NOISE GENERATORS

GENERATION OF NOISE

APPLICATIONS OF NOISE

Noise is a broadbanded signal generated by environmental effects, such as lightning, or by man-made electrical devices. Two common categories of noise are thermal noise and shot noise. Looney (1) describes thermal noise as an electromotive force generated at the open terminals of a conductor due to the charges bound to thermally vibrating molecules. This type of noise is often referred to as Johnson noise in recognition of the first observations of the phenomenon (2). On the other hand, shot noise is associated with the passage of current across a barrier. For instance, a circuit or an appliance that produces electric arcing produces noise. Shot noise was first described by Schottky using the analogy of a small shot patterning into a container (3). Noise can be felt in audio systems as a crackle. Noise appears as white or black spots on a television screen.

Noise is generally characterized as a source of corruption of information and therefore is treated as an undesired signal. Noise contaminates informational signals to a certain extent by superimposing extrasignal fluctuations that assume unpredictable values at each instant. Noise has been studied extensively in the literature because noise reduction is one of the major goals. A more compelling reason for the study of noise is its potential application in real life. These applications encompass biomedical engineering, electronic circuits, communication systems, cryptography, computers, electroacoustics, geosciences, instrumentation, and reliability engineering. This article addresses the various noise generation techniques and implementing them in analog and digital circuit technology and concludes with a discussion of typical applications.

MODELING OF NOISE

A mathematical model of a phenomenon, such as noise, allows us to understand its generation, characteristics and application well. We start with the observation that the structures of thermal and shot noise are similar, although their sources are different. Both types of noise can be represented as a random wave form consisting of a sequence of peaks randomly distributed in time. A noise signal can be modeled by a random process $X(t)$ with a probability distribution for the values of x it assumes. Any particular set of outcomes $\{(t, x_t)\}$ of the random variable X_t is called a realization of the noise process. An adequate characterization of such a random process can be often made with first- and second-order statistics. The first-order statistic of $X(t)$ is the expected value $E[X(t)]$ and the second-order statistic is the autocorrelation function $R_X(\tau) = E[X(t)X(t + \tau)]$, where E is the expectation operator. When the first- and second-order statistics do not change over time, the process is called wide-sense stationary (4).

Power spectral density, a standard measure used to describe a wide-sense stationary process, is defined as the Fourier transform of the autocorrelation function $R_X(\tau)$ (4):

$$S_X(f) = \int_{-\infty}^{\infty} R_X(\tau) e^{-j2\pi f\tau} \, d\tau \tag{1}$$

With this modeling, we can analyze the spectra of noise. White noise is a wide-sense stationary process with zero mean. It has constant power spectral density over all frequencies. Stated another way, white noise is a process that is uncorrelated over time. The most mathematically tractable noise is the Gaussian wide-sense stationary process, where at each time t the probability distribution for the random variable $X_t = X(t)$ is Gaussian.

Colored noise is a variation of white noise which arises from the fact that actual circuits attenuate signals above certain frequencies. Therefore it makes sense to truncate the white noise spectral density at both extremes. Noise with this spectral characteristic is termed pink noise.

Apart from thermal noise and shot noise, a third category of noise observed in electronic systems is the $1/f$ noise. It is so called because the power spectral density of this noise varies with frequency as $|f|^{-\alpha}$, where α takes values between 0.8 and 1.2. This type of noise is exhibited by biological and musical systems in addition to electronics (3). $1/f$ noise is variously called current noise, excess noise, flicker noise, semiconductor noise, and contact noise. It is applied in medical treatment and also in engineering, justifying the need for inclusion in our study.

NOISE GENERATION TECHNIQUES

Noise can be generated in many different ways. A diode tube operating at its saturation point produces broadband noise. A semiconductor diode is an inexpensive source of noise generation. When operated in the fully conducting region, the diode produces broadband noise. A current-carrying resistor produces thermal noise. It is necessary to condition noise signals by proper amplification, modulation, and filtering to suit one's application at a desired bandwidth. In our discussion of noise generation, we concentrate only on semiconductor techniques because approaches based on vacuum tubes are antiquated now.

The noise generation schemes range from simple mechanical techniques to electronic methods employing both analog and digital circuits. Inexpensive noise generators can be realized with discrete components and basic building blocks available in the IC market. We classify the noise generators into two categories, namely, analog and digital, based on their implementation.

Analog Techniques

Under this category, we discuss three different approaches: (1) a mechanical scheme, (2) amplifying inherent noise in op-amps, (3) oscillator method, and (4) using the chaotic behavior of deterministic systems.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 2007 John Wiley & Sons, Inc.

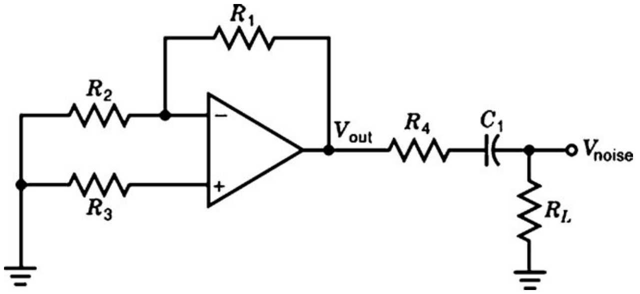

Figure 1. A simple analog noise generator based on amplification of op-amp input noise.

Mechanical Approach. For audio-frequency noise, a very simple scheme can be devised at home or in the laboratory without any sophisticated circuits or components. Dunn (5) uses just a linen-covered phonograph and a foam-covered microphone. A piece of linen cloth is tied to the turntable and a foam-covered microphone is used to pick up the signal. As the turntable rotates, the microphone's foam cover rubs along the surface of the linen, producing sound with a nearly flat spectral density in the audio-frequency range of 20 Hz to 20 kHz. Dunn shows that by using a good hi-fi microphone and a broadband amplifier, the output signal closely approximates white noise over the audio-frequency range. Other mechanical approaches include the use of gears and radioactive decay (6).

Amplification of Inherent Noise. The schematic of a relatively simple op-amp noise generator is shown in Fig. 1, which uses a single bipolar input amplifier and some discrete components. The principle used here to generate wideband noise is to amplify its own input noise in a decompensated op-amp (7). Many op-amps have large 1/*f* input noise components. A bipolar input op-amp is chosen because bipolar devices exhibit much less 1/*f* noise than MOSFET devices.

In the figure, the op-amp is used as a fixed-gain stage amplifier with a closed-loop gain factor:

$$G = 1 + R_1/R_2 \tag{2}$$

If the input resistors R_2 and R_3 are chosen small, the thermal noise of the amplifier is forced to a small value. This choice of low values for the resistors also helps keep the amplifier's current noise component negligibly small when it is converted to voltage noise. Thus, the dominant noise of the circuit is the input voltage noise of the amplifier.

The choice of a single gain stage amplifier of the type shown in Fig. 1 results in a frequency-independent noise. This contrasts with multistage amplifiers which may have peaks in the output noise response caused by frequency compensation effects. The values for resistors R_1 and R_2 can be designed by knowing the typical noise of the op-amp from data sheets and the required level of noise across the load R_L. The output is coupled through a blocking capacitor C_1 which removes any amplified dc value at the output of the amplifier. However, the value of this capacitor should be large enough to pass the lowest noise frequencies of interest. Interested readers may refer to Ref. 7 for a detailed circuit diagram and typical component values used to generate a noise of 50 nV/$\sqrt{Hz}$. Op-amp AD829 is used in the circuit which features flat voltage noise in the range of 100 Hz to 10 MHz.

Oscillator Method. A popular analog class of noise generators is the oscillator method (8), which samples the frequency noise or instability of free-running oscillators. In this scheme, the output of a fast oscillator is sampled on the rising edge of a slower clock using a D flip-flop. Oscillator jitter causes uncertainty in the exact sample values, ideally producing a random bit for each sample. For further details, readers may refer to 9.

Using Chaos in Deterministic Systems. Another elegant way of generating white noise is based on the observation that certain simple deterministic systems exhibit chaotic behavior (10). The chaos or noise is generated by iterating a map either electronically or in a software program. A simple and most widely studied system for generating chaos is the logistic map (10) given by:

$$x_{i+1} = 4\lambda x_i(1 - x_i), \quad i = 0, 1, 2, \ldots, 0 \le x_0 \le 1 \tag{3}$$

The asymptotic behavior of the system described by the parabolic transfer function of Eq. (3) depends on the value of λ. McGonigal and Elmasry (11) show that values of λ between 0.89 and 1.0 result in oscillations without any detectable period. In fact, this is the region of chaotic behavior leading to power spectral density corresponding to white noise.

A noise generator can be implemented in hardware to test actual instruments or in software for simulation. McGonigal and Elmasry (11) use a multiplier and a difference amplifier to realize the term $x_\mathrm{i} - x2_\mathrm{i}$ of the parabolic transfer function of Eq. (3). A variable-gain amplifier connected to the output of the differential amplifier, as shown in Fig. 2, allows variation of λ. The iteration of the transfer function is realized by the feedback of the $x_{\mathrm{i}+1}$ signal as the next x_i input. The clock-driven multiplexer and the storage capacitors shown in the figure separate the impulses at the output of the circuit. During clock signal ck, the voltage on capacitor C_1 provides the input x_i whereas the resulting output $x_{\mathrm{i}+1}$ is stored on C_2. During <overline>ck</overline>, the roles of the capacitors are reversed leading to two iterations of the parabolic function in every clock cycle. The IC numbers and typical values of the discrete components are shown in the figure to generate a power spectrum from dc to 1 kHz. Experimental study in 11 confirms that the signal is uncorrelated in the chaotic region and that the power spectral density remains flat in this region. Interested readers may refer to 11 for further details of the circuit and a trace of the power spectrum.

The software implementation of the deterministic-chaotic, variably colored, noise generator is shown in Fig. 3. Colored noise is generated by organizing chaotic elements into a hierarchy and coupling them (12). Each element of the hierarchy is modeled as a recursive loop whose output is a sequence of impulses. The unit delay element shown in the figure separates the instances of impulses of varying amplitude at the output. The gain unit and the nonlinear amplifier implement the map $x_{\mathrm{i}+1} = g_\mathrm{n} f(x_\mathrm{i})$. The output at

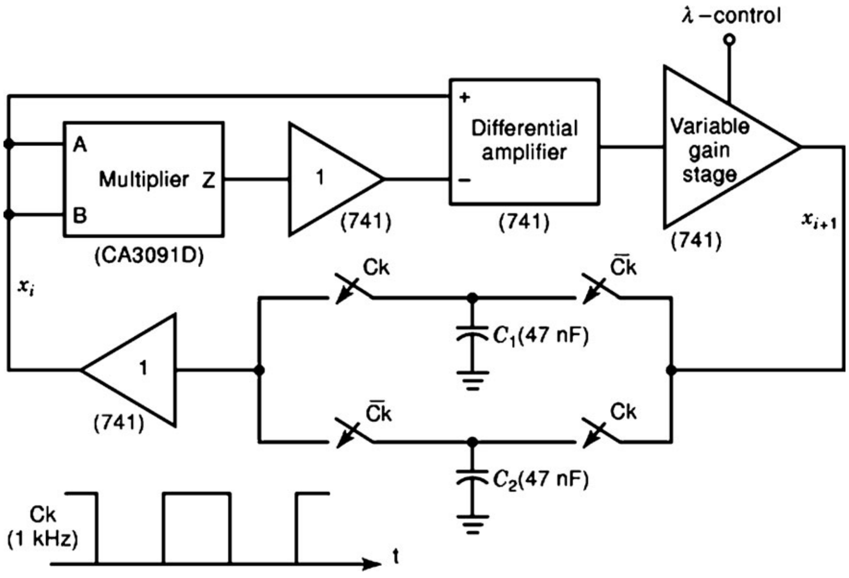

Figure 2. A low-frequency noise generator based on logistic map (from 11, courtesy of IEEE, © 1987 IEEE).

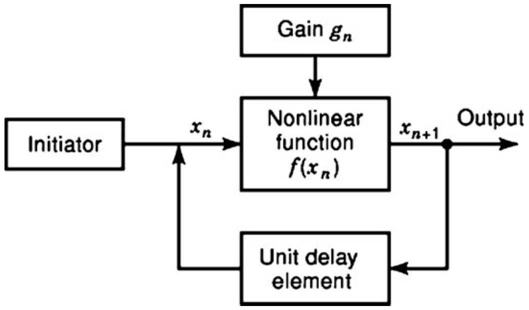

Figure 3. Block schematic of a software-based, deterministic-chaotic, variably colored noise generator.

any instant becomes the input at the next instant. The initiator block is used only to set the amplitude of the first impulse and is then disconnected. This software setup yields sequences of impulses which are essentially aperiodic and hence noiselike from a practical point of view (12).

Researchers have used discrete, nonlinear, one-dimensional maps (13) that yield a transition between regions of chaotic motion to produce 1/*f* noise. The circuits used to implement such discrete maps are usually switched-capacitor type because discrete maps are described by nonlinear, finite-difference equations and they can be easily and accurately implemented by switched-capacitor circuits. Delgado–Restituto et al. (14) build a programmable prototype to generate colored noise to test systems with spectral density proportional to 1/*f*. They use op-amps and switched capacitors to realize a chaotic, one-dimensional, piecewise-linear discrete map that yields a hopping transition between regions of chaotic motion. Murao et al. (15) propose a simple switched-capacitor circuit that realizes a one-dimensional, nonlinear, discrete map as opposed to a piecewise-linear approximation. With an IC and a couple of logarithmic and antilogarithmic amplifiers, they can synthesize a simple 1/*f* noise generator over a wide range of frequencies compared with the previous method of Delgado–Restituto et al. (14).

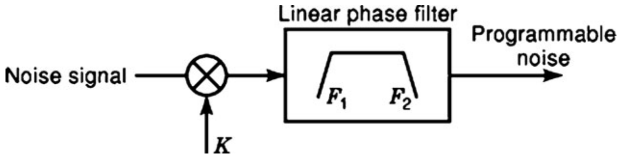

Figure 4. Structure of a programmable noise generator.

Of the four techniques of noise generation based on chaotic behavior of deterministic systems discussed here, the first is used for white noise generation, whereas the next three implementations generate colored noise. Although colored noise is derived by properly filtering the output of white noise sources (16), the direct methods described here are simpler and lend themselves to easy VLSI implementation. Some other simple IC-compatible chaos generators are found in 17 and 18.

Programmable Noise Generators. It is often desirable to have a programmable noise generator. The variability is achieved by multiplying the noise signal by a factor K and then passing the signal through a noise filter, as shown in Fig. 4. A linear phase filter passes frequencies between F_1 and F_2, thus band-limiting the filter output noise. In the simulated noise generator of (19), the output is sampled at a particular rate and stored in a data array. The statistics of the output data, such as mean, variance, min, and max are stored in another data array. This kind of programmable noise generator produces uniform Gaussian noise whose output noise power is set by adjusting the K factor shown in the figure.

Digital Techniques

The first generation digital noise generators utilized random waveforms based on telegraph signals to obtain random noise (20). For application in modern digital circuits, however, pseudorandom number sequence generators provide a better basis. Pseudorandom numbers are generated with linear congruent algorithms (21). If noise is needed

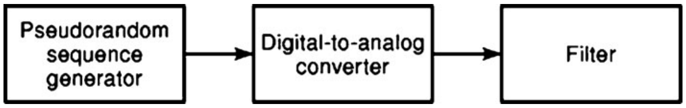

Figure 5. Block schematic of a basic digital noise generator.

in analog form, the numbers generated in binary form are converted to analog quantity. The analog output at the converter is essentially Gaussian white noise. This signal can be filtered appropriately to obtain colored noise. Figure 5 shows the block schematic of a digital noise generator.

Linear Feedback Shift Register as Random Number Generator. The digital circuitry implementing the pseudorandom number generator can be realized using a linear feedback shift register (*LFSR*). An LFSR consists of two basic digital building blocks, D-type flip-flops and exclusive-or gates. The LFSR draws theory from cyclic error-detecting codes (22) where all algebraic manipulations on polynomials are done in GF(2), that is, Galois field-modulo-2 addition, subtraction, multiplication, and division of binary vectors. A k-stage LFSR generates at most $(2^k - 1)$ distinct binary patterns which then repeat on itself. In general, the length of the sequences generated depends on the size of the LFSR and the polynomial representing it. If the polynomial representing the LFSR is primitive (22), the LFSR generates a maximal length sequence $[(2^k - 1)$ vectors$]$. If the polynomial is irreducible but nonprimitive, then the length of the sequence is not maximal and depends on the initial contents of the LFSR, called the seed. The presence of internal memory in the LFSR makes the choice of the seed critical for nonprimitive case. In the primitive case, the seed does not affect the statistical properties of the output. However, if all of the flip-flops are set to zero, the LFSR remains dormant and is useless.

The upper block of Fig. 6 shows an LFSR implementation of a primitive polynomial of degree six:

$$x^6 \oplus x \oplus 1 \tag{4}$$

where $\oplus$ is the exclusive-or operator. In this implementation of LFSRs, the output and selected internal stages of the LFSR corresponding to the nonzero terms of the polynomial are exclusive-ored and fed back to the input. The pseudorandom digital output sequence is plotted in Fig. 7. A clock frequency of 1 MHz is used to run the LFSR. Because a six-stage LFSR is used, the period of the pseudorandom output waveform is 63 μs. For clarity the figure shows a couple of periods of the waveform.

In the following, we describe several implementations of digital noise generators. They all have LFSRs as the basis for random number generation and use low-pass filtering to obtain the analog noise signal.

Analog Conversion by Time Integration. Alspector et al. (23) use a low-pass filter to convert the digital waveform at the outputs of the LFSR to a voltage signal. The cutoff frequency of the filter is kept at just a few percent of the clock frequency used to drive the LFSR. This arrangement has the effect of performing a time integration over many bits. If each bit is equally likely (i.e., a 0 or 1 with equal probability) as is the case in LFSRs, the value of this integration follows a binomial distribution that approaches Gaussian for a large number of bits. This creates a Gaussian pseudorandom noise source whose statistical properties are analogous to thermal or shot noise. A variable amplifier with gains low enough to avoid any coupling is used at the output.

Analog Conversion by a Resistive Network. D'Alvano and Badra (24) use a resistive network to convert the digital signal to an analog signal, as shown in the lower block of Fig. 6. The shift register outputs are linearly combined through the resistive network which also plays the role of the coefficient set of a discrete-time FIR filter. These weights provide a low-pass transfer function with a raised-cosine impulse response. The output level at the filter is adjusted through a 1 kΩ trimmer.

The probability density function of the noise signal at the output can be predicted because of the random nature of the binary sequence generated at each of the shift-register outputs. The random binary variables added to form the noise signal are statistically independent from one another. From the central limit theorem (4), it follows that the probability density function of the signal at the output is asymptotically Gaussian.

To illustrate noise generation, we have performed a simulation using commercial software produced by MicroSim Corporation, USA. Figure 8 shows a trace of analog noise observed at the output of the op-amp (see Fig. 6). What is shown in Fig. 8 is repetitive noise. The periodicity in the noise is an undesirable feature, yet inevitable when small-size LFSRs are used for pseudorandom number sequence generation. The periodicity can be broken by randomly changing the seed of the LFSR. The periodicity can also be improved by lengthening the shift register. Interested readers may refer to (24) for details of the circuit which produces truly random noise.

High-Frequency Noise Generation. A shift-register-based noise generator can be realized for *RF* noise power metrology (25). Superconducting rapid, single-flux, quantum (*RSFQ*) logic (26) is used to meet the requirements of low noise and fast switching necessary to generate noise in the gigaHertz range. In the RSFQ logic, the binary information is coded by flux quanta with the value $\phi_0 = h/2e$ in superconducting interferometers and is transmitted and processed as very short voltage pulses $V(t)$ of quantized area. The active circuit components are overdamped Josephson junctions (*JJ*) which need only dc bias currents set to values slightly below their critical currents. With these elements, *SFQ* pulses can be created, transmitted, reproduced, amplified, processed, and detected (25). The basic RSFQ logic elements for constructing complex digital circuits are available in current technology. Superconducting microstrip lines together with JJ technology allow transmitting picosecond waveforms with very low attenuation and dispersion. In a pseudorandom noise generator of this

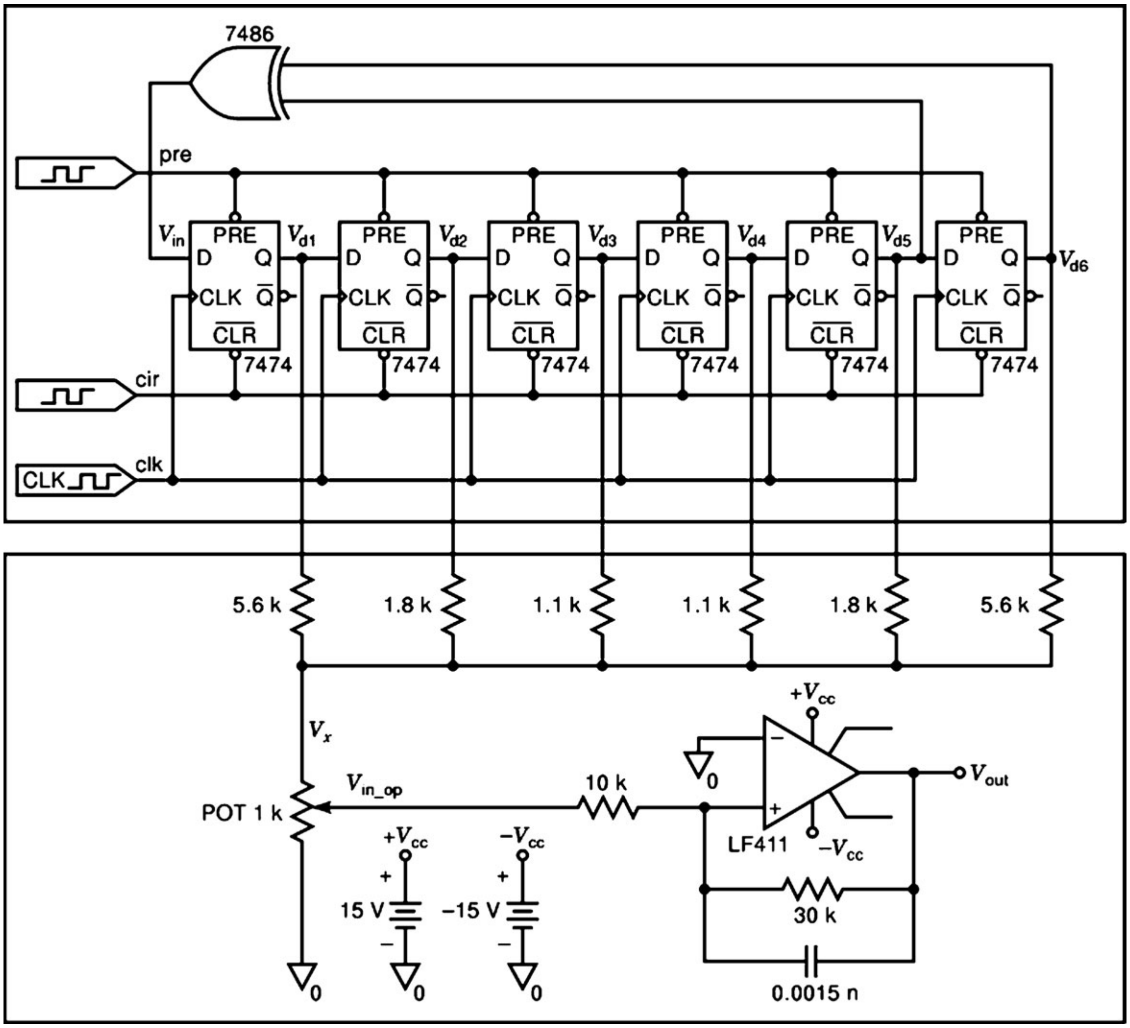

Figure 6. A six-stage linear feedback shift register with a resistive network for digital-to-analog conversion.

type, the logic enables the generation of pseudostatistical SFQ pulse sequences, operating as quasi-shot noise sources.

Arrays of Noise Generators. It is often necessary to have an array of noise generators, especially in neural networks (25). Although such noise generators can be designed with LFSRs, one should be careful to avoid any correlation among the outputs of these noise generators. Alspector et al. (23) accomplish this by tapping the outputs from various stages of the LFSR and processing them using exclusive-or gates and low-pass filters. A cellular automaton is used by Dupret et al. (27) to generate arrays of Gaussian white noise sources. Cellular automata feature regular structure leading to compact VLSI layouts.

APPLICATION OF NOISE GENERATORS

Noise generators are used in a variety of testing, calibration, and alignment applications especially with radio receivers. Some of the other applications are in digital communication, analog integrated circuit diagnosis, and learning processes of stochastic neural networks. In digital communication, noise is added as an "uncertainty" to a cryptographic exchange to confuse the information and to prevent unauthorized use or forgery. This is increasingly important in today's electronic-commerce society. Random signals are also used for dithering in analog electronic circuits, forcing a signal to use the entire dynamic range of an analog system, one which reduces distortion. These applications can be classified into four categories: noise used as a broadband random signal, measurements in which noise is used as a test signal, measurements in which noise is used as a probe into microscopic phenomena, and noise as a conceptual tool. This categorization of applications was first made by Gupta (28) and is used here. We include some examples and illustrations.

Noise as a Broadband Random Signal

This kind of signal is widely used in electronic countermeasures, microwave heating, simulation of random quantities, stochastic computing, and generation of random numbers. Noise generators are used to simulate random vibrations in mechanical systems. The combination of a random

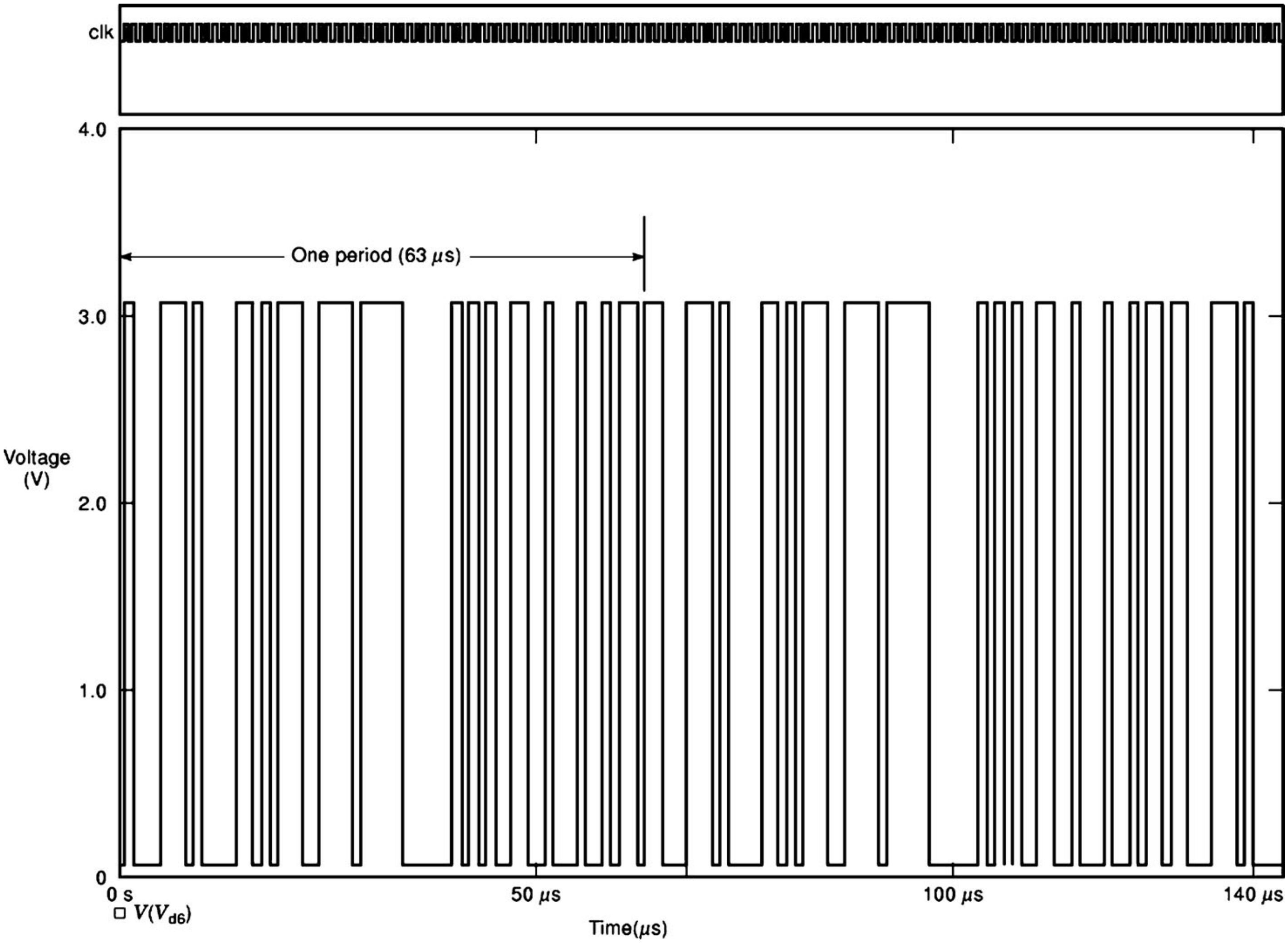

Figure 7. The waveform of the digital sequence at the output of LFSR.

noise generator and a shake table is widely used to test the response of mechanical structures to random vibrations.

A well-known application of a high-power broadband noise generator is active jamming of radar and communication equipment. Radar jamming is called active if the jammer radiates a signal at the operating frequency of the radar system, as distinguished from passive jamming which employs nonradiating devices like chaff. The broadband jamming signal can be generated either by a noise generator centered at the carrier frequency or by noise modulating a continuous wave signal.

An interesting medical application is inducing sleep or anesthesia and suppressing dental pain in a technique called audio-analgesia. A dental patient listens to relaxing music via earphones, and switches to filtered random noise on feeling pain, increasing the intensity of noise as necessary to suppress pain. It is reported that audio-analgesia has about the same level of effectiveness as morphine (29).

In modern musical instruments, white or color noise generators are successfully used to generate the sound effect of desert wind, ocean surf, thunderstorm, lightning, and even the virtual cosmic background sound.

Noise as a Test Signal in Measurements

There are several cases of measurements where one needs a broadband signal with known properties like amplitude probability density and an autocorrelation function. Random noise is one such source and is ideal for measuring impulse response, insertion loss, linearity and intermodulation of communication equipment, and in noise-modulated distance-measuring radar.

It is well known (4) that if a random signal $X(t)$ with autocorrelation function $R_X(\tau)$ is applied at the input of a linear system with an impulse response $H(t)$, the cross-correlation between the input and the resulting output $Y(t)$ is given by the convolution integral

$$R_{XY}(\tau) = \int_{-\infty}^{\infty} H(t) R_X(\tau - t)\, dt \tag{5}$$

This relationship can be used to calculate the impulse response $H(t)$ if R_X and R_{XY} are known. For causal, lumped, linear, time-invariant systems, this calculation can be carried out algebraically. However, solving the integral equation for $H(t)$ is greatly simplified by using white noise as the input signal. If the bandwidth of the input signal is

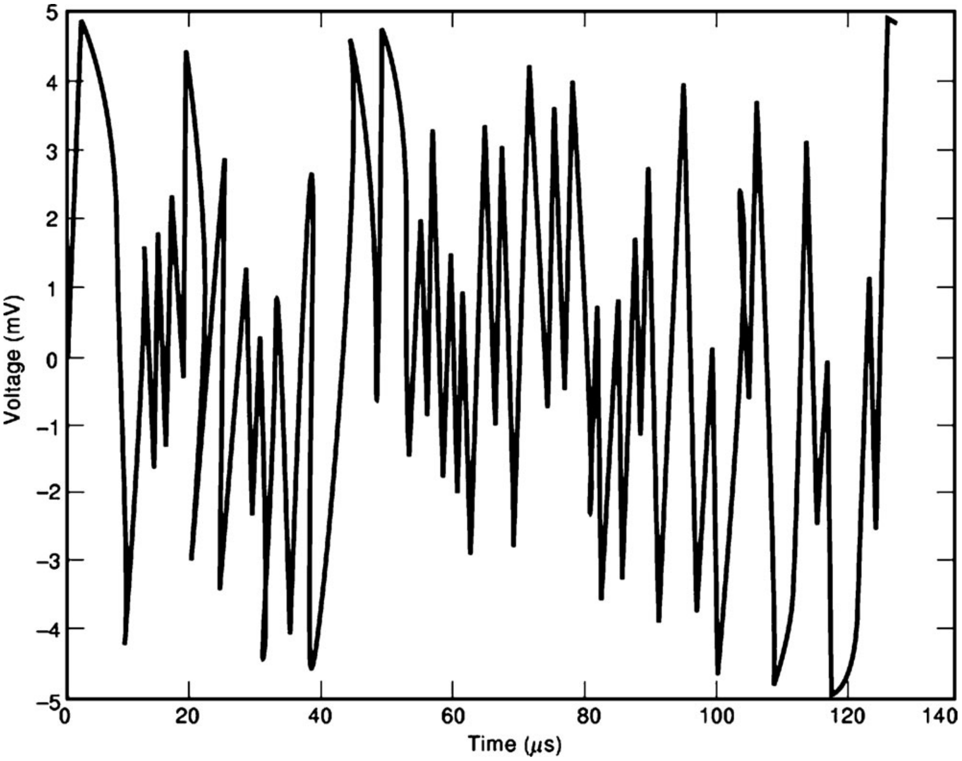

Figure 8. A simulation trace of an analog noise signal.

much larger than that of the system under test, $R_X(\tau)$ is effectively the impulse function $\delta(\tau)$, and the equation simplifies to

$$R_{XY}(\tau) = H(\tau) \tag{6}$$

Thus the impulse response is directly measured without involved calculation.

Spina and Upadhyaya (30) use the previous observation on impulse response measurement in testing and diagnosing analog VLSI. Here, a white noise generator is used as input stimuli to the analog chip. At the output of the circuit under test, a pattern classifier which is usually an artificial neural network does the signature analysis and hence fault diagnosis. Alspector et al. (23) study application of noise as input to facilitate learning in parallel stochastic neural networks.

Noise is used in measuring linearity and intermodulation in a communication channel as follows. When a large number of telephone channels are to be carried by a coaxial cable or a broadband radio link, any existing nonlinear distortions in the system introduce unwanted intermodulation products of the various components of the multiplexed signal. Calculation of the intermodulation noise so introduced is very difficult because of the large number of channels. Because statistical properties of white noise are similar to those of a complex multichannel signal with a large number of intermittently active channels, white noise is used to simulate such a signal. A band-limited Gaussian white noise is introduced at the input into the system under test. The noise power in a test channel is measured first with all channels loaded with white noise and then with all but the test channel loaded with white noise. The ratio of the first to the second measurement is called the noise power ratio from which the channel noise due to intermodulation can be calculated. The spectral density of input noise can be shaped to match the signal under actual operating conditions.

The use of noise generators for checking system performance in manufacturing or in the laboratory is commonly known. The procedure can be extended to in-service monitoring of radar and communication equipment in the field because of the development of solid-state noise generators which have smaller power consumption, weight, volume, radio-frequency interference, turn-on time, and turn-off time, but higher noise power output and reliability than gas-discharge noise generators. As a result, the need for retuning or servicing the equipment is recognized before its performance becomes unacceptable. As the noise signal is very small and unrelated to all other signals, the monitoring can be carried out while the equipment is in operation, thus reducing the downtime due to checkups.

Noise is specifically used in the noise immunity test of several digital systems and TV pictures (31). High frequency noise generators are needed in RF noise-power calibration. The shift-register-based noise generator using RSFQ logic can function at frequencies up to 45 GHz (25) and can be used for this purpose. Digital, pseudorandom numbers are also used to test a random collection of input possibilities with test circuits built on-chip.

Noise as a Probe into Microscopic Phenomena

Noise measurements can be used for estimating physical parameters related to microscopic phenomena, such as emission, recombination, or ionizing collision. Noise can also be used in testing semiconductors for uniformity and for estimating the reliability of semiconductor devices. Us-

Table 1. Commercial noise generators and their characteristics

Designation	Function	Name of Manufacturer	Noise Type and Range	Technique Used
TSC-300	White Noise Generator	Marpac	Sound Generator White noise	Electronic
DNG 7500	Digital Noise Generator	Noise/Com	White Gaussian noise	Digital
K4301	Pink Noise Generator	QualityKits	Pink Noise	Pseudorandom (Digital noise)
ANG	Automated Noise Generator	Micronetics	Truly Gaussian	Analog
CNG-70/140	Carrier to Noise Generator	dBm	White Noise (50-180 MHz)	Not available
AM700	Mixed Signal Audio Measurement Set	Tektronix	Shaped Noise White & Pink	Analog
3024	Very Random noise Generator	ACO Pacific, Inc.	White & Pink (1.6 Hz to 39 kHz)	Digital (pseudorandom)
SMT02 SMT03, 06	Signal Generator	Rohde & Schwarz	500 kHz bandwidth	Not Available
IE-20B	Pink and White	Ivie Technologies, Inc.	Pink & White	Digital
PNG-2000	Portable Noise Generator	Research Electronics, Intl.	Audio frequency (300 Hz to 3 kHz)	Not Available
DS345	Waveform Generator	Stanford Research Systems	White Noise Wideband (10 MHz)	Digital
DS360	Low Distortion Function Generator	Stanford Research Systems	White and Pink	Digital
NG-1	Audible Noise Generator	Audio Technologies, Inc.	White & Pink	Not Available
PNG-7000	Precision Noise Generator	Noise/Com	Gaussian White Noise	Not Available
UFX7000	Programmable Noise Generator	Noise/Com	Broadband Noise (10 Hz to 40 GHz)	Microprogram controlled

ing noise in device reliability prediction has several advantages over conventional lifetime tests. Noise testing is nondestructive and does not take up a considerable fraction of the life of the device being tested. It also allows testing a specific individual device rather than measuring an average lifetime for a lot.

There are many ways in which measuring the noise in a device can be used to make reliability predictions. For instance, transistors with low $1/f$ noise exhibit longer life spans, and reverse-biased *p–n* junction diodes having a noise power spectral density with multiple peaks undergo rapid degradation. It has been found experimentally that the low-frequency $1/f$ noise output of a transistor increases by two or three orders of magnitude shortly before failure (28).

Noise as a Conceptual Tool

Noise is the motivating cause for developing new disciplines like information theory, the statistical theory of communication, and circuit theory. It is also useful as a vehicle for theoretical investigations and for modeling other physical systems. For example, the concepts and principles developed with electrical noise have been used as guides in working with thermodynamics. Noise has been used as a tool for interpreting impedance in circuit theory. It has also led to the development of some analogies between quantum mechanics and the analyses of noisy circuits and systems and has helped simplify the concept of the quantum mechanical uncertainty principle. For further details, readers may refer to (28).

COMMERCIAL NOISE GENERATORS

A number of companies sell noise generators either as separate instruments or as part of an apparatus, such as a function generator. Table 1 lists the model numbers and the names of the manufacturers along with various features of the instruments including noise range, the technique used in the design, and application areas where known. Some of the instruments are portable and battery-powered, whereas others are somewhat bulky. This list is not exhaustive and is provided only as a quick reference. The address of each company is provided in Table 2 as a ready reference. Although the internal circuitry of these noise generators is not available, the reader may refer to other guidebooks on electronics circuits, such as (32) which contains the circuit diagram of digital white noise generators, thermal noise generators using incandescent lamp, and a simple diode noise generator.

ACKNOWLEDGMENTS

The author acknowledges Yi-Hao Wang, Shu Xia, and Arshad Nissar for their help in the simulation effort.

Table 2. Companies that make noise generators

Marpac Corporation
P.O. Box 560
Rocky Point, NC 28457 USA

QKits Limited
49 McMichael St.
Kingston, ON K7M 1M8, Canada

Micronetics
26 Hampshire Drive
Hudson, NH 03051 USA

dBm
6 Highpoint Drive
Wayne, New Jersey 07470 USA

Tektronix, Inc.
1500 North Greenville Avenue
Richardson, TX 75081 USA

ACO Pacific, Inc.
2604 Read Avenue
Belmont, CA 94002, USA

Rohde & Schwarz
Muhldorfstrasse 15
81671 Munchen (Munich), Germany

Ivie Technologies, Inc.
1605 N West State St.
Lehi, UT 84043-1084 U.S.A.

Research Electronics International
455 Security Place
Algood, TN 38506, USA

Stanford Research Systems
1290-D Reamwood Avenue
Sunnyvale, California 94089, USA

ATI - Audio Technologies, Incorporated
154 Cooper Rd. # 902
West Berlin, NJ 08091 USA

Noise Com
25 Eastmans Road
Parsippany, New Jersey 07054-3702 USA

Tundra Semiconductor Corporation
603 March Road
Kanata, Ontario, K2K 2M5, Canada

BIBLIOGRAPHY

C. Looney Noise, in R. Dorf (ed.), *The Electrical Engineering Handbook*, 2nd ed., Boca Raton, FL: CRC Press, 1997, pp. 1642–1653.

2. J. Johnson Thermal agitation of electricity in conductors, *Nature*, **119**: 50–51, 1927.
3. M. Buckingham *Noise in Electronic Devices and Systems*, New York: Wiley, 1983.
4. A. Papoulis *Probability, Random Variables, and Stochastic Processes*, 3rd ed., New York: McGraw-Hill, 1991.
5. J. Dunn White-noise generator, *Electron. Design*, **44**: 90, 1996.
6. B. Schneier *Applied Cryptography*, New York: Wiley, 1994.
7. W. Jung Simple wideband noise generator, *Electron. Design*, **44**: 102, 1996.
8. L. Letham *et al.* A 128K EPROM using encryption of pseudorandom numbers to enable read access, *IEEE J. Solid State Circuits*, **21**: 881–889, 1986.
9. C. S. Petrie J. A. Connelly A noise-based random bit generator IC for applications in cryptography, *Proc. Int. Symp. Circuits Systems*, 197–201, June 1998.

10. R. May Simple mathematical models with very complicated dynamics, *Nature*, **261**: 459–467, 1976.
11. G. McGonigal M. Elmasry Generation of noise by electronic iteration of the logistic map, *IEEE Trans. Circuits Syst.*, **CAS-34**: 981–983, 1987.
12. R. Bates A. Murch Deterministic-chaotic variably-colored noise, *Electron. Lett.*, **23** (19): 995–996, 1987.
13. R. Devaney *An Introduction to Chaotic Dynamical Systems*, Menlo Park: Benjamin/Cummings, 1986.
14. M. Delgado–Restituto *et al.* A chaotic switched-capacitor circuit for $1/f$ noise generation, *IEEE Trans. Circuits Syst. I*, **39**: 325–328, 1992.
15. K. Murao *et al.* $1/f$ noise generator using logarithmic and antilogarithmic amplifiers, *IEEE Trans. Circuits Syst. I*, **39**: 851–853, 1992.
16. G. Corsini R. Saletti A $1/f^{\gamma}$ power spectrum noise sequence generator, *J. Solid State Circuits*, **37**: 615–619, 1988.
17. M. Delgado-Restituto *et al.* Nonlinear switched-current CMOS IC for random signal generation, *Electronics Lett.*, **29**: 2190–2191, 1993.
18. J. T. Bean P. J. Langlois A current-mode analog circuit for tent maps using piece-wise linear functions, *Proc. Int. Symp. Circuits Syst.*, 125–128, 1994.
19. F. Vitaljic Programmable noise generator, *Electron. Design*, **44**: 122, 1996.
20. H. Sutcliffe K. Knott Standard LF noise sources using digital techniques and their application to the measurement of noise spectra, *Radio Electron. Eng.*, **40**: 132–136, 1970.
21. D. Knuth *The Art of Computer Programming: Seminumerical Algorithms*, Reading, MA: Addison-Wesley, 1981, Vol. 2.
22. W. Peterson E. Weldon *Error correcting codes*, 2nd ed., Cambridge, MA: MIT Press, 1972.
23. J. Alspector *et al.* A VLSI efficient technique for generating multiple uncorrelated noise sources and its application to stochastic neural networks, *IEEE Trans. Circuits Syst.*, **38**: 109–123, 1991.
24. F. D'alvano R. Badra A simple low-cost laboratory hardware for noise generation, *IEEE Trans. Educ.*, **39**: 280–281, 1996.
25. W. Kessel, *et al.* Development of a rapid single-flux quantum shift register for applications in RF noise power metrology, *IEEE Trans. Instrum. Meas.*, **46**: 477–480, 1997.
26. K. Likharev V. Semenov RSFQ logic/memory family: A new Josephson-junction technology for sub-terahertz-clock-frequency digital systems, *IEEE Trans. Appl. Supercond.*, **1**: 3–28, 1991.
27. A. Dupret E. Belhaire P. Garda Scalable array of Gaussian white noise sources for analogue VLSI implementation, *Electron. Lett.*, **31**: (N17): 1457–1458, 1995.
28. M. Gupta Applications of electrical noise, *Proc. IEEE*, **63**: 996–1010, 1975.
29. K. Kryter *The Effects of Noise on Man*, New York: Academic Press, 1970.
30. R. Spina S. Upadhyaya Linear circuit fault diagnosis using neuromorphic analyzers, *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, **44**: pp. 188–196, 1997.
31. T. Takagi Composite noise generator as a noise simulator and its application to noise immunity test of digital systems and TV picture, *IEICE Trans. Commun.*, **78B** (N2): 127–133, 1995.

32. J. Markus *Guidebook of Electronic Circuits*, New York: McGraw-Hill, 1974.

SHAMBHU J. UPADHYAYA

Department of Computer
Science & Engineering, State
University of New York at
Buffalo, Buffalo, NY, 14260