase and passband flatness depending on the severity). Higher frequency bands and directional antennas tend to limit these effects in most non-mobile broadband systems, but some multipath must be anticipated depending on the earth terminal placement. Simulators with accurate Ricean distributions and controls for the amount of reflected signal power (K) and fluctuation rate are useful in evaluating the effects of Ricean fading on system performance. In addition to the Ricean modules, high-speed, glitch-free attenuators can simulate rain fade and $1/R^2$ loss accurately over long scenarios. Figure 8 is the plot of received signal power over a 60-second period from a Ricean simulator module with a $K = 5$ setting.

Finally, *I/Q imbalance* needs to be considered in broadband communications systems design. Broadband modulators and demodulators are commonly designed with baseband I and Q paths. As signal bandwidths increase in broadband systems, it becomes increasingly difficult to maintain I/Q balance across the entire signal bandwidth, resulting in I/Q gain, I/Q phase, and I/Q DC offset imbalances. I/Q modulators and demodulators are part of the terrestrial terminals and regenerative satellite payloads. If severe enough, I/Q imbalance results in errors in the demodulated data and a higher BER. While simulators are useful for simulating these effects, other tools like broadband signal and environment generators can generate complex signals with adjustable precision I/Q imbalance for testing.

Conclusion

The effects of thermal noise, I/Q imbalance, phase noise, phase and amplitude distortion, gain linearity, channel loading, multipath, and interference must all be considered to optimize the system-wide design and avoid performance pitfalls. Challenges abound, but with the proper simulation and real-time real-world test tools and careful attention to these impairments, designs can be proven, performance optimized, and problems minimized prior to system production. RFD

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