Receiver Test: Overcoming Five Fundamental Challenges

Wireless system development is a demanding task, with tight constraints and innumerable tradeoffs. Constant improvements are expected in performance, cost, and time-to-market. Whether you're testing components, subsystems, or complete radios, you'll face tough challenges in RF testing. This application note offers solutions that will help you address five fundamental challenges in the development of wireless receivers:

- Managing noise figure
- Optimizing phase noise performance
- Throttling power consumption
- Making accurate RF power measurements
- Generating today's complex signals

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Managing Noise Figure in All Stages of the Receiver

Noise, and specifically signal-to-noise ratio (SNR), is a fundamental issue in wireless receivers. High noise levels will limit system capacity and coverage area, along with many associated characteristics that matter to system operators and end users. In some cases it may be possible to increase transmit power to improve SNR, but regulations and issues with power consumption usually limit this approach. In most cases, designers will need to carefully manage SNR in their receivers, subject to cost, available power, and space.

Designers often choose to optimize the noise performance of a wireless system by managing SNR within each section of the block diagram using a performance goal or a "budget" for each block. Because the effective noise performance of the blocks depends on the noise they add in comparison to their gain, the appropriate metric is the difference in SNR between each block's input and output. This r*atio of ratios*, expressed in log form, is *noise figure*.

Performance optimization, then, involves ready access to accurate measurements of the noise figure of components and subsystems. Preferably, these measurements are convenient enough to be made frequently during receiver design.

Making your best noise figure measurements

Two techniques are generally used for measuring noise figure: Y-factor method and cold-source method The *Y-factor method* is the most common for RF and microwave frequencies (Figure 1). To use this technique, connect a switchable, calibrated noise source to the DUT input and connect a noise figure analyzer or signal analyzer to the output to measure the resulting noise, and then calculate the ratio. A separate calibration measurement directly measures the output of the noise source in its on ("hot") and off states, and measures the gain of the DUT.
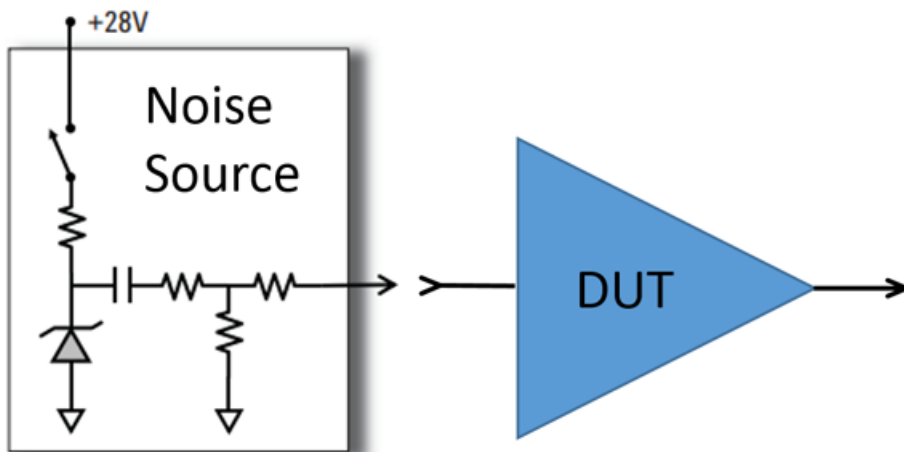

Figure 1. In the Y-factor method, the central element of the noise source is a diode, driven to an avalanche condition to produce a known quantity of noise power. The diode is not a dependable 50 Ω impedance, so it is often followed by an attenuator to improve impedance match with the presumed 50 Ω DUT.

The *cold-source method* uses a vector network analyzer (VNA) with a two-port connection to the DUT. A separate noise source is not required, and a single connection to the DUT is sufficient for the entire measurement.

Both methods are capable of yielding accurate measurements for receiver design, and both face challenges in some measurement conditions. Generally speaking, these challenges come in two forms: accurately compensating for sources of error, and separating noise in the measuring receiver from noise originating in the DUT. For this application note we have limited our discussion to amplifiers as the DUT.

Choosing a measurement method

The most accurate measurements, especially those made under unfavorable conditions (summarized below), are made using the cold source method. This method is especially valuable for millimeter-frequency measurements or when the input and output match of the DUT is poor—that is, substantially different from the 50 ohms assumed for instruments, cables, and accessories.

The vector calibration techniques of a VNA are able to account for the multiple potential mismatch errors in the measurement configuration. This reduces what is normally the largest single source of error in noise figure measurements. Impedance mismatches result in erroneous power measurements, which directly affect noise figure calculations.

Common sources of mismatch include the use of wafers, probes, or fixtures (or any type of non-coaxial connection); mismatch between the DUT and noise source or analyzer; and test system signal switching. Mismatch also generally degrades as frequency increases, so the cold-source method is often the best approach for millimeter-frequency measurements.

In practice, though, most noise figure measurements are made at RF and microwave frequencies, with coaxial connections and a reasonable impedance match between the noise source, analyzer, and DUT. For these measurements, cost and convenience lead many RF engineers to choose the Y-factor method. It takes advantage of the signal analyzer that is more likely to be on their bench. These are usually less expensive than VNAs and can provide a good combination of accuracy and measurement cost.

With these tradeoffs in mind, it important to pay some attention to the unfavorable conditions that can make measurements difficult or substantially increase error:

- **DUTs with a combination of low gain and very good noise figure:** Such devices will generate very little incremental noise. This may result in a signal at the analyzer input that is difficult to measure accurately because it is very close to the analyzer's own noise floor.
- **Conducted or radiated interference:** Analyzers have no way of separating power that is due to either conducted or radiated interference. If possible, measurements should be made in shielded enclosures, with mobile phones and networks excluded, and on battery power if practical.
- **Complex or lengthy connections or adapters:** Cabling and adapters can spoil impedance match and attenuate the noise power that is supplied or measured. Custom cabling, which eliminates the need for adapters or extra length, can be an inexpensive way to improve measurement performance and reduce error.
- **Inconsistent connections between calibration and measurement steps:** Cable and connector care and connection techniques, including proper torque, are especially important.

– **Devices that change temperature and drift during measurements:** Noise figure measurements and uncertainty calculations assume static parameters. Any drift (or other changes) after calibration or during the measurement process will have a direct effect on accuracy.

Finally, external or internal preamplifiers can improve noise figure accuracy by improving the noise floor of the measuring instruments. To be beneficial, these preamplifiers themselves should have extremely low noise figure over the frequencies of interest.

Optimizing Phase Noise Performance for Dense Constellations and Narrow Channel Spacing

Phase noise is a common issue in receivers, and it may degrade performance in a variety of ways. In particular, it can introduce errors in the process of demodulation by distorting I/Q symbol locations and by introducing inter-carrier interference in OFDM systems. It can also compromise SNR. Some amount of phase noise is present in signals at the receiver input, and more is inevitably added in subsequent downconversion processes.

Phase noise increases substantially at small offsets from carriers and, as you would expect, its effects are more consequential at narrower carrier spacings. Many current wireless systems use OFDM physical layers, with subcarrier spacings that are getting narrower in an effort to increase spectral efficiency.

Narrower subcarrier spacings tend to increase the problems associated with a given amount of phase noise; however, the obvious solution of simply reducing the phase noise of oscillators or synthesizers in receivers may not be practical. Overall reduction in phase noise usually has monetary costs, and often requires more power or physical space. Fortunately, OFDM systems expand the envelope of tradeoffs in this area through the use of subcarrier tracking. OFDM demodulators continuously track known "pilot" subcarriers and symbols embedded in transmitted signals, using this information to correct for some amount of phase noise in real time.

In receiver designs, the challenge is to understand the effectiveness of the tracking, and therefore the maximum amount of allowable phase noise in the design, as a way to optimize receiver performance, cost, and battery life.

Controlling the phase noise in your test system

Some signal generators are able to produce signals with extremely low phase noise, well below that of the devices or subsystems they'll be used to substitute for. This performance is useful as a reference in measuring residual phase noise or narrowing down issues in troubleshooting. However, the more important function of a signal generator in the overall optimization of a receiver—especially with pilot tracking—may be to generate signals with a known, appropriate amount and spectral distribution of phase noise.

For the generation of downconversion chain signals or OFDM with precisely impaired phase noise performance, the Keysight N5182B MXG X-Series signal generators use real-time baseband processing to provide a phase-noise-injection capability. In most cases the amount of noise and the spectral shape can be specified by a phase noise pedestal level and the frequency break points for the beginning and end of the pedestal. Figure 2 shows the relevant signal generator configuration screen with its target curve and the corresponding measurement by a signal analyzer with a phase noise measurement application.
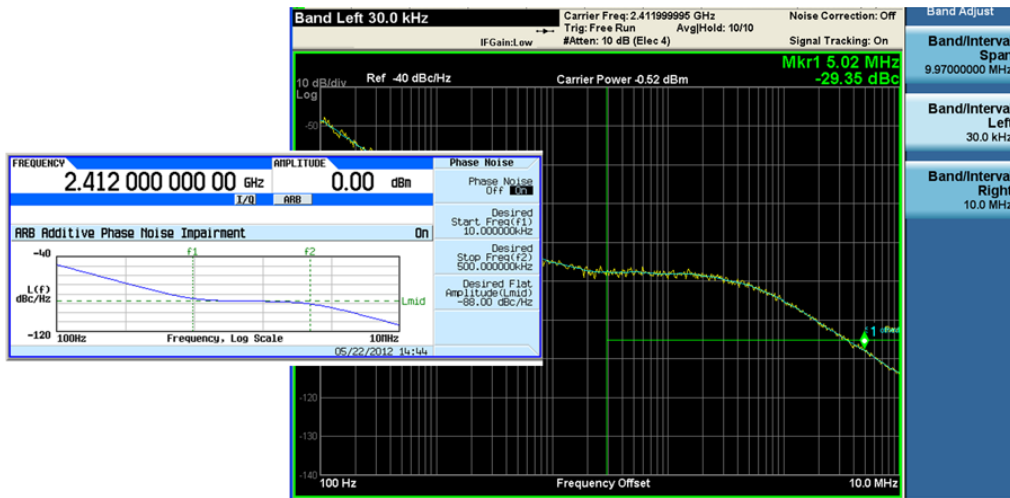
Figure 2. The configuration screen for specifying added phase noise in the Keysight N5182B MXG signal generator is shown at left, including the anticipated phase noise curve. The corresponding measurement of actual phase noise by a signal analyzer measurement application is shown at right.

Assessing modulation quality

Another major element of testing and system optimization is to verify the effect of this phase noise on modulation quality as the receiver sees it, with measures such as error vector magnitude (EVM). EVM is a common linear measurement of signal impairment. For the purpose of optimizing phase noise, it's useful to assume the signal impairment is dominated by phase noise. It is then straightforward to use the rule-of-thumb that the pilot tracking effectively "tracks out" phase noise at offsets up to about 10 percent of the OFDM subcarrier spacing (e.g., 31 kHz for a 312.5 kHz subcarrier spacing). [1]

EVM can then be estimated by integrating the single-sideband (SSB) phase noise power at offsets greater than 10 percent of the subcarrier spacing and less than the channel bandwidth, and adding 3 dB to convert SSB power to double sideband (DSB) or total power:

$$\text{EVM (dB)} \approx \text{[integrated SSB phase noise]} + 3 \text{ (dB)}$$

Here, the SSB phase noise is integrated starting at 10 percent of the subcarrier spacing and extending up to the channel bandwidth.

In Figure 2, the power integration is performed by band-power markers in the measurement application and the result is –26.35 dBc when 3 dB is added to the –29.35 dBc marker reading. The loop-closing process of generating impaired signals and verifying their impact on receivers is a powerful tool for optimizing OFDM systems and other complex designs.

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1. The "10 percent of subcarrier spacing" rule-of-thumb is thought to be slightly conservative; however, it is sufficiently accurate for most optimization estimates.

Throttling Power Consumption While Ensuring Signal Quality

As with traditional mobile devices that demand frequent charging, customer satisfaction and competitive success involves optimizing power management. Consequently, the physical size and weight of power sources must be compatible with design goals.

Because most portable devices are powered by rechargeable batteries with limited capacity, they are expected to operate with low power consumption. In particular, batteries and power converters often have significant output resistance and limited dynamic power capability in the form of voltage or current slew rates. The use of standard lab power supplies, with their extra capacity, may actually obscure underlying problems.

The limitations of batteries, power supplies and or power converters create tradeoffs in the form of instantaneous and total power versus RF performance. These tradeoffs are important to both functional capability and competitive viability. For example, device size, weight and battery-life drive customer preference and can be important competitive differentiators.

One fast-growing area has special challenges: Internet of Things (IoT) devices, specifically those that intermittently exchange small amounts of data with hosts or other devices. These devices are often powered by small primary batteries instead of rechargables or AC power, and are expected to operate months or years between battery replacements. Household examples include thermostats, motion sensors, light switches, and alarm sensors.

Low power draw during active operation is essential. However, RF engineers face another layer of challenges driven by ultra-low power quiescent modes. Understanding quiescent power consumption, along with managing the transitions between sleep states and active operation, is essential to achieving customer expectations of extremely long maintenance or replacement intervals.

Mastering the tradeoffs in power consumption

Achieving reliable, power-efficient operation—especially at low or very low power levels—demands additional engineering tradeoffs and related tests that inform them. Whether your focus is devices or subsystems, understanding actual power consumption is a good place to begin, and DC power analyzers that combine multiple DC power supplies and detailed power measurement are a convenient solution. This relatively new product category makes it easier to understand power consumption in greater detail (Figures 3 and 4).
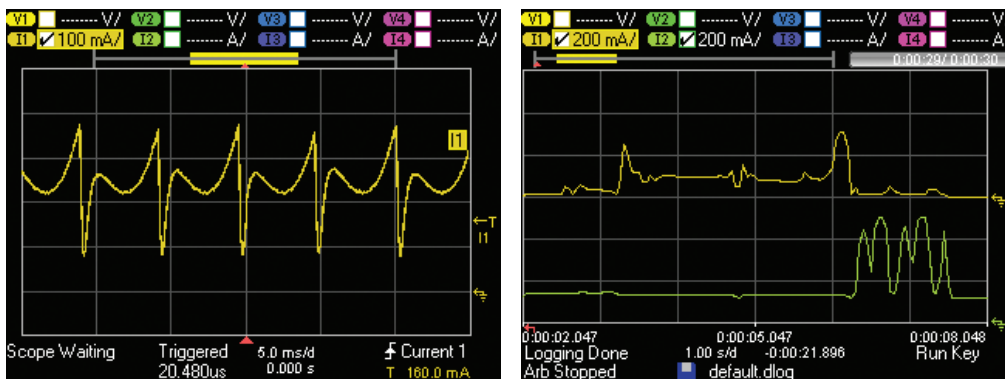

Figure 3. The dynamics of current consumption are shown over 30 ms in scope view (left) and over 30 seconds in data logger view (right). Measurements such as these provide a more complete understanding of the real-world power demands of a device or subsystem.
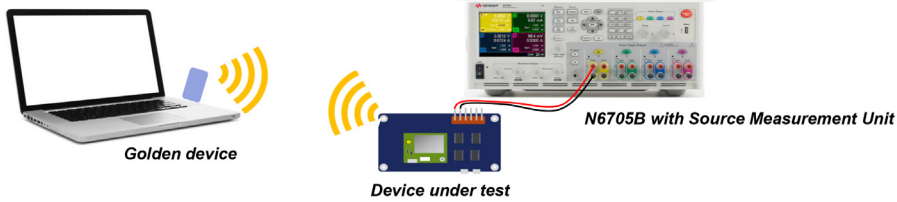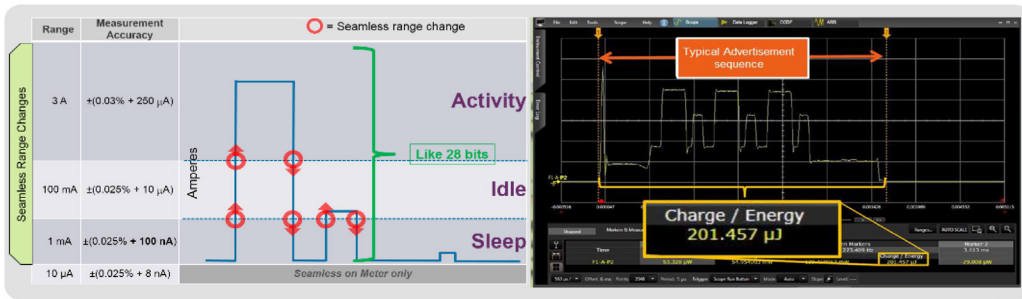
Figure 4. A DC power analyzer performs dynamic power consumption analysis, as a way to understand battery drain and power supply demands in detail.

Challenges related to power consumption have short- and long-term aspects, and both must be addressed. Power analyzers include time-domain (oscilloscope) measurements that will help you understand power demand variations, especially peak power that may quickly drain a device's power source. For another perspective, data-logger or strip-chart views reveal power requirements over longer periods, typically seconds or minutes. These measurements are often needed to characterize total power consumption when designing power supplies, converters, and batteries. They can also help you understand power dissipation of subsystems or components that, for example, have a specific thermal budget.

Emulating voltage and current profiles

With the preceding as a foundation, the next step is tackling the tradeoffs in providing an adequate power supply while minimizing space and cost. Relevant tools include power supplies that can provide deliberately and realistically limited power outputs. These supplies allow engineers to optimize tradeoffs at the margins, and ensure adequate performance without over-sizing the supply (Figure 5).
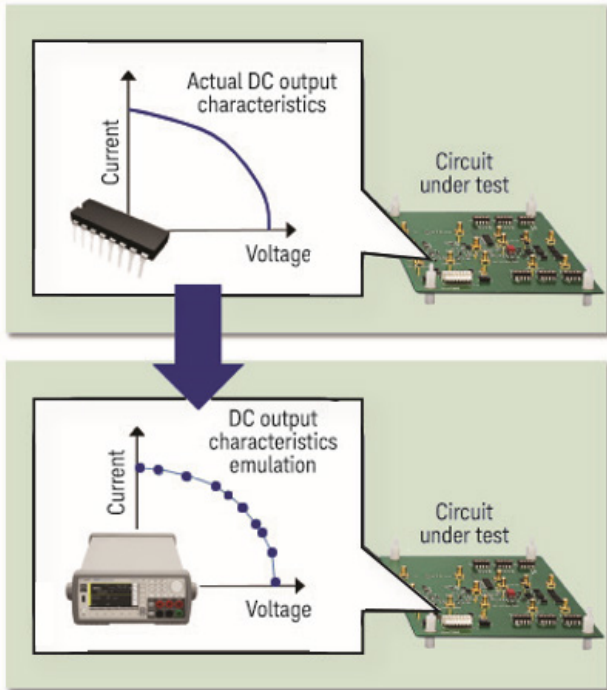

Figure 5. Keysight's low-noise power source can emulate the DC voltage and current output characteristics of many different power sources, providing insight into real-world behavior in limited-power conditions.

Products such as the Keysight B2961/62A low-noise power sources provide realistic output emulation, including programmable output resistance, very low current values, and very low noise. These sources can operate in voltage/current emulation mode, useful for supplying ADCs, DACs, RFICs, VCOs, sensors/transducers, and crystal oscillators. The emulation mode can be configured using a map of voltage/current points to simulate devices such as solar cells.

Measuring and analyzing extremely low current levels

In portable devices, achieving extended operation on extremely low power may require a form of power scheduling to avoid excessive demand from simultaneous digital and RF activities. To characterize this scenario, instruments capable of measuring low currents at wide bandwidths can be used in combination with external power supplies or the system's own supply. One such instrument is a device current waveform analyzer such as the Keysight CX3300A, another relatively new solution in DC power measurement. The analyzer is generally used with analog probes appropriate to the circuit under test, and can also be equipped with digital probes to coordinate measurements of power and device control activity (Figure 6).
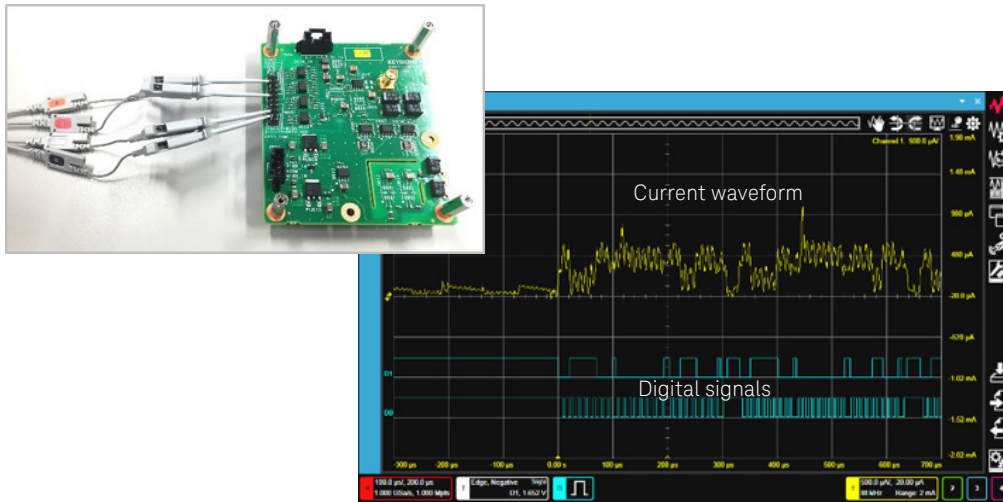

Figure 6. The device current waveform analyzer has analog and digital inputs, and can align their analysis. Data bus status can be correlated with current consumption, and can be used to trigger other measurements such as those of an RF or vector signal analyzer.

In making these measurements, the analyzer's 200-MHz bandwidth captures current transients that may tax the power supply or damage circuits. Digital probing provides a measurement trigger, and deep memory allows captured current waveforms to be reviewed at times other than the trigger itself. [2]

In some devices, adequate DC power is a concern at any stage, state of charge, or design configuration—and all of these can affect RF performance. RF power and distortion are logical consequences of system DC power limitations, but there are other possible effects, including increased modulation error. The ability to couple RF measurements with instantaneous DC power status and system digital activity is a powerful optimization and troubleshooting technique, especially during transmit or receive transitions, multiple radio operations, and heavy DSP activity.

The device current waveform analyzer's ability to trigger on patterns, states, and glitches is a good match with the signal capture, playback, and post-processing capability of vector signal analyzers (VSAs). The general measurement sequence starts with the device current waveform analyzer's triggering features, using them to generate an external trigger that activates a single measurement or signal capture with the VSA. Positive or negative (pre-trigger) delays can then be used to align measurements of voltage or power consumption (and associated glitches or other problems) with measurements of RF power, spectrum, or modulation quality.

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2. For additional tips, check out **7 Hints for Precise Current Measurements**.

Making Comprehensive, Accurate RF Power Measurements of Complex Signals

Accurate power measurements are critical at all phases in development and production, and frequently will be made on time-varying signals. While the signal in question may be the output of a complete transmitter, it may also be the input to or output from a separate component or subsystem in either a transmitter or receiver.

In wireless systems, many RF signals are noise-like and the power level must be measured across a specified frequency band or channel. In these cases, the ability to produce accurate and repeatable measurements requires that we integrate measured power over a range of frequencies and then average over time, over signal bursts, or both.

Power meters and signal analyzers both have roles in wireless measurements, and have different strengths. Let's take a closer look at each.

Choosing the right tool: power meters

Power meters are inexpensive and precise, providing excellent frequency range and source match. Those that use interchangeable *power sensors* provide exceptionally broad frequency coverage while maintaining good impedance match that contributes to measurement accuracy. Power meters can be used at different points in a transmitter block diagram, or on individual blocks, to characterize gain elements, attenuators, or frequency converters. Some have a very useful peak power capability, enabling measurements of time-varying signals, dynamic elements, thermal phenomena or power supply-related effects (Figure 7).
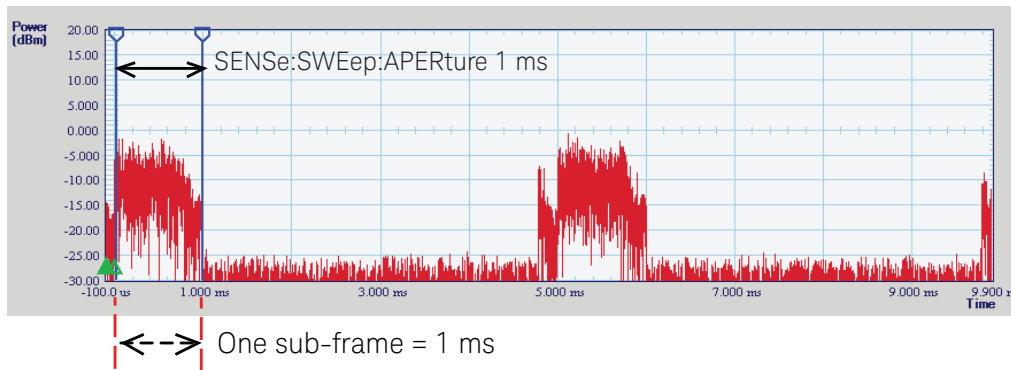

Figure 7. Many power meters can measure power versus time, with selectable timing parameters. This trace is a measurement of one sub-frame of an LTE signal, using a burst average power setting.

The broadband nature of power meters is a key limitation. Their broadband response means that they may not accurately measure low-level signals that are near large ones, and that they have a higher amplitude floor for accurate measurements. As broadband devices, they cannot use narrow measurement bandwidths to filter out broadband noise, spurious, interference, etc.

Choosing the right tool: signal analyzers

Signal analyzers have less ultimate power accuracy than power meters for high-level individual signals. However, the analyzer has many advantages in RF transmitter testing, whether characterizing complete transmitters or specific subsystems.

The primary advantages for signal analyzers in power measurements for wireless systems are a result of their frequency and time selectivity and often a combination of both. Frequency selectivity allows for channel or band power measurements such as ACPR (Figure 8). This selectivity also reduces the broadband noise power (noise floor) included the measurements, thus increasing accuracy and dynamic range, principally for small signals or signals near the noise floor.
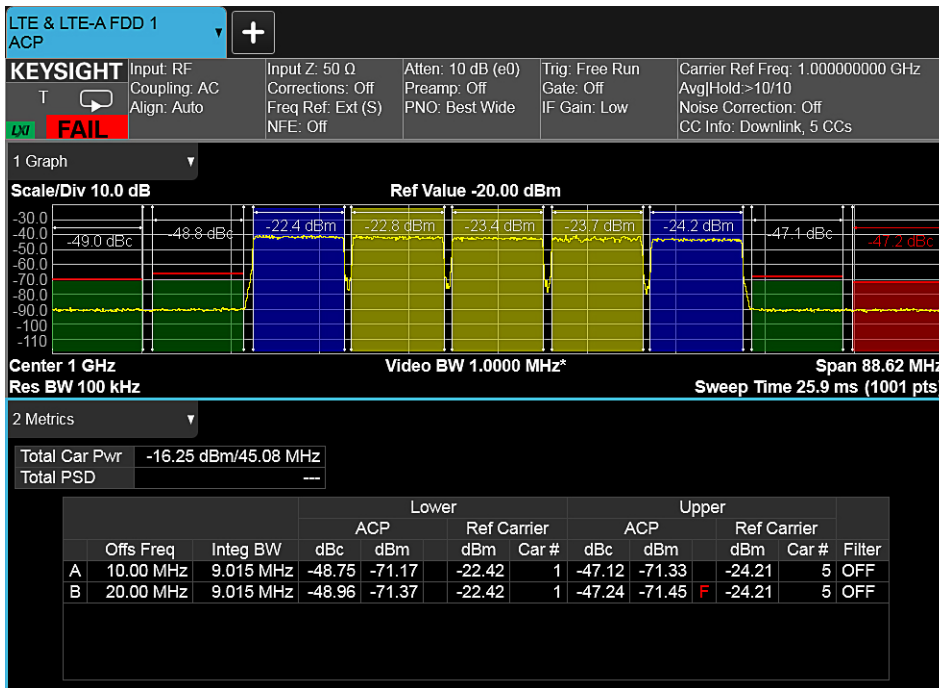

Figure 8. A common power and distortion measurement in wireless systems is adjacent channel power ratio (ACPR). Measurement applications automatically configure and compare measurements of main and adjacent/alternate channels, and present results in graphical and tabular form.

Compared to peak power meters, signal analyzers have greater time-domain selectivity for power vs. time measurements. In fact, one of their principal uses in power measurements is the selective measurement of power vs. time in a single channel, revealing the dynamic power behavior of that channel during a burst or frame.

Using measurement apps to handle complexity

It is often necessary to make relative measurements over multiple adjacent and alternate channel bandwidths, focusing on specified channel spacings and power limits. Measurement applications can easily handle the following measurement challenges:

– Signal power and statistics vary over the transmission intervals, so it is frequently necessary to measure specific portions of transmitter bursts or frames. One example is the training sequence in OFDM signals, where power and timing are well defined.
– Averaging types and detectors should be compatible and consistent, otherwise there will be inconsistent and unpredictable (i.e., non-repeatable) results.
– The distortion reflected in an ACPR measurement may be part of a budget, where there may be different limits at different stages of a device.

Generating Today's Complex Signals

Wireless mobile-data and voice services have a constant need for increased channel capacity, and the same is generally true for wireless LANs. To meet these needs, designers are using a variety of techniques that make receiver testing and signal generation more challenging for the RF engineer. Examples include complex modulation types, frame structures, and multiplexing schemes. Multi-carrier schemes and multi-channel extensions such as MIMO and carrier aggregation only add to the complexity.

The complexity of these techniques is equaled or exceeded by the standards and regulations that govern them, making it difficult to reliably create the fully compliant signals needed to test components, subsystems, and receivers. For many wireless systems, this complexity and the need for dynamically changing and non-repeating signals have made it necessary to employ specialized software to drive RF and microwave signal generators.

On their own, signal generators are useful for many aspects of receiver testing. They can substitute for oscillators and synthesizers, and can produce a variety of continuous wave (CW) and modulated interference and blocking signals. Some generators are also available with built-in vector arbitrary waveform capability, deep memory, and wide modulation bandwidth. Thus, they're an ideal platform to combine with application software to generate complex, standard-compliant signals.

For example, the Keysight X-Series signal generators are designed to utilize the dozens of Keysight Signal Studio software products, many of which address the complex and proliferating wireless-data and wireless-networking standards.

The basic capabilities of Signal Studio software are designed for component and transmitter test. They generate the signals needed to test ACPR/ACLR, EVM, channel power and occupied bandwidth. For receivers, more advanced capabilities are available for testing sensitivity, selectivity, intermodulation, and blocking. The software provides validated, standards-compliant signals as well as predefined test setups. The signals are optimized for ACPR and EVM, and can be used for multi-carrier and multi-format testing.

While many signals can be generated by downloading blocks of data to arbitrary waveform memory in a signal generator, some receiver tests require real-time signal generation. Examples include closed-loop HARQ and timing-adjustment testing for LTE systems. The advanced capabilities of the software can also be used to create fully channel-coded signals for analysis of receiver bit/block/packet/frame-error-rate (Figure 9).
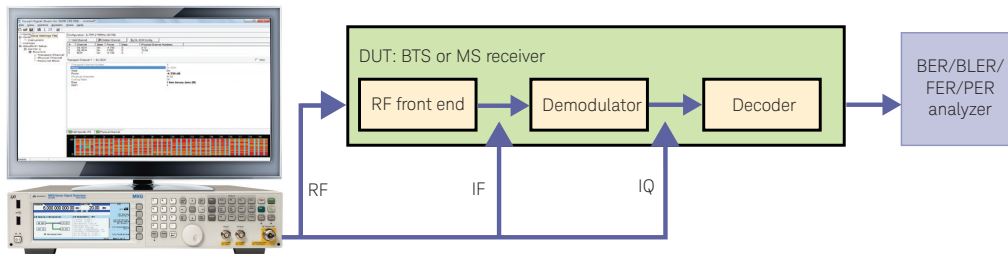

Figure 9. The Signal Studio software's advanced capabilities allow it, in combination with vector signal generators, to generate fully channel-coded signals to realistically evaluate receiver throughput.

One compounding aspect of the challenges of modern wireless signals is the rapid evolution of standards. A benefit of standards-based signal generation software is its ability to be updated and re-validated to keep up with ongoing changes.

Conclusion

Wireless systems pose design and measurement challenges in many areas, from DC to RF, microwave, and even millimeter frequencies. The best solutions will come from your experience, insight, and creativity, combined with signal generators and measurement software that allow you to generate the signals required to effectively test your DUT.

For more tips on making better measurements, visit the RF Test blog. For more information about Keysight signal generators, visit www.keysight.com/find/sg.

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