

The Origins of Spread-Spectrum Communications

ROBERT A. SCHOLTZ, FELLOW, IEEE

Abstract—This monograph reviews events, circa 1920–1960, leading to the development of spread-spectrum communication systems. The WHYN, Hush-Up, BLADES, F9C-A/Rake, CODORAC, and ARC-50 systems are featured, along with a description of the prior art in secure communications, and introductions to other early spread-spectrum communication efforts. References to the available literature from this period are included.

I. INTRODUCTION

"Whuh? Oh," said the missile expert. "I guess I was off base about the jamming. Suddenly it seems to me that's so obvious, it must have been tried and it doesn't work."

"Right, it doesn't. That's because the frequency and amplitude of the control pulses make like purest noise—they're genuinely random. So trying to jam them is like trying to jam FM with an AM signal. You hit it so seldom, you might as well not try."

"What do you mean, random? You can't control anything with random noise."

The captain thumbed over his shoulder at the Luanæ Galaxy. "They can. There's a synchronous generator in the missiles that reproduces the same random noise, peak by pulse. Once you do that, modulation's no problem. I don't know how they do it. They just do. The Luanæ can't explain it; the planetoid developed it."

England put his head down almost to the table. "The same random," he whispered from the very edge of sanity.

—from "The Pod in the Barrier" by Theodore Sturgeon, in *Galaxy*, Sept. 1957; reprinted in *A Touch of Strange* (Doubleday, 1958).

LED by the Global Positioning System (GPS) and the Joint Tactical Information Distribution System (JTIDS), the spread-spectrum (SS) concept has emerged from its cloak of secrecy. And yet the history of this robust military communication technique remains largely unknown to the modern communication engineer. Was it a spark of genius or the orderly evolution of a family of electronic communication systems that gave birth to the spread-spectrum technique? Was it, as Frank Lehan said, an idea whose time had come? Was the spread-spectrum technique practiced in World War II, as Eugene Fubini declares? Was it invented in the 1920's as the U.S. Patent Office records suggest? Was Theodore Sturgeon's lucid description of a jam-proof guidance system precognition, extrasensory perception, or a security leak? Let's examine the evidence.

Manuscript received August 26, 1981; revised January 29, 1982. This work was supported in part by the Army Research Office under Grant DAAG-29-79-C-0054.

The author is with the Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90007.

The basic signal characteristics of modern spread-spectrum systems are as follows.

1) The carrier is an unpredictable, or pseudorandom, wide-band signal.

2) The bandwidth of the carrier is much wider than the bandwidth of the data modulation.

3) Reception is accomplished by cross correlation of the received wide-band signal with a synchronously generated replica of the wide-band carrier.

The term "pseudorandom" is used specifically to mean random in appearance but reproducible by deterministic means. A key parameter of SS systems is the number of essentially orthogonal signaling formats which could be used to communicate a data symbol. Here two signaling formats are orthogonal in the sense that the signals employed in one format for communication would not be detected by a processor for the other format, and vice versa. We shall call the number of possible orthogonal signaling formats the multiplicity factor of the communication link.

While conventional communication systems other than wide-band frequency modulation (FM) have a multiplicity factor near unity, SS systems typically have multiplicity factors in the thousands. Thus, a well-designed SS system forces a jammer to guess which of a multiplicity of orthogonal signaling formats is being used, or to reduce significantly his power per format by jamming all possibilities. The receiver is not confronted with a similar problem since it is privy to the pseudorandom sequence of signaling formats which the transmitter will use for communication. Excluding the notion 2) that the multiplicity factor be large, all of these characteristics are apparent in Sturgeon's story.

The multiplicity factor is the nominal value of the more widely used term, processing gain. In terms of signal-to-interference power ratios (SIR's), the processing gain of an SS system is the factor by which the receiver's input SIR is multiplied to yield the SIR at the output of the receiver's correlation detector. The input SIR can be interpreted as a computation over the ensemble of possible orthogonal signaling formats, while the output SIR pertains only to the system selected by the transmitter and receiver for communication.

Spread-spectrum systems, because of the nature of their signal characteristics, have at least five important performance attributes.

1) Low probability of intercept (LPI) can be achieved with high processing gain and unpredictable carrier signals when power is spread thinly and uniformly in the frequency domain, making detection against noise by a surveillance receiver difficult. A low probability of position fix (LPPF) attribute goes one step further in including both intercept and direction finding (DFing) in its evaluation. Low probability of signal exploita-

tion (LPSE) may include additional effects, e.g., source identification, in addition to intercept and DFing.

2) Antijam (AJ) capability can be secured with an unpredictable carrier signal. The jammer cannot use signal observations to improve its performance in this case, and must rely on jamming techniques which are independent of the signal to be jammed.

3) High time resolution is attained by the correlation detection of wide-band signals. Differences in the time of arrival (TOA) of the wide-band signal, on the order of the reciprocal of the signal bandwidth, are detectable. This property can be used to suppress multipath and, by the same token, to render repeater jammers ineffective.

4) Transmitter-receiver pairs using independent random carriers can operate in the same bandwidth with minimal cchannel interference. These systems are called spread-spectrum code-division multiple-access (CDMA) systems.

5) Cryptographic capabilities result when the data modulation cannot be distinguished from the carrier modulation, and the carrier modulation is effectively random to an unwanted observer. In this case the SS carrier modulation takes on the role of a key in a cipher system. A system using indistinguishable data and SS carrier modulations is a form of privacy system.

We will see how the search for a system with one or more of these features led to independent discoveries of the spread-spectrum concept.

Three basic system configurations for accomplishing the reception of a wide-band, seemingly unpredictable carrier have been pioneered:

1) Transmitted reference (TR) systems accomplish detection of the unpredictable wide-band carrier by transmitting two versions of the carrier, one modulated by data and the other unmodulated. These versions, being separately recoverable by the receiver (e.g., they may be spaced apart in frequency), are the inputs to a correlation detector which extracts the data (see Fig. 1).

2) Stored reference (SR) systems require independent generation at transmitter and receiver of pseudorandom wide-band waveforms which are identical in their essential characteristics. The receiver's SS carrier generator is adjusted automatically to keep its output in close synchronism with the arriving SS carrier. Detection then proceeds in a manner similar to the TR system (see Fig. 2).

3) Filter systems generate a wide-band transmitted signal by pulsing a matched filter (MF) having a long, wide-band, pseudorandomly controlled impulse response. Signal detection at the receiver is accomplished by an identically pseudorandom, synchronously controlled matched filter which performs the correlation computation (see Fig. 3). Rapid pseudorandom variation of the transmitter's impulse response ensures the unpredictability of the wide-band carrier.

Theodore Sturgeon's missile guidance system was an SR-SS system, the configuration which is prevalent today.

Spread-spectrum systems are also classified¹ by the tech-

¹ In the sequel, the uncapitalized word "classified" will usually be a formal security designation; likewise for the words "secret" and "confidential."

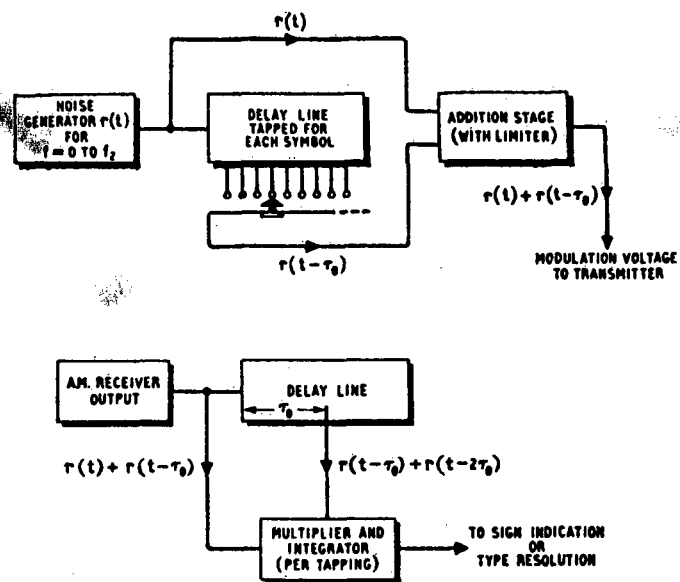


Fig. 1. Block diagram of a basic transmitted reference system using pure noise as a carrier and time-shift keying for data modulation. No effort has been made to separate the data and reference channels in this system proposed by the East German Professor F. H. Lange. His configuration is nearly identical to that suggested in Project Hartwell a decade earlier. (Diagram from [11].)

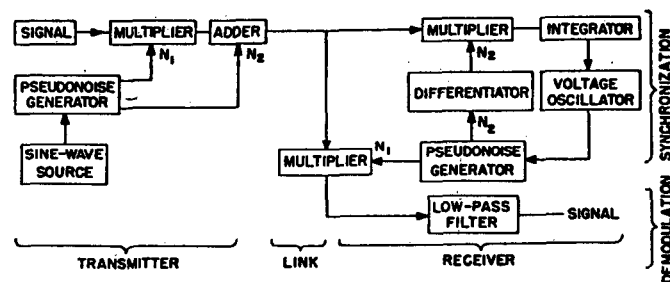


Fig. 2. JPL's first attempt at a stored reference spread-spectrum design is shown here. This particular system uses one unmodulated noise signal N_2 for synchronizing the receiver's pseudonoise generator and another N_1 for carrying data. Most SR-SS systems do not use a separate signal for SS signal synchronization. (Diagram from [132].)

nique which they employ to achieve the wide-band carrier signal. Here are some digital system examples.

1) Pure noise was sometimes used as a carrier in early experimental systems, giving ideal randomness properties. However, pure noise is useful only in a TR system. If a jammer for some reason cannot use the reference channel signal to jam the data channel signal, then the multiplicity factor for a system using antipodal modulation of binary data on the noise carrier is

$$\text{multiplicity factor} = 2(\text{data bit time})(\text{carrier bandwidth}).$$

When the jammer can gain access to both channels, the multiplicity factor reduces to unity, i.e., there is no AJ advantage.

2) Direct sequence (DS) systems employ pseudorandom sequences, phase-shift-keyed (PSK) onto the carrier, for spreading. The time spent in transmitting a single carrier symbol from this sequence is called the chip time of the system. With

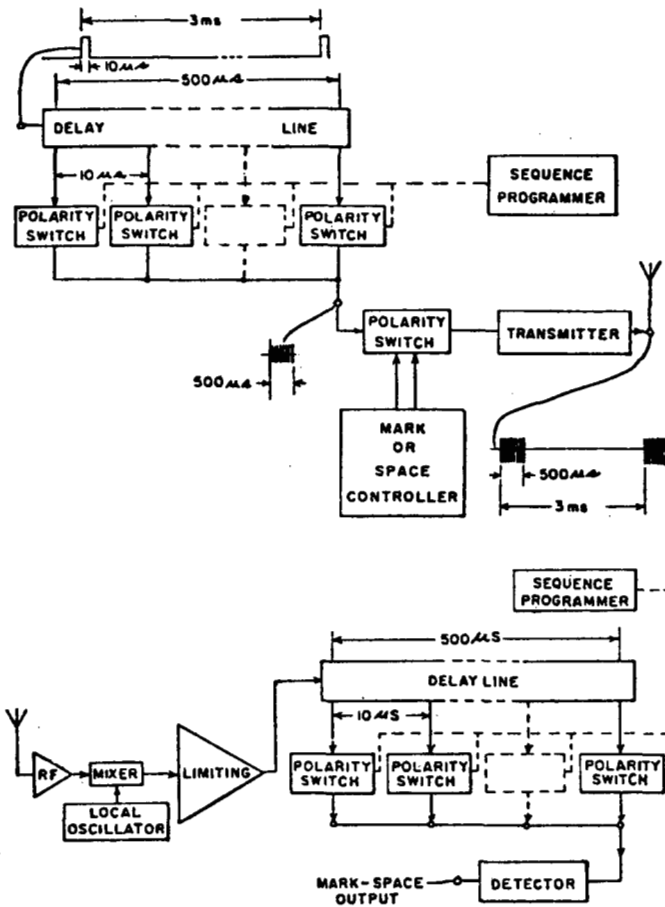


Fig. 3. Costas and Widmann's Phantom system employs a pulsed delay line with pseudorandomly controlled taps summed to provide an SS signal for modulation. An identically structured system with a synchronous replica of the tap controller is used to construct a matched pseudorandom filter for data detection at the receiver. (Diagrams modified from [157].)

binary PSK data antipodally modulated on this SS carrier, the resultant system's multiplicity factor is given by

$$\text{multiplicity factor} = (\text{data bit time})/(\text{chip time}).$$

Direct sequence systems possess excellent TOA resolution and are efficient in power amplifier operation.

3) Frequency modulation with frequency wobbled over a wide bandwidth is a carryover from early radar technology. Some FM-SS systems may have more predictable carrier modulation formats (e.g., linear FM, chirp) and, hence, may be more susceptible to jamming. If the jammer does not use the modulation structure to its advantage then the multiplicity factor for an FM system is approximately

$$\text{multiplicity factor} = (\text{data bit time})(\text{FM carrier bandwidth}).$$

4) Frequency hopping (FH) systems achieve carrier spreading by driving a frequency synthesizer with a pseudorandom sequence of numbers spanning the range of the synthesizer. In the pure form of this system, data is usually frequency-shift-keyed (FSK) onto the spread carrier. With binary FSK modulation at one data bit per carrier hop, the multiplicity factor is

given by

$$\text{multiplicity factor} = (\text{hop time})(\text{frequency range})$$

assuming the frequencies used are packed as tightly as orthogonality permits. Typically the new carrier phase cannot be predicted when a frequency hop occurs. However, fully coherent FH is possible, e.g., with a minimum-shift-keying (MSK) format, which is virtually indistinguishable from DS operation. Present technology achieves the highest multiplicity factor using frequency hopping, provided that a sufficient bandwidth can be allocated.

5) Time hopping (TH) to spread the carrier is achieved by randomly spacing narrow transmitted pulses. In TH systems, the reciprocal of the average duty factor is a measure of the multiplicity factor. That is,

$$\text{multiplicity factor} = (\text{average pulse spacing})/(\text{pulse width}).$$

Time hopping is useful as a form of random time multiplexing allowing both transmitter and receiver use of the same antenna.

Some systems are hybridized from the above to achieve the advantages of several different techniques. For example, JTIDS uses TH, FH, and DS modulation simultaneously for carrier spreading.

Analog (e.g., voice) modulated SS systems have been developed, with the multiplicity factor for a well-designed system given approximately by

$$\text{multiplicity factor} = (\text{carrier bandwidth})/(\text{output bandwidth})$$

the output bandwidth being the bandwidth of the receiver correlator's output signal.

A historical look at the development of spread-spectrum systems will not only shed light on their origins, but will also provide an interesting case history of the interaction between basic research and the evolution of technology.

II. PRIOR KNOWLEDGE

Before we can assess the ingenuity which went into the development of the first spread-spectrum systems, we must examine the state of the art in communication theory and technology in the 1940's. Here are capsule summaries of technical events in the prehistory of SS communications.

Radar Innovations

From the 1920's through World War II, many systems incorporating some of the characteristics of spread-spectrum systems were studied. The birth of RADAR, i.e., Radio Detection And Ranging, occurred in the mid-1920's when scientists used echo sounding to prove the existence of an ionized gas layer in the upper atmosphere. British scientists E. V. Appleton and M. A. F. Barnett performed this feat by transmitting a frequency modulated wave upward and listening for the return echo [1]. Applications of this concept to aircraft instrumentation were obvious and FM altimetry became a reality in the 1930's, with all major combatants in World War II making

use of this technology [2]. Typically, linear-sawtooth or sinusoidal modulations were used in these early systems. The frequency modulation generally serves two purposes, 1) it ameliorates the problem of interference due to leakage of the transmitted signal directly into the receiver, and 2) it makes possible the measurement of propagation delay and, hence, range.

Historically, the development of pulsed radars has received more attention than that of continuous wave (CW) radars, since isolation of the transmitting and receiving systems is a lesser problem in this case. By the end of World War II, the Germans were developing a linear FM pulse compression (chirp) system called Kugelschale, and a pulse-to-pulse frequency-hopping radar called Reisslaus [3]. In 1940 Prof. J. Huttman was issued a German patent on a chirp pulse radar, while U.S. patents on this type of system were first filed by R. H. Dicke in 1945 and by S. Darlington in 1949 [4]. The mid-1940's also saw the formulation of the matched filter concept for maximum signal-to-noise ratio (SNR) pulse detection by North [5] and Van Vleck and Middleton [6]. This development indicated that the performance of optimum signal detection procedures in the presence of white noise depends only on the ratio of signal energy to noise power spectral density, thus leaving the choice of waveform open to satisfy other design criteria (e.g., LPI or AJ). Resolution, accuracy, and ambiguity properties of pulse waveforms finally were placed on a sound theoretical basis by P. M. Woodward [7] in the early 1950's and excellent treatises on this subject are now available [8], [9].

Spectrum spreading was a natural result of the Second World War battle for electronic supremacy, a war waged with jamming and antijamming tactics. On the Allied side by the end of the war, every heavy bomber, excluding Pathfinders, on the German front was equipped with at least two jammers developed by the Radio Research Laboratory (RRL) at Harvard [10]. The use of chaff was prevalent, the Allies consuming 2000 tons per month near the end. On the German side, it is estimated that at one time as many as 90 percent of all available electronic engineers were involved in some way in a tremendous, but unsuccessful, AJ program. Undoubtedly Kugelschale and Reisslaus were products of this effort.

In a postwar RRL report [10], the following comment on AJ design is notable:

"In the end, it can be stated that the best anti-jamming is simply good engineering design and the spreading of the operating frequencies."

Certainly, spectrum spreading for jamming avoidance (AJ) and resolution, be it for location accuracy or signal discrimination (AJ), was a concept familiar to radar engineers by the end of the war.

• • •

In the late 1950's and early 1960's the East German scientist F. H. Lange toured Europe and the United States collecting (unclassified) material for a book on correlation techniques. Published first in 1959 with its third edition being translated into English [11] a few years later, Lange's book contains some references all but unnoticed by researchers on this

side of the Atlantic. The most intriguing of these is to the work of Gustav Guanella of Brown, Boveri, and Company in Switzerland. Among Guanella's approximately 100 patents is one [12] filed in 1938, containing all the technical characteristics of an SR-SS radar! The radiated signal in Guanella's CW radar is "composed of a multiplicity of different frequencies the energies of which are small compared with the total energy" of the signal. His prime examples of such signals are acoustic and electrical noise, and an oscillator whose frequency is "wobbled at a high rate between a lower and upper limit."

Ranging is accomplished by adjusting an internal signal delay mechanism to match the external propagation delay experienced by the transmitted signal. Delay matching errors are detected by cross correlating the internally delayed signal with a 90 degree phase-shifted (across the whole transmission band) version of the received signal. Thus, if the transmitted signal is of the form

$$\sum_n a_n \cos(\omega_n t + \phi_n),$$

the propagation delay is τ_p , and the internal delay is τ_i , then the measured error is proportional to

$$\sum_n a_n^2 \sin[\omega_n(\tau_p - \tau_i)].$$

This ensemble of phase-locked loops, all rolled up into one neat package, possesses a tracking loop S-curve which looks like the Hilbert transform of the transmitted signal's autocorrelation function. Undoubtedly, Guanella's patent contains possibly the earliest description of a delay-locked loop. In addition to accurate range measurement, the patent further indicates improved performance against interference.

Guanella used the same type of error-sensing concept in an earlier patent filed in 1936 [13]. Many of his inventions are cited as prior art in later patents. For a modern treatment of delay-locked loops see [14], [15].

Developments in Communication Theory

Probabilistic modeling of information flow in communication and control systems was the brainchild of the preeminent mathematician Norbert Wiener of the Massachusetts Institute of Technology (M.I.T.). In 1930 Wiener published his celebrated paper "Generalized Harmonic Analysis" [16] developing the theory of spectral analysis for nonperiodic infinite-duration functions. When World War II began, Wiener was asked by the National Defense Research Committee (NDRC) to produce a theory for the optimal design of servomechanisms. Potential military applications for this theory existed in many gunfire control problems [17]. The resultant work [18], published initially in 1942 as a classified report and often referred to as the "Yellow Peril," laid the groundwork for modern continuous-parameter estimation theory. By 1947 Wiener's filter design techniques were in the open literature [19].

• • •

In 1915 E. T. Whittaker concluded his search for a distinctive function among the set of functions, all of which take on

the same specified values at regularly spaced points along the real line. This "function of royal blood whose distinguished properties set it apart from its bourgeois brethren" is given by

$$x(t) = \sum_n x(n/2W) \sin [\pi(2Wt - n)] / [\pi(2Wt - n)]$$

where $x(n/2W)$ represents the specified values and $x(t)$ is the cardinal function of the specified values, a function whose Fourier transform is strictly band limited in the frequency domain [20]–[23]. Based on this result, the sampling theory used in a communication context by Hartley [24], Nyquist [25], Kotelnikov [26], and Shannon [27] states that a function band limited to W Hz can be represented without loss of information by samples spaced $1/(2W)$ seconds apart. Generalizations [28], [29] of this result indicate that a set of approximately $2TW$ orthogonal functions of T seconds duration and occupying W Hz can be constructed. In SS theory, this provides the connection between the number of possible orthogonal signaling formats and system bandwidth. Although earlier Nyquist [25] and later Gabor [30] both had argued using Fourier series that $2TW$ samples should be sufficient to represent a T -second segment of such a band-limited signal, it was Shannon who made full use of this classical tool.

• • •

Claude E. Shannon, who had known Wiener while a graduate student at M.I.T., joined the Bell Telephone Laboratories (BTL) in 1941, where he began to establish a fundamental theory of communication within a statistical framework. Much of his work, motivated in good part by the urge to find basic cryptographic and cryptanalytic design principles [31], was classified well past the end of the Second World War. In a paper [27] first presented in 1947, Shannon invoked the cardinal expansion in formulating a capacity for delivering information (negentropy [31]) over channels perturbed solely by additive Gaussian noise. He showed that this channel capacity was maximized by selectively spreading the signaling spectrum so that wherever deployed within designated bandwidth confines—but only there—the sum of its power spectral density plus that of the independent noise should lie as uniformly low as possible, yet utilize all the average transmitter power available. Moreover, this capacity was met by sending a set of noise-like waveforms and distinguishing between them at the receiver via a minimum-distance criterion akin to correlation-testing the observed signal against locally stored waveform replicas. Even though Shannon's theory did not apply directly to many interference/jamming situations, his remarkable concepts and results [32] profoundly influenced communication engineers' thinking.

Driven by the intense interest in the theories of Wiener and Shannon, the Institute of Radio Engineers (IRE) formed the Professional Group on Information Theory, which commenced publishing in 1953 [33]. The first three chairmen of this Group were, in order, Nathan Marchand, W. G. Tuller, and Louis deRosa. Marchand and deRosa, close friends, were at that time playing key roles in the development of SS systems; Tuller had independently but rather heuristically arrived at one of Shannon's capacity formulas.

Correlator Mechanization

One of the difficult problems which Guanella faced (by his account without any knowledge of Wiener's work) was to fabricate a device which will perform a weighted correlation computation on two inputs. Specifically, a means was needed for taking two inputs $x_1(t)$ and $x_2(t)$ and computing

$$y(t) = \int^t x_1(u)x_2(u)w(t-u)du$$

where $y(t)$ is the device output and $w(t)$ is the weighting function. The difficulty here is not with the weighting (i.e., filtering) operation, but with the prior multiplication of $x_1(t)$ by $x_2(t)$, and in particular with the range of inputs over which accurate multiplication can be accomplished. As shall be seen later, the ability to mechanize the correlation operation precisely is essential in building high-performance SS systems.

• • •

In 1942 Nathan Marchand, then a 26-year-old engineer working for ITT's Federal Telephone and Radio Corporation in New York, discussed his radio receiver invention with ITT engineer and patent attorney Paul Adams. Marchand had developed a converter for demodulating a received FM signal of known frequency wobble by mixing it with a time-aligned, heterodyned replica of the wobbled signal to produce a signal of constant intermediate frequency (IF) which could then be narrow-band filtered. The receiver's antimultipath attributes designed by Marchand and additional anti-interference features suggested by Adams appear in a 1947 patent [34]. Later during World War II, after studying Wiener's "Yellow Peril," Marchand was able to dub his converter a band-pass correlator.

• • •

At M.I.T. in 1947, Prof. Yuk Wing Lee commenced research into the implications of Wiener's theories and the new directions they inspired for engineering science. Soon thereafter Lee was joined by Jerome Wiesner and Thomas Cheatham, and their collective efforts led to the development of the first high-performance electronic correlators. In August, 1949, they applied for a patent [35] and in October they reported applications of correlation techniques to detection problems [36]. Continuing this work, Henry Singleton proceeded to innovate an all-digital correlator [37].

Protected Communications

The earliest patent [38] presently construed by the U.S. Patent Office as being spread spectrum in nature was filed in 1924 by Alfred N. Goldsmith, one of the three founders of the IRE. Goldsmith proposed to counteract the fading effects encountered in short wave communication, due to multipath, by

"radiating a certain range of wave frequencies which are modulated in accordance with the signal and actuating a receiver by means of energy collected on all the frequencies, preferably utilizing a wave which is continu-

ously varied in wave frequency over a certain range of cycles recurring in a certain period.”

Certainly, we can identify this as a form of FM-SS transmission. However, the envisioned data modulation was by amplitude (AM) with reception by a broadly tuned AM receiver. Hence, the correlation detector necessary to achieve the full benefits of SS operation was not inherent in Goldsmith's disclosure. For a World War II disclosure on an FM-SS chirp communication system with a more sophisticated receiver, claiming a primitive form of diversity reception for multipath signals and a capability against narrow-band interference, see [39].

• • •

In 1935 Telefunken engineers Paul Kotowski and Kurt Dannehl applied for a German patent on a device for masking voice signals by combining them with an equally broad-band noise signal produced by a rotating generator [40]. The receiver in their system had a duplicate rotating generator, properly synchronized so that its locally produced noise replica could be used to uncover the voice signal. The U.S. version of this patent was issued in 1940, and was considered prior art in a later patent [48] on DS-SS communication systems. Certainly, the Kotowski-Dannehl patent exemplifies the transition from the use of key-stream generators for discrete data encryption [4] to pseudorandom signal storage for voice or continuous signal encryption. Several elements of the SS concept are present in this patent, the obvious missing notion being that of bandwidth expansion.

The Germans used Kotowski's concept as the starting point for developing a more sophisticated capability that was urgently needed in the early years of World War II. Gottfried Vogt, a Telefunken engineer under Kotowski, remembers testing a system for analog speech encryption in 1939. This employed a pair of irregularly slotted or sawtoothed disks turning at different speeds, for generating a noise-like signal at the transmitter, to be modulated/multiplied by the voice signal. The receiver's matching disks were synchronized by means of two transmitted tones, one above and one below the encrypted voice band. This system was used on a wire link from Germany, through Yugoslavia and Greece, to a very- and/or ultra-high frequency (VHF/UHF) link across the Mediterranean to Rommel's forces in Derna, Libya.

Bell Telephone Laboratories improved on Telefunken's original scheme and applied for patents on their telephony apparatus in 1941 [42], [43]. BTL's disclosures and applications were placed under secrecy order since their system was being depended on by Roosevelt, Churchill, and other Allied leaders during World War II [44]. This system, officially called the X System and nicknamed the Green Hornet, changed its prerecorded keys daily for security. BTL continued its work on key-stream generation and in the mid-1940's filed for patents on all-electronic key generators which combined several short keys of relatively prime lengths to produce key streams possessing long periods [45], [46]. Such schemes also had been studied by Shannon [31] at BTL, but his comments on these were deleted before republication of his declassified report on secrecy systems in the *Bell System Technical Journal*. All of these BTL

patent filings remained under secrecy order until the 1970's when the orders were rescinded and the patents issued.

• • •

One can view the advanced Telefunken system as an avatar of a TR system since specialized signals are transmitted to solve the disk synchronization problem. Another novel variation of TR voice communication was conceived in the U.S. during the war years by W. W. Hansen. This Sperry/M.I.T. Radiation Laboratory scientist is noted for his invention of the microwave cavity resonator and for his joint effort with the Varian brothers in originating the Klystron. In a 1943 patent application [47], Hansen describes a two-channel system with the reference channel used solely for the transmission of noise, and the intelligence channel bearing the following signal (in complex notation):

$$\exp \left\{ j \int^t [\omega_1 + An(t')] dt' \right\} \cdot \exp \left\{ j \int^t [\omega_2 + Bv(t')] dt' \right\}$$

where $n(t)$ is a filtered version of the noise communicated via the reference channel, $v(t)$ is the voice signal, and assuming $n(t)$ and $v(t)$ are at comparable levels, $A \gg B$. The intelligence signal is the result of combining a wide-swing noise-modulated FM waveform with a narrow-swing voice-modulated FM waveform in a device “similar in principle of operation to the mixers used in superheterodyne receivers.”

At the receiver, the reference channel signal is used to reconstruct the first of the above factors, and that in turn is mixed with the received intelligence signal to recover the voice-modulated waveform represented by the second factor. This receiver mixer appears to be similar in many respects to Marchand's bandpass correlator.

To overcome some of the fundamental weaknesses of TR systems (more on this later), Hansen threw in an additional twist: the filtering of the reference channel signal, used to generate $n(t)$, was made time dependent, with transmitter and receiver filters required to change structure in virtual synchronism under the control of a chronometer. This structural change could not be detected in any way by observing the reference channel.

When presenting his design along the TR-FM-SS lines, Hansen notes that the intelligence signal cannot be heard by unauthorized narrow-band receivers because “such wide-swing modulations in effect tune the transmitted wave outside the frequency band of the unauthorized listener's receiver for the greater portion of the time and thus make such a receiver inoperative.” Concerned about the fact that a wide-band FM receiver might conceivably recover the signal $An(t) + Bv(t)$, he also concludes that “if therefore the noise $[n(t)]$ has important components throughout the range of signal frequencies and if the swing due to the noise is large compared to the swing due to the signal $[v(t)]$, deciphering is impossible.”

Curiously enough, due to the use of an exponential form of modulation, Hansen's design is constructed as a TR-FM-SS communication system at radio frequency (RF), but equivalently at demodulated baseband, it is simply a “typical noise masking” add/subtract TR system. (This latter appraisal of

[47] is from the case file—open to the public as for any issued patent—in Crystal City on an SR-SS invention [48] of major importance to a later period in this history.) Moreover, except for its TR vulnerabilities, Hansen's system is good AJ design, and as he points out, a large amount of additional noise can be injected at the RF output of the transmitter's intelligence channel for further masking without seriously degrading system performance.

Surprisingly, without the spectral spreading and chronometer-controlled reference signal filters, Hansen's system would bear a strong resemblance to a TR-FM system described in 1922 by Chaffee and Purington [49]. Hence, the concept of transmitting a reference signal to aid in the demodulation of a disguised information transmission is at least 60 years old!

• • •

Dr. Richard Gunther, an employee of the German company Siemens and Halske during World War II, recalls another speech encryption system involving bandwidth expansion and noise injection. In a fashion similar to the Western Electric B1 Privacy System, the voice subbands were pseudorandomly frequency scrambled to span 9 kHz and pure noise was added to fill in the gaps. The noise was later eliminated by receiver filtering in the speech restoration process. Tunis was the terminus of a link operated at 800 MHz and protected by this system.

• • •

With a German invasion threatening, Henri Busignies of ITT's Paris laboratories made an unprecedented visit to the French Patent Office to remove all vestiges of material on his latest inventions. He then headed across the Atlantic, joined ITT's Federal Telephone and Radio Corporation, and quickly filed a landmark patent on a radar moving-target indicator. Busignies, a remarkably prolific inventor who over his lifetime was granted about 140 patents, soon collaborated with Edmond Deloraine and Louis deRosa in applying for a patent [50] on a facsimile communication system with intriguing antijam possibilities here set forth:

The system uses a transmitter which sends each character "a plurality of times in succession," and a receiver in which the character signals are visually reproduced, "one on top another . . . to provide a cumulative effect." If "the interference signals are not transmitted to provide such a cumulative effect, the interference will form only a bright background but will not prevent the signals from being read."

From a jamming viewpoint, the real novelty in the disclosure is in the fact that the mechanisms which read the characters at the transmitter and write the characters at the receiver synchronously vary in rate of operation. Thus, attempts to jam the system with periodic signals which might achieve the "cumulative effect" at the receiver output will be unsuccessful.

In a sequel patent filed six weeks later [51], it is specified that the facsimile pulse modulation should have a low average duty cycle, be characterized by steep wavefronts, and have high peak-to-average power, in order to attain superior protec-

tion. This time-wobbling system is obviously an early relative of modern TH-SS systems. Concurrently with these efforts, deRosa covered similar applications in the field of radar by filing what may be the first patent on random jittering of pulse repetition frequencies [52].

Test results of the facsimile system are mentioned briefly in a 1946 NDRC Division 15 report [53] which also points out in a radar context that

"There is factual evidence that tunability is foremost as an AJ measure. Frequency spread of radars, which serves the same function, is a corollary and equally important." With regard to communications, "RF carrier frequency scrambling and time modulation of pulses with time scrambling" are possible communication antijam measures.

The report's final recommendations state that "any peacetime program to achieve protection against jamming should not be concerned with the type of equipment already in service, but should be permitted an unrestricted field of development." This was sensible advice to follow, when practical, in the post-war years.

• • •

Another study of protected communications was launched when ITT submitted Proposal 158A to the NDRC for consideration. Although the original proposal only suggested the use of redundancy in time or frequency as a possible AJ measure, a 1944 report [54] stated with regard to jamming that

"The enemy can be forced to maintain a wide bandwidth if we use a coded frequency shifting of our narrower printer bandwidth so that it might at any time occupy any portion of a wider band."

This clear suggestion of FH-SS signaling was not explored further in the last year of the contract. Several different tone signaling arrangements were considered for communication to a printer at rates on the order of one character per second. Synchronization of these digital signaling formats was accomplished in open-loop fashion using precision tuning forks as reference clocks.

"These forks are temperature compensated over a wide range and are mounted in a partial vacuum, so that their rate is not affected by the low barometric pressures encountered at high altitudes. Their accuracy is of the order of one part in a million, so that once the receiving distributor was phased with the transmitted signal, it remained within operable limits for two hours or more. A differential gear mechanism, operated by a crank handle on the front panel, was provided for rephasing the receiving distributor whenever this became necessary."

The receiving distributor controlled the reinitializing of L - C tank circuits tuned to detect transmitted tones. Due to their high Q , these circuits performed an integrate-and-dump operation during each distributor cycle. This detector was a significant improvement over the prior art, a fact indeed recognized

intuitively by ITT, rather than derived from correlation principles.

ITT's printer communication system was tested at Rye Lake Airport on February 21, 1945. The printer performed well in the presence of jamming 11 dB stronger than the desired signal, and under conditions where voice on the same channel was not intelligible [55]. The interference in this test consisted of an AM radio station.

• • •

As far as technology is concerned, all of the above communication systems share a common propensity for the use of electromechanical devices, especially where signal storage and synchronization are required. Undoubtedly in the 1940's the barriers to be overcome in the development of SS communications were as much technological as they were conceptual. The final 1940's state-of-the-art vignette to follow is in an area whose need for lightweight, rugged systems did much to drive communication technology toward all-electronic and eventually all-solid-state systems.

Missile Guidance

During World War II the NDRC entered the realm of guided missiles with a variety of projects [56] including the radio control in azimuth only (AZON) of conventionally dropped bombs (VB's) which trailed flares for visibility, radar-controlled glide bombs (GB's) such as the Pelican and the Bat, and the remotely controlled ROC VB-10 using a television link. Now documented mostly through oral history and innocuous circuit patents, one of several secure radio guidance efforts took place at Colonial Radio, predecessor of the Sylvania division at Buffalo, NY. This project was under the direction of Madison Nicholson, with the help of Robert Carlson, Alden Packard, Maxwell Scott, and Ernest Burlingame. The secret communications system concept was stimulated, so Carlson thinks, by talks with Navy people who wanted a system like the "Flash" system which the Germans used for U-boat transmissions. However, it wasn't until the Army Air Force at Wright Field posed the following problem that the Colonial Radio effort began seriously.

The airfoil surfaces of the glide bombs were radio controlled by a mother plane some distance away, sometimes with television display (by RCA) relayed back to the plane so that closed-loop guidance could be performed. It was feared that soon the Germans would become adept at jamming the control. To solve this problem Colonial Radio developed a secure guidance system based on a pulsed waveform which hopped over two diverse frequency bands. This dual band operation led to the system's nickname, Janus, after the Roman god possessing two faces looking in opposite directions. Low duty cycle transmission was used, and although the radio link was designed to be covert, the system could withstand jamming in one of its two frequency bands of operation and still maintain command control.

The Colonial Radio design's transmitter for the mother aircraft was designated the AN/ARW-4, and the corresponding glide bomb receiver was the AN/CRW-8. Testing of the radio

guidance system took place at Wright Field in 1943, under the direction of Lt. Leonhard Katz, Capt. Walter Brown and Theodore Manley, and Project Engineer Jack Bacon. The contract, including procurement of two transmitters and seven receivers, was completed by June 1944 [57].

ITT also participated in these World War II guidance programs, notably with a system called Rex [58]. One patent, evidently resulting from this work and filed in 1943 by Emile Labin and Donald Grieg [59], is interesting because it suggests CDMA operation in pulse code modulation (PCM) systems by slight changes in the pulse repetition frequency. In addition, the patent notes the jammer's inherent problem of trying to deliver its interference to the victim receiver in synchronism with the transmitted pulse train. However, the notion of multiplicity factor or spectrum spreading is not mentioned.

A third guidance system for the control of VB's and GB's was proposed by the Hammond Laboratory, a privately organized research group with a history in radio guidance dating back to 1910 [60], [61]. The Hammond system used a complicated modulation format which included a carrier wobbled over 20 kHz to protect against tone interference, and FM control signals amplitude modulated onto this frequency-modulated carrier [58]. More notable in this history than the system itself is the fact that Ellison Purington of the Hammond Laboratory in 1948 came close to describing a TH and FH carrier for a radio control system in a patent application [62]. The actual details describe a TH-SS system with control signals coded into the transmission using frequency patterns. Magnetic or optical recording "on a rotating member driven by a constant speed motor" was one suggestion for the storage of different time hopping patterns, while another possibility mentioned involves delay line generation of pulse train patterns. Control keys are hidden in the way that the patterns are mapped onto different frequencies to create "radiations... randomly distributed in time and in frequency."

Other salient patents, based on World War II AJ and command/control efforts, include those of Hoepfner [63] and Krause and Cleeton [64].

III. EARLY SPREAD-SPECTRUM SYSTEMS

The following accounts of early SS developments are given to some extent as system genealogies. As we shall see, however, the blood lines of these system families are not pure, there being a great deal of information exchange at the conceptual level despite the secrecy under which these systems were developed. Approximate SS system time lines for several of the research groups tracked here are shown in Fig. 4. Since the SS concept was developed gradually during the same period that Shannon's work on information theory became appreciated, J. R. Pierce's commentary [65] on the times should be borne in mind:

"It is hard to picture the world before Shannon as it seemed to those who lived in it. In the face of publications now known and what we now read into them, it is difficult to recover innocence, ignorance, and lack of understanding. It is easy to read into earlier work a generality that came only later."

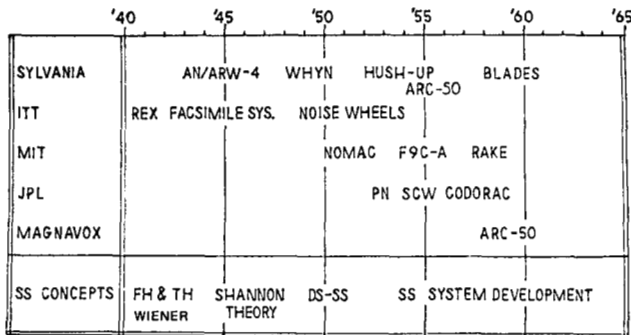


Fig. 4. Approximate time lines for the systems and concepts featured in this history.

WHYN

Many of the roots of SS system work in the U.S.A. can be traced back to the pioneering of FM radar by Major Edwin Armstrong during the early phases of World War II. The Armstrong technique involved transmitting a sinusoidally modulated wide-band FM signal, and then heterodyne-mixing the return from the target with a frequency offset replica whose identical sinusoidal modulation could be phase-shifted manually. When properly adjusted, the output of the mixer was very narrow-band and the phase difference between the transmitted modulation and that of the replica then gave a measure of the two-way propagation delay to the target. Certainly, this created a bandwidth expansion and compression methodology, primitive though it was since the FM wobble was simply a sine wave.

Sylvania's Bayside Laboratories on Long Island received the contract in World War II to continue development of the Armstrong radar, and Bayside engineers started considering more exotic modulation signals to improve its ranging characteristics. This led, in 1946, to a Sylvania subcontract from Republic Aviation under Army Air Force Project MX-773, to develop a guidance system for a 500-1500 mile surface-to-surface missile. Although celestial and inertial navigation were possibilities, it was decided that a radio-controlled system using FM ranging would be the most easily realized. Two navigation systems were studied, the first being a circular-navigation, two-ground-station system in which the range to each station was determined separately using the FM radar technique. For each range measurement a pair of ultrastable oscillators would be used, one in the ground station and one in the missile. After oscillator initialization at launch, the phase difference between the received signal modulation and the replica modulation would be proportional to range.

The second system was designed to overcome location errors that would occur in the first system due to drift between the oscillators. A third ground station was introduced for transmitting a reference signal to which the missile and ground station oscillators were locked. Then the difference between the ranges to the three ground stations could be measured at the missile, the intersection of the corresponding hyperbolic loci indicating its location. The acronym WHYN, standing for Wobblated HYperbolic Navigation, was the descriptor coined by Norman Harvey for this system. From the receiver's point of view, the circular navigation system was a

primitive SR-FM-SS system while the WHYN system was TR-FM-SS.

Accurate high-frequency (HF) ranging requires that the receiver extract the ground wave propagation and ignore the potentially strong skywave multipath, as well as atmospheric noise and jamming. The MX-773 subcontract specifications called for satisfactory discrimination against interferences of the following types:

1) Skywave, identical in modulation to the ground wave guidance signal, but 40 times greater in amplitude and delayed 100-250 μ s.

2) Other guidance signals identical in modulation, but 15 times greater in amplitude and differing in arrival time by 50-2000 μ s.

3) Unmodulated, pulse, or noise-modulated interference up to 20 times the guidance signal in amplitude.

The Bayside engineering team, headed by Norman Harvey, Walter Serniuk, and Meyer Leifer, and joined in 1947 by Nathan Marchand, felt that an FM signal with a more complex modulation than Armstrong's would satisfy requirements. The concept was bench tested via analog simulation with perfect guidance signal synchronization being wired in. Using multiple tone modulation under a maximum frequency deviation constraint of 10 kHz, no simple multitone FM modulation satisfying the contractual constraints could be found. However, low-frequency noise modulation was shown on the bench test to give "an excellent discrimination function with no secondary peaks."

The Sylvania team recognized that noise modulation was "very appealing from the anti-jamming and security aspects," but its utility in WHYN was questionable since the recording and reproduction requirements in the actual system would be severe. Accordingly, electronic generation of a reproducible multitone modulation function remained the preferred approach. Although the above are quoted from [66], these revealing results were in classified print by October, 1948 [67], simultaneously with Shannon's open publication of pseudorandom signaling.

When Republic Aviation's missile development was discontinued, Sylvania work proceeded on WHYN under the auspices of the Air Force's Watson Laboratories [later to become the Rome Air Development Center (RADC)] with this support spanning the 1948-1952 time frame. Noise modulation never made it into the WHYN system but correlation detection certainly did. In fact, it was noted [68] in 1950 that "Had the full significance of cross-correlation been realized [at the beginning], it is probable that the name [WHYN] would be different." Advocacy of correlation detection reached an artistic peak when the following classified Sylvania jingle was heard at a 1950 autumn meeting in Washington.

*"Correlation is the best,
It outdoes all the rest,
Use it in your guided missile
And all they'll hear will be a whistle.
Whistle, whistle, whistle . . ."*

Sung to the tune of a popular Pepsi-Cola commercial, this bit of creativity may have been inspired by the arrival, at Sylvania's helm, of Pepsi's chief executive.

The earliest public disclosure of the concepts which had evolved in the first WHYN study appears circumspectly in the last paragraph of an October, 1950, article by Leifer and Marchand in the *Sylvania Technologist* [69]:

“... The factors determining signal bandwidth and receiver noise bandwidth are entirely different; in the former it is resolution and in the latter, rate of flow of information. A signal that provides good resolution and, hence, has fairly large bandwidth, should be made more complex in nature within this bandwidth for anti-jamming characteristics. Finally, it is important to note that nowhere has the type of modulation of the signals been specified; the conclusions apply equally to pulse-, frequency-, and phase-modulated signals.”

Ideas and analyses which were prompted by the Sylvania Bayside work appeared in the literature [70]–[73], in two Harvey patents, the first on WHYN [74] and the second on a collision warning radar [75] which could employ noise modulation, and in another patent [76] on spectrum shaping for improving TOA measurement accuracy in correlation detectors. With continued study, the need for bandwidth expansion to improve system performance became even more apparent, and it was declared that [77]

“Jamming signals which are noise modulated or non-synchronous cw or modulated signals are rejected to the same extent that general noise is rejected, the improvement in signal over interference in terms of power being equivalent to the ratio of the transmission bandwidth to the receiver bandwidth.”

This improvement property of SS systems is usually referred to as processing gain, which nominally equals the multiplicity factor of the system. By suitably setting these bandwidth parameters, acceptable receiver operation from 40 to 60 dB interference-to-signal ratio was reported in laboratory tests, and navigation receivers operating at -25 dB SNR were predicted [78].

A Note on CYTAC

WHYN was one of the competitors in the development of LORAN (LONG RANGE Navigation), a competition which was eventually won by Sperry Gyroscope Company's CYTAC [79]. Developed in the early 1950's, the CYTAC system and its CYCLAN predecessor had many of the attributes of WHYN, but signal-wise, CYTAC was different in two regards. First, pulse modulation was used so that earliest arriving skywaves could be rejected by gating, and second, phase coding of the pulses was innovated to reject multihop skywaves. These same properties, designed into the system and later patented by Robert Frank and Solomon Zadoff [80], were also used to discriminate between signals from different LORAN stations. The polyphase codes originally designed for CYTAC's pulse modulation were patented separately by Frank [81], but were eventually replaced in LORAN-C by biphasic codes to reduce complexity [82]. A certain degree of receiver mismatching also was employed for enhancing time resolution, a similar stratagem having been used for the WHYN system [76].



Fig. 5. One of the last snapshots of Madison “Mad” Nicholson, at age 51, on a cold Easter day in 1958. As a tribute to this dedicated scientist who died suddenly in mid-January, 1959, the library at Sylvania's Amherst Laboratory was named the Madison G. Nicholson, Jr., Memorial Library. (Photo courtesy of Dana Cole.)

Since narrow-band interference was a potential problem in LORAN, the anti-interference capabilities of this pulse-compression type of signaling were appreciated and reported in 1951 [83]. To further improve performance against in-band CW interference, manually tuned notch filters were added to CYTAC in 1955 and automatic anti-CW notch filters [84], [85] were added to LORAN-C in 1964. To indicate progress, Frank notes that LORAN receivers with four automatically tunable notch filters are now on the market, some for under \$1600.

Hush-Up

In the summer of 1951 Madison Nicholson (see Fig. 5) of Sylvania Buffalo headed a proposal effort for the study of a communication system which he called “Hush-Up.” Undoubtedly, the SS ideas therein were distilled versions of those brought to Colonial Radio from the WHYN project by Norman Harvey shortly before that subsidiary lost its identity and was absorbed by Sylvania in February, 1950. Nicholson coaxed his old colleague, Robert M. Brown, who had worked at Bayside on the Armstrong radar in World War II while Nicholson had led the AN/ARW-4 team at Colonial, back to Sylvania to work with him and Allen Norris for the duration of the proposal effort. Harvey, by then chiefly responsible for commercial television work, left the realm of military communications research and development. In due course Wright Air Development Center (WADC) gave Sylvania a contract beginning in May, 1952, and Nicholson's team went “behind closed doors” to begin work.

Having boned up on Sylvania Bayside's WHYN reports, the engineers at Buffalo set out to verify that a noise-like signal could be used as a carrier, and received coherently, without

causing insoluble technical problems. Independently adopting a pattern of experimentation which was being pursued secretly by other researchers at the time, detector operation was initially examined in the laboratory using a broad-band carrier whose source was thermal noise generated in a 1500 Ω resistor. This wide-band carrier signal was wired directly to the receiver as one input of the correlation detector, thereby temporarily bypassing the remaining major technical problem, the generation of a noise-like carrier at the transmitter and the internal production of an identical, synchronous copy of the same noise-like carrier at the receiver.

In 1953, as the follow-on contract for Hush-Up commenced, James H. Green was hired specifically to develop digital techniques for producing noise-like carriers. John Raney, a Wright Field Project Engineer who had worked on WHYN, also joined Nicholson as System Engineer in early 1953. Nicholson and Raney almost certainly deserve the credit for coining the now universally recognized descriptor "spread spectrum," which Sylvania termed their Hush-Up system as early as 1954.

During the second contractual period, which lasted into 1957, Green and Nicholson settled on the form of noise-like carrier which Hush-Up would employ in place of WHYN's FM, namely, a pseudorandomly generated binary sequence PSK-modulated (0 or 180 degrees) onto an RF sinusoid. Such binary sequences with two-level periodic correlation were called "perfect words" by Nicholson. In the end a variety of perfect word known as an m -sequence was advocated for implementation (more on m -sequences later). Synchronization of the DS-SS signal was accomplished by an early-late gate, dithered tau tracker (τ = delay). Nicholson and Green's tau tracker invention has been, until recently, under patent secrecy order.

As development progressed, the system evolving from the Hush-Up effort was officially designated the ARC-50. Sylvania engineer Everard Book fabricated the ARC-50/XA-2 "flying breadboards." In 1956, flight testing began at Wright-Patterson Air Force Base (WPAFB) with WADC Project Engineers Lloyd Higginbotham and Charles Arnold at the ground end of the ARC-50/XA-2 test link and Capt. Harold K. Christian in the air. The assigned carrier frequency for the tests was the WPAFB tower frequency; the ground terminal of the ARC-50 was about 100 yards from the tower antenna, and communication with the airborne terminal was acceptable at ranges up to 100 miles. Vincent Oxley recalls that tower personnel, and the aircraft with whom they were conducting normal business, were never aware of ARC-50 transmissions. While the tests were successful, it must have been disheartening to Buffalo engineers when Sylvania failed to win the production contract for the ARC-50.

BLADES²

In the mid-1950's, Madison Nicholson spent part of his considerable creative energies in the development of methods for generating signals having selectable frequency deviation from

a reference frequency. Nicholson achieved this goal with notable accuracy by creating an artificial Doppler effect using a tapped delay line. Even though patent searches uncovered similar frequency-synthesis claims by the Hammond Organ Company, the resulting inventions [86], [87] were a breakthrough for Sylvania engineers working on SS systems.

In addition to being used to slew the time base in the Hush-Up receiver, Nicholson's "linear modulator" (or "cycle adder") was an essential part of another system which Jim Green named the Buffalo Laboratories Application of Digitally Exact Spectra, or BLADES for short. Initiated with company funds in 1955 and headed by Green and Nicholson, the BLADES effort was originally intended to fill Admiral Raeburn's Polaris submarine communications requirements.

Perhaps due to concern for the serious distortions that multipath could cause in long-range HF communications, the ARC-50 DS configuration was abandoned in favor of an FH-SS system. In 1957 a demonstration of the breadboard system, operating between Buffalo, NY, and Mountain View, CA, was given to a multiservice group of communications users. Vincent Oxley was system engineer on this development, as well as for the follow-on effort in 1958 to produce a packaged prototype.

The original breadboard contained only an FH-SS/FSK anti-jam mode. The system achieved its protection ratio (Sylvania's then current name for processing gain) by using the code generator to select two new frequencies for each baud, the final choice of frequency being dictated by the data bit to be transmitted. To be effective, a jammer would have to place its power on the other (unused) frequency, or as an alternative, to place its power uniformly over all potentially usable frequencies. Because of the possibility that a jammer might put significant power at the unused frequency, or that the selected channel frequency might be in a fade, a (15, 5) error-correcting code was developed and implemented for the prototype, and was available as an optional mode with a penalty of reducing the information transmission rate to one-third.

While apparently no unclassified descriptions of BLADES are available, glimpses of the system can be seen in several "sanitized" papers and patents produced by Sylvania engineers. Using the results of Pierce [88], Jim Green, David Leichtman, Leon Lewandowski, and Robert Malm [89] analyzed the performance improvements attainable through the diversity achieved by FH combined with coding for error correction. Sylvania's expertise in coding at that time is exemplified by Green and San Soucie's [90] and Fryer's [91] descriptions of a triple-error-correcting (15, 5) code, Nicholson and Smith's patent on a binary error-correction system [92], and Green and Gordon's patent [93] on a selective calling system. All are based on properties of the aforementioned perfect words called m -sequences, which were investigated in Sylvania Buffalo's Hush-Up studies. Also involved in BLADES development were R. T. Barnes, David Blair, Ronald Hileman, Stephen Hmelar, James Lindholm, and Jack Wittman at Sylvania, and Project Engineers Richard Newman and Charles Steck at the Navy's Bureau of Ships.

The prototype design effort was aimed at equipment optimization. Extremely stable, single quartz crystal, integrate-

² It is convenient to recount this Sylvania system next, even though chronologically it would belong toward the end of the monograph.

and-dump filters were developed. Based on their success, a bank of 32 "channel" filters was implemented for an M -ary FSK optional mode to transmit a full character (5 bits) per baud. Loss of a single baud in this case meant loss of a full character because the (15, 5) decoder could only correct 3 bit errors per codeword. A "noodle slicer" was implemented to avoid this problem by interleaving five different codewords, so that each baud carried one bit from each word. This interleaving technique was the subject of a patent filed in 1962 by Sylvania engineers Vincent Oxley and William De Lisle [94]. Noodle slicing was never employed in the FH binary FSK mode.

BLADES occupied nearly 13 kHz of bandwidth in its highest protection mode. In addition to being a practical AJ system, Vincent Oxley recalls that during initial breadboard on-air tests, the system also served very well as an unintentional jammer, efficiently clearing all other users from the assigned frequency band.

After considerable in-house and on-air testing between the Amherst Laboratories at Williamsville, NY, and San Juan, PR, the packaged prototype was finally delivered for shipboard testing in 1962. Such a system was evidently carried into the blockade associated with the Cuban missile crisis but was not tested there due to a radio silence order. In 1963 BLADES was installed on the command flagship Mt. McKinley for operational development tests. Successful full-duplex field trials over intercontinental distances were observed by Sylvania engineer Gerry Meiler, who disembarked at Rota, Spain, leaving the system in the hands of Navy personnel. Further into the Mediterranean, intentional jamming was encountered, and BLADES provided the only useful communication link for the Mt. McKinley. Thus, BLADES was quite likely the earliest FH-SS communication system to reach an operational state.

Noise Wheels

At the end of World War II, ITT reorganized and constructed a new facility at Nutley, NJ, incorporated as Federal Telecommunication Laboratories (FTL), with Henri Busignies as Technical Director. There in 1946 a group of engineers in Paul Adams's R-16 Laboratory began working on long-range navigation and communication techniques to meet the requirements of the expanding intercontinental air traffic industry. In the available frequency bands, it was expected that multipath generated by signal ducting between the ionosphere and the earth would cause significant distortion, while the prime source of independent interference at the receiver would consist of atmospheric noise generated for the most part by lightning storms in the tropics. A major effort was initiated to study the statistical properties of the interference and to learn how to design high performance detectors for signals competing with this interference.

This was the situation in 1948 when Shannon's communication philosophy, embracing the idea that noise-like signals could be used as bearers of information, made a distinct impression on FTL engineers. Mortimer Rogoff, one of the engineers in R-16 at the time, was an avid photographic hobbyist. He conceived of a novel experimental program using photographic techniques for storing a noise-like signal and for build-

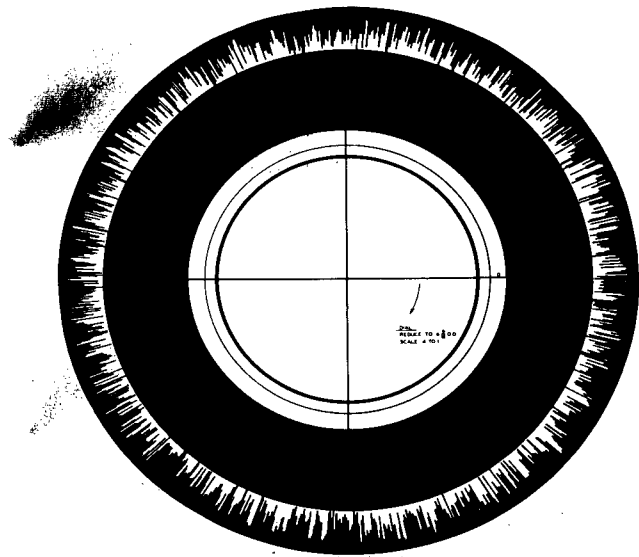


Fig. 6. Only two copies of Rogoff's secret noise wheel, shown here, were made to support ITT's early research on spread-spectrum systems. The noise wheel concept was revived briefly in 1963 when two more wheels were produced and tested in a system at ITT. (Photo from [96], courtesy of ITT.)

ing an ideal cross correlator. Supported by ITT funds and doing some work in a makeshift home lab, Rogoff prepared a 4 in X 5 in sheet of film whose transmissivity varied linearly in both directions, thus creating a mask whose transmission characteristic at every point (X, Y) was proportional to the product XY . Two signals then were correlated by using them as the X and Y inputs to the oscilloscope, reading the light emitted from the masked oscilloscope face with a photomultiplier, and low-pass filtering the resultant output.

Rogoff's noise-like carrier came straight from the Manhattan telephone directory. Selecting at random 1440 numbers not ending in 00, he radially plotted the middle two of the last four digits so that the radius every fourth of a degree represented a new random number (see Fig. 6). This drawing was transferred to film which, in turn, when rotated past a slit of light, intensity-modulated a light beam, providing a stored noise-like signal to be sensed by a photocell.

In initial experiments Rogoff mounted two identical noise wheels on a single axle driven by a Diehl 900 rpm synchronous motor (see Fig. 7). Designed and assembled by Rogoff and his colleague, Robert Whittle, separate photocell pickups were placed on each wheel, one stationary and one on an alidade, so that the relative phase between the two signals could be varied for test purposes. Using time shift keying (an extra pickup required) to generate MARK or SPACE, one noise wheel's signal was modulated and then combined with interference to provide one correlator input, while the other input came directly from the second noise wheel. These baseband experiments, with data rates on the order of a bit per second and, hence, a multiplicity factor of well over 40 dB, indicated that a noise-like signal hidden in ambient thermal noise could still accurately convey information.

In another part of FTL, highly compartmentalized for security purposes, Louis deRosa headed the R-14 Electronic Warfare Group. DeRosa, who earlier had collaborated with

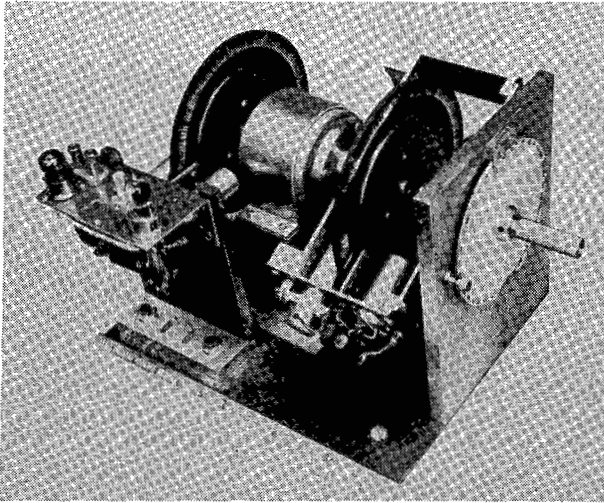


Fig. 7. ITT's equipment constructed for bench-testing a communication system based on noise-like carriers stored on wheels. (Photo from [96], courtesy of ITT.)

Busignies and Deloraine, and who had exchanged many friendly arguments with Nathan Marchand concerning the merits of IF correlation (à la Marchand [34]) versus baseband correlation via homodyning (deRosa's favorite), held an umbrella contract through Dr. George Rappaport, Chief of the Electronic Warfare Branch at WADC, to pursue a variety of electronic countermeasures and counter-countermeasures. The contract, codenamed Project Della Rosa, spanned the 1947-1951 time frame and, hence, was concurrent with Rogoff's work.

The first written indication of deRosa's visualization of an SR-SS technique occurs in one of this prolific inventor's patents, filed in January, 1950, with L. G. Fischer and M. J. DiToro [95], and kept under secrecy order for some time. The fine print of this patent calls out the possibility of using an arbitrarily coded waveform generated at the transmitter and an identical, synchronous, locally generated waveform at the receiver to provide a reference for a correlation detector, to reliably recover signals well below the noise level.

On August 1, 1950, deRosa gave a laboratory demonstration of Rogoff's noise wheels to visiting U.S. Air Force personnel, with the system extracting signals 35 dB below the interfering noise. Later the same month deRosa and Rogoff produced a secret proposal [96] outlining Rogoff's work and proposing several refinements including PSK data modulation, wider bandwidth carrier generation (either by scaling Rogoff's original system or by introducing flying spot scanners reading a pseudorandom image), and quicker-response drives for the receiver's noise wheel synchronizing servo.

Whittle recalls that in mid-1951 the wheels were separated by about 200 yards in the first test of his synchronization system for the noise wheel drives. During these tests Bing Crosby's crooning on radio station WOR provided the jamming as Morse code was successfully transmitted at -30 dB SNR. Tapes of the test were made and taken on unsuccessful Washington, DC, marketing trips, where there was considerable interest but evidently the government could not grasp the full significance of the results.

In 1952 an FTL Vice President, retired General Peter C. Sandretto, established relations between deRosa and Eugene Price, then Vice President of Mackay Marine, whereby Mackay facilities in Palo Alto, CA, were made available for transcontinental tests of the FTL equipment. Testing began in late November and ended before Christmas, 1952, with Whittle and Frank Lundburg operating an ARC-3 Collins transmitter at the Mackay installation, and deRosa and Frank Bucher manning the receiver at Telegraph Hill, NJ.

Coordination of these field trials was done by telephone using a codeword jargon, with

"crank it" = bring up transmitter power,

"take your foot off" = reduce transmitter power,

"ring it up" = advance the sync search phase,

"the tide is running" = severe fading is being encountered,

"go north" = increase transmission speed.

Initial synchronization adjustments typically took 3-5 min. Matched tuning forks, ringing at a multiple of 60 Hz, provided stable frequency sources for the drives with the receiver synchronizer employing a war-surplus Bendix size 10 selsyn resolver for phase shifting purposes. Rogoff's original noise wheels were retained for the transcontinental tests, as was his photo-optical multiplier, although the multiplier was improved to handle both positive and negative inputs. Using ionospheric prediction charts, transmission was near the maximum usable frequency (where multipath is least), in the 12-20 MHz range, without FCC license. The system bandwidth was fixed at 8 kHz, the data rate varied down to a few bits per second, and the transmitter power was adjustable between 12 and 25 W.

Although documentation of the test results has not yet been made available, Whittle recalls that during a magnetic storm that happened to occur, a 50 kW Mackay transmitter could not communicate with the East Coast using its conventional modulation, while FTL's test system operated successfully on 25 W. Often the noise-wheel system communicated reliably, even while interference in the same frequency band was provided by the high-power Mackay transmitter. Air Force observer Thomas Lawrence, Project Engineer on Della Rosa and Chief of the Deceptive Countermeasures Section at WADC (another WADC team member was Frank Catanzarite), also recalls witnessing these capabilities.

However, some problems were encountered. In addition to the FTL system once being detected out-of-band (probably in the vicinity of the transmitter), propagation effects apparently caused trouble at times. The signals received at Telegraph Hill were preserved by a speed-lock tape recorder which had been built from scratch to have adequate stability. In the months following the transcontinental tests, John Groce performed correlation recovery experiments on the taped signals, experiencing considerable difficulty with multipath.

Due to government-decreed project isolation, Rogoff was not told about the above tests of his noise wheels. In fact, Rogoff could not follow developments after 1950, except to

participate in a patent application with deRosa, for which [96] served as the disclosure. With the help of patent attorney Percy Lantzy, the application, which described a full-fledged SR-SS single-sideband communication system based on Rogoff's noise wheels, was filed in March, 1953. (Incidentally, the original patent claims placed few restrictions on the DS modulation technique to be employed, but subsequently these were struck out in favor of single-sideband specification.)

In June, 1953, the Bureau of Ships placed a secrecy order against the application, which stood until July, 1966, when the Navy recommended rescission of the order and issuance of the patent. Technically, this was accomplished in November, 1966, but before the printing presses in the U.S. Patent Office had begun to roll, a civil servant at the National Security Agency (NSA) noted the invention and was able to get secrecy reimposed. This order stood until 1978 when NSA permitted wholesale rescission on scores of patents including at least a dozen on SS techniques. The deRosa-Rogoff patent [48] was finally awarded in November, 1979, nearly thirty years after the invention's conception.

The emphasis in both invention and early experimental work at FTL was on covert communication and on suppressing atmospheric noise. It is impossible to determine exactly when FTL engineers appreciated the fully robust AJ capabilities of their system. In 1950 they suspected that broad-band noise jamming would be the best attack against the receiver's signal processor, while the receiver itself might be disabled by any strong signal if it did not possess sufficient dynamic range. The deRosa-Rogoff patent, although using the phrase "secrecy and security" several times, never specifically claims AJ capabilities. However, during the course of their work, FTL engineers coined the term "chip" to denote an elementary pulse which is modulated by a single random or pseudorandom variable, and they realized that high performance against atmospheric noise, or when hiding beneath a strong signal like radio station WOR, required many chips per data bit of transmission.

For unknown reasons, FTL was unable to capitalize significantly on this early entrance into the SS field. When in June, 1970, as an Assistant Secretary of Defense, Louis deRosa (see Fig. 8) was asked about later developments involving the FTL system, he mentioned only Project Dog, a U.S. Navy covert communications operation in the North Korean theater.

The Hartwell Connection

In January, 1950, the Committee on Undersea Warfare of the National Research Council addressed a letter to Admiral C. B. Monsen, Assistant Chief of Naval Operations, in which the committee urged the determination of a long-range program against submarines [97]. This was the beginning of a sequence of events which led to the formation of a classified study program known as Project Hartwell, held at M.I.T. in June through August, 1950. Under the direction of Prof. Jerrold Zacharias, the study brought together highly qualified experts from the military, industry, and universities, to find new ways to protect overseas transportation.

A subsequent history [98] of the Research Laboratory of Electronics (RLE) at M.I.T. indicates that Hartwell was pos-



Fig. 8. Louis deRosa remained with ITT until 1966 when he joined the Philco-Ford Corporation as Director of Engineering and Research. In 1970 he left a Corporate Vice President position at Philco-Ford to be sworn in (above) by Melvin Laird as Assistant Secretary of Defense for Telecommunications, the first holder of that office. He died unexpectedly in 1971 after a long workout on the tennis court. (Photo courtesy of Mrs. Louis deRosa, standing next to Secretary Laird.)

sibly the most successful of M.I.T.'s summer study projects, motivating the development of "the Mariner class of merchant vessels; the SOSUS submarine detection system; the atomic depth charge; a whole new look at radar, sonar, and magnetic detection; and a good deal of research on oceanography." This 1966 history omitted (perhaps due to classification) the fact that transfer of an important concept in modern military communications took place at Hartwell.

One of the many ideas considered was the possibility of hiding fleet communication transmissions so that enemy submarines could not utilize them for direction finding. Appendix G of the secret final report on Project Hartwell suggested that a transmitter modulated by a wide band of noise be employed, reducing the energy density of the transmitted signal "to an arbitrarily small value." If at the same time the actual intelligence bandwidth were kept small, covert communications should be possible in certain situations.

Three systems for accomplishing covert communications were described in the report. One, acknowledged to be the suggestion of FTL's Adams and deRosa (Adams alone was an attendee), was an SR-SS system. A second system, attributed to J. R. Pierce of BTL, used very narrow pulses to achieve frequency spreading, pulse pair spacing to carry intelligence, and coincidence detection at the receiver. It was noted that if synchronized (random) pulse sources were available at transmitter and receiver, then cryptographic-like effects were possible, presumably by transmitting only the second of each pulse pair.

A third system, with no proponent cited, is the only one described by a block diagram in the final report (see Fig. 1). To avoid the synchronization problems inherent in stored reference systems, it was proposed that the noise-like carrier alone be transmitted on one channel, and that an information-bearing delay-modulated replica of the carrier also be transmitted at either the same frequency or at an offset frequency. A cross-correlation receiver still would be employed in this TR-SS sys-

tem, but the carrier storage and synchronization problems of an SR-SS system would be traded for the headaches of a second channel.

The Hartwell report noted that the SR system was cryptographically more secure than the TR system, which transmitted a copy of the wide-band carrier in the clear. Furthermore, it would be improper to transmit the intelligence-free wide-band carrier on the same channel as the intelligence-modulated carrier with a fixed delay τ between them, since this delay-line addition would impose a characteristic $\cos(\pi f\tau)$ periodic ripple on the power spectral density of the transmitted signal. This ripple might be detectable on a panoramic receiver, compromising the covertness of the transmission. Although not mentioned in the report, it was realized at about the same time that multipath could produce a similar delay-line effect with similar results on any wide-band signal, including SR-SS transmissions.

To close this revealing discussion on noise modulation, the Hartwell report suggested that several of these kinds of systems, using different wide-band carriers, could operate simultaneously in the same band with little effect on each other. This concept, which, it is noted, would eliminate the cooperative synchronization required in time-division multiple-access (TDMA) systems, is one of the earliest references to CDMA operation.

Among the attendees at Project Hartwell was Jerome B. Wiesner, then Professor of Electrical Engineering at M.I.T. and Associate Director of RLE. Concerning Wiesner's place in the development of modern communications, it was later said by an M.I.T. professor [99], "Perhaps one might put it that Wiener preached the gospel and Wiesner organized the church. Jerry's real strength . . . lies in his ability to spot the potential importance of an idea long before others do."

Certainly Wiesner appreciated the possibilities of the wide-band communication systems discussed at Hartwell. Shortly after Hartwell, Wiesner met Robert Fano in a hallway near the Building 20 bridge entrance to the RLE secret research area and told Fano of a "Navy study idea" for using a noise-modulated carrier to provide secure military communications. Even though Fano was familiar with Shannon's precepts and had been an early contributor to the new field of information theory, this made a profound impression on him. He in turn discussed the concept with Wilbur Davenport, a then recent recipient of the Sc.D. degree from M.I.T. They decided to split the research possibilities, with Fano studying radar applications and Davenport developing the communication applications. This was a fortunate juxtaposition with radar work alongside communications since covertness could not be maintained in radar applications and jamming was always a possibility. The AJ potential of SS systems was appreciated immediately and reported in a series of RLE secret Quarterly Progress Reports.

The year 1951 saw another secret summer study, known as Project Charles, in action at M.I.T. Under the direction of F. W. Loomis of the University of Illinois, Project Charles investigated air defense problems, including electronic warfare. Appendix IV-1 of the Charles Report [100], written by Harry Nyquist of BTL, suggests that carrier frequencies be changed

in accordance with a predetermined random sequence, and that by using this FH pattern over a wide band, the effects of jamming could be minimized. (Nyquist's experience as an NSA consultant may have played a role here.) In the next section of Appendix IV, the Charles Report proposes that a ground wave radar use a noise-modulated CW carrier to achieve security against countermeasures, and indicates that M.I.T. is investigating this technique (over a decade after Guanello's original conception).

NOMAC

Correlation methodology is so basic to modern communications that it may be difficult to imagine a time when the technique was not widely accepted. Fano, commenting on that era, has said, "There was a heck of a skepticism at the time about crosscorrelation . . . it was so bad that in my own talks I stopped using the word crosscorrelation. Instead I would say, 'You detect by multiplying the signals together and integrating.'" Nevertheless, by 1950 M.I.T. researchers were leading proponents of correlation techniques, and were finding more and more problems which correlation might help solve.

It was into this climate that Wiesner brought the noise-like wide-band carrier concept from Project Hartwell to M.I.T. researchers. Within a year of this event Lincoln Laboratory received its organizational charter and commenced operation, its main purpose being the development of the SAGE (Semi-Automatic Ground Environment) air defense system defined by Project Charles. Soon thereafter, the classified work at RLE was transferred to Lincoln Laboratory and became Division 3 under the direction of William Radford. There, fundamental SS research was performed, to a significant extent by M.I.T. graduate students, guided by Group Leaders Fano and Davenport. The acronym NOMAC, classified confidential at the time and standing for "NOise Modulation And Correlation," was coined by one of these students, Bennett Basore, to describe the SS techniques under study. The term "spread spectrum" was never heard at M.I.T. in those days.

Basore's secret Sc.D. thesis [101], the first on NOMAC systems, was completed under Fano, Davenport, and Wiesner in 1952. It consisted of a comparison of the performances of transmitted- and stored-reference systems operating in the presence of broad-band Gaussian noise. An RF simulation of a NOMAC system with multiplicity factors up to 45 dB was used to back up theoretical analyses. As in Nicholson's and Rogoff's initial experiments, the synchronization problem of the SR system was bypassed in the experimental setup. The carrier was obtained by amplifying thermal and tube noise, while the interfering noise was produced by some old radar RF strips made originally for M.I.T.'s Radiation Laboratory. Data were on-off keyed. A bandpass correlator was employed in which two inputs at offset frequencies were inserted into an appropriate nonlinearity, the output signal then observed at the difference frequency through a narrow bandpass integrating filter, and the result envelope-detected to recover correlation magnitude. Basore's conclusion was that the effect of noise in the reference channel was to reduce the receiver's

output SNR by the ratio of the signal power level to the signal-plus-noise power level in the reference channel.

The main advantages of TR-SS systems are

- 1) no SS carrier synchronization problems at the receiver
- 2) no SS carrier storage or generation required at receiver.

On the other hand, there are apparent disadvantages to the TR system:

- 1) relatively poor performance at low SNR's in the signal and reference channels
- 2) extra bandwidth may be required for reference channel
- 3) no privacy feature when the clear SS carrier is available to all listeners
- 4) difficulties in matching reference and data channel characteristics, e.g., group delays
- 5) easily jammed when the difference between the reference and data channel center frequencies is known
- 6) no multipath rejection capability.

While the advantages of TR systems have since dwindled due to the development of synchronization techniques for the SR system, the disadvantages of TR systems are to a great extent fundamental. Considerable experimental work on TR-NOMAC systems was performed at M.I.T. in the 1950-1952 time frame. Davenport's Group 34 at Lincoln Laboratory developed several TR-SS systems, including one called the P9D. An HF version of the P9D was tested between Lincoln Laboratory and a Signal Corps site in New Jersey and, according to Davenport, worked "reasonably well." This led to the development of a VHF version intended for an ionospheric scatter channel to a Distant Early Warning (DEW) radar complex near Point Barrow, AK. Since the need for LPI and AJ was marginal, SS modulation was not considered necessary and the DEW-Line link was eventually served by more conventional equipment.

A TR system study also was carried out by U.S. Army Signal Corps Capt. Bernard Pankowski in a secret Master's degree thesis [102], under the direction of Davenport. Published at the same time as Basore's thesis, Pankowski's work details several ideas concerning jamming, multiplexing, and CDMA operation of TR-NOMAC systems. In particular, it noted that jamming a TR system is accomplished simply by supplying the receiver with acceptable alternative reference and data signals, e.g., a pair of sine waves in the receiver's passbands at the appropriate frequency separation.

Bernie Pankowski offered three possible solutions to the jamming problem, namely, going to the MF or SR systems which others were studying at the time, or developing a hybrid pure noise-TR, FH-SR system with one of the two channels frequency hopped to deny offset frequency knowledge to the jammer. Similarly, CDMA operation was achieved by assigning each transmitter-receiver pair a different frequency offset between their data and reference channels. Laboratory experiments on various single-link TR system configurations with two multiplexed circuits sharing the same reference channel were carried out for a channel bandwidth of 3000 Hz and a data bandwidth of 50 Hz.

There were several exchanges of ideas with other research groups during the time period following Basore's and Pankowski's theses. For example, at Lincoln Laboratory on October 2,

1952, Sylvania, Lincoln, and Air Force personnel participated in discussions led by Meyer Leifer and Wilbur Davenport on the subject of secure communications [103]. In February, 1953, Sylvania, Lincoln, and Jet Propulsion Laboratory researchers attended the (Classified) RDB Symposium on the Information Theory Applications to Guided Missile Problems at the California Institute of Technology [78], [104]. Detailed records of these kinds of exchanges appear to be virtually nonexistent. (RDB: the Pentagon's Research and Development Board.)

As Group 34 studied the TR approach, it became apparent that the SR approach had advantages that could not be overlooked. The task of solving the key generation and synchronization problems for an SR system was given to another of Davenport's Sc.D. candidates, Paul Green. Green's secret thesis [105] is a clearly written comparison of several NOMAC system configurations, the aim of which is to determine a feasible SR design. Comparisons are based on the relationship between input and output signal-to-noise (or jamming) ratios for the receiver's signal processor, and the degradations in this relationship due to synchronization error and multipath. Green deduced that correlation at baseband would require a phase-locked carrier for good correlator performance, while correlation at IF à la Basore, with the correlator output being the envelope of the bandpass-filtered IF signal, would require SS carrier sync error to be bounded by the reciprocal of the SS carrier bandwidth.

Green then designed and built (see Fig. 9) a digitally controlled SS carrier generator in which five stagger-tuned resonant circuits were shock-excited by pseudorandom impulse sequences which in turn were generated from 15 stored binary sequences of lengths 127, 128, and 129 (see Fig. 10). The resultant signal had a long period and noise-like qualities in both the time and frequency domains, yet was storable and reproducible at an electronically controlled rate at both ends of a communication link. The proposed SS carrier synchronization procedure at the receiver was quite similar to then contemporary tracking-radar practice, progressing through search, acquisition, and track modes with no change in signal structure. Tracking error was sensed by differencing correlator outputs for slightly different values of clock oscillator phase. Based on Green's results which indicated that an SR system was feasible, and on jamming tests which confirmed TR system vulnerability [106], Group 34's resources were turned toward prototyping an SR system. This marked the end of TR system research at Lincoln Laboratory.

F9C-A/Rake

The prototype SR-NOMAC system developed for the Army Signal Corps by Lincoln Laboratory was called the F9C. Its evolution to a final deployed configuration, which spanned the 1953-1959 time frame, was carried out in cooperation with the Coles Signal Laboratory at Ft. Monmouth, in particular with the aid of Harold F. Meyer, Chief of the Long Range Radio Branch, and Bernard Goldberg, Chief of the Advanced Development Section, and also Lloyd Manamon and Capt. H. A. ("Judd") Schulke, all of that Laboratory. This effort had the

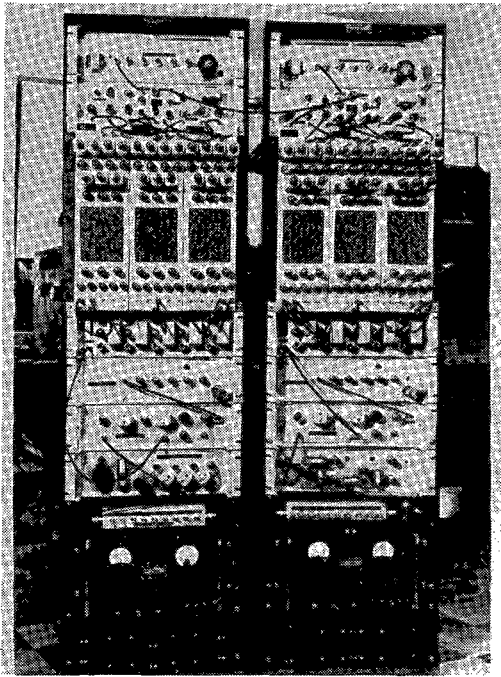


Fig. 9. These two racks of equipment constitute the transmitter and receiver used to carry out the experimental portion of Paul Green's secret Sc.D. dissertation. The SS carrier generators occupy the upper half of each rack, with the plug boards allowing the operator to change the structure of the 15 stored binary sequences. Later in the F9C system, these plug boards were replaced by punched card readers. (Photo from [105], courtesy of M.I.T. Lincoln Laboratory.)

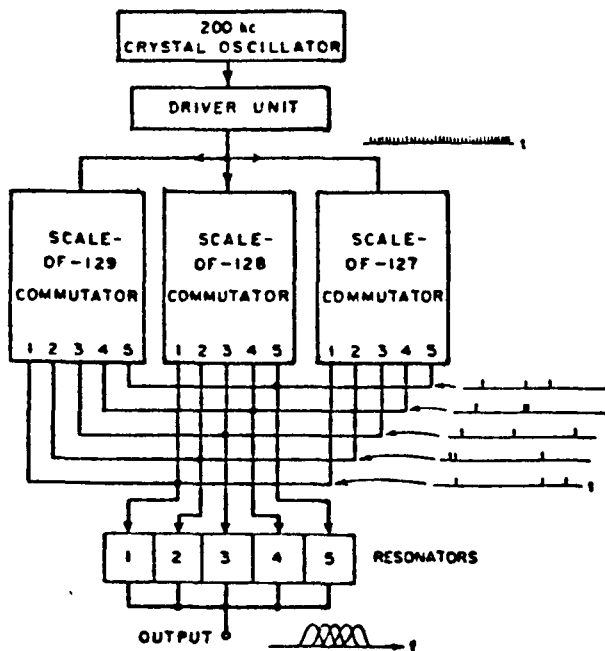


Fig. 10. The boxes in the above diagram of Paul Green's SS signal generator are located so that they correspond to the physical layout in the equipment racks of Fig. 9. An SS signal generator similar to the one shown here, combining waveforms of relatively prime periods, was chosen for the F9C system. (Diagram from [105].)

wholehearted support of Lt. Genl. James D. O'Connell, then Chief Signal Officer of the U.S. Army.

Paul Green remained at Lincoln Lab after completing his thesis, and was placed in charge of building and testing F9C equipment. Included in the group of engineers contributing to the development of the F9C were Bob Berg, Bill Bergman, John Craig, Ben Eisenstadt, Phil Fleck, Bill McLaughlin, Bob Price, Bill Smith, George Turin, and Charles Wagner (originator of the Wagner "code," the simplest version of the Viterbi algorithm).

The F9C system [107] occupied 10 kHz of bandwidth and originally employed frequency-shift data modulation at a rate of approximately 22 ms/bit. This resulted in a multiplicity factor greater than 200. The F9C radioteletype system was intended for long-range fixed-plant usage over HF channels. Initially, SS signal generation was accomplished by combining the 28 outputs of four 7-stage counters (fixed to have periods 117, 121, 125, and 128) using an array of "and" gates, and driving a bandpass filter with the resultant pulse train. For security against jamming, the gate array connections were controlled by changeable punched cards and this served the role of a key for the system. At the time there were discussions concerning the possibility of making the SS signal provide cryptographic security as well, but this idea was eventually dropped in favor of conventional data encryption before modulation.

Both the SS signal generator and data modulation technique were later modified to improve spectral and correlation characteristics and change the SS signal period, thereby increasing AJ and privacy capabilities [108]. (For a discussion of the effects encountered in combining sequences of different periods, see [109]-[111]. Also, in a March, 1955, secret report, Price proposed improving DS-SS by resorting to error correction coding in combination with soft or hard decisions against CW or pulse jammers; but this AJ strategy was not implemented in the F9C system.)

At the suggestion of Signal Corps Capt. John Wozencraft, the bandpass filter in Basore's bandpass correlator was replaced by an active filter [112] employing a diode-quenched high- Q L - C tank circuit, thereby attaining true IF integrate-and-dump correlation operation. A different circuit achieving the same matched-filter-type improvement on sinusoids was developed independently by M. L. Doelz for the Collins Radio Company [113].

Synchronization of the SS signal was accomplished initially by sending a tone burst at a preagreed frequency to start the four 7-stage counters in near synchronism. A fine search then began to bring the receiver's SS modulation clock into precise alignment with the received modulation. When synchronism was achieved, a tracking loop was closed to maintain sync. The fine search was conducted at a rate of 1000 s for each second of relative delay being swept. The frequency standards used in the system were stable enough that even with propagation variations, a disablement of the tracking loop for a day would cause a desynchronization of at most 10 ms. Eventually it was demonstrated [114] that the tone burst was not necessary and the four 7-stage clocks were approximately aligned by time of day at 5 min intervals in initial search situations.

RGR
 PHIL MOVED YESTERDAY MOST OF HIS JUNK THAT IS THOUGH HE IS STILL AT
 ROBINSON RD
 THERE IS NOT TOO MUCH DOING AT THE LAB AT THE MOMENT
 WE ARE TRYING TO FIND EQUIPMENT FOR THE ATLANTIC PULSE TESTS
 THE IPSWICH SITE IS COMING ALONG SLOWLY BECAUSE OF THE LONG DELAY IN
 STARTING
 MARIE WILL BE FLYING OUT TO SFO ON MONDAY
 SHE SAYS R THAT SHE WILL GIVE YOU A CALL WHEN SHE GETS TR THERE
 I DONT KNOW IF SHE HAS A JOB YET

RGR I WAS WONDERING WHEN SHE WOULD ARRIVE OUT HERE AND ALSO IF I COULD
 BE OF ANY ASSISTANCE TO HERE I WILL WAIT FOR HER CALL AT EDL ON MONDAY
 IN REGARD TO MY OWN PLANS I PLAN TO STAY OUT HERE UNTIL THE FIRST EQUIP
 AT EDL IS SHOWN TO BE OK AND THE IF TIME PERMITS WILL GO BACK TO THE

LAB FOR A SHORT STAY IT WILL BE SHORT SINCE I AM GOING UP TO TACOMA
 TO BE MARRIED ON THE 25 OF AUGUST AND THEN I PLAN TO GO TO SWEDEN ON
 THE 28 OF SEPTEMBER FOR AT LEAST A MONTH
 SO I WILL BE ON VACATION FOR ABOUT THREE MONTHS GA

OH REALLY ??
 YES
 WE ARE ALL BREAKING OUR NECKS TRYING TO GET AT THIS

MACHINE TO SAY CONGRATULATIONS!

AND WER I EXPECTED PITY MURDER

WELL THIS IS RATHER SUDDEN AS THE GIRLS SAY

YEP

HELLO BOB THIS IS P GREEN I KNEW IT WOULD COME TO THIS SOME DAY
 CHEER UP THE WORST IS YET TO COME CONGRATULATIONS

CI
 YES I UNDERST, S 9-3
 THAT IS THE BEST THING YOU SHOULD HOPE FOR THE BEST AND BE SATE SATISFIR SATISM
 M
 AND BE SATISFIED WITH THE WORST GA

Fig. 11. This duplex teletype output, made during coast-to-coast tests of the F9C system, includes undoubtedly the first wedding announcement afforded the security of spread-spectrum communications. (Copy courtesy of the announcer at the West Coast station, Robert Berg.)

Transcontinental field trials of the F9C system commenced in August, 1954 [108]. The transmitter was located in Davis, CA, and the receiver in Deal, NJ, to provide an eastbound HF link for F9C tests. A conventional teletype link was supplied for westbound communication (see Fig. 11). Initial tests verified what many suspected, namely, that multipath could severely reduce the effectiveness of SS systems. While at low data rates an ordinary FSK receiver would operate based on the energy received over all propagation paths, the high time resolution inherent in an SS receiver would force the receiver to select a single path for communication, resulting in a considerable loss in signal level. Based on these early trials, several of the previously mentioned modifications were made, and in addition it was decided to add diversity to the system to combat multipath. Two receivers with antennas displaced by 550 feet were used for space diversity tests, and two correlators were employed to select signals propagated by different paths, in tau-diversity (time delay) tests.

A second set of field trials began in February, 1955, to determine the effects of these changes on performance of the transcontinental link. Results showed that an ordinary FSK system with space diversity and integrate-and-dump reception still significantly outperformed the F9C, with tau-diversity showing some hope of improving F9C performance. Both local and remote jamming tests were conducted in this second series, the interfering signal being an in-band FSK signal with MARK and SPACE frequency spacing identical to that of the F9C data modulation. The remote jammers were located at Army Communication Station ABA in Honolulu, HI, and at the Collins Radio Company in Cedar Rapids, IA. With tau-diversity, the F9C achieved a rough average of 17 dB improvement over FSK against jamming in the presence of multipath, justifying transition to an F9C-A production phase.

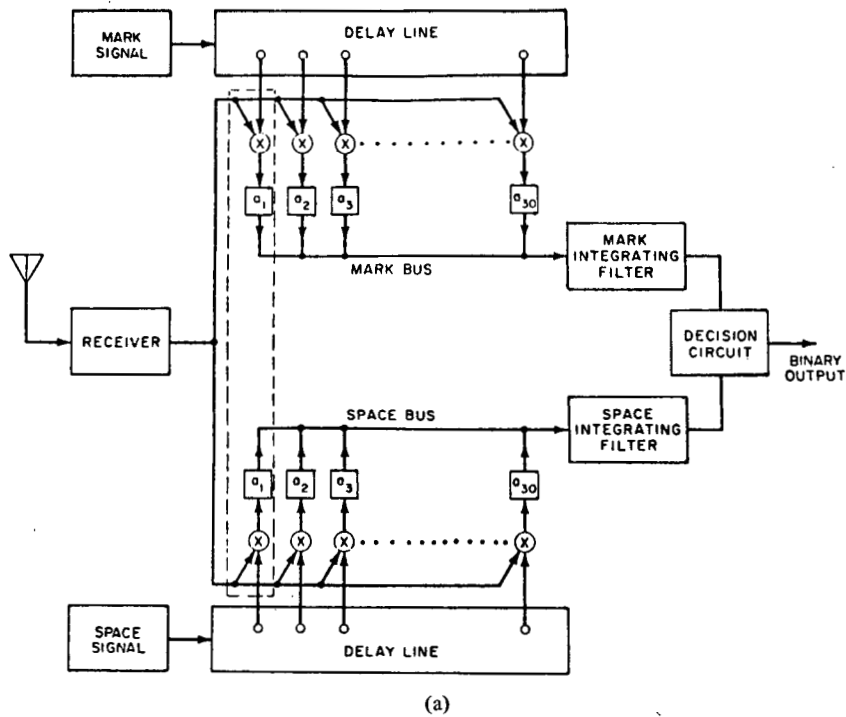
While initially the F9C MARK-SPACE modulation was FSK, this was eventually changed to another, equally phase-insensitive form of orthogonal signaling called the "mod-clock" approach. The mod-clock format, conceived by Neal Zierler and Bill Davenport, consisted of either transmitting the SS code in its original form (SPACE), or transmitting it with every other pulse from the SS code generator inverted (MARK).

Perhaps it was a case of serendipity that several years earlier Fano had suggested communication-through-multipath as an Sc.D. thesis topic to Bob Price. In any event, after a particularly frustrating day of field tests in which they encountered highly variable F9C performance, Price and Green got together in their Asbury Park boarding house to discuss multipath problems. Price already knew the optimal answer to some questions that were to come up that evening. Since receiving his doctorate and having been rehired by Davenport after trying his hand at radio astronomy in Australia, he had been polishing his dissertation with "lapidary zeal" (Green's witticism). Price had in fact statistically synthesized a signal processing technique for minimum-error-probability reception of signals sent over a channel disturbed by time-varying multipath as well as noise [115].

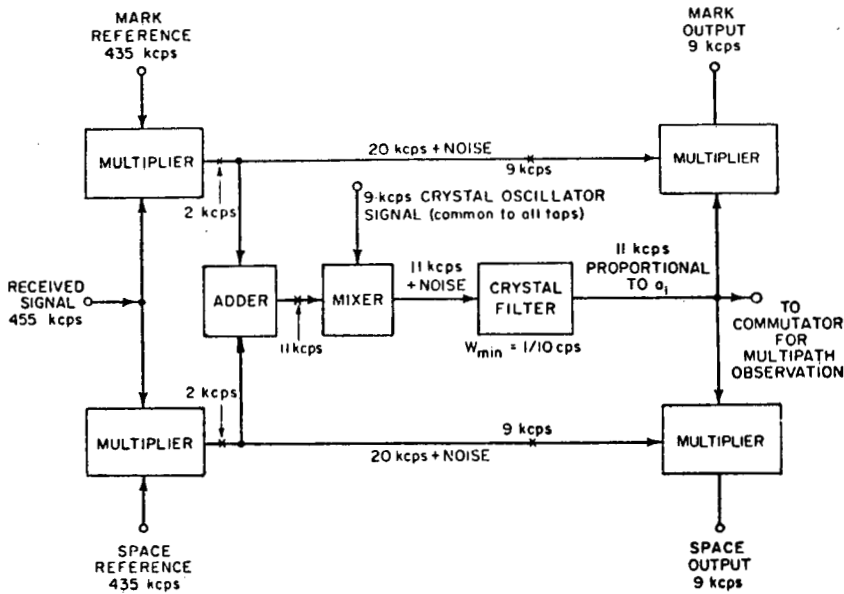
Green separately had been trying to determine how to weight the outputs of a time-staggered bank of correlators in order to improve F9C performance, and, acting on Jack Wozencraft's suggestion, had decided to choose weights to maximize the resultant transversal filter's output signal-to-noise ratio. Of course, the TOA resolution capability of the F9C was sufficient to guarantee that the outputs of different correlators in the bank represented signals arriving via different paths. Thus, the problem was one of efficiently recombining these signals. It took little time for Price and Green to realize that the results of their two approaches were nearly identical, and from that evening onward, the "Rake" (coined by Green) estimator-correlator became part of their plans for the F9C. Price took charge of building the Rake prototype, with the assistance of John Craig and Robert Lerner.

Related to Wiesner and Lee's work on system function measurements using cross correlation [116], Brennan's work on signal-combining techniques [117], and Turin's multipath studies [118], the Rake receiver could in turn be viewed as a predecessor of adaptive equalizers [119]. The Rake processor [120]-[122] (patented at Davenport's prompting) is adaptive in the sense that the weight on each MARK-SPACE tap pair is determined by the outputs of that MARK-SPACE tap pair, averaged over a multipath stability time constant. (See Fig. 12.) In its ultimate form, the magnetostrictive tapped delay line (patented by Nicholson [123]), around which the processor was built, contained 50 taps spanning 4.9 ms, the spacing being the reciprocal of the NOMAC signal bandwidth.

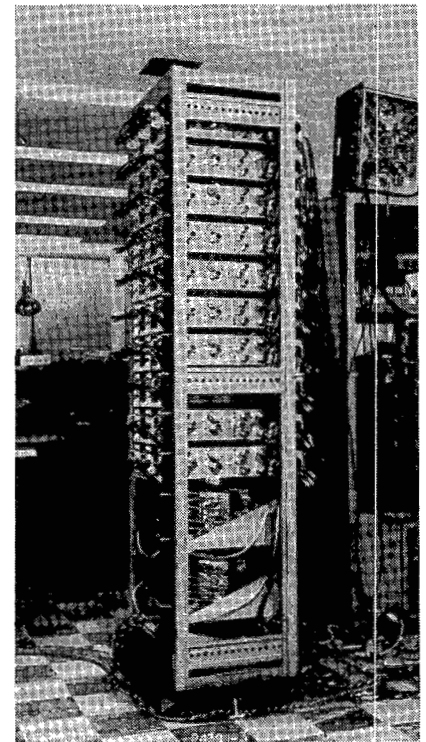
In addition to solving the multipath dilemma and thereby securing the full 23 dB of potential processing gain, Rake also allowed the sync search rate to be increased so that only 25 s were necessary to view one second of delay uncertainty [114]. (Readers of this early literature should note that to prevent disclosure of the actual F9C SS signal structure, all unclassified discussions of Rake, e.g., [121], invoked *m*-



(a)



(b)



(c)

Fig. 12. (a) This two-delay-line version of Rake shows how signals arriving via different path delays are recombined for MARK and SPACE correlation detection. In practice, a single delay line configuration was adopted. (b) The tap unit diagrammed here includes a long-time-constant crystal filter whose output signal envelope is proportional to the combining weight (a_j). This processing corresponds to that shown in the dashed box in (a). Rejection traps to eliminate undesirable cross products are shown by X's. (c) This Rake rack contains 30 tap units, two helical magnetostrictive delay lines, and a commutator chassis. (Diagrams taken from [120], photo courtesy of M.I.T. Lincoln Laboratory.)

sequences for signal spreading. In addition, mod-clock MARK-SPACE modulation was never mentioned in this open literature.)

The F9C-A production contract was let to Sylvania Electronic Defense Laboratory (EDL) at Mountain View, CA, in 1955, with Judd Schulke acting as Project Engineer for the Signal Corps, and Bob Berg as Lincoln Lab's representative, resident at EDL. By December, 1956, the first training manuals had been published [124]. Originally 16 F9C-A transmitter-receiver pairs were scheduled to be made, but funds ran out after production of only six pairs. The first installation was made for Washington, DC, near Woodbridge, VA/La Plata, MD. Worldwide strategic deployment commenced with the installation in Hawaii in January, 1958, and was followed by installations in Germany (Pirmasens/Kaiserslautern, February, 1958), Japan, and the Philippines. With the threat of a blockade of Berlin, the equipment assigned to Clark Field in the Philippines was moved in crates of Philippine mahogany to Berlin in the spring of 1959.

Rake appliques for the F9C-A receivers were fabricated later by the National Company of Malden, MA. These were produced with an improved yet simplified circuit configuration, invented by General Atronics [125], which employed tap units having a full 10 kHz of internal bandwidth instead of being structured as in Fig. 12(b). Additionally, the F9C-A/Rake appliques introduced a novel method of ionospheric multipath display, in which the multipath-matched tap-combining weights were successively sensed by a short pulse traveling along the magnetostrictive delay line, the pulse duty cycle being low enough to have negligible effect on the Rake signal processing. Bernie Goldberg was the Project Director for this effort and Robert L. Heyd served as the Project Engineer. Together they also developed Goldberg's innovative "stored ionosphere" concept [126] in which the F9C-A/Rake's multipath measurement function was used to record ionospheric channel fluctuations for their later re-creation in testing short-wave apparatus. This measurement capability was also employed to assess multipath effects, between Hawaii and Tokyo, of a high altitude nuclear detonation in the Pacific in July, 1962.

The F9C-A/Rake is no longer on-site, operational, or supported by the Army.

A Note on PPM

As the Hartwell report indicated, J. R. Pierce of BTL had suggested that covertness be achieved by using extremely narrow pulses for communication, thereby spreading the transmission spectrum. This idea was undoubtedly based on BTL's postwar work on pulse position modulation (PPM) [65]. After discussing the CDMA idea generally in a 1952 paper [127], Pierce and Hopper make the following observations:

"There are a number of ways in which this sort of performance can be achieved. One has been mentioned: the use of random or noise waveforms as carriers. This necessitates the transmission to or reproduction at the receiver of the carrier required for demodulation. Besides this, the signal-to-noise ratio in such a system is relatively poor even in the absence of interference unless the bandwidth used is many times the channel bandwidth. . . . In

the system discussed here, the signal to be sent is sampled at somewhat irregular intervals, the irregularity being introduced by means of a statistical or 'random' source. The amplitude of each of the samples is conveyed by a group of pulses, which also carries information as to which transmitter sent the group of pulses. A receiver can be adjusted to respond to pulse groups from one transmitter but to reject pulse groups from other transmitters."

This early unclassified reference not only mentions the disadvantages of certain SS systems, but also indicates a PPM technique for achieving the CDMA property of an SS system. PPM systems evidently remained of interest to BTL engineers for some time (e.g., see [128]), and also formed the basis for some Martin Company designs [129], [130].

CODORAC

In 1952 the Jet Propulsion Laboratory (JPL) of the California Institute of Technology was attempting to construct a radio command link for the purpose of demonstrating remote control of the Corporal rocket. The two groups most closely connected with the formulation of a system for accomplishing this task were the Telemetry and Control Section under Frank Lehan and the Guidance and Control Section under Robert Parks, both reporting to William Pickering.

One novel concept was formulated by Eberhardt Rechten, a recent Cal Tech Ph.D. under Parks, who decided that the current radio design approach, calling for the IF bandwidth to match the Doppler spread of the signal, could be improved dramatically. Rechten's solution was to adjust the receiver's local oscillator automatically to eliminate Doppler variations, thereby significantly reducing the receiver's noise bandwidth. This automated system used a correlator as its error detector, with the correlator inputs consisting of the received signal and the derivative of the estimate of the received signal. The resultant device, called a phase-locked loop (PLL), with its characteristics optimized for both transient and steady-state performance [131], was a key ingredient of all later JPL guidance and communication systems. Surprisingly, when attempts were made to patent an advanced form of PLL, the prior claim which precluded the award did not come from television, which also had synchronization problems, but came instead from a 1905 patent on feedback control. In retrospect, Eb Rechten feels that perhaps his greatest contribution in this area consisted of "translating Wiener's 'Yellow Peril' into English," and converting these elegant results into practice.

In struggling with blind-range problems occurring in the integration of a tracking range radar into the Corporal guidance system, Frank Lehan realized that his problems were due to the shape of the radar signal's autocorrelation function. The thought that the autocorrelation function of broad-band noise would be ideal led Lehan to formulate the concept of an elementary TR-SS communication system using a pure noise carrier. In May, 1952, Lehan briefly documented his partially developed ideas and their potential for LPI and AJ in a memo to Bill Pickering. Lincoln Laboratory's NOMAC work was quickly discovered, both JPL's and Lincoln's being sponsored by the Army, and the wealth of information con-

tained in Lincoln's detailed reports was made available to JPL researchers.

By the spring of 1953 JPL had decided upon a DS-SS configuration for the Corporal guidance link, and Rehtin, noting applications for his tracking loop theory in SS code synchronization, transferred to Lehan's section to head a group studying this problem. Seeing the value of the M.I.T. documentation, JPL began a series of bimonthly progress reports in February, 1953, these later being combined and annotated for historical purposes in 1958 [132].

The term "pseudonoise" with its abbreviation "PN" was used consistently from 1953 onward in JPL reports to denote the matched SS signal generators used in a DS system. Two PN generators initially were under consideration (see Fig. 13), the first being a product of 12 digitally generated (± 1) square waves having relative periods corresponding to the first 11 primes. This type-I generator was eventually dropped due to its excessive size and weight. The type-II PN generator was

"... based on the equation

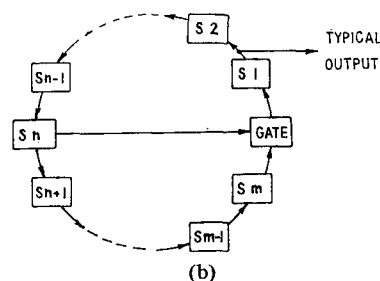
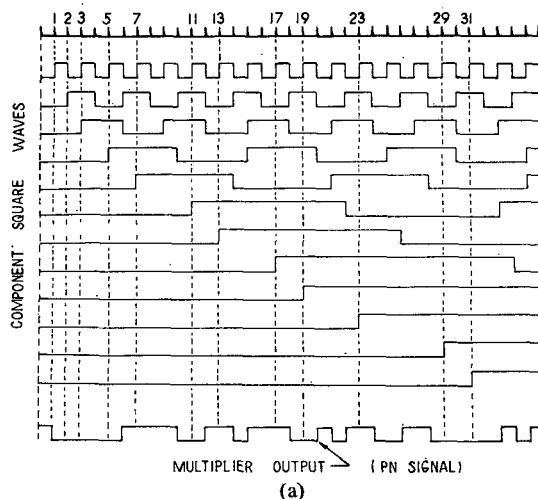
$$x(t + m) = x(t)x(t + n)$$

where t represents time, m and n are integers (m represents a time displacement greater than n), and the functions $x(t + m)$, $x(t)$, and $x(t + n)$ may equal ± 1 only. . . . If the correct values of m and n are chosen, the period before repeat is $2^m - 1$ The correlation function of all type-II PN generators consists of a triangle of height unity and of a width equal to twice the shift time standing on a block of height $(2^m - 1)^{-1}$."

This origination of an almost perfect spike-like autocorrelation function, accompanied by descriptions of shift register hardware, positive results of baseband synchronization experiments at -20 dB SNR's, and a table of suitable values of m and n for values of m up to 20, was reported as progress through August, 1953 [132], [133]. In later works by other researchers, these PN sequences were called shift-register sequences or linear-recurring sequences due to their particularly convenient method of generation, and were also termed m -sequences since their period is maximal.

On January 18, 1954, a JPL PN radio system was operated over a 100 yard link and two independent commands were communicated. Initial synchronization was achieved with the aid of a land line which was disconnected after sync acquisition. The system was able to withstand jammer-to-signal power ratios of 15-20 dB before losing lock, against a wide variety of jamming threats. This test was the assurance that JPL engineers needed regarding the practicality of SR-SS communications.

At this point work on the command system was temporarily dropped and a major effort was begun to optimize a pure ranging system, called the Scrambled Continuous Wave (SCW) system, which consisted of a "very narrow-band CW system scrambled externally by a PN sequence." On July 27, 1954, Corporal round 1276-83 carrying an SCW transponder was launched at White Sands Proving Ground. The transponder operated successfully from takeoff to near impact 70 miles away, providing range and range rate without loss of lock in



Time Displacement		Length of Sequence
Value of m	Value of n or $m-n$	
2	1	3
3	1	7
4	1	15
5	2	31
6	1	63
7	1	127
7	3	127
9	4	511
10	3	1023
11	2	2047
15	1	32767
15	4	32767
15	7	32767
17	3	131071
17	5	131071
18	7	262143
20	3	1048575

(c)

Fig. 13. (a) The type-I PN generator uses a multiplier to combine the outputs of binary (+1 or -1) signal shapers which in turn are driven by the outputs of relatively prime frequency dividers operating on the same sinusoid. The component square waves and the resultant PN product signal are shown here. (b) JPL's type-II generator was an m -stage linear-feedback shift register which produced binary (0 or 1) sequences of maximum period. The output of the m th and n th stages are added modulo 2 to produce the input of the first stage S1. (c) This first list of connections for the type-II generator was produced at JPL by hand and computer search. (Diagrams and table redrawn from [132].)

the synchronization circuitry. Rehtin, engineer Walter Victor, and Lehan (who left JPL in 1954) later filed an invention disclosure based on the SCW system results from this test, and called the system a COded DOppler RADar Command (CODORAC) system. This acronym was used to describe the radio guidance systems developed for the Sergeant and later the Jupiter missiles in the 1954–1958 time frame.

Throughout this period one of the major problems in establishing one-way communication to a missile was to make the PN generator tough enough to withstand high temperatures and vibrations as well as small and light enough to fit into the missile design. A variety of devices (e.g., subminiature hearing aid tubes) and potting compounds were tested. In 1954 Signal Corps liaison official G. D. Bagley was able to obtain approximately 100 of the Western Electric type 1760 transistors (the first available outside BTL) for use by JPL engineer Bill Sampson in the construction of a PN generator. The resulting circuitry was an interesting combination of distributed-constant delay lines and transistor amplifiers and logic, chosen because it minimized the number of active elements required [134]. This general method of construction remained the norm at JPL through 1958.

Late in 1954 a separate group under Sampson was formed for the purpose of investigating possible countermeasures against the SCW system equipment designed by a group headed by Walt Victor. Designed to make this phase of the program as objective as possible, this organization brought forth a thoroughly designed system with high countermeasures immunity. Here are three issues on which significant progress was made.

1) It was hoped that repeater jamming would be ineffective due to the high TOA resolution capability of SS and to the excess propagation delay incurred by the repeater. The period of the PN sequence was made longer than the missile flight time so that it would be impossible for a repeater to store a PN coded signal for nearly a full period and deliver it to the victim receiver in synchronism with the directly transmitted PN sequence one period later. A weakness in this regard still existed in a simple m -sequence generator based on a linear recursion. Specifically, these sequences possessed a “cycle-and-add” property (for example, see [135]) by which the modulo 2 sum of a sequence and a delayed version of that sequence results in the production of the same sequence at still another delay. The equivalent “shift-and-multiply” property for the ± 1 version of these m -sequences, satisfying the equation quoted earlier in this subsection, conceivably could be used by a jammer to produce an advance copy of the sequence without waiting a full period. In an effort to completely rule out this possibility, Cal Tech graduate student Lloyd Welch was hired in 1955 to study the generation of sequences which avoid the cycle-and-add property by resorting to nonlinear recursions [136]. Although laboratory system work continued to use linearly generated PN sequence for test purposes, final designs were to be based on nonlinear generators.

2) Initial jamming tests revealed weaknesses in the SCW system when confronted by certain narrow-band jammers. Most of these were due to problems in the mechanization of the multiplications required in the PN scrambler and corre-

lator descrambler. For example, if the descrambler effectively mechanizes a multiplication of the jamming signal by a constant plus the receiver’s PN sequence replica (the constant representing a bias or imbalance in the multiplication/modulation process), then the multiplier output will contain an unmodulated replica of the jamming signal which has a free ride into the narrow-band circuitry following the descrambler. The sure cure for this problem is to construct better balanced multipliers/modulators, since the processing gain achievable in an SS system is limited by the “feedthrough” (or bias) in its SS multipliers. In the mid-1950’s JPL was able to build balanced modulators which would support systems with processing gains near 40 dB. For a recent discussion of this problem area, see [137].

3) Another major concern of system designers was the decibel range and rates of variation of signal strength, due to missile motion and to pulsed or intermittent jamming. At the circuit level the two approaches to controlling signal levels in critical subassemblies were automatic gain control (AGC) and limiting. The AGC approach suffers from the possibility that its dynamics may make it susceptible to pulse jamming, while limiters, although instantaneous in nature, generate harmonics which might be exploited by a jammer. The eventual design rule-of-thumb was that limiters could be used when necessary on narrow-band signals (e.g., prior to PLL phase detectors), and that AGC techniques should be used in the wide-band portions of the system. Analytical support for this work came from JPL’s own studies of AGC circuits [138], [139], and from Davenport’s classic paper on limiters [140]. It was not realized until much later that in some instances the limiter theory was not appropriate for coherent signal processing analyses [141].

Many of these kinds of problems remain with the designer today, the differences being in the technology available to solve them.

Both the Sergeant and Jupiter guidance programs were terminated when decisions were made to choose all-inertial jam-proof guidance designs as the baseline for those missile systems. However, CODORAC technology survived in the JPL integrated telemetry, command, tracking, and ranging system for the Deep Space Program, and in the later projects of subcontractors who had worked for JPL in the Jupiter program. A modified version of CODORAC became the Space Ground Link Subsystem (SGLS) now used routinely in U.S. Department of Defense missile and space instrumentation.

m-Sequence Genesis

The multiplicative PN recursion given in [132] and its linear recursion counterpart in modulo 2 arithmetic, namely

$$y(t + m) = y(t) \oplus y(t + n)$$

were among those under study by 1954 at several widely separated locations within the United States. Lehan recalls that the idea of generating a binary sequence recursively came out of a discussion which he had with Morgan Ward, Professor of Mathematics at Cal Tech, who had suggested a similar decimal arithmetic recursion for random number generation.

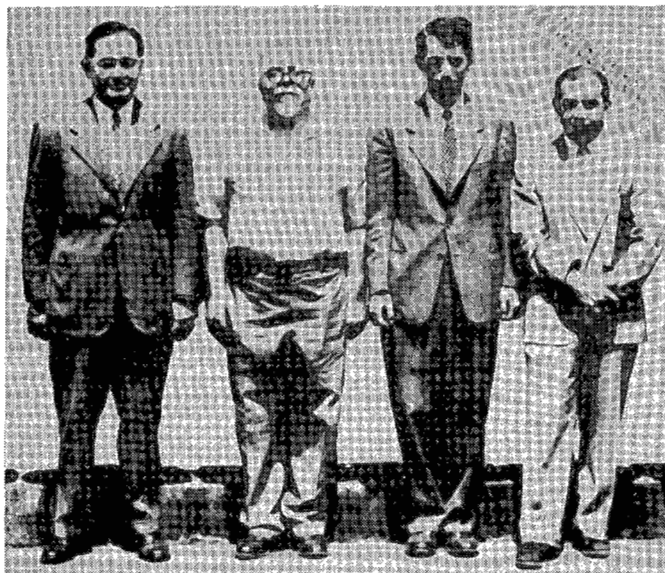


Fig. 14. Cut from a 1953 photograph of a summer session class on mathematical problems of communication theory, this picture salutes (from left to right) Yuk Wing Lee, Norbert Wiener, Claude Shannon, and Robert Fano. It is ironic that Wiener could not prevent the transfer of his theories, through meetings like the one at which this picture was taken, to the military research which he refused to support after World War II. (Photo courtesy of M.I.T.)

It is hard to determine if this idea was mentioned at the (Classified) RDB Symposium held at Cal Tech in February, 1953. Lincoln Laboratory's Bill Davenport remembers that the first time that he had seen a PN generator based on the above recursion was in Lehan's office on one of his trips west. This generator, built to Rehtin's specifications, was used to extend Rehtin's hand-calculated table of m -sequence generators from a shift register length of at most 7, to lengths up to 20 (see Fig. 13).

Sol Golomb, then a summer hire at the Glenn L. Martin Company in Baltimore, MD, first heard of shift register-generated sequences from his supervisor, Tom Wedge, who in turn had run across them at a 1953 M.I.T. summer session course on the mathematical problems of communication theory. (This meeting included an elite group of the founding fathers of information theory and statistical communications. See Fig. 14.)

On the other hand, Neal Zierler, who joined Lincoln Laboratory in 1953, recalls discovering shift register generation of PN sequences while looking for ways to simplify the SS signal generators used for the F9C system. Golomb's [135], [142], [143] and Zierler's [144]–[146] work established them as leading theorists in the area of pseudonoise generation. However, Zierler's shift register-generated sequences were never used in the F9C-A system due to their cryptanalytic weaknesses. Golomb's work gained further recognition after he joined JPL in August, 1956.

Madison Nicholson's early attempts at PN sequence design date back to 1952 [103]. Nicholson's first exposure to the pseudorandomness properties of linearly recurring sequences probably came from Allen Norris, who remembers relating to Nicholson ideas developed from lectures by the noted mathematician, A. A. Albert, of the University of Chicago. Co-workers recollect that Nicholson used paper-and-pencil

methods for finding shift register logics which generated m -sequences. Jim Green in due course joined in this exploration, and built demonstration hardware. Bob Hunting was assigned to investigate the generation of long m -sequences and spent a considerable amount of time exercising Sylvania's then-new UNIVAC 1 in the Corporate Computer Center at Camillus, NY, and eventually produced an extensive list of "perfect word" generators. R. L. San Soucie and R. E. Malm developed nonlinear sequence-combining techniques for the BLADES prototype, the result being an SS carrier with a period of about 8000 centuries. Oliver Selfridge of Lincoln Laboratory's Group 34 became the government representative whose approval was required on Sylvania's SS code designs for Air Force contracts, but was not involved with the Navy's BLADES effort.

Early work by others on linear-feedback shift registers includes that of Gilbert [147], Huffman [148], and Birdsall and Ristenbatt [149]. Additional insights were available from the prewar mathematical literature, especially from Ward [150], Hall [151], and Singer [152], [153]. Of course, in the top secret world of cryptography, key-stream generation by linear recursions very well may have been known earlier, particularly since Prof. Albert and others of similar stature were consultants to NSA. But it is doubtful that any of these had a direct impact on the pioneering applications to SS communication in 1953–1954.

ARC-50

In 1953 a group of scientists interested in the design of computers left the University of California at Los Angeles and formed a research laboratory under an agreement with the Magnavox Corporation. Their first contact with SS systems came when JPL approached them with the problem of building DS-SS code generators for the Jupiter missile's proposed radio navigation link. This exposure to JPL's work on PN sequences and their application to radio guidance paid dividends when Lloyd Higginbotham at WADC became interested in getting high-speed, long-period generators for the ARC-50 system which was emerging from the Hush-Up study at Sylvania Buffalo. At Sylvania, Hush-Up had started out under the premise of radio silence, and was aimed for an application to the then-new air-to-air refueling capability developed by the Strategic Air Command (SAC). After a demonstration of the wired system at Sylvania, a SAC representative made the "obvious" statement, "When you are in radar range, who needs radio silence?" From that time onward, the design was based on AJ considerations.

The AJ push resulted in NSA being brought into the program for their coding expertise. However, due to the nature of NSA, they passed technical judgment rather than provided any concrete guidance. The NSA view was that the SS codes had to be cryptographically secure to guarantee AJ capability, and Lincoln Laboratory had established that the proposed ARC-50 SS PN code was easily breakable. On this point Lloyd Higginbotham says, "At that time we felt we were being treated unfairly because the system was still better than anything else then in existence."

By 1958 Magnavox had parlayed their knowledge of high-speed PN generators into a development contract for the ARC-50 system, won in competition with Sylvania. Magnavox Research Laboratories operated out of a garage on Pico Boulevard in Santa Monica in those early days, with Jack Slattery as General Manager and Ragnar Thorensen as Technical Director. From their few dozen employees a team was organized to design the code generators and modem, while RF equipment was built at Magnavox's Fort Wayne facility. Shortly thereafter, Magnavox Research Laboratories moved to Torrance, CA, into a new facility sometimes referred to as "the house the ARC-50 built." Harry Posthumus came from Fort Wayne as Program Manager and teamed with system designers Tom Levesque, Bob Grady, and Gene Hoyt, system integrator Bob Dixon, and Bill Judge, Bragi Freymodsson, and Bob Gold.

Although retaining the spirit of the DS-SS system developed at Sylvania, technologically the design evolved through several more phases at Magnavox. Nowhere was this more obvious than in the design of the SS code generators, the heart of the system. The earliest Magnavox code generators were built using a pair of lumped constant delay lines, run in syncopated fashion to achieve a rate of 5 Mchips/s. This technology was expensive with a code generator costing about \$5000, and was not completely satisfactory technically. The first improvement in this design came when the delay lines were transistorized, and a viable solution was finally achieved when 100 of the first batch of high- β , gold-doped, fast rise-time 2N753 transistors made by Texas Instruments were received and used to build a single-register code generator operating at 5 Mchips/s.

Originally to facilitate SS code synchronization, the system employed a synchronization preamble of 1023 chips followed by an m -sequence produced by a 31 stage shift register. Register length 31 was chosen because the period of the resultant m -sequence, namely, 2, 147, 483, 653, is prime, and it seemed unlikely that there would exist some periodic substructure useful to a jammer. Lacking knowledge of the proper connections for the shift register, a special machine was built which carried out a continuing search for long m -sequences. Problems were encountered involving false locks on correlation sidelobe peaks in the sync preamble (sometimes it seemed that a certain level of noise was necessary to make the system work properly), and concerning interference between different ARC-50 links due to poor cross-correlation properties between SS codes.

The ARC-50 was configured as a fully coherent system in which the SS code was first acquired, and the sinusoidal carrier was then synchronized using PLL techniques. Because of apprehension that jamming techniques might take advantage of coupling between the RF oscillator and the code chip clock, these two signals were generated independently in the transmitter. The receiver's PLL bandwidth was constrained by the fact that no frequency search was scheduled in the synchronization procedure, the assumption being that the pull-in range of the PLL was adequate to overcome both oscillator drifts and Doppler effects. Being a push-to-talk voice system which could operate either as a conventional AM radio or in an SS mode, a 5 s sync delay was encountered each time the SS modem was activated. Ranging up to 300 miles was possible with the measurement time taking about 40 s. To retain LPI

capability in this AJ system, transmitter power was adjustable from minute fractions of a watt up to 100 W.

Testing of the Magnavox ARC-50 began in 1959. Bob Dixon, joined by John G. Smith and Larry Murphy of Fort Wayne, put the ARC-50 through preliminary trials at WPAFB, and later moved on to the Verona site at RADC. One radio was installed in a C131 aircraft and the other end of the link resided in a ground station along with a 10 kW, CW jammer (the FRT-49). Testing consisted of flying the aircraft in the beam of the jammer's 18 dB antenna while operating the ARC-50. Limited results in this partially controlled environment indicated that the receiver could synchronize at jammer-to-noise ratios near those predicted by theory.

Shortly after these flight tests, an upgraded version of the ARC-50 was developed with significantly improved characteristics. To alleviate SS-code correlation problems, a new design was adopted, including an m -sequence combining procedure developed by Bob Gold [154], [155] which guaranteed low SS-code cross correlations for CDMA operation. The SS sync delay was reduced to one second and an improved ranging system yielded measurements in two seconds.

Even though the ARC-50 possessed obvious advantages over existing radios such as the ARC-27 or ARC-34, including a hundredfold improvement in mean time between failures, there was Air Force opposition to installing ARC-50's in the smaller fighter aircraft. The problem revolved around the fact that pilots were accustomed to having two radios, one being a backup for the other, and size-wise a single ARC-50 would displace both of the prior sets.

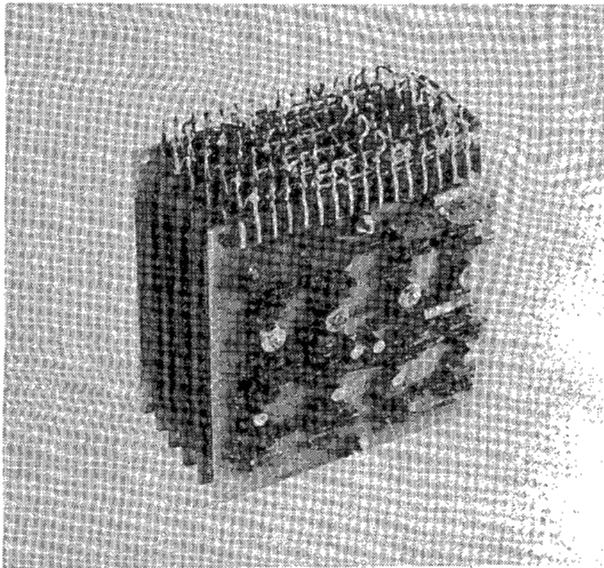
Certainly, the ARC-50 was a success, and Magnavox became an acknowledged leader in SS technology. Among the descendants of the ARC-50 are the GRC-116 troposcatter system which was designed free of a sync preamble, and the URC-55 and URC-61 ground-station modems for satellite channels. An applique, the MX-118, for the Army's VRC-12 family of VHF-FM radios was developed, but never was procured due in part to inadequate bandwidth in the original radios (see Fig. 15).

IV. BRANCHES ON THE SS TREE

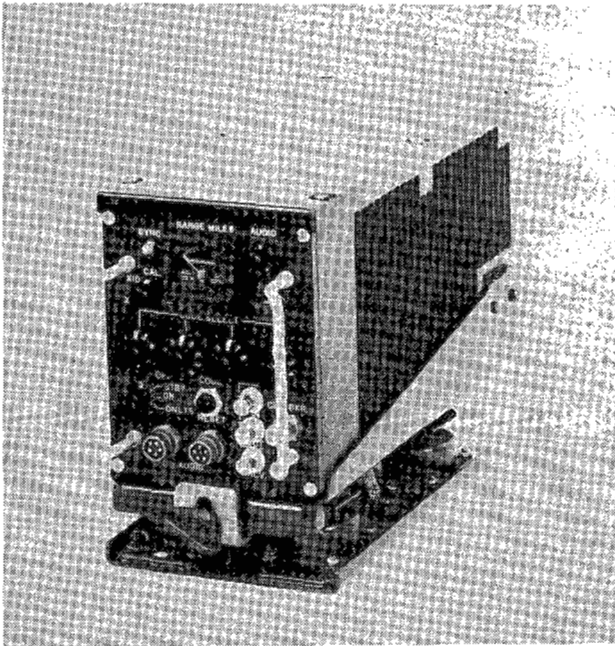
Many designs of the 1940's and 1950's have not yet been mentioned, but those described thus far seem in retrospect to have been exemplary pioneering efforts. It is time now to take notice of several SS systems left out of the previous accounting, some of which were never even prototyped.

Spread-Spectrum Radar

With the exception of the 1940's state-of-the-art descriptions of technology, we have made a distinction between the use of SS designs for communication and their use for detection and ranging on noncooperative targets, and have omitted a discussion of the latter. The signal strength advantage which the target holds over the radar receiver in looking for the radar's transmission versus its echo means that LPI is very difficult to achieve. Moreover, the fact that an adversary target knows *a priori* its relative location means that even with pure noise transmission the radar is vulnerable to false echo creation by a delaying repeater on the target.



(a)



(b)

Fig. 15. Examples of early- and mid-1960's technology. (a) SS code generator portion of a TH system developed by Brown, Boveri, and Company for surface-to-air missile guidance. (Photo courtesy of I. Wigdorovits of Brown, Boveri, and Co.) (b) 1965 picture of the MX-118 applique, a member of the ARC-50 radio family and the first to use Gold codes. (Photo courtesy of Robert Dixon.)

Nonetheless, SS signaling has some advantages over conventional low time-bandwidth-product radar signaling: in better range (TOA) resolution for a peak-power-limited transmitter (via pulse compression techniques), in range ambiguity removal, in greater resistance to some nonrepeater jammers [4], and in a CDMA-like capability for sharing the transmission band with similar systems. Modern uses of SS radars include fusing (for a patent under wraps for 24 years, see [156]) and pulse compression, the latter's applications extending to high-resolution synthetic-aperture ground mapping.

Other Early Spread-Spectrum Communication Systems

Despite the security which once surrounded all of the advances described in previous sections, the SS system concept could not be limited indefinitely to a few companies and research institutions. The following notes describe several other early SS design efforts.

Phantom: An MF-SS system developed by General Electric (GE) for the Air Force, this system was built around tapped delay line filters. As shown in Costas and Widmann's patent [157], the tap weights were designed to be varied pseudorandomly for the purpose of defeating repeater jammers (see Fig. 3). Constructed in the late 1950's, the Phantom spread its signal over 100 kHz. As with the F9C-A, this system was eventually used also to measure long-haul HF channel properties. For a description of other SS-related work performed at GE, this in the 1951-1954 time frame and under the direction of Richard Shuey, see [158].

WOOF: This Sylvania Buffalo system hid an SS signal by placing within its transmission bandwidth a high-power, friendly, and overt transmitter. Thereby the SS transmission would be masked by the friendly transmitter, either completely escaping notice or at least compounding the difficulties encountered by a reconnaissance receiver trying to detect it.

RACEP: Standing for Random Access and Correlation for Extended Performance, RACEP was the name chosen by the Martin Company to describe their asynchronous discrete address system that provided voice service for up to 700 mobile users [129]. In this system, the voice signal was first converted to pulse position modulation, and then each pulse in the resultant signal was in turn converted to a distinctive pattern of three narrow pulses and transmitted at one of a possible set of carrier frequencies. With the patterns serving also as addresses, this low duty cycle format possessed some of the advantages of SS systems.

Cherokee: Also by the Martin Company, this was a PN system with a transmission bandwidth of nearly a megahertz and a processing gain of about 16 dB [129]. Both RACEP and Cherokee were on display at the 15th Annual Convention of the Armed Forces Communications and Electronics Association in June, 1961.

MUTNS: Motorola's Multiple User Tactical Navigation System was a low frequency, hyperbolic navigation system employing PN signaling. Navigation was based on stable ground wave propagation with the SS modulation used to discriminate against the skywave, as it was in Sylvania's WHYN. Motorola, a subcontractor to JPL on the Jupiter CODORAC link, began Army-supported work on MUTNS in 1958. The first complete system flight test occurred on January 23, 1961 [159], [160].

RADA: RADA(S) is a general acronym for Random Access Discrete Address (System). Wide-band RADA systems developed prior to 1964 include Motorola's RADEM (Random Access Delta Modulation) and Bendix's CAPRI (Coded Address Private Radio Intercom) system, in addition to RACEP [161].

WICS: Jack Wozencraft, while on duty at the Signal Corps Engineering Laboratory, conceived WICS, Wozencraft's Iterated Coding System. This teletype system was an SR-FH-SS system employing 155 different tones in a 10 kHz band to communi-

cate at 50 words/min. Each bit was represented by two successively transmitted tones generated by either the MARK or the SPACE pseudorandomly driven frequency programmer. Bit decisions were made on detecting at least one of the two transmitted frequencies in receiver correlators, and parity checking provided further error correction capability. The subsequent WICS development effort by Melpar in the mid-1950's contemplated its tactical usage as an applique to radios then in inventory [114]. However, just as in ITT's early system concepts, the intended generation of pseudorandom signals via recording [162] did not result in a feasible production design.

Melpar Matched Filter System: A more successful mid-1950's development, this MF-SS design was largely conceived by Arthur Kohlenberg, Steve Sussman, David Van Meter, and Tom Cheatham. To transmit a MARK in this teletype system an impulse is applied to a filter composed of a pseudorandomly selected, cascaded subset of the several hundred sections of an all-pass lumped-constant linear-phase delay line. The receiver's MARK matched filter is synchronously composed of the remaining sections of the delay line. The same technique was used to transmit SPACE [114]. Patents [163], [164] filed on the system and its clever filter design, the latter invented by Prof. Ernst Guillemin who was a Melpar consultant, were held under secrecy along with the WICS patent until the mid-1970's. An unclassified discussion of an MF-SS system for use against multipath is given in [165].

Kathryn: Named after the daughter of the inventor, William Ehrich, and developed by General Atronics, Kathryn's novel signal processing effected the transmission of the Fourier transform of a time-multiplexed set of channel outputs combined with a PN signal. Upon reception, the inverse transform yielded the original $PN \times$ multiplexed-signal product, now multiplied by the propagation medium's system function, thereby providing good or bad channels in accordance with that function. When jamming is present, the data rate is reduced by entering the same data bit into several or all data channels. In this case a Rake-like combiner is used to remerge these channels at the output of the receiver's inverse Fourier transformer [114], [166]. The modern SS enhancement technique of adaptive spectral nulling against nonwhite jamming was at least implicitly available in this system.

Lockheed Transmitted Reference System: Of the several TR-SS systems patented, this one designed by Jim Spilker made it into production in time to meet a crisis in Berlin, despite the inherent weaknesses of TR systems [167]. The interesting question here is, "What circumstances would cause someone to use a TR system?" Evidently, extremely high chip rates are part of the answer. For an earlier TR patent that spent almost a quarter-century under secrecy order, see [168].

NOMAC Encrypted-Voice Communications: In 1952 at the suggestion of Bob Fano, Bennett Basore, with the help of Bill McLaughlin and Bob Price, constructed and briefly tested an IF model of a NOMAC-TR-FM voice system. At first surprised by the clarity of communication and lack of the self-noise which typifies NOMAC-AM systems, Basore soon realized that SS-carrier phase noise was eliminated in the bandpass correlation process and that SS-carrier amplitude noise was re-

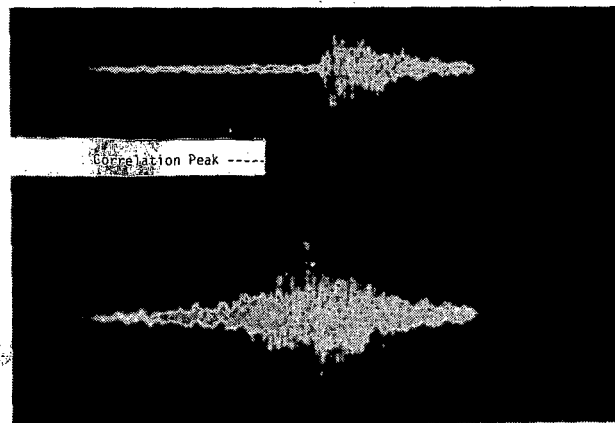


Fig. 16. Fano's elegant matched filter experiment consisted of transmitting an acoustic pulse into a chamber containing many reflectors. The upper signal shown here represents the sound sensed by a microphone in the room, and tape recorded. The tape was then reversed (not rewound) and replayed into the chamber, the microphone this time sensing the lower of the above two signals, specifically intended as the autocorrelation of the upper signal. Fano recalls being startled by his inability to see at first the extremely narrow peak of the autocorrelation function on the oscilloscope screen. The peak was soon discovered when the display intensity was increased. (Photo courtesy of Robert Fano.)

moved by the limiting frequency-discriminator. Little more was done until years later when, in 1959, John Craig of Lincoln Laboratory designed an experimental SR-SS system based on low-deviation phase modulation of a voice signal onto an F9C-like noise carrier. The system provided fair quality voice with negligible distortion and an output SNR of about 15 dB, the ever-present noise deriving from system flaws. Simulated multipath caused problems in this low-processing-gain system, and it was postulated that Rake technology might alleviate the problem [169], [170], but the work was abandoned.

NOMAC Matched Filter System: Based on Fano's research into high time-bandwidth-product matched filters (see Fig. 16), an MF-SS teletype communication system was suggested in 1952 [171]. Research at Lincoln Laboratory on this SS communication system type was confined to exploring a viable filter realization. This communication approach apparently was dropped when full scale work began on the F9C system. Fano later patented [172] the wide-band matched filter system concept, claiming improved performance in the presence of multipath.

Spread Eagle: This matched filter system was pursued by Philco in the late 1950's.

SECRAL: This ITT missile guidance system development of the late 1950's was a DS-SS design.

Longarm and Quicksilver: These are both early FH antimultipath systems built by Hughes Aircraft Company, under the leadership of Samuel Lutz and Burton Miller, and sponsored by Edwin McCoppin of WPAFB.

Spread-Spectrum Developments Outside the United States

This historical review has concentrated on SS developments in the United States for several reasons.

1) The theories of Wiener and especially Shannon, which propounded the properties of and motivated the use of random and pseudorandom signals, were available in the U.S. before such basics were appreciated elsewhere (with the exception of Guanella). This gave U.S. researchers a significant lead time, an important factor near the outset of the Cold War when the Voice of America was being jammed intensively. Additional impetus for SS development came in urgent response to the threats posed by the onslaught of the Korean War and the tense confrontations over Berlin.

2) SS development occurred just after the Second World War, at a point in time when many of the world's technological leaders had suffered tremendous losses in both manpower and facilities, and additionally in Germany's case, political self-control. Research and industry in the U.S., on the other hand, were unscathed and the U.S. became the home for many leading European scientists, e.g., Henri Busignies and Wernher von Braun, to name two among many.

3) The unclassified literature available to this author (virtually all the references in this history are now unclassified)³ points to the earliest SS developments having arisen in the United States.

We will now look at evidence of some SS beginnings outside the U.S.A.

Bill Davenport remembers a secret interchange with a visiting British delegation in which pre-Rake NOMAC concepts were discussed. Later he was informed that the British had not pursued that approach to secure, long-range communication because they envisioned major problems from multipath [173]. Frank Lehan recalls a discussion with a British scientist who told him that the British had studied PN sequences several years before JPL developed the idea. Bob Dixon dates Canada's experimental Rampage system to the early 1950's, with no further details yet available [174]. So it seems that the closest friends of the U.S. were at least cognizant of the SS concept, knew something of PN generation, and to some extent had experimented with the idea. Further information on these early efforts has not been uncovered.

In neutral Switzerland, Brown, Boveri and Company developed, starting in the late 1950's, an SS guidance system (see Fig. 15). This was no doubt stimulated by the pioneering inventor of noise-modulated radar [12] (and of encryption schemes which the NDRC had sought to decipher during World War II), Gustav Guanella. He quickly appreciated, and may well have seen the true significance of, the Rake concept upon its publication. Now, an intriguing question is, "When did the Soviet bloc become privy to the SS concept and realize its potential?"

In the mid-1950's some members of a high-level task force were convinced that the Russians knew about SS techniques and in fact might be using it themselves. For example, Eugene Fubini personally searched the U.S. Patent Office open files to see what a foreign country might be able to learn there of this new art; nomenclature was a problem and he had to look under "pulse communications" as well as many other patent clas-

sifications. (This difficulty was eased recently when the Patent Office created a special subclass 375-1 entitled Spread Spectrum.) Also curious about this issue, Paul Green determined to try to find out for himself the status of Russian knowledge about NOMAC techniques. After studying the language he examined the Russian technical literature, surveying their work in information theory and attempting to uncover clues that might lie there to noise modulation concepts. Green came to believe that there was no plausible reason to suspect that the Soviets were then developing spread-spectrum systems, due in part to lack of technology and possibly to no perceived need for AJ communications capability.

Later Paul Green visited the Soviet Union and gave a talk in Russian on the use of Rake to measure properties of the ionosphere, which seemingly was accepted at face value. Because of this contact and his literature scrutiny, in the mid-1960's Green decided to postpone his plans to write an unclassified account of Lincoln Laboratory's NOMAC work, toward which full military clearances had already been granted.

The earliest Soviet reference (as cited in, e.g., [175]) proposing noise-like, intelligence-bearing signals is a 1957 publication by Kharkevich [176] on amplitude or frequency modulation of pure noise. Like Goldsmith's [38], Kharkevich's work is missing a key ingredient, namely, the attainment of synchronous detection via correlation with a stored or transmitted reference. Within a few months of the approved 1958 publication of the Rake concept for using wide-band signals ostensibly to counter multipath, that paper was translated into Russian, and hardly a year later an exposition of Rake appeared in Lange's first book *Korrelationselektronik* [177]. Thus began the revelation of the SS concept in the U.S. literature from scientific journals and conference proceedings to magazines such as *Electronics*, *Electronic Design*, and *Aviation Week*. Here is a small sample of U.S. open papers referenced in the Soviet literature:

- a) March 1958. Rake remedy for multipath, using wide-band signals [121].
- b) December 1959. Use of wideband noise-like signals, CDMA, and jamming [178], [179].
- c) Fall 1960. PN-controlled TH-SS command link for missile guidance [130].
- d) January 1961. Analysis of a pure noise (TR) communication system [180].
- e) March 1961. Discussion of RADA systems [181].
- f) 1963. 200 Mcps PN generator construction [182].
- g) December 1963. Wideband communication systems including Rake, RACEP, and RADEM [161].

It is clear from these citations and other evidence that the Russians were studying PN sequences no later than 1963 [183], and by 1965 had carefully searched and reported [184] on the U.S. open literature discussing Rake, Phantom, and the various RADA systems. Between 1965 and 1971 the Soviets published several books [175], [185]-[188] concerned with SS principles and their applications to secure communication, command, and control.

V. A VIEWPOINT

One can paint the following picture of the development of spread-spectrum communications. During World War II the

³ There is available from the author upon request an extensive bibliography compiled by J. M. Smith, which focuses on the prime documentation for those Sylvania, FTL (ITT), M.I.T., and JPL spread-spectrum developments that are of major significance.

Allies and the Axis powers were in a desperate technological race on many fronts, one being secure communications. Jamming of communication and navigation systems was attempted by both sides and the need for reliable communication and accurate navigation in the face of this threat was real. One major AJ tactic of the war was to change carrier frequency often and force the jammer to keep looking for the right narrow band to jam. While this was possible to automate in the case of radar, communication frequency hopping was carried out by radio operators, in view of the major technological problem of providing an accurate synchronous frequency reference at the receiver to match the transmitter. Thus, at least frequency hopping and, to a similar extent, time hopping were recognized AJ concepts during the early 1940's.

Many of the early "secure" or "secret" non-SS communication systems seem to have been attempts to build analog equivalents of cryptographic machines and lacked the notion of bandwidth expansion (e.g., the Green Hornet, the Telefunken dual wheels system). The initial motivation for direct sequence systems appears, on the other hand, to have come from the need for accurate and unambiguous time-of-arrival measurements in navigation systems (e.g., WHYN and CODORAC), and from the desire to test or extend Shannon's random-signaling concept and thus communicate covertly (e.g., Rogoff's noise wheels experiment). The DS concept followed the FH and TH concepts by several years partly because the necessary correlation detection schemes were just emerging in the late 1940's.

Who first took these diverse system ideas and recognized the unifying essential requirements of a spread-spectrum system (e.g., high carrier-to-data bandwidth ratio, an unpredictable carrier, and some form of correlation detection)? From the available evidence it appears that Shannon certainly had the insight to do it but never put it in print, and that two close friends, Nathan Marchand and Louis deRosa, both key figures in the formation of the IRE's Group on Information Theory, led Sylvania Bayside and FTL, respectively, toward a unified SS viewpoint. It seems that Sylvania Bayside had all the ingredients of the direct sequence concept as early as 1948, but did not have the technology to solve some of the signal processing problems. It remained for Mortimer Rogoff to provide a method for storing pseudonoise (a technique reminiscent of Telefunken's wheels), giving ITT the complete system assembled and tested under the Della Rosa contract and documented to a government agency.

Meanwhile the idea either was propagated to or was independently conceived by several research and design groups, notably at M.I.T. in 1950 and at JPL in 1952. Group 34 at M.I.T. Lincoln Laboratory, sparked by Bill Davenport, Paul Green, and Bob Price, is generally credited with building the first successful SS communication system for several reasons.

1) The Rake system was the first wide-band pseudorandom-reference system to send messages reliably over the long-range HF multipath channel.

2) The F9C-A system, soon followed by the Rake applique, was probably the first deployed (nonexperimental) broadband communication system which differed in its essentials from wide-deviation FM, PPM, or PCM.

3) The Rake system was the first such SR communication

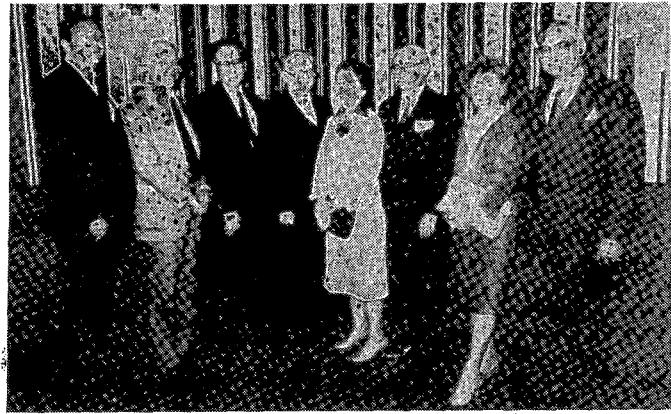


Fig. 17. VIP's at the IEEE NAECON '81 included Robert Larson, Wilbur Davenport, Paul Green, B. Richard Climie, Mrs. Mortimer Rogoff, Mortimer Rogoff, Mrs. Louis deRosa, and Robert Price. Featured at this meeting was the presentation of the Pioneer Award to deRosa (posthumously), Rogoff, Green, and Davenport for their ground-breaking work in the development of spread-spectrum communications. (Photo courtesy of W. Donald Dodd.)

system to be discussed in the open literature, other than information theoretic designs.

JPL's radio control work, in competition with inertial guidance systems, did not reach a deployment stage until suitable applications appeared in the Space Program. In addition to opening new vistas in the development of PN generation techniques, JPL's contribution to SS technology has been the innovation of tracking loop designs which allow high-performance SS systems to be placed on high-speed vehicles with results comparable to those of stationary systems. Both the M.I.T. and JPL programs have left a legacy of excellent documentation on spread-spectrum signal processing, spectral analysis, and synchronization, and have provided some of the finest modern textbooks on communications.

A very successful long-term SS system development began at Sylvania Buffalo under Madison Nicholson and later Jim Green, and ended up merging with some JPL-based experience at Magnavox in the production of the ARC-50 family of systems. The ARC-50 was the first deployed SS system with any of the following characteristics:

- 1) avionics packaging,
- 2) fully coherent reception (including carrier tracking),
- 3) a several megahertz chip rate, and
- 4) voice capability.

Although losing the ARC-50 final design and production contract to Magnavox, Sylvania continued on to develop BLADES, the earliest FH-SS communication system used operationally. Moreover, BLADES represented, by publication (e.g., [90]) and actual hardware, the start of real-world application of shift-register sequences to error correction coding, an algebraic specialty that would flourish in coming years.

Since the 1950's when the SS concept began to mature, the major advances in SS have been for the most part technological, with improvements in hardware and expansion in scope of application continuing to the present day. Now with the veil of secrecy being lifted, the contributions of some of the earliest pioneers of SS communications are being recognized (see Fig. 17). We hope that this historical review has also served that

purpose by highlighting the work of the many engineers who have figured prominently in the early conceptual development and implementation of spread-spectrum systems.

ACKNOWLEDGMENT

This history is the result of the efforts of a great number of dedicated people. Paul E. Green gave this work its initial impetus by making his own archive of declassified Lincoln Laboratory documents available to the author and by backing them up with his personal commentary. The breadth of this account is due to a significant extent to the untiring work of Robert Price, who nearly single-handedly has supplied the author with a file drawer full of material culled from publications worldwide and numerous interviews, and whose comments have appreciably aided the production of this monograph.

Unreferenced as well as referenced items for this history have been collected over a period of almost three years by the author, Paul, and Bob, from many sources and in many forms. We would like to thank the following for their first-hand recollections: Paul R. Adams (deceased), Bennett Basore, Robert S. Berg, Nelson Blachman, Everard Book, Robert M. Brown, William Budd, Henri Busignies (deceased), Robert Carlson, Dana Cole, John Costas, Wilbur Davenport, Donald Disinger, Robert Dixon, Robert Fano, Robert Frank, Edgar Gilbert, Bernard Goldberg, Solomon Golomb, Harold Graves, James H. Green, John Groce, Richard Gunther, Hunter Harris, Norman Harvey, Lloyd Higginbotham, Leonhard Katz, Leon Kraft, Ernst Krause, Frank Lehan, David Leichtman, Leon Lewandowski, James Lindholm, Nathan Marchand, Charles J. Marshall, Harold F. Meyer, Allen Norris, Vincent Oxley, Bernard Pankowski, Ellison Purington, John Raney, George Rappaport, Eberhardt Rehtin, Mortimer Rogoff, Donald Rothschild, William Sampson, Peter Sandretto, Robert San Soucie, Herbert Schulke, Oliver Selfridge, Walter Serniuk, Robert A. Smith, William B. Smith, James Spilker, Seymour Stein, Steven Sussman, Ragnar Thorensen, John Travis, Richard Turyn, Walter Victor, Gottfried Vogt, Lloyd Welch, Robert Whittle, John Wozencraft, and Neal Zierler.

The author additionally wishes to thank the following people for their support in various ways: J. Meredith Smith for his diligent searching of sources (including a 1970 interview with Louis deRosa), Robert Kulinyi for uncovering the early German work, Mrs. Louis deRosa for information on her husband's career, and John R. Pierce (pseudonym J. J. Coupling) for aid in locating Theodore Sturgeon.

The following librarians, archivists, historians, and document control officers have also been very helpful: John Hewitt of the M.I.T. Research Laboratory of Electronics, H. Alan Steeves of the Sperry Research Center, Mary Granese and Robert S. Clarke (deceased) of the M.I.T. Lincoln Laboratory, Kay Haines of the Jet Propulsion Laboratory, R. Dean Porter of the Wright-Patterson Air Force Base, Charles Dewing and Franklin Burch of the U.S. National Archives, Karl Wildes of M.I.T., and Stephen L. Johnston.

Among the many other people whose ready assistance, encouragement, or significant interest have made this research a memorable experience, are: James W. Allen, J. Neil Birch, Ian

Blake, Robert Bowie, Walter Braun, Charles R. Cahn, John W. Craig, Michael DiToro (deceased), Paul Drouilhet, Benjamin Eisenstadt, Laurin Fischer, Eugene Fubini, Irving Gabelman, Gustav Guanella, George Harvey, Leon Himmel, Conrad Hoepfner, George Hulst, George Jacoby, Thomas Lawrence, Yuk Wing Lee, Meyer Leifer, Arnold Levine, William C. Lindsey, Robert Malm, Theodore Manley, James Massey, Walter Morrow, David Nicholson, J. Francis Reintjes, R. Kenneth Ricker, James Roche, Theodore Sturgeon, Charles Stutt, George Valley, Richard Waer, Jérôme Wiesner, I. Wigdorovits, and Henry Zimmermann.

We only regret that we have not been able to express here our sincere appreciation to everyone contacted in this fascinating pursuit.

REFERENCES

- [1] E. V. Appleton and M. A. F. Barnett, "On some direct evidence for downward atmospheric reflection of electric rays," *Proc. Roy. Soc., Ser. A*, vol. 109, pp. 621-641, Dec. 1, 1925.
- [2] D. G. C. Luck, *Frequency Modulated Radar*. New York: McGraw-Hill, 1949.
- [3] S. L. Johnston, "Radar ECCM history," in *Proc. NAECOM*, May 1980, pp. 1210-1214.
- [4] G. R. Johnson, "Jamming low power spread spectrum radar," *Electron. Warfare*, pp. 103-112, Sept.-Oct. 1977.
- [5] D. O. North, "An analysis of the factors which determine signal/noise discrimination in pulsed carrier systems," RCA Lab., Princeton, NJ, Rep. PTR-6C, June 25, 1943; see also *Proc. IEEE*, vol. 51, pp. 1015-1028, July 1963.
- [6] J. H. Van Vleck and D. Middleton, "A theoretical comparison of the visual, aural, and meter reception of pulsed signals in the presence of noise," *J. Appl. Phys.*, vol. 17, pp. 940-971, Nov. 1946.
- [7] P. M. Woodward, *Probability and Information Theory, with Applications to Radar*. New York: Pergamon, 1953.
- [8] C. E. Cook and M. Bernfeld, *Radar Signals, An Introduction to Theory and Application*. New York: Academic, 1967.
- [9] A. W. Rihaczek, *Principles of High Resolution Radar*. New York: McGraw-Hill, 1969.
- [10] F. E. Terman, "Administrative history of the Radio Research Laboratory," Radio Res. Lab., Harvard Univ., Cambridge, MA, Rep. 411-299, Mar. 21, 1946.
- [11] F. H. Lange, *Correlation Techniques*. Princeton, NJ: Van Nostrand, 1966.
- [12] G. Guanella, "Distance determining system," U. S. Patent 2 253 975, Aug. 26, 1941 (filed in U. S. May 27, 1939; in Switzerland Sept. 26, 1938).
- [13] —, "Direction finding system," U.S. Patent 2 166 991, July 25, 1939 (filed in U.S. Nov. 24, 1937; in Switzerland Dec. 1, 1936).
- [14] J. J. Spilker, Jr. and D. T. Magill, "The delay-lock discriminator—An optimum tracking device," *Proc. IRE*, vol. 49, pp. 1403-1416, Sept. 1961.
- [15] J. J. Spilker, Jr., "Delay-lock tracking of binary signals," *IRE Trans. Space Electron. Telem.*, vol. SET-9, pp. 1-8, Mar. 1963.
- [16] N. Wiener, "Generalized harmonic analysis," *Acta Math.*, vol. 55, pp. 117-258, May 9, 1930; reprinted in *Generalized Harmonic Analysis and Tauberian Theory (Norbert Wiener: Collected Works, Vol. 2)*, P. Masani, Ed. Cambridge, MA: M.I.T. Press, 1979.
- [17] "Gunfire control," Nat. Defense Res. Committee, Office Sci. Res. Develop., Washington, DC, Summary Tech. Rep., Div. 7, 1946 (AD 200795).
- [18] N. Wiener, *Extrapolation, Interpolation, and Smoothing of Stationary Time Series with Engineering Applications*. Cambridge, MA: M.I.T. Press, 1949.
- [19] N. Levinson, "The Wiener rms (root mean square) error criterion in filter design and prediction," *J. Math. Phys.*, vol. 25, pp. 261-278, Jan. 1947.
- [20] J. M. Whittaker, *Interpolatory Function Theory* (Cambridge Tracts in Mathematics and Mathematical Physics, no. 33). New York: Cambridge Univ. Press, 1935.
- [21] E. T. Whittaker, "On the functions which are represented by the

- expansions of the interpolation theory," *Proc. Roy. Soc. Edinburgh*, vol. 35, pp. 191-194, 1915.
- [22] J. McNamee, F. Stenger, and E. L. Whitney, "Whittaker's cardinal function in retrospect," *Math. Comput.*, vol. 25, pp. 141-154, Jan. 1971.
- [23] A. J. Jerri, "The Shannon sampling theorem—Its various extensions and applications: A tutorial review," *Proc. IEEE*, vol. 65, pp. 1565-1596, Nov. 1977.
- [24] R. V. L. Hartley, "The transmission of information," *Bell Syst. Tech. J.*, vol. 7, pp. 535-560, 1928.
- [25] H. Nyquist, "Certain topics in telegraph transmission theory," *AIEE Trans.*, vol. 47, pp. 617-644, Apr. 1928.
- [26] V. A. Kotelnikov, "Carrying capacity of 'ether' and wire in electrical communications" (in Russian), *Papers on Radio Communications, 1st All-Union Conv. Questions of Technical Reconstruction of Communications*, All-Union Energetics Committee, USSR, 1933, pp. 1-19.
- [27] C. E. Shannon, "Communication in the presence of noise," *Proc. IRE*, vol. 37, pp. 10-21, Jan. 1949.
- [28] D. Slepian, "On bandwidth," *Proc. IEEE*, vol. 64, pp. 292-300, Mar. 1976.
- [29] A. H. Nuttall and F. Amoroso, "Minimum Gabor bandwidth of M orthogonal signals," *IEEE Trans. Inform. Theory*, vol. IT-11, pp. 440-444, July 1965.
- [30] D. Gabor, "Theory of communication," *J. Inst. Elec. Eng. (London)*, vol. 93, part 3, pp. 429-457, Nov. 1946.
- [31] C. E. Shannon, "A mathematical theory of cryptography," *Bell Tel. Lab.*, memo., Sept. 1, 1945; later published in expurgated form as "Communication theory of secrecy systems," *Bell Syst. Tech. J.*, vol. 28, pp. 656-715, Oct. 1949.
- [32] —, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, pp. 379-423, July, and 623-656, Oct. 1948.
- [33] *Report of Proceedings, Symp. Inform. Theory*, London, England, Sept. 26-29, 1950; reprinted in *Trans. IRE Professional Group Inform. Theory*, vol. PGIT-1, Feb. 1953.
- [34] N. Marchand, "Radio receiver," U.S. Patent 2 416 336, Feb. 25, 1947 (filed May 21, 1942).
- [35] Y. W. Lee, J. B. Wiesner, and T. P. Cheatham, Jr., "Apparatus for computing correlation functions," U.S. Patent 2 643 819, June 30, 1953 (filed Aug. 11, 1949).
- [36] Y. W. Lee, T. P. Cheatham, Jr., and J. B. Wiesner, "The application of correlation functions in the detection of small signals in noise," M.I.T. Res. Lab. Electron., Tech. Rep. 141, Oct. 13, 1949 (ATI 066538, PB 102361).
- [37] H. E. Singleton, "A digital electronic correlator," M.I.T. Res. Lab. Electron., Tech. Rep. 152, Feb. 21, 1950.
- [38] A. N. Goldsmith, "Radio signalling system," U.S. Patent 1 761 118, June 3, 1930 (filed Nov. 6, 1924).
- [39] C. B. H. Feldman, "Wobbled radio carrier communication system," U.S. Patent 2 422 664, June 24, 1947 (filed July 12, 1944).
- [40] P. Kotowski and K. Dannehl, "Method of transmitting secret messages," U.S. Patent 2 211 132, Aug. 13, 1940 (filed in U.S. May 6, 1936; in Germany May 9, 1935).
- [41] D. Kahn, *The Codebreakers*. New York: Macmillan, 1967.
- [42] R. C. Mathes, "Secret telephony," U.S. Patent 3 967 066, June 29, 1976 (filed Sept. 24, 1941).
- [43] R. K. Potter, "Secret telephony," U.S. Patent 3 967 067, June 29, 1976 (filed Sept. 24, 1941).
- [44] S. V. Jones, "After 35 years, secrecy lifted on encoded calls," *New York Times*, p. 27, July 3, 1976.
- [45] A. J. Busch, "Signalling circuit," U.S. Patent 3 968 454, July 6, 1976 (filed Sept. 27, 1944).
- [46] A. E. Joel, Jr., "Pulse producing system for secrecy transmissions," U.S. Patent 4 156 108, May 22, 1979 (filed Jan. 21, 1947).
- [47] W. W. Hansen, "Secret communication," U.S. Patent 2 418 119, Apr. 1, 1947 (filed Apr. 10, 1943).
- [48] L. A. deRosa and M. Rogoff, "Secure single sideband communication system using modulated noise subcarrier," U.S. Patent 4 176 316, Nov. 27, 1979 (filed Mar. 20, 1953); reissue appl. filed Sept. 4, 1981, Re. Ser. No. 299 469.
- [49] E. Chaffee and E. Purington, "Method and means for secret radiosignalling," U.S. Patent 1 690 719, Nov. 6, 1928 (filed Mar. 31, 1922).
- [50] E. M. Deloraine, H. G. Busignies, and L. A. deRosa, "Facsimile system," U.S. Patent 2 406 811, Sept. 3, 1946 (filed Dec. 15, 1942).
- [51] —, "Facsimile system and method," U.S. Patent 2 406 812, Sept. 3, 1946 (filed Jan. 30, 1943).
- [52] L. A. deRosa, "Random impulse system," U.S. Patent 2 671 896, Mar. 9, 1954 (filed Dec. 13, 1942).
- [53] "Radio countermeasures," Nat. Defense Res. Committee, Office Sci. Res. Develop., Washington, DC, Summary Tech. Rep. Div. 15, vol. I, 1946 (AD 221601).
- [54] E. M. Deloraine, "Protected communication system," Fed. Radio Tel. Lab., New York, NY, Rep. 937-2, Apr. 28, 1944 (from the National Archives, Record Group 227; this report was written to Division 15 of the National Defense Research Committee, Office of Scientific Research and Development, on Project RP-124).
- [55] H. Busignies, S. H. Dodington, J. A. Herbst, and G. R. Clark, "Radio communication system protected against interference," Fed. Tel. Radio Corp., New York, NY, Final Rep. 937-3, July 12, 1945 (same source as [54]).
- [56] B. Gunston, *Rockets and Missiles*. New York: Crescent, 1979.
- [57] Air Force Corresp. File on Contr. W535-sc-707 with Colonial Radio Corp., May 1943-June 1944.
- [58] "Guided missiles and techniques," Nat. Defense Res. Committee, Office Sci. Res. Develop., Washington, DC, Summary Tech. Rep. Div. 5, vol. I, 1946 (AD 200781).
- [59] E. Labin and D. D. Grieg, "Method and means of communication," U.S. Patent 2 410 350, Oct. 29, 1946 (filed Feb. 6, 1943).
- [60] J. H. Hammond, Jr. and E. S. Purington, "A history of some foundations of modern radio-electronic technology," *Proc. IRE*, vol. 45, pp. 1191-1208, Sept. 1957.
- [61] L. Espenschied *et al.*, "Discussion of 'A history of some foundations of modern radio-electronic technology,'" *Proc. IRE*, vol. 47, pp. 1253-1268, July 1959.
- [62] E. S. Purington, "Radio selective control system," U.S. Patent 2 635 228, Apr. 14, 1953 (filed June 2, 1948).
- [63] C. H. Hoepfner, "Pulse communication system," U.S. Patent 2 999 128, Sept. 5, 1961 (filed Nov. 4, 1945).
- [64] E. H. Krause and C. E. Cleeton, "Pulse signalling system," U.S. Patent 4 005 818, Feb. 1, 1977 (filed May 11, 1945).
- [65] J. R. Pierce, "The early days of information theory," *IEEE Trans. Inform. Theory*, vol. IT-19, pp. 3-8, Jan. 1973.
- [66] "The WHYN guidance system," Phys. Lab., Sylvania Elec. Products, Bayside, NY, Final Eng. Rep., Modulation Wave Form Study & F-M Exciter Develop., Contr. W28-099ac465, June 1949 (AD895816).
- [67] "The WHYN guidance system," Phys. Lab., Sylvania Elec. Products, Flushing, NY, Interim Eng. Rep. 5, Contr. W28-099ac465, Oct. 1948 (ATI 44524).
- [68] "The WHYN guidance system," Phys. Lab., Sylvania Elec. Products, Bayside, NY, Final Eng. Rep., Equipment Develop. & East Coast Field Test, Contr. W28-099ac465, June 1950 (AD 895815).
- [69] M. Leifer and N. Marchand, "The design of periodic radio systems," *Sylvania Technologist*, vol. 3, pp. 18-21, Oct. 1950.
- [70] N. Marchand and H. R. Holloway, "Multiplexing by orthogonal functions," presented at the IRE Conf. Airborne Electron., Dayton, OH, May 23-25, 1951.
- [71] N. Marchand and M. Leifer, "Cross-correlation in periodic radio systems," presented at the IRE Conf. Airborne Electron., Dayton, OH, May 23-25, 1951.
- [72] W. E. Budd, "Analysis of correlation distortion," M.E.E. thesis, Polytech. Inst. Brooklyn, Brooklyn, NY, May 1955.
- [73] N. L. Harvey, M. Leifer, and N. Marchand, "The component theory of calculating radio spectra with special reference to frequency modulation," *Proc. IRE*, vol. 39, pp. 648-652, June 1951.
- [74] N. L. Harvey, "Radio navigation system," U.S. Patent 2 690 558, Sept. 28, 1954 (filed Feb. 4, 1950).
- [75] —, "Collision warning radar," U.S. Patent 2 842 764, July 8, 1958 (filed Feb. 21, 1951).
- [76] H. C. Harris, Jr., M. Leifer, and D. W. Cawood, "Modified cross-correlation radio system and method," U.S. Patent 2 941 202, June 14, 1960 (filed Aug. 4, 1951).
- [77] "The WHYN guidance system," Phys. Lab., Sylvania Elec. Products, Bayside, NY, Final Eng. Rep., Equipment, Syst. Lab. Tests & Anal., Contr. W28-099ac465, June 1953 (AD 024044).
- [78] M. Leifer and W. Serniuk, "Long range high accuracy guidance system," presented at the RDB Symp. Inform. Theory Appl. Guided Missile Problems, California Inst. Technol., Pasadena, Feb. 2-3, 1953.
- [79] W. P. Frantz, W. N. Dean, and R. L. Frank, "A precision

- multi-purpose radio navigation system," in *IRE Nat. Conv. Rec.*, New York, NY, Mar. 18-21, 1957, part 8, pp. 79-98.
- [80] R. L. Frank and S. Zadoff, "Phase-coded hyperbolic navigation system," U.S. Patent 3 099 835, July 30, 1963 (filed May 31, 1956).
- [81] R. L. Frank, "Phase-coded communication system," U.S. Patent 3 099 795, July 30, 1963 (filed Apr. 3, 1957).
- [82] W. Palmer and R. L. Frank, in "1971 Pioneer Award," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-7, pp. 1015-1021, Sept. 1971.
- [83] [R. L. Frank and S. A. Zadoff], "Study and field tests of improved methods for pulse signal detection," Sperry Gyroscope, Great Neck, NY, Final Eng. Rep., Contr. AF28(099)-333, Sperry Eng. Rep. 5223-1245, June 1951 (ATI 150834).
- [84] E. J. Baghdady, "New developments in FM reception and their application to the realization of a system of 'power-division' multiplexing," *IRE Trans. Commun. Syst.*, vol. CS-7, pp. 147-161, Sept. 1959.
- [85] R. L. Frank, "Tunable narrowband rejection filter employing coherent demodulation," U.S. Patent 3 403 345, Sept. 24, 1968 (filed July 19, 1965).
- [86] M. G. Nicholson, Jr., "Apparatus for generating signals having selectable frequency deviation from a reference frequency," U.S. Patent 2 972 109, Feb. 14, 1961 (filed June 11, 1956).
- [87] —, "Generator of frequency increments," U.S. Patent 2 923 891, Feb. 2, 1960 (filed July 6, 1956).
- [88] J. N. Pierce, "Theoretical diversity improvement in frequency shift keying," *Proc. IRE*, vol. 46, pp. 903-910, May 1958.
- [89] J. H. Green, Jr., D. K. Leichtman, L. M. Lewandowski, and R. E. Malm, "Improvement in performance of radio-teletype systems through use of element-to-element frequency diversity and redundant coding," presented at the 4th Annu. Symp. Global Commun., Washington, DC, Aug. 1-3, 1960.
- [90] J. H. Green, Jr. and R. L. San Soucie, "An error correcting encoder and decoder of high efficiency," *Proc. IRE*, vol. 46, pp. 1741-1744, Oct. 1958.
- [91] R. G. Fryer, "Analytical development and implementation of an optimum error-correcting code," *Sylvania Technologist*, vol. 13, pp. 101-110, July 1960.
- [92] M. G. Nicholson, Jr. and R. A. Smith, "Data transmission systems," U.S. Patent 3 093 707, June 11, 1963 (filed Sept. 24, 1959).
- [93] J. H. Green, Jr. and J. Gordon, "Selective calling system," U.S. Patent 3 069 657, Dec. 18, 1962 (filed June 11, 1958).
- [94] V. C. Oxley and W. E. De Lisle, "Communications and data processing equipment," U.S. Patent 3 235 661, Feb. 15, 1966 (filed July 11, 1962).
- [95] L. A. deRosa, M. J. DiToro, and L. G. Fischer, "Signal correlation radio receiver," U.S. Patent 2 718 638, Sept. 20, 1955 (filed Jan. 20, 1950).
- [96] L. A. deRosa and M. Rogoff, Sect. I (Communications) of "Application of statistical methods to secrecy communication systems," Proposal 946, Fed. Telecommun. Lab., Nutley, NJ, Aug. 28, 1950.
- [97] "A report on security of overseas transport," Project Hartwell, M.I.T., Cambridge, MA, Sept. 21, 1950 (ATI 205035, ATI 205036; not available from M.I.T.).
- [98] "R.L.E.: 1946 + 20," M.I.T. Res. Lab. Electron., Cambridge, MA, May 1966.
- [99] D. Lang, *An Inquiry into Enoughness*. New York: McGraw-Hill, 1965.
- [100] "Problems of air defense," Project Charles, M.I.T., Cambridge, MA, Final Rep., Aug. 1, 1951 (not available from M.I.T.).
- [101] B. L. Basore, "Noise-like signals and their detection by correlation," M.I.T. Res. Lab. Electron. and Lincoln Lab., Tech. Rep. 7, May 26, 1952 (AD 004641).
- [102] B. J. Pankowski, "Multiplexing a radio teletype system using a random carrier and correlation detection," M.I.T. Res. Lab. Electron. and Lincoln Lab., Tech. Rep. 5, May 16, 1952 (ATI 168857; not available from M.I.T.).
- [103] "Engineering study and experimental investigation of secure directive radio communication systems," Sylvania Elec. Products, Buffalo, NY, Interim Eng. Rep., Contr. AF-33(616)-167, Aug. 5-Nov. 5, 1952 (AD 005243).
- [104] W. B. Davenport, Jr., "NOMAC data transmission systems," presented at the RDB Symp. Inform. Theory Appl. Guided Missile Problems, California Inst. Technol., Pasadena, Feb. 2-3, 1953.
- [105] P. E. Green, Jr., "Correlation detection using stored signals," M.I.T. Lincoln Lab., Tech. Rep. 33, Aug. 4, 1953 (AD 020524).
- [106] B. M. Eisenstadt, P. L. Fleck, Jr., O. G. Selfridge, and C. A. Wagner, "Jamming tests on NOMAC systems," M.I.T. Lincoln Lab., Tech. Rep. 41, Sept. 25, 1953 (AD 020419).
- [107] P. E. Green, Jr., "The Lincoln F9C radioteletype system," M.I.T. Lincoln Lab., Tech. Memo. 61, May 14, 1954 (not available from M.I.T.).
- [108] P. E. Green, Jr., R. S. Berg, C. W. Bergman, and W. B. Smith, "Performance of the Lincoln F9C radioteletype system," M.I.T. Lincoln Lab., Tech. Rep. 88, Oct. 28, 1955 (AD 080345).
- [109] N. Zierler, "Inverting the sum generator," M.I.T. Lincoln Lab., Group Rep. 34-48, Feb. 13, 1956 (AD 310397).
- [110] B. M. Eisenstadt and B. Gold, "Autocorrelations for Boolean functions of noiselike periodic sequences," *IRE Trans. Electron. Comput.*, vol. EC-10, pp. 383-388, Sept. 1961.
- [111] R. C. Titsworth, "Correlation properties of cyclic sequences," Ph.D. dissertation, California Inst. Technol., Pasadena, 1962.
- [112] J. M. Wozencraft, "Active filters," U.S. Patent 2 880 316, Mar. 31, 1959 (filed Mar. 21, 1955).
- [113] M. L. Doelz and E. T. Heald, "A predicted wave radio teletype system," in *IRE Conv. Rec.*, New York, NY, Mar. 22-25, 1954, part 8, pp. 63-69.
- [114] B. Goldberg, "Applications of statistical communications theory," presented at the Army Sci. Conf., West Point, NY, June 20-22, 1962 (AD 332048); republished in *IEEE Commun. Mag.*, vol. 19, pp. 26-33, July 1981.
- [115] R. Price, "Notes on ideal receivers for scatter multipath," M.I.T. Lincoln Lab., Group Rep. 34-39, May 12, 1955 (AD 224559).
- [116] J. B. Wiesner and Y. W. Lee, "Experimental determination of system functions by the method of correlation," *Proc. IRE*, vol. 38, p. 205, Feb. 1950 (abstr.).
- [117] D. G. Brennan, "On the maximum signal-to-noise ratio realizable from several noisy signals," *Proc. IRE*, vol. 43, p. 1530, Oct. 1955.
- [118] G. L. Turin, "Communication through noisy, random-multipath channels," in *IRE Conv. Rec.*, New York, NY, Mar. 19-22, 1956, part 4, pp. 154-166.
- [119] P. Monsen, "Fading channel communications," *IEEE Commun. Mag.*, vol. 18, pp. 16-25, Jan. 1980.
- [120] R. Price and P. E. Green, Jr., "An anti-multipath communication system," M.I.T. Lincoln Lab., Tech. Memo. 65, Nov. 9, 1956 (not available from M.I.T.).
- [121] —, "A communication technique for multipath channels," *Proc. IRE*, vol. 46, pp. 555-570, Mar. 1958.
- [122] —, "Anti-multipath receiving system," U.S. Patent 2 982 853, May 2, 1961 (filed July 2, 1956).
- [123] M. G. Nicholson, Jr., "Time delay apparatus," U.S. Patent 2 401 094, May 28, 1946 (filed June 23, 1944).
- [124] "Lincoln F9C-A radio teletype system," Sylvania Electron. Defense Lab., Mountain View, CA, Instruction Manual EDL-B8, Dec. 21, 1956.
- [125] D. E. Sunstein and B. Steinberg, "Communication technique for multipath distortion," U.S. Patent 3 168 699, Feb. 2, 1965 (filed June 10, 1959).
- [126] B. Goldberg, R. L. Heyd, and D. Pochmerski, "Stored ionosphere," in *Proc. IEEE Int. Conf. Commun.*, Boulder, CO, June 1965, pp. 619-622.
- [127] J. R. Pierce and A. L. Hopper, "Nonsynchronous time division with holding and with random sampling," *Proc. IRE*, vol. 40, pp. 1079-1088, Sept. 1952.
- [128] A. R. Eckler, "The construction of missile guidance codes resistant to random interference," *Bell Syst. Tech. J.*, vol. 39, pp. 973-994, July 1960.
- [129] A. Corneretto, "Spread spectrum com system uses modified PPM," *Electron. Design*, June 21, 1961.
- [130] R. Lowrie, "A secure digital command link," *IRE Trans. Space Electron. Telem.*, vol. SET-6, pp. 103-114, Sept.-Dec. 1960.
- [131] R. M. Jaffe and E. Reichtin, "Design and performance of phase-lock loops capable of near optimum performance over a wide range of input signal and noise levels," Jet Propulsion Lab., Pasadena, CA, Progress Rep. 20-243, Dec. 1954; see also *IRE Trans. Inform. Theory*, vol. IT-1, pp. 103-114, Mar. 1955.

- [132] E. Rechtin, "An annotated history of CODORAC: 1953-1958," Jet Propulsion Lab., Pasadena, CA, Rep. 20-120, Contr. DA-04-495-Ord 18, Aug. 4, 1958 (AD 301248).
- [133] Corporal Bimonthly Summary Rep. 37a (July 1-Sept. 1, 1953). Jet Propulsion Lab., Pasadena, CA, Oct. 1, 1953.
- [134] W. F. Sampson, "Transistor pseudonoise generator," Jet Propulsion Lab., Pasadena, CA, Memo. 20-100, Dec. 7, 1954 (AD 056175).
- [135] S. W. Golomb, *Shift Register Sequences*. San Francisco: CA Holden-Day, 1967.
- [136] B. L. Scott and L. R. Welch, "An investigation of iterative Boolean sequences," Jet Propulsion Lab., Pasadena, CA, Sect. Rep. 8-543, Nov. 1, 1955.
- [137] R. C. Dixon, *Spread Spectrum Systems*. New York: Wiley, 1976.
- [138] Jupiter Bimonthly Summary No. 6 (Mar. 15-May 15, 1957), Jet Propulsion Lab., Pasadena, CA, June 1, 1957.
- [139] W. K. Victor and M. H. Brockman, "The application of linear servo theory to the design of AGC loops," *Proc. IRE*, vol. 48, pp. 234-238, Feb. 1960.
- [140] W. B. Davenport, Jr., "Signal-to-noise ratios in bandpass limiters," *J. Appl. Phys.*, vol. 24, pp. 720-727, June 1953.
- [141] J. C. Springett and M. K. Simon, "An analysis of the phase coherent-incoherent output of the bandpass limiter," *IEEE Trans. Commun. Technol.*, vol. CT-19, pp. 42-49, Feb. 1971.
- [142] S. W. Golomb, "Sequences with randomness properties," Glenn L. Martin Co., Baltimore, MD, Terminal Progress Rep., Contract Req. No. 639498, June 1955.
- [143] —, "Remarks on orthogonal sequences," Glenn L. Martin Co., Baltimore, MD, Interdepartment communication, July 28, 1954.
- [144] N. Zierler, "Two pseudo-random digit generators," M.I.T. Lincoln Lab., Group Rep. 34-24, July 27, 1954.
- [145] —, "Several binary sequence generators," M.I.T. Lincoln Lab., Tech. Rep. 95, Sept. 12, 1955 (AD 089135).
- [146] —, "Linear recurring sequences," *J. SIAM*, vol. 7, pp. 31-48, Mar. 1959.
- [147] E. N. Gilbert, "Quasi-random binary sequences," Bell Tel. Lab., unpublished memo., Nov. 27, 1953.
- [148] D. A. Huffman, "Synthesis of linear sequential coding networks," presented at the 3rd London Symp. Inform. Theory, Sept. 12-16, 1955; published in *Information Theory*, C. Cherry, Ed. New York: Academic, 1956.
- [149] T. G. Birdsall and M. P. Ristenbatt, "Introduction to linear shift-register generated sequences," Univ. Michigan Res. Inst., Ann Arbor, Tech. Rep. 90, Oct. 1958 (AD 225380).
- [150] M. Ward, "The arithmetical theory of linear recurring sequences," *Trans. Amer. Math. Soc.*, vol. 35, pp. 600-628, July 1933.
- [151] M. Hall, "An isomorphism between linear recurring sequences and algebraic rings," *Trans. Amer. Math. Soc.*, vol. 44, pp. 196-218, Sept. 1938.
- [152] J. Singer, "A theorem in finite projective geometry and some applications to number theory," *Trans. Amer. Math. Soc.*, vol. 43, pp. 377-385, May 1938.
- [153] R. J. Turyn, "On Singer's parametrization and related matters," Appl. Res. Lab., Sylvania Electron. Syst., Waltham, MA, Eng. Note 197, Nov. 10, 1960.
- [154] R. Gold, "Optimal binary sequences for spread spectrum multiplexing," *IEEE Trans. Inform. Theory*, vol. IT-13, pp. 619-621, Oct. 1967.
- [155] —, "Maximal recursive sequences with 3-valued cross-correlation functions," *IEEE Trans. Inform. Theory*, vol. IT-14, pp. 154-156, Jan. 1968.
- [156] T. B. Whiteley and D. J. Adrian, "Random FM autocorrelation fuze system," U. S. Patent 4 220 952, Sept. 2, 1980 (filed Feb. 17, 1956).
- [157] J. P. Costas and L. C. Widmann, "Data transmission system," U. S. Patent 3 337 803, Aug. 22, 1967 (filed Jan. 9, 1962).
- [158] "Reliable tactical communications," General Electric Res. Lab., Schenectady, NY, Final Rep., Contr. DA-36-039sc-42693, Mar. 2, 1954 (AD 30344).
- [159] E. J. Groth, "Notes on MUTNS, a hybrid navigation system," Conf. 6733 on Modern Navigation Systems, Univ. Michigan, Ann Arbor, Summer 1967 (Univ. Michigan Library Call No. VK 145.M624, 1967).
- [160] E. J. Groth *et al.*, "Navigation, guidance, and control system for drone aircraft," Motorola, Final Eng. Rep., Contr. DA36-039sc78020, June 6, 1961 (AD 329101, AD 329102, AD 329103).
- [161] L. S. Schwartz, "Wide-bandwidth communications," *Space/Aeronautics*, pp. 84-89, Dec. 1963.
- [162] J. M. Wozencraft, "Reliable radio teletype coding," U.S. Patent 3 896 381, July 22, 1975 (filed Nov. 2, 1960).
- [163] A. Kohlenberg, S. M. Sussman, and D. Van Meter, "Matched filter communication systems," U.S. Patent 3 876 941, Apr. 8, 1975 (filed June 23, 1961).
- [164] E. Guillemin, "Matched filter communication systems," U.S. Patent 3 936 749, Feb. 3, 1976 (filed June 23, 1961).
- [165] S. M. Sussman, "A matched filter communication system for multipath channels," *IRE Trans. Inform. Theory*, vol. IT-6, pp. 367-373, June 1960.
- [166] W. G. Ehrich, "Common channel multipath receiver," U.S. Patent 3 293 551, Dec. 20, 1966 (filed Dec. 24, 1963).
- [167] J. J. Spilker, Jr., "Nonperiodic energy communication system capable of operating at low signal-to-noise ratios," U.S. Patent 3 638 121, Jan. 25, 1972 (filed Dec. 20, 1960).
- [168] H. G. Lindner, "Communication security method and system," U.S. Patent 4 184 117, Jan. 25, 1980 (filed Apr. 16, 1956).
- [169] J. W. Craig and R. Price, "A secure voice communication system," *Trans. Electron. Warfare Symp.*, 1959.
- [170] J. W. Craig, Jr., "An experimental NOMAC voice communication system," M.I.T. Lincoln Lab., Rep. 34G-0007, Aug. 29, 1960 (AD 319610).
- [171] D. J. Gray, "A new method of teletype modulation," M.I.T. Lincoln Lab., Tech. Rep. 9, Sept. 22, 1952 (AD 000928).
- [172] R. M. Fano, "Anti-multipath communication system," U.S. Patent 2 982 852, May 2, 1961 (filed Nov. 21, 1956).
- [173] L. A. deRosa, M. Rogoff, W. B. Davenport, Jr., and P. E. Green, Jr., in "1981 Pioneer Award," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-18, pp. 153-160, Jan. 1982.
- [174] R. C. Dixon, Ed., *Spread Spectrum Techniques*. New York: IEEE Press, 1976.
- [175] A. M. Semenov and A. A. Sikarev, *Shirokopolosnaya Radio-svyazy* [Wideband Radio Communications]. Moscow, USSR: Voenizdat, 1970.
- [176] A. A. Kharkevich, "The transmission of signals by modulated noise," *Telecommunications (USSR)*, vol. 11, no. 11, pp. 43-47, 1957.
- [177] F. H. Lange, *Korrelationselektronik* [Correlation Electronics]. Berlin, Germany: VEB Verlag Technik, 1959.
- [178] J. P. Costas, "Poisson, Shannon, and the radio amateur," *Proc. IRE*, vol. 47, pp. 2058-2068, Dec. 1959.
- [179] —, "Author's comment," *Proc. IRE*, vol. 48, p. 1911, Nov. 1960 (see also "Information capacity of fading channels under conditions of intense interference," *Proc. IEEE*, vol. 51, pp. 451-461, Mar. 1963).
- [180] P. Bello, "Demodulation of a phase-modulated noise carrier," *IRE Trans. Inform. Theory*, vol. IT-7, pp. 19-27, Jan. 1961.
- [181] H. Magnuski, "Wideband channel for emergency communication," in *IRE Int. Conv. Rec.*, New York, NY, Mar. 20-23, 1961, part 8, pp. 80-84.
- [182] R. A. Marolf, "200 Mbit/s pseudo random sequence generator for very wide band secure communication systems," in *Proc. NEC*, Chicago, IL, 1963, vol. 19, pp. 183-187.
- [183] A. I. Alekseyev, "Optimum noise immunity of noise like signals" (in Russian), presented at the 19th All-Union Conf. Popov Society, May 1963; trans. in *Telecommun. Radio Eng. (USSR)*, pt. 2, vol. 19, pp. 79-83, Aug. 1965.
- [184] M. K. Razmakhnin, "Wideband communication systems" (in Russian), *Zarubezhnaya Radioelektronika [Foreign Radio Electron.]*, no. 8, pp. 3-29, 1965.
- [185] N. T. Petrovich and M. K. Razmakhnin, *Sistemy Svyazi s Shumopodobnymi Signalami [Communication Systems with Noise-Like Signals]*. Moscow: Sovetskoye Radio, 1969.
- [186] A. I. Alekseyev, A. G. Sheremet'yev, G. I. Tuzov, and B. I. Glazov, *The Theory and Application of Pseudorandom Signals* (in Russian). Moscow: 1969.
- [187] Yu. B. Okunev and L. A. Yakovlev, *Shirokopolosnye Sistemy Svyazi s Sostavnymi Signalami [Wideband Systems of Communication with Composite Signals]*. Moscow: Svyaz, 1968.
- [188] L. S. Gutkin, V. B. Pestryakov, and V. N. Tipugin, *Radio-upravleniye [Radio Control]*. Moscow: 1970.



Robert A. Scholtz (S'56-M'59-SM'73-F'80) was born in Lebanon, OH, on January 26, 1936. He received the B.S. degree from the University of Cincinnati, Cincinnati, OH, in 1958, the M.S. degree from the University of Southern California, Los Angeles, in 1960, and the Ph.D. degree from Stanford University, Stanford, CA, in 1964, all in electrical engineering.

He joined Hughes Aircraft Company as a Masters Fellow in 1958 and continued at Hughes part-time until 1978, working on missile radar signal processing problems. In 1963, he joined the faculty of the University of Southern California, where he is now a Professor of

Electrical Engineering. He has published extensively in communication theory, coding, and radar. He presently is a Consultant to the LinCom Corporation and Axiomatix, Inc.

In 1980, Dr. Scholtz was elected to the grade of Fellow in the IEEE, "for contributions to the theory and design of synchronizable codes for digital communications and radar systems." An active member for many years, he has manned important organizational posts for major technical meetings, the most recent being Program Chairman for the 1981 International Symposium on Information Theory. He presently is on the Board of Governors of both the IEEE Communications Society and the IEEE Information Theory Group. He is a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Phi Eta Sigma.