The NOMAC and Rake Systems

William W. Ward

■ In the 1950s, Lincoln Laboratory developed the spread-spectrum Noise Modulation and Correlation (NOMAC) system for improved high-frequency radio communications. The production version of NOMAC, named the F9C, generated a pseudonoise (PN) sequence at the receiving terminal in synchronism with the PN modulation of the transmitted signal. The F9C achieved as much as 17 dB of jamming protection.

Obtaining an additional 6 dB of protection (the original NOMAC design had promised 23 dB) required addressing the effects of multipath propagation. Lincoln Laboratory solved the multipath problem by adding a Rake receiver to the NOMAC system. The Rake receiver synthesized an adaptive matched filter corresponding to the collection of linear propagation paths that produced the actual received signal. The insights that led to Rake ultimately found application to sonar problems, the analysis of seismic signals, the radar mapping of the moon and nearby planets, and the radar imaging of orbiting satellites.

The year 1991 marked the 40th anniversary of the formal organization of MIT Lincoln Laboratory. Today it is interesting to look back at the frontier problems of that time and the techniques that were used to solve them. To be sure, the technologies of the 1950s have long since been surpassed by successive generations of innovation, and the theoretical insights that were epochal then have by now become standard. Nevertheless, we can learn much today by looking at how people then dealt with difficult problems. The underlying principles for choosing effective courses of action and for carrying them out are timeless.

At this point we must make a determined effort to forget momentarily the reliable worldwide satellite and submarine-cable communications systems that we currently take for granted. Four decades ago there were no worldwide high-capacity communications circuits and no intercontinental television. Transoceanic communications relied on teletype-rate submarine cables (which were few and, of necessity, fixed in place), high frequency (HF) radio (roughly 3 to 30 MHz), and the physical transport of messages by plane or ship.

For several reasons, the HF medium, or short wave, has always been challenging to communications engineers. HF links are often subject to natural interference arising from phenomena associated with solar storms. Also, immediately after a high-altitude nuclear burst, the character of the HF propagation medium changes in several ways—almost always for the worse—for lengthy intervals. Long periods of widespread blackout of HF communications have been noted following nuclear explosions in the upper atmosphere [1]. Furthermore, HF links are easy targets for jamming.

Under favorable conditions, however, the HF medium can provide worldwide communications from one specific point to another, at a particular time, with relatively small, low-power transmitting and receiving terminal equipment. Because of its compactness, HF equipment can be installed on ships, aircraft, trucks, and even a person's back.

Research at Lincoln Laboratory

The Army Signal Corps was already sponsoring classified research at MIT's Research Laboratory of Electronics (RLE) to improve HF communications and to reduce the vulnerabilities of this medium when Project Lincoln was established in 1951. (Project Lincoln would later become Lincoln Laboratory.) This work was directed at improving long-range radio communications between the continental United States (CONUS) and overseas locations of military interest. At that time (a few years after the end of World War II), links between Washington, D.C., and points in Europe had become critical because of the cold war with the Soviet Union. Reliable links to Korea were also needed, for the U.S. had become involved in a medium-scale hot war there in 1950. The establishment of Project Lincoln provided a better setting for this classified work than RLE, so the enterprise was gradually transferred.

Improvements in HF communications also promised to solve some of the problems of the nascent Semi-Automatic Ground Environment (SAGE) system, which Lincoln Laboratory had been primarily established to support. SAGE, a large-scale electronic air-surveillance and weapons-control system designed to blanket CONUS [2, 3], needed reliable long-range communications for the ground-based distant-early-warning (DEW) radars spread across upper Canada and for the airborne-early-warning (AEW) radar aircraft on patrol far from land. Both sets of radars were to be on guard around the clock for intruding bombers.

One approach to improving long-range radio communications lay in pushing beyond the customary boundaries of HF practice. Lincoln Laboratory achieved considerable success in communicating at frequencies higher than the generally accepted maximum usable frequency (MUF) for a given HF link. Lincoln Laboratory's development and demonstration of ionospheric-scatter technology (at VHF) and of tropospheric-scatter technology (at UHF and at SHF) are reviewed in References 4 and 5, respectively. In this article we follow the work that was performed to make the basic HF medium itself more serviceable than it had been before.

Lincoln Laboratory was not the first organization to work on reducing the vulnerability of radio links to interference, whether natural or artificial, intentional or unintentional. Neither was Lincoln Laboratory the first to perceive that measures taken to assure link integrity against interference could also provide covertness and link privacy, i.e., security against interception. (Note: The history of these efforts worldwide has been reviewed in various articles [6–11].) Lincoln Laboratory, however, was unique both in the way it addressed these issues and in the early operational success that it achieved.

Approaches to Antijam Communications

The central feature of antijam communications is intuitively plausible. If you are worried about someone listening in on or interfering with your radio link, one way to minimize the problem is to move the nominally-constant-frequency carrier signal (which carries the information stream to be communicated) around in frequency often, transmitting for a little time here, a little time there, according to a pattern known only at the transmitter and the intended receiver. After allowing for the time delay for the propagation of the signal, the intended receiver listens for a little time here, a little time there, according to the same pattern. This frequency-hopping technique occupies much more of the electromagnetic spectrum than would a fixed-carrier-frequency link, albeit on a part-time basis. The technique offers protection against broadband noise jamming by the ratio of the spread bandwidth to the data bandwidth.

The next stage in sophistication is an elegant alternative that accomplishes the same end. The information stream is associated with a carrier signal of a radically different kind. That signal, for example, can be generated from a constant-frequency reference signal by giving it 180° phase shifts with respect to itself according to a particular pattern in time. A well-known pattern is the linear-shift-register sequence (used in NOMAC), in which the pattern of decisions to phase-shift or not to phase-shift can be represented by a corresponding sequence of 1s and 0s that can be readily generated with digital electronic circuitry [12, 13]. A linear-shift-register sequence is one example of a direct sequence, which can be used to generate pseudonoise (PN) signals. As with frequency-hopping systems, PN systems also offer protection against jamming by the ratio of the spread to the data bandwidths.

(Note: PN systems such as NOMAC were developed and fielded *before* frequency-hopping techniques were introduced into operational practice. In the discussion above, however, frequency hopping was presented first as an aid to understanding.)

Nature can be a great equalizer. The theoretical studies cited in Reference 10 led to the understanding that the above two approaches to spectrum spreading are equivalent in a practical sense. For any specific link, the same minimum average transmitted power is required to enable the receiver to meet a given standard of fidelity, i.e., to enable the receiver to make no more than a given percentage of wrong decisions about the detected information stream. A frequency-hopping system performs the spectrum spreading by means of successive transmissions at a given power level, the transmissions being scattered one after another over the occupied band. With a direct-sequence system, the given power level is spread across the occupied band at all times.

Direct-sequence systems offer a measure of covertness because of the lower peak power levels that are transmitted in any given frequency interval, each interval being a small fraction of the spread bandwidth. Without knowledge of the sequence being used, a receiver might find it difficult to determine that a transmission was even taking place, let alone to make sense of the transmission.

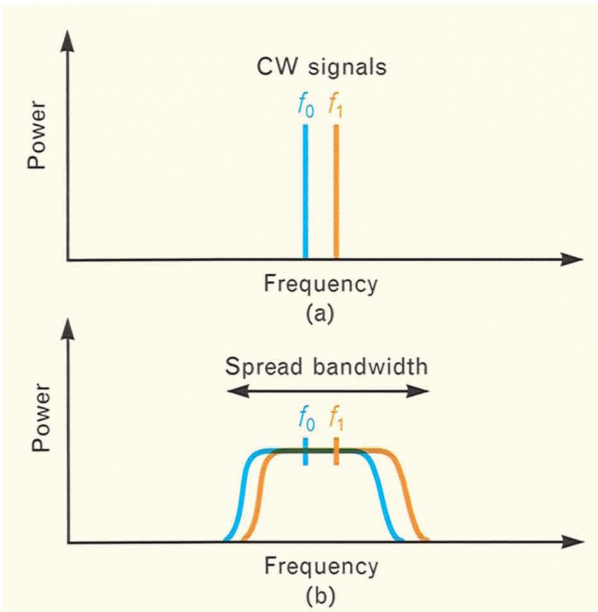

FIGURE 1. Signal spectra of (a) binary frequency-shift keying (BFSK) system and (b) stored-reference Noise Modulation and Correlation (NOMAC) system.

There are different ways to associate the information stream with the PN carrier signal. One approach is to have available at the transmitter two spread-spectrum carrier signals, derived from the same sequence but slightly offset in their nominal center frequencies and overlapping each other for the most part. The successive 1s and 0s of the information stream of binary data would key the transmission of one or the other carrier signal. This scheme is the noisy counterpart of conventional binary frequency-shift keying (BFSK), in which a frequency f_1 is transmitted to represent a 1, and a frequency f_0 to represent a 0 (Figure 1).

For detecting the 1s and 0s (MARKs and SPACEs in teletype parlance), two types of receivers—the matched-filter receiver and the correlation receiver—are equally impressive (see the box "Matched Filters and Correlators"). In a matched-filter receiver (see Figure 2 and Reference 14),

a. two copies of the received signal $s(t)$ are passed through linear filters whose impulse responses $h_i(t)$ are the time reverses of the transmitted signals $s_i(t)$ of duration T (one corresponding to a 0 and the other to a 1),
b. the filter outputs $r_i(t)$ are compared after an interval T, and
c. the larger of the two is declared the winner of the bit decision.

In a correlation receiver (see Figure 3 and Reference 14),

a. two copies of the received signal $s(t)$ are multiplied by replicas of the transmitted signals $s_i(t)$ of duration T (one corresponding to a 0 and the other to a 1),
b. the smoothed multiplier outputs $p_i(t)$ are compared after an interval T, and
c. the larger of the two is declared the winner of the bit decision.

The above two approaches to spread-spectrum signal detection are equally optimal. The choice between them is made as part of the system engineering

MATCHED FILTERS AND CORRELATORS

IN SIGNAL ANALYSIS, the 1950s were the decade of optimum detection. In the preface to a special journal issue [1], P.E. Green, Jr., compared and contrasted matched-filter and correlation receivers, and found them to be essentially identical in terms of what they could accomplish:

> This Special Issue takes as its point of departure a disarmingly humble and specific notion: that the correlation of one waveform with another can be carried out by 1) passing the first waveform through a linear system whose impulse response is the time reverse of the second waveform, and 2) observing the output at a certain instant of time. If the two waveforms are made the same, we say that the filter is "matched" to the input waveform. The filter output as a function of real time is then the autocorrelation function of the waveform.
>
> The subject was introduced in 1943 in North's study [2] of maximization [of the] signal-to-noise ratio out of the IF of a pulse radar. Correlation detection was studied at first as a separate subject, but the equivalence of the two operations was soon appreciated. By now they have long since fused and the only meaningful distinction lies in the matter of actual hardware—whether the correlation operations take place using multipliers and integrators, or alternatively by observing the sampled outputs of matched filters. Often, but not always, there are compelling engineering reasons for preferring the latter approach.
>
> No matter what formalism is used to view a given communication or detection situation, Gaussian noise statistics lead usually to some form of correlation or matched filtering as a part of the set of operations that will perform the desired function most efficiently. This appears to be true even when in addition to the noise there are other perturbing factors present, such as randomly varying multipath [-propagation effects], uncertainties in signal delay or Doppler shift, Doppler or delay smearing, or unwanted clutter.

As described in the section "NOMAC Systems" of the main text, matched-filter/correlation detection played a key role in the system engineering of the Noise Modulation and Correlation communications system.

References

1. Special issue on matched filters, *IRE Trans. Info. Theory* **6**, 310 (1960).
2. D.O. North, "An Analysis of the Factors Which Determine Signal/Noise Discrimination in Pulsed-Carrier Systems," *Tech. Rpt. PTR-6C,* RCA Laboratories, Princeton, N.J. (25 June 1943). (Note: This classic paper was reprinted in *Proc. IEEE* **51**, 1016 [1963], along with a preface by L.V. Blake on p. 1015.)

that must be carried out to bring an invention from idea to reality. Although the hardware for either approach may turn out to be somewhat different from that described above, its operation will be functionally equivalent.

Strictly speaking, conventional frequency modulation (FM) broadcasting involves a spectrum-spreading technique, too. FM offers a significant amount of interference immunity, as evidenced by the comparatively noise-free reception in the commercial FM band during a lightning storm in comparison with the static-plagued reception in the commercial amplitude modulation (AM) band. FM, however, provides no privacy. A definition of modern spread spectrum that adequately reflects the characteristics of this technology is given in Reference 15:

> Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery.

In a spread-spectrum communications system, the receiving terminal must know the pattern, or key sequence, of phase shifts that the transmitting terminal is applying to the nominally-constant-frequency carrier signal. The receiving terminal must also know (to the requisite accuracy) the time at which a particular portion of that pattern will be employed. The operation of the communications system

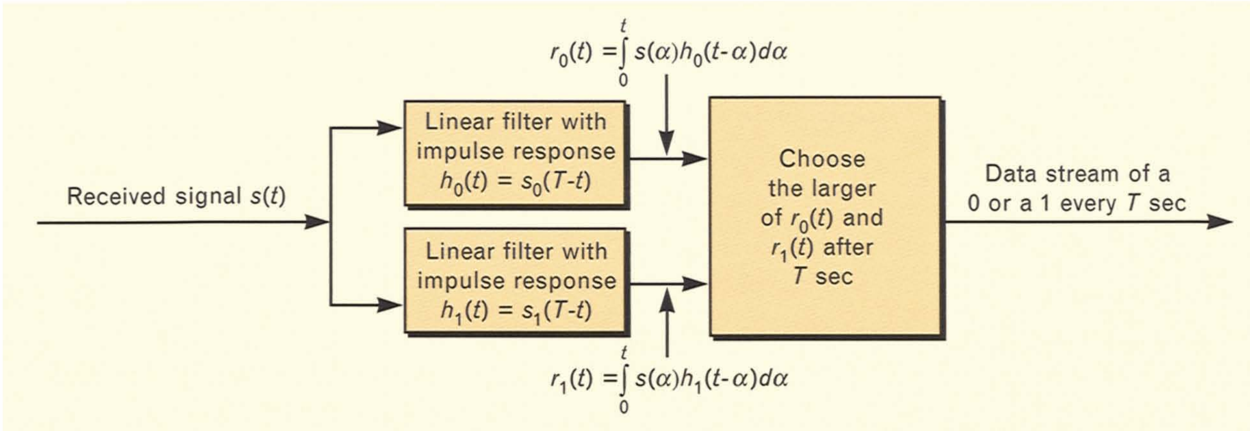

FIGURE 2. Matched-filter receiver (see Reference 14).

is much like the process of enciphering and deciphering messages in cryptography.

NOMAC Systems

The notions of correlation detection and of using noise-like carrier signals were extant in MIT's Research Laboratory of Electronics before Lincoln Laboratory was established. In those days immediately after the end of World War II, MIT accepted classified theses for degrees. Three of those theses [16–18] laid the foundation for the NOMAC communications system [19]. As understanding of the system deepened, other reports were published [20, 21].

Transmitted-Reference NOMAC Systems

In the first implementation of NOMAC, the key sequence was transmitted to the receiving terminal via a separate radio channel. This approach (an outgrowth of ideas discussed in the Project Hartwell 1950 Summer Study at MIT [22]) had obvious vulnerabilities. For it to work, a second communications link, itself vulnerable to interference and jamming, had to be set up and operated. Furthermore, there was always the worry that the second link for carrying the key sequence would itself be detected and exploited. (Note: Another suggested approach was for both terminals to listen to the noise signal in a given frequency band from the same radio star, each using that detected signal to form the key sequence [23].)

A transmitted-reference NOMAC system was first demonstrated over the air by Lincoln Laboratory on 23 October 1952 with teletype transmission at 5.4325 MHz from the Signal Corps Engineering Laboratories at Fort Monmouth, N.J., to Lexington, Mass., a distance of about 370 km. In early 1953, a transmitted-reference NOMAC system operable at any of five

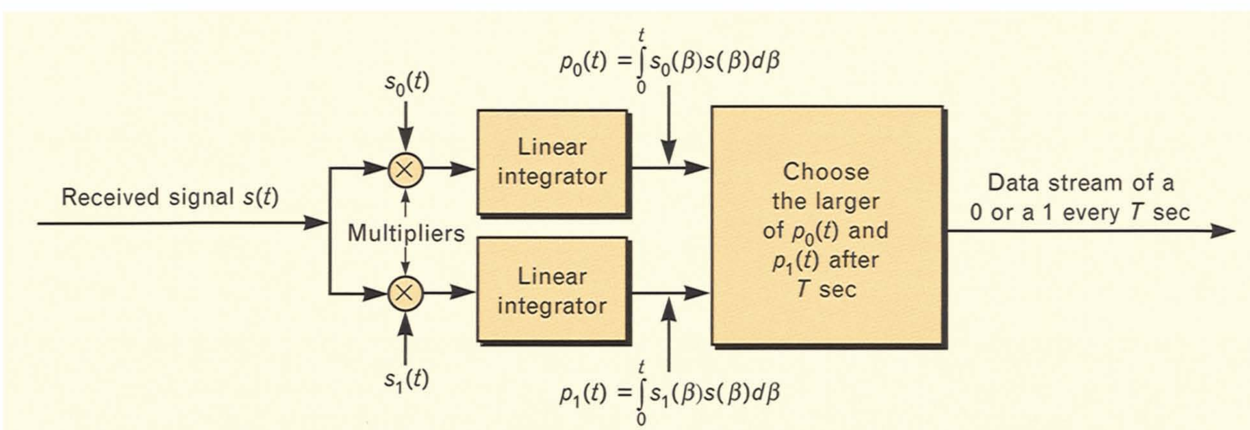

FIGURE 3. Correlation receiver (see Reference 14).

frequencies from 31 to 38 MHz was implemented at Lincoln Laboratory in the form of the P9D VHF dual-diversity NOMAC teletype system [24].

Designed for dual-diversity reception, the P9D had two physically separated receiving antennas, each with its own receiver, together with circuitry for combining the detected data streams most effectively to yield a single output. The space diversity provided by the two receiving installations offered some promise of ameliorating the multipath-propagation problem of the HF medium. (Note: The HF medium had long been known for its susceptibility to signal fading caused in part by the destructive interference among several signals reaching a given receiving site via different paths [Figure 4].)

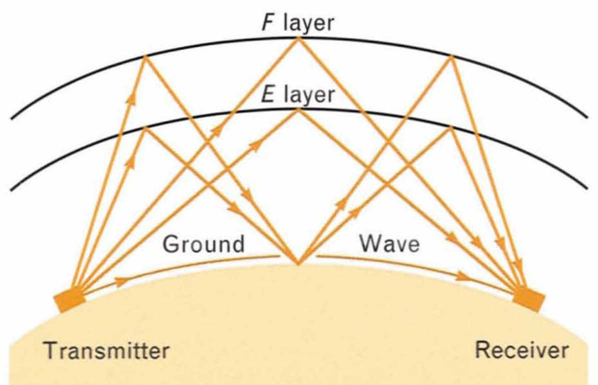

FIGURE 4. In this example of multipath propagation at HF, five versions of the transmitted signal arrive at the receiver via different paths. The effects of ground-wave propagation and of reflections from the earth and from the *E* and *F* ionospheric layers introduce phase and Doppler shifts as well as time delays. An actual situation can be even more complex than this example.

The P9D system was developed with the intent of incorporating the desirable features of NOMAC in the radio links that connected the radar stations of the DEW Line with SAGE Direction Centers in CONUS. Six sets of equipment were built, and a one-way NOMAC link was operated from a Western Electric test site at Streator, Ill., to a Bell Telephone Laboratories receiving site at Crawfords Hill in Holmdel, N.J. (Western Electric was the prime contractor of the DEW Line.) Ultimately, though, the shortcomings of the transmitted-reference system—i.e., the second link's vulnerability to interference, jamming, and detection—discouraged use of the technology, and forward-scatter communications systems with conventional FSK modulation were chosen for the DEW-Line application.

Attempts were made to apply NOMAC principles to other tasks. A NOMAC forward-scatter link was successfully demonstrated when a transmitted-reference system at 49.6 MHz (in the low VHF) was put into operation from Cedar Rapids, Iowa, to MIT's Round Hill Field Station at South Dartmouth, Mass., in July 1953. NOMAC ground-to-air data links at UHF for SAGE communications were also considered, but the state of the art in electronic componentry at that time made the airborne terminals impractical.

Stored-Reference NOMAC Systems

In a stored-reference system, the key sequence (perhaps in the form of a data tape, for example) is transferred to the receiving terminal before the sequence is needed. Stored-reference systems have a long history of success in cryptography. There, the problem of synchronizing the receiver to the incoming signal can be solved by using a plain-text preamble symbol in the enciphered message or by relying on accurate clocks at both ends of the link. At Lincoln Laboratory, bench tests that bypassed the synchronization problem confirmed the analytical conclusion that stored-reference systems are much less vulnerable to jamming than are transmitted-reference systems [25].

Lincoln Laboratory's second approach to implementing a NOMAC spread-spectrum communications system—the F9C [26, 27]—relied on a novel solution to the stored-reference problem. In the F9C, whose design and construction commenced in July 1953, digital circuitry (clocked by primary frequency standards) generated long-period trains of pulses (the PN key sequences) to provide the required reference signals at both ends of the link. The pulses were used to shock-excite bandpass filters of the same width as the spectrum width of the transmission. The filter transient responses to this excitation provided noise-like signals of long period (easily greater than a day, the rekeying interval).

The signal in the transmitter could be used to generate the spread-spectrum 1s and 0s. The signal in the receiver could be used (by cross correlation with the received signal) to determine which detected-signal segments corresponded to 1s and which to 0s. This method of generating the required reference signals was sometimes called the matched-filter approach, but it is inherently a stored-reference scheme.

The synchronization problem was solved by relying on the transmission and reception of a single tone-burst signal at a predetermined frequency (the counterpart of the plain-text preamble symbol) to start each of the sequence generators. Thereafter, the receiver maintained synchronism of its reference signal by tracking the received signal in time.

The F9C used a spread band of 10 kHz for 60-wpm teletype service. The rate corresponded to 22 msec per baud (the elemental MARK/SPACE component of a teletype symbol), equivalent to a bandwidth of 1/0.022 = 45 Hz. Thus the F9C promised a factor of 10,000/45 = 220 (≈ 23 dB) in jamming resistance. However, it was recognized long before the first NOMAC signal was radiated that the signal would probably reach the receiver as a set of replicas of itself, spread out in time (Figure 4).

Multipath propagation had proven to be a major handicap for the transmitted-reference P9D, but the effect on Lincoln Laboratory's implementation of the stored-reference F9C was not then known. Although attempts had been made to analyze the problem [28, 29], researchers felt that only a realistic field test could determine with certainty the effects of multipath propagation on the F9C. Thus a transcontinental HF NOMAC link was put into operation from an Army site at Davis, Calif., to a Signal Corps facility at Deal, N.J., on 12 August 1954.

The equipment on the West Coast—including the exciter for the high-power AN/FRT-22 HF transmitter and a receiver for local-loop testing—is shown in Figure 5; the equipment on the East Coast—including the receiver and a low-power transmitter for local-loop testing—is shown in Figure 6. Note that although vacuum tubes continued to perform most of the functions, significant numbers of transistors were used: 100 each for the equipment at both locations.

Of the equipment on both coasts, the East Coast equipment (for reception) was the more complex. Among other things, it had to keep the locally generated stored-reference signal synchronized with the incoming signal, despite changes in the length of the HF propagation path due to variations in the ionosphere. Without this time-tracking function, the F9C could not have worked. An example of the system's early operational use is shown in Figure 7.

The designers and developers of the F9C understood that the system offered no advantage (and, in some circumstances, a disadvantage) over conventional FSK when interference was absent. Indeed, the additional complexity of NOMAC equipment could be justified only for communications links in which jamming could be expected or in which covertness was a paramount issue. Thus the following were included in the system: provisions for parallel testing with a conventional FSK link and the capability for introducing jamming signals at 12.27 and 17.46 MHz by transmitters in Cedar Rapids, Iowa, and Honolulu, Hawaii, respectively. During the test program, researchers soon discovered that multipath propagation caused the F9C to perform poorly in the unjammed environment. The simultaneous arrival of NOMAC signals via several different paths that incorporated several different propagation delays (Figure 4) introduced an element of self-jamming at the receiving site that was not so significant for conventional FSK.

The testing was halted in October 1954 so that the F9C could be modified. The performance of the new system, named the F9C-B, improved significantly through the use of a time-diversity approach in which much of the receiver circuitry was duplicated to enable two separate channels to track the two strongest received signals independently. The two detected signals were then combined to yield a single data stream that was superior to either. The F9C-B was also adapted to make use of space diversity—that is, the two receiving channels were connected to antennas that were physically separated.

The transcontinental tests resumed in February 1955 and concluded three months later. In the tests, the time-diversity approach helped to achieve as much as 17 dB of the 23 dB of jamming protection that the F9C design had promised. (Obtaining the remaining 6 dB required the development of the Rake system, which detected and summed the received signals from many propagation paths. Rake is discussed in detail in the following section.) On the basis of that success,

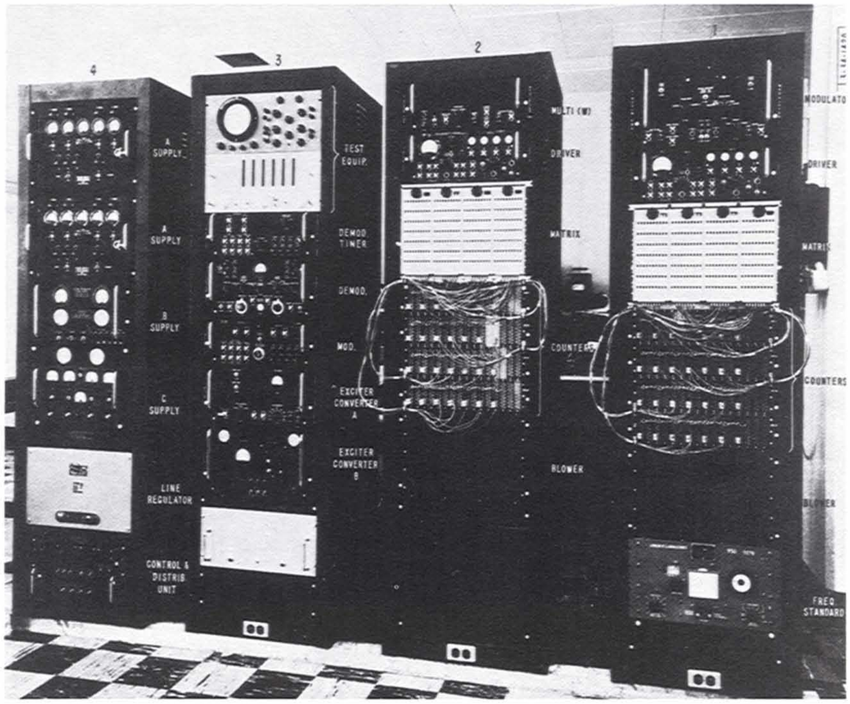

FIGURE 5. Physical layout of NOMAC transmitter (West Coast equipment), containing 388 vacuum tubes and 100 transistors. For a feel for the scale of the photograph, the floor tiles are 9" × 9".

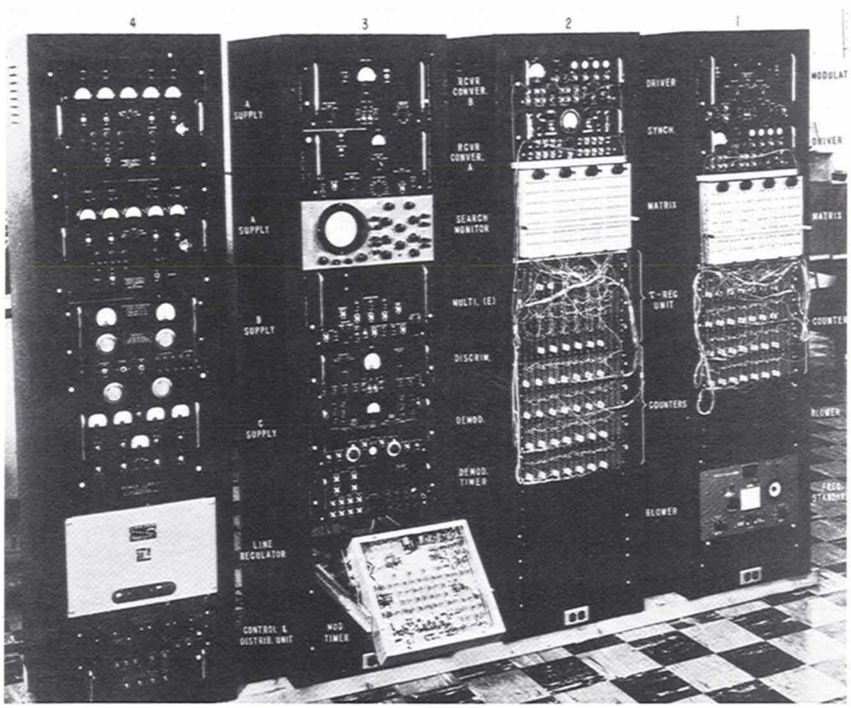

FIGURE 6. Physical layout of NOMAC receiver (East Coast equipment), containing 502 vacuum tubes and 100 transistors.

the Signal Corps funded the production and manufacture of the F9C-A, an HF NOMAC system with time diversity. Two Lincoln Laboratory staff members were stationed at Sylvania's Electronic-Defense Laboratory in Mountain View, Calif., to facilitate the technology transfer, and there was also strong interaction with another Sylvania laboratory in Waltham, Mass. Sylvania built six F9C-A systems, and two more were built by Fischback & Moore of Dallas [30]. Lincoln Laboratory's experience helped the contractors achieve in the field the benefits of NOMAC that were predicted by theory and had been verified by test.

The Rake System

As discussed in the previous section, implementation of the NOMAC technique with two signal-tracking channels (time diversity) achieved as much as 17 dB of the 23 dB of jamming protection that the design of the F9C HF radioteletype equipment had promised. The accomplishment was respectable but not good enough. The F9C processed only the two strongest received signals (ignoring all the rest) by the brute-force technique of tracking them in time and detecting them independently, compensating for the differential time delay between them, and combining the resulting signals into a single output. As discussed earlier, however, the transmitted signal typically arrives at the receiver as a number of fuzzy replicas of itself (Figure 4), spread out in time after traversing the numerous (there might be as many as 20 or 30 in practical cases) distinct ionospheric-propagation paths often encountered by HF/VHF radio [27, 28]. Lincoln Laboratory researchers felt that if they could find an efficient way to compensate for the effects of most of the signal-path delays, they could recover most of the remaining 6 dB of potential jamming protection.

The ionosphere continually changes as the earth revolves in the light of the sun, which itself emits varying particle fluxes that also affect the earth's upper atmosphere. Any vertical motion of a reflecting layer in the ionosphere will lengthen or shorten the propagation path between two fixed communications terminals on earth. The dynamic manifestation of this change in path length is a shift in the frequency of the received signal (equivalently, the Doppler effect caused by the moving ionospheric mirror). The signals arriving at the receiver by several paths can thus be spread in frequency as well as in time. The product of the delay spread L (in seconds) and the frequency spread B (in Hz) is a dimensionless number BL that characterizes the channel. For HF radio, BL is less than unity, and that channel is said to be underspread. For the propagation of sound in the ocean, BL is greater than unity, and that channel is said to be overspread.

Multipath propagation in HF/VHF radio manifests itself in two ways. First, the several received signals add up according to their relative phases at the antenna. Sometimes the signals combine to yield a strong signal at a given frequency. At other times the

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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 ATLATIC 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 TACOME
TO BE MARRIED ON THE 25 OF AUGUST AND THEN I PLAN TO GO TO SWEDEN ON
THE 2Ø OF SEPTEMBER FOR AT LEST A MONTH
SO I WILL BE ON VACATION FOR ABOUT THREE MONTHS  GA

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

MACHINE TO SAY CONGRATULATIONS!

AND HER I EXPECTED PITY  MMMMMM
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FIGURE 7. This duplex teletype output, made during coast-to-coast tests of the F9C system in 1954, includes undoubtedly the first engagement announcement afforded the security of spread-spectrum communications. (Copy courtesy of Robert Berg, the announcer at the West Coast station.)

signals may nearly cancel one another out at that same frequency. Moving to a neighboring frequency can change the situation completely, because the relative phases of the several signals will generally be entirely different. Anyone who has heard a shortwave signal fade out slowly and then return as a reflection point in the ionosphere moves has experienced this effect of multipath propagation. Second, the time difference between the arrival of a strong signal by one path and of another signal by a different path can be large enough to confuse the detection of the modulation carried by the two signals. *Intersymbol interference*, the modern name for the echo-chamber effect that results, limits the rate at which information can be transmitted over the channel because more time is required to make sense of each element of the somewhat garbled stream of received data than if the signal had arrived uncorrupted.

In essence the Rake system for HF radio communications synthesized and continuously refined in the receiving terminal an adaptive matched filter corresponding to most of the linear propagation paths that produced the received signal, which arrived spread in time [31–33]. The filter was thus able to compensate for component dispersions in the received signal. In fact, to a large extent the filter restored the signal to what it would have been had there been only one fixed propagation path from transmitter to receiver.

The maximum spread in HF radio was less than about 3 msec. Thus at any instant an analog acoustic delay line of a practical length (3 msec) [34] would

SIMULTANEOUS INVENTIONS

THE HISTORY OF science and technology is replete with instances of simultaneous inventions and discoveries by two or more individuals or groups. Often these circumstances have led to protracted, bitter, fruitless controversy. But it does not always have to be that way. E. Rechtin, working at the California Institute of Technology's Jet Propulsion Laboratory, wrote the following:

> In recent years, the designers of guided missiles employing radio links have been confronted with a continually increasing electronic-countermeasures threat. . . . This situation was predictable several years ago, and certain steps were taken to counteract it. . . . Apparently the essential feature of jam-resistant radar systems was the transmission of a pseudorandom signal rather than a readily recognized signal. The advantages of such transmission, first proposed by C.E. Shannon, were apparent to those attempting to add countermeasures resistance to their radio links. In 1953, . . . the Lincoln Laboratory of the Massachusetts Institute of Technology was in the research and development phase of a short-wave long-distance communications link using noise-like transmission. For various reasons, this system was not applicable to guided missiles, however, considerable experience was gained in the technique, and this experience was made available to the Jet Propulsion Laboratory (JPL). Within a short time, ideas were being exchanged between the two organizations. Occasionally, research projects would be specifically designed so that similar areas would be supported and complemented rather than paralleled. As might be expected, after about a year the hardware in the two programs began to differ markedly because of the difference in application. Nonetheless, the theory involved in systems of this type was more often identical than in conflict. This Laboratory [JPL] tended to specialize in constructing extremely small, highly efficient pseudonoise generators, in effecting extremely accurate radio-frequency synchronization, and in designing systems which were as simple as possible consistent with the advantages predicted by theory. A notable difference in the requirements of the system being developed at Lincoln (later called the Rake [NOMAC] system) and the system being developed at JPL (later called [the] Codorac system [for Coded Doppler Radar Command]) concerned the deciphering of intelligence sent on the radio link. In the Rake [NOMAC] system it was imperative that the enemy not decipher the message. In the Codorac system it made no difference whether the enemy could decipher the message, provided he could not take effective countermeasures against the [missile] guidance system. For this reason the Rake [NOMAC] system is called a secure communications system while Codorac is called a jam-resistant system. Another significant difference was that the Codorac system was required to measure velocity, range, and angle, and to transmit information in both directions.

(Excerpted from "An Annotated History of Codorac: 1953–1958," *JPL Report 20–120,* E. Rechtin, ed. [4 Aug. 1958], p. 1–2, DTIC #AD 301-248L.)

have collected enough of the actual received signal to include all of the information corresponding to the condition of the ideal received signal. For the digital signals that were each spread over essentially the same 10-kHz bandwidth in NOMAC, a delay line with 30 taps—spaced every 1/(10 kHz) = 100 μsec—was sufficient for the full characterization of the actual received signal. Feedback circuitry adjusted the amplitude and shifted the phase of each tap output so that the algebraic sum of all 30 of the weighted outputs was a good approximation of the ideal received signal.

Teletype communications at 60 wpm required making a MARK/SPACE decision every 22 msec. Such an interval allowed the averaging of several delay-lines' worth of received-signal information, thus enhancing the reliability of each decision. The channel's fading rate was slow enough so that the channel was essentially stable for periods of 0.3 to 3 sec. Thus the way in which the outputs from the delay-line taps were weighted before being added needed to be changed only very slowly in comparison with the MARK/SPACE decision rate.

The image of a delay line bristling with a row of taps reminded people of a garden rake with tines, hence the sobriquet "Rake" for the communications system. For convenience, the actual delay line, which was of crucial importance to the successful demonstration of the system, was built in the form of a helix (Figure 8). The technology was similar to that used in the receiver/exciter of the AN/FPS-17 coded-pulse radar system [35, 36]. Figure 9 shows the Rake receiver rack.

During the mid-1950s and early 1960s a number of reports and papers [37–39] put Rake firmly on the record, and the concept received a patent in 1961 [40]. (NOMAC itself was not widely known until the 1980s, after publication of several historical reviews of spread-spectrum research and development [6–8, 10]).

The brief description of the Rake system given in the preceding paragraphs does not do justice to the profundity of the concept. The configuration of the receiving system can be derived by using heuristic arguments. Deeper study shows that Rake approaches the bounds of achievable performance, meriting the label "optimum" in several respects.

Rake was tested over the same HF link from Davis, Calif., to Deal, N.J., that had been used to evaluate the effectiveness of NOMAC. The transmissions were essentially the same because Rake is a receiving-system concept. During the transcontinental tests, Rake performed well; it nearly achieved the full 23 dB of antijam margin promised by the ratio of the spread-signal bandwidth (10 kHz) to the reciprocal of the baud interval (22 msec). The Army Signal Corps promptly contracted the National Co. of Malden, Mass., to manufacture 12 Rake modification kits for the F9C-A NOMAC equipment that Sylvania was building. Lincoln Laboratory worked closely with the contractors to ensure that the Rake technology was transferred effectively. The production units of NOMAC/Rake equipment saw widespread service. Of particular importance was the availability of this spread-spectrum, antijam, anti-multipath communications system between Washington, D.C., and West Berlin during tense times in the early 1960s.

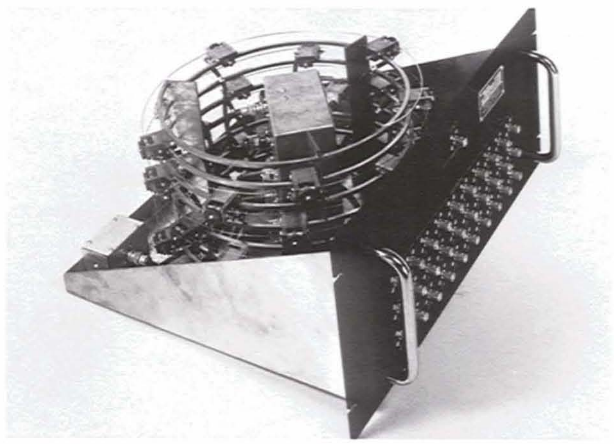

FIGURE 8. Helical ultrasonic delay line (1.5 msec) for the Rake receiver. The 1/32-inch-diameter Invar rod is driven piezoelectrically at 455 kHz in a longitudinal mode. The line has a 50-kHz bandwidth. Two of these lines in series feed 30 equally spaced tap circuits and can accommodate multipath-propagation time differences of up to 3 msec (see Figure 9).

Applications of the Rake Technology

With the passage of years and the advent of wideband communications links incorporating satellites and cables, the importance of Rake as a practical means for taming the often unruly HF medium has dimin-

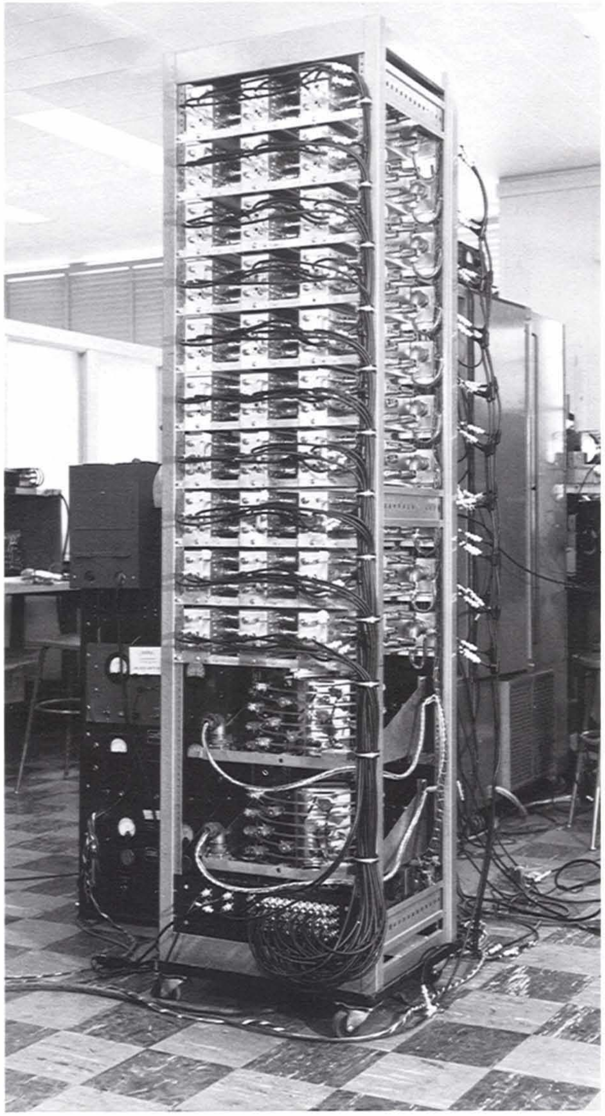

FIGURE 9. Rake receiver rack. The 30 modules filling the top of the rack are connected to the taps on the two delay lines (see Figure 8) at the bottom.

ished. Rake principles, however, continue to be found in the professional toolkits of systems analysts [41– 43]. It may not be an exaggeration to say that the combination of NOMAC and Rake was the first practical implementation of a channel-adaptive communications system. Rake also appears to be the earliest example of what later became the whole field of adaptive modems [44, 45]. (Note: Rake tries to maximize the signal-to-noise ratio. Adaptive modems try to minimize the intersymbol interference.)

The conception, practical realization, and successful field operation of the Rake system have led to fertile insights and knowledge, particularly in the field of spread-channel technology, that have proven useful in other applications. For example, sound waves radiated by a submerged submarine can reach a distant sonar hydrophone by several different propagation paths, perhaps after passing through ocean currents of different temperatures. The concepts that led to Rake found application in sorting out the resulting mixture of received signals [46].

As another example, the elastic waves that propagate through the earth from an earthquake or a subterranean nuclear explosion can reach a distant seismometer by several different propagation paths. In such cases, there is little or no frequency spread in the received signals because the propagation medium is essentially static. The application of Rake principles to the sorting of these seismic signals has extended geophysical knowledge and established a technique for monitoring compliance with nuclear-test-ban treaties [47].

Finally, these ways of thinking about doubly spread (in time and in frequency) communications channels have carried over into radar astronomy. For instance, the radar echo received on earth from the moon at any given instant is the sum of signals that have been reflected from many different portions of the lunar surface. Each component of the echo has a distinctive two-way Doppler frequency shift that is determined by the rotational velocities of the radar on the earth and the scatterer on the moon, as well as by the relative translational velocities of the two locations. Sorting this mixture of received signals has made possible the detailed mapping of the moon and nearby planets [48–53]. It is only a small conceptual step from the radar range/Doppler-shift mapping of the moon to the radar imaging of satellites orbiting the earth [54].

Professional Recognition

A glance at the historical reviews of the development of spread-spectrum technology [6–11] shows the tremendous importance that this field has assumed. In 1981 the Aerospace and Electronics Systems Society of the Institute of Electrical and Electronics Engineers (IEEE) presented its annual Pioneer Award to four individuals for their "pioneering contributions and leadership in the development of spread-spectrum-communication technology." Two of the recipients—Wilbur B. Davenport, Jr., and Paul E. Green, Jr.—were central to the success of the NOMAC project at Lincoln Laboratory. Their reminiscences on the occasion of the award [55] bear reading today.

In 1981 the Communications Society of the IEEE presented its Edwin Howard Armstrong Achievement Award to Robert Price "for innovative application of communication theory to adaptive receivers, radar astronomy, and magnetic recording" [56]. Much of that work was done at Lincoln Laboratory in connection with NOMAC and Rake.

It is worth noting that NOMAC went from Green's doctoral thesis through field tests to serial production of the F9C-A in less than three years. Such a pace of innovation is seldom achieved today.

Summary

We have seen that the NOMAC concept, when first reduced to practice, worked tolerably well. Its failure by 6 dB to achieve ideal antijamming performance during field tests was not a surprise. The cause—multipath-propagation effects—was understood well enough to allow the conception of Rake, which regained most of the missing 6 dB. The NOMAC/Rake equipment was produced in quantity and saw service until it was, like many other inventions, superseded by newer technologies, in this case, satellite and submarine-cable communications systems.

Lincoln Laboratory's work on NOMAC and Rake flourished because of the confluence of four distinct factors:

1. The information-theoretical work of C.E. Shannon [57] and the spectral-estimation work of N. Wiener [58] had filtered down to engineers with strong academic backgrounds who were primarily interested in applications. Old problems were seen in a new light. J.B. Wiesner's vivid description of the intellectual ferment at MIT's Research Laboratory of Electronics during those days recalls a veritable Golden Age [59].
2. The increasing availability of electronic components and know-how for digital circuitry had made it practicable to build devices that would otherwise have remained only concepts.
3. There were heightened military needs, and substantial resources were available to carry out full-scale development and the testing of promising ideas.
4. A comparatively small group of people (never numbering more than 15 to 20) who possessed diverse skills and talents and who interacted closely, continuously, and constructively under enlightened management performed the actual development work.

The success of the research proved that the heritage of the Radiation Laboratory [60–62] was still strong at MIT. When required by national defense, first-class scientific and technical talents could be mustered to address the needs.

Acknowledgments

The author could not have written this article without the cooperation of a number of people who, working at Lincoln Laboratory during its early years, conceived NOMAC and Rake and brought them into existence. The author is indebted to those people for their patience during his learning process. In addition, the Lincoln Laboratory library, and the archives section in particular, provided invaluable support.

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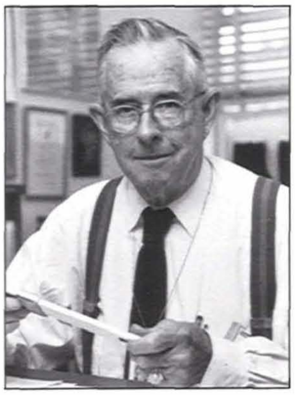

WILLIAM W. WARD
was born and raised in Texas. He attended Texas A&M College, served in the Army Signal Corps during World War II, and, at the end of the war, returned to Texas A&M, where he received a B.S. degree in electrical engineering in 1948. He then attended the California Institute of Technology and graduated with an M.S. degree in electrical engineering in 1949 and a Ph.D. degree in electrical engineering (minors in physics and mathematics) in 1952.

Bill came to MIT in 1952 and joined Lincoln Laboratory shortly after it was established. His first 13 years at Lincoln were devoted to radar-system engineering—airborne-early-warning and ground-based surveillance radars, space-tracking equipment, and range instrumentation for ballistic-missile testing and for NASA's Project Mercury. Since 1965, Bill's research has been devoted to space communications, primarily the development of satellite systems that serve the diverse needs of the military and civilian communities. He helped to design, build, test, and operate in orbit Lincoln Experimental Satellites 5 and 6 (LES-5 and LES-6), which were launched in 1967 and 1968, respectively. He also served as an associate project leader for LES-8 and LES-9, which were launched together in 1976. His particular area of responsibility with LES-8 and LES-9 was in the planning and execution of an extensive program of post-launch testing. Bill now serves as Manager of Satellite Operations in the Satellite Communications Technology Group, where he supervises the operation of LES-6, LES-8, and LES-9, and participates in advanced research and development in space communications.

Bill is a member of Tau Beta Pi, Sigma Xi, and the American Institute of Aeronautics and Astronautics (AIAA), and a life senior member of the IEEE. He has been an IEEE Regional Outstanding Lecturer and an AIAA Distinguished Lecturer. He is also a registered professional engineer in the Commonwealth of Massachusetts and a member of the Massachusetts and the National Societies of Professional Engineers.