Use precise, tunable noise to test data systems

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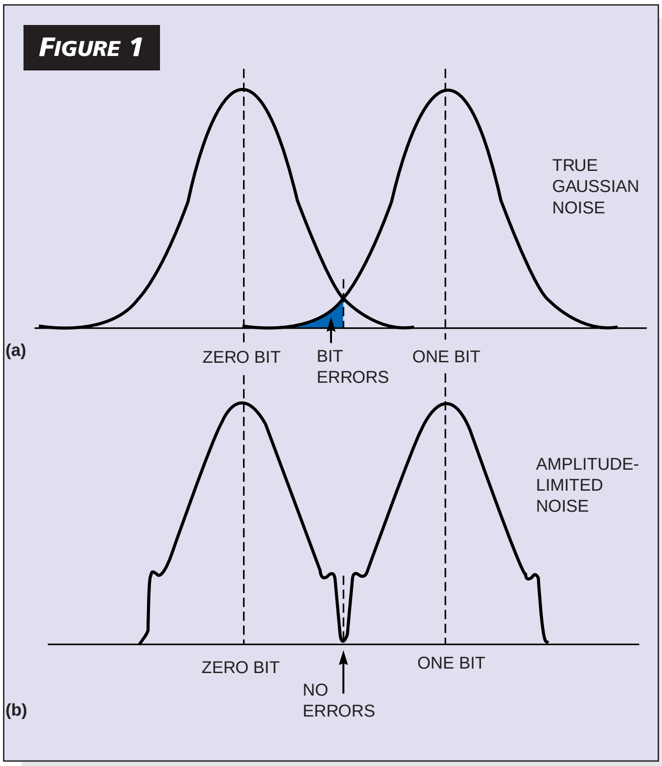
A binary sequence generates wideband tunable analog noise more accurately than a commercial noise generator does.

You cannot quantify the response of a data-transmission system to a noisy input unless you test it with noise having precisely known characteristics. The accuracy of your measurements cannot be better than the calibration of the level, bandwidth, and amplitude distribution of the noise source. You can simplify the measurement of data receivers' performance by using an accurate synthetic noise source.

You should test a bit synchronizer, the part of a receiving system that translates a demodulated signal into clean digital data, by feeding it with a mixture of binary data and Gaussian noise and then measuring its output bit-error rate for SNR. A bit-error-rate tester (BERT) measures the error rate of a network under normal operating conditions (**Reference 1**). It rarely provides noise injection because generating calibrated, variable-bandwidth, Gaussian noise is difficult to do at a reasonable cost.

Traditionally, a skilled technician used a BERT; several noise generators; a wideband rms power meter and an array of mixers, filters, and attenuators to measure the performance of a bit synchronizer. This technician would plot the bit-error rate against the signal-to-noise level one point at a time. The setting, measurement, and adjustment of the noise level for each point took perhaps 10 minutes of painstaking work. Plotting the complete curve at one bit rate took a couple of hours or much longer if the application required measurements at low bit-error rates. (Even an approximate bit-error-rate measurement can take a great deal of time. Because 10% accuracy requires counting 100 errors, confirming that a 10-kbps system has an error rate better than 10^{-9} takes more than 16 weeks.)

FIGURE 1



Bit errors occur when noise peaks cross the bit polarity threshold. The shaded area shows the fraction of "one" bits that are mistaken for "zero" bits (a). If the noise generator limits its output, the tester counts no errors (b).

The characterization of a bit synchronizer requires you to plot its error-rate curve at many bit rates. This task can take several days and does not take place too often. When choosing which bit synchronizer to buy, you have to assume that the manufacturers have done such a test and have accurately reported the results. Generating binary data for the test is easy; the data comprises a continuous stream of bits from a pseudorandom sequence. This sequence simulates random data but is predictable. Most BERTs offer a dozen or more sequence lengths and can synchronize themselves to the received data even if it contains as much as 10% of bit errors. Once synchronized, the

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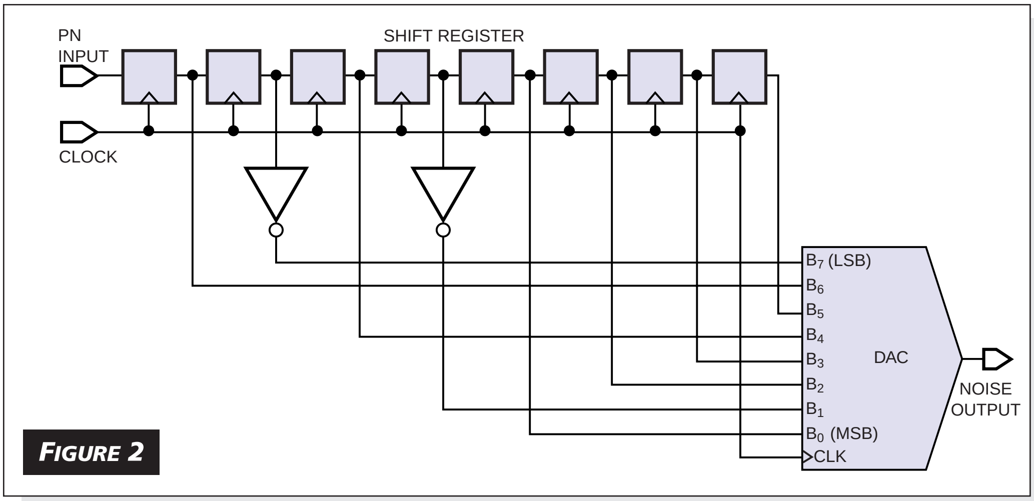
BERT knows what bits to expect and can thus report how many errors it finds. Knowing the bit rate and the elapsed time, the BERT can calculate the bit-error rate.

FIGURE 2

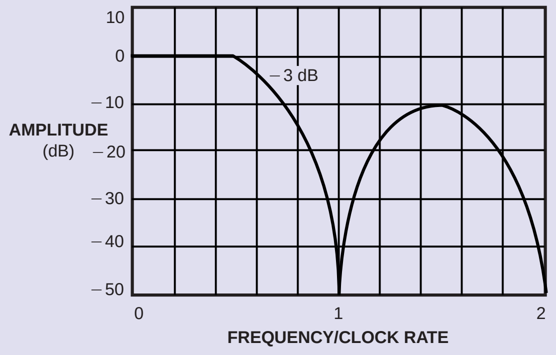


The spectrum-flattening filter uses a unique interconnection between the shift register and the DAC inputs. You can combine the outputs of 12 such filters to generate Gaussian noise.

You can easily set the data amplitude because the signal is, in effect, switching between two dc levels. The tough problem is mixing the correct level of noise with the binary signal. This noise is easy enough to specify. The InteRange Instrumentation Group standard for testing bit synchronizers says that the synchronizers' 3-dB bandwidth should be five times their bit rate. Within this bandwidth, the noise power should not vary significantly with frequency (**Reference 2**). In telemetry testing, you measure the reference-noise power in a bandwidth equal to the bit rate. You must know this power to an accuracy better than the resolution that the test requires; an absolute accuracy of 0.1 dB is desirable. To measure the bit-error-rate with both light and heavy noise, the noise power must be adjustable over approximately 12 dB.

The amplitude distribution of the noise should be Gaussian, implying that the noise contains occasional peaks that are many times the noise's mean amplitude. To avoid getting misleading test results, the noise amplifier must not clip these peaks, because you are trying to count the bit errors they induce. A noise generator that clips its output can lead to the generation of no errors (**Figure 1**). Even the test signal generator's output amplifier needs a head room approximately ten times the amplitude of the binary signal.

FIGURE 3



The synthetic noise spectrum is flat to 45% of the clock rate but has secondary peaks at 150 and 250% of the rate.

A typical commercial noise generator is a fixed-bandwidth, fixed-amplitude device. Its rms output amplitude is usually specified to lie within a 6-dB range. Its flatness (the variation of its output amplitude with frequency) may be no better than 1 or 2 dB. Its amplitude distribution is specified only as a peak-to-rms ratio of, typically, 5-to-1. Even at a single bit rate, a commercial noise generator can give misleading results (**Reference 3**). When you change the bit rate, you must change the bandwidth of the noise generator to match the rate. The good news is that lowpass filtering makes the noise more Gaussian; the bad news is that it reduces the noise's rms amplitude. You have to amplify the noise to retain the same SNR.

At low bandwidths, the output of a wideband noise generator is so tiny that you need to switch to a generator designed for a low-frequency output. An instrument intended to test bit-error rates over a six-decade bit-rate range, a common requirement, might need a dozen noise generators, a wideband variable-gain amplifier, and a wideband rms power meter to set the amplitude of the noise. This equipment could be expensive and cumbersome. In designing such a BERT, you quickly realize that noise generation is the crux of the problem. The BERT requires a noise generator with a calibrated amplitude and a Gaussian distribution that you can tune over a wide frequency range without a change in amplitude.

In the late 1960s, Hewlett-Packard sold generators that lowpass-filtered the output of a binary pseudorandom sequence to achieve audio-frequency noise. The advantage of such a generator was that, because what you now know as a FIR filter performed the filtering, the output amplitude was constant. The noise bandwidth was proportional to the frequency of the clock driving the sequence generator. A litera-

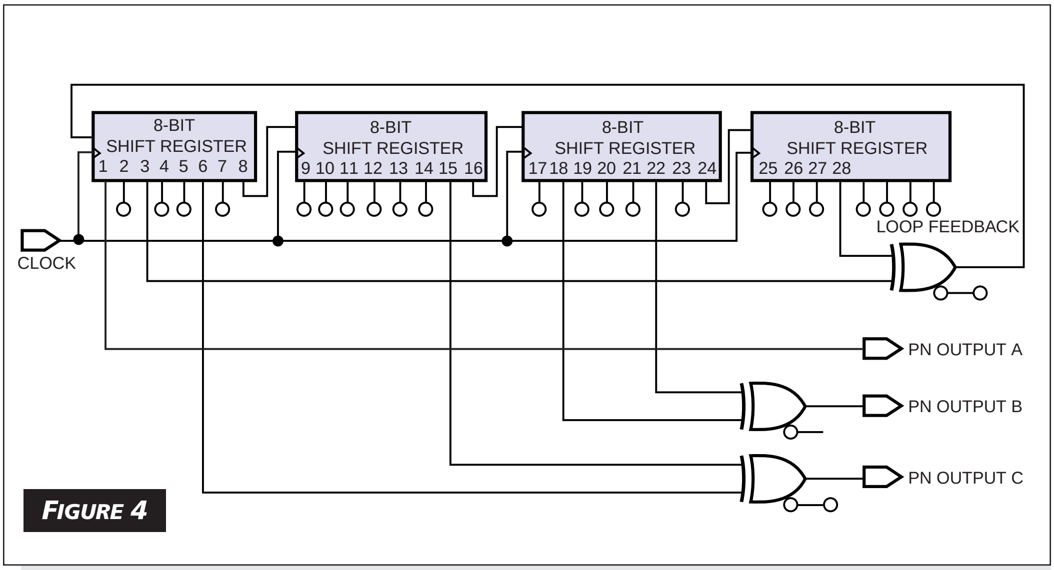


FIGURE 4

In a pseudorandom sequence, you can achieve taps many millions of bits apart by exclusive-ORing the shift-register bits. For example, the delay between outputs A and B is 77,111,602 bits and that between A and C is 199,945,782 bits. This number provides effectively uncorrelated output sequences.

ture search reveals many papers describing variants of this idea. They all have one thing in common: The noise bandwidth is about one-twentieth of the shift-register clock rate. This tester needs noise flat to 100 MHz, so the classical designs would require a 2-GHz shift register.

Previous designs achieved a Gaussian output by averaging a binary sequence over time. This approach uses only the lower part of the (sine ω)/ω frequency spectrum of the pseudorandom sequence, inherently making the noise white. To solve this problem, you can separate the two problems: making the spectrum flat and making the distribution Gaussian. A little experimentation shows that you can approximate a FIR filter having the inverse of the (sine ω)/ω shape using a shift register and a DAC. The binary weighted inputs to the DAC are not the optimum coefficients for a FIR filter but at least the amplitude distribution of the DAC output is uniform. That is, when you feed a long pseudorandom sequence to the shift register, all possible DAC input states, other than the all-zeros state, occur equally often. (This situation is the “window property” of a pseudorandom sequence.)

By tinkering, you may find the optimum 5-bit interconnection between the shift-register bits and the DAC inputs. **Figure 2** shows the 8-bit arrangement that leads to the flattest and widest bandwidth correction for the (sine ω)/ω spectrum. The DAC output has a spectrum that is flat to within 0.2 dB to as much as 45% of the shift clock rate (**Figure 3**). Its 3-dB bandwidth is 59% of the clock rate. Incidentally, **Reference 4** shows an approach using a shift-register-to-DAC interconnection to achieve odd output spectra, albeit not this flattened one. Once you generate a wideband, uniformly distributed noise source, the remaining problem is to make it Gaussian. A brute-force solution is based on the Central Limit Theorem. Loosely stated, this theorem is that the sum of many uncorrelated uniform distributions tends to a Gaussian distribution.

A total of 12 summed distributions is enough to give an output that has a 6-to-1 peak-to-rms ratio. This approach is better than using a typical commercial noise generator because you can predict the deviation from a true Gaussian distribution (**Reference 5**). You can compensate for this difference in the bit-error-rate computation. You can get “uncorrelated” sequences by using two master pseudorandom sequence generators, one with 28 bits and another with 31. These generated patterns repeat every 268,435,455 and 2,147,483,647 bits, respectively. By exclusive-ORing bits from the shift register, you can make taps into each sequence at points many millions of bits apart (**Figure 4**).

Each tap drives an individual 8-bit shift register connected to its own high-speed DAC. Using triple-video DACs saves space. You trim the output of each DAC to a standard level and sum the 12 currents to generate the analog noise output. The noise bandwidth is more than half the shift clock frequency, and you can use boards that generate noise tunable to 100 MHz. At a 200-MHz clock rate, the noise pattern repeats about every 91 years. However, if you reset the shift registers to a given initial pattern, the noise repeats exactly. This approach is useful when testing two competing bit synchronizers because you can test both with exactly the same data and noise, eliminating statistical artifacts from the results. This noise source allows you to automate bit-error-rate measurements, greatly speeding the production-line testing of bit synchronizers.

The analog noise output makes a small step every clock period. This step reflects the fact that the FIR filter flattens the first lobe of the (sine ω)/ω spectrum but does not suppress the lobes that occur at frequencies higher than the clock rate. Because you are testing with a noise bandwidth five times the bit rate, the shift clock rate is 10 times the bit rate. The equipment under test significantly attenuates the higher frequencies in the noise. Other applications might require a tunable lowpass filter to remove the noise above the clock frequency.

If the high-frequency lobes are present in the output, measuring the noise amplitude with an rms meter can give misleading results. However, you can easily calculate the effective output noise power from the known output from each DAC. You can rely on the inherent accuracy of the noise generator in routine measurements, but it is wise to check it from time to time with a spectrum analyzer. Generating noise tunable to 100 MHz requires expensive ECL parts, fast DACs, and skill in laying out high-frequency circuits. If you need, say, 10-MHz noise, you can use common TTL parts and cheap DACs. You can implement the shift registers and FIR filters as an FPGA, yielding a more accurate noise generator than any current commercial generator. You could tune this generator down to zero frequency, and it could be cheaper than today's fixed-bandwidth units (**Reference 6**). EDN

References

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Author's biography

Tom Napier graduated from Aberdeen University in Scotland with a BS in physics and an MS in electronics. He spent nine years developing spacecraft-communications equipment for the Signal Recovery Group of Aydin Corp and is now a consultant and writer.