L-Band Transmitter Using Kahn EER Technique

Frederick H. Raab, *Senior Member, IEEE,* Bernard E. Sigmon, *Senior Member, IEEE,*
Ronald G. Myers, and Robert M. Jackson

***Abstract*— This paper describes a 20-W peak-envelope power linear L-band transmitter based upon the Kahn envelope-elimination-and-restoration technique. A double envelope-feedback loop assures high linearity. The radio-frequency (RF) power amplifier employs a two-stage monolithic-microwave integrated-circuit driver amplifier and a 20-W power amplifier biased for class-AB operation. The class-S modulator includes a high-speed comparator and 1/2-μm heterojunction field-effect transistors in its output stage. A double envelope-feedback loop assures both high linearity and time-delay equalization for RF bandwidths to 150 kHz. With a two-tone signal, the transmitter achieves an efficiency of 56% at full power (41 dBm), and 35% at 18 dB into back-off. The third-order intermodulation distortions for a two-tone signal vary from −30 to −40 dBc over a 20-dB range of back-off. For quaternary phase-shift keying, the first and second adjacent-channel powers are −48 and −57 dBc.**

***Index Terms*—Amplifier, average efficiency, class-S amplifier, EER, Kahn technique, L-band, power, transmitter.**

I. Introduction

MODERN transmitters for applications such as cellular, personal, and satellite communications employ digital modulations such as quaternary phase-shift keying (QPSK) and offset QPSK (OQPSK), often in combination with code-division multiple-access (CDMA) communication. Shaping of the data pulses keeps energy out of adjacent channels, but produces a time-varying envelope. Transmitters for base stations and frequency-division-multiplexing (FDM) signals (including multitone modems) must also produce signals with time-varying envelopes. Power control is also generally required, both to minimize interference to other stations and to conserve battery power. Since the transmitters are portable and battery-operated, there is a need for a linear transmitter that maintains both high efficiency and good linearity over a wide dynamic range.

II. Average Efficiency

The probability density function (PDF) of the envelope gives the relative amount of time a signal spends at various amplitudes (Fig. 1). Continuous wave (CW), FM, and hard phase-shift keying (hard-PSK) (PSK with rectangular pulses) signals have constant envelopes and are, therefore, always at peak-envelope power (PEP). Shaped-pulse data modulations produce PDFs that are concentrated primarily in the upper half of the voltage range and have peak-to-average ratios on the order of 3–6 dB [1]. Noise and multiple carriers amplified simultaneously have a Rayleigh-distributed envelope [2] with a peak-to-average ratio (typically) from 6 to 13 dB.

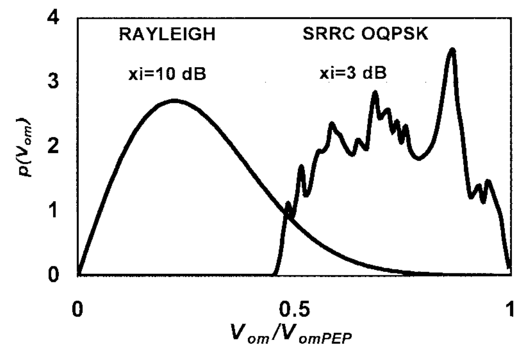


Fig. 1. Probability densities of signal envelopes.

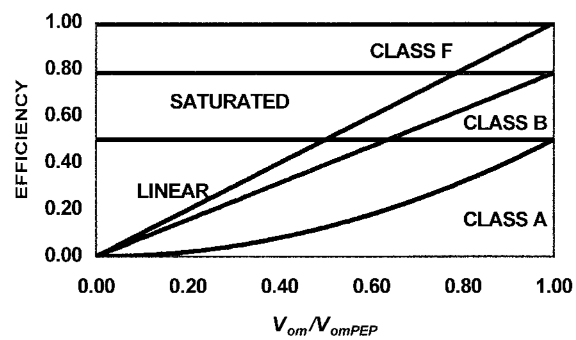


Fig. 2. Instantaneous efficiency of ideal power amplifiers.

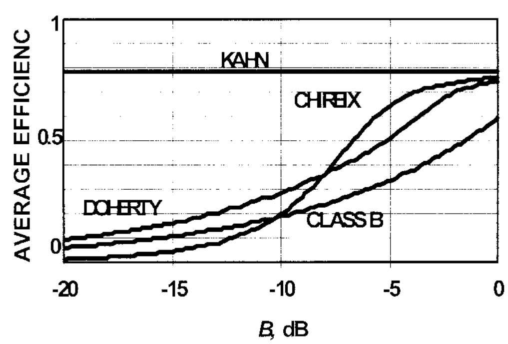


Fig. 3. Average efficiency of ideal PAs in back-off.

For linear amplification, the instantaneous efficiency of an ideal power amplifier (PA) increases with the output voltage (Fig. 2). The efficiency of a class-A PA reaches 50% at PEP, while that of class-B reaches 78.5% $(= \pi/4)$ [3]. The behavior

Manuscript received March 24, 1998; revised September 1, 1998.
F. H. Raab is with Green Mountain Radio Research, Colchester, VT 05446 USA.
B. E. Sigmon, R. G. Myers, and R. M. Jackson are with Motorola Satellite Communications, Scottsdale, AZ 85257 USA .
Publisher Item Identifier S 0018-9480(98)09217-5.

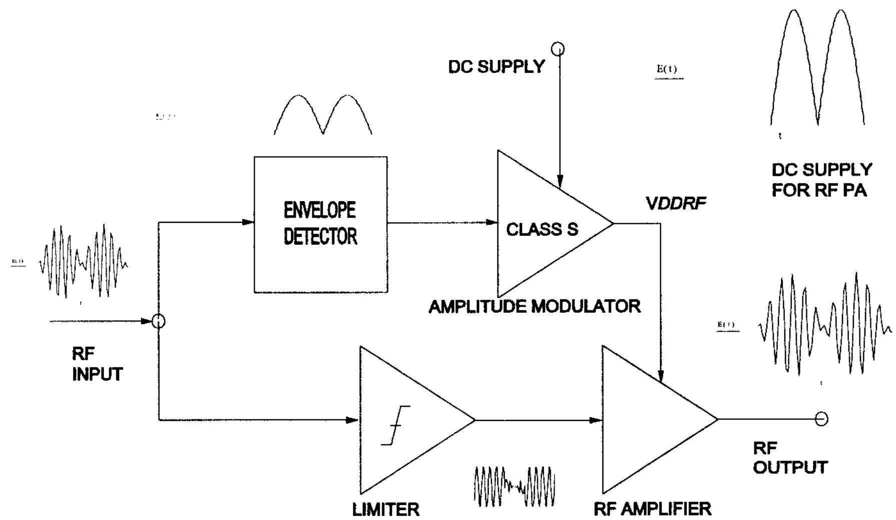


Fig. 4. Simplified Kahn-technique transmitter.

of class F is similar to that of class B, but the PEP efficiency depends upon the specific resonators used [4]. Efficiency is, of course, reduced from these values by on-state resistance, output reactance, losses in the output network, and the like.

If the PAs are operated in saturation and their output controlled by varying the supply voltage, the efficiency remains at the PEP value for all output voltages. This mode of operation is, however, generally suitable only for full-carrier amplitude modulation.

The average efficiency of a transmitter depends upon both the instantaneous efficiency of its PA and the PDF of the signal it is amplifying. It is obtained [3] by averaging the output and input powers and then computing

$$\eta_{\text{AVG}} = P_{o\text{AVG}}/P_{i\text{AVG}}. \quad (1)$$

The average efficiency of an ideal class-B PA is 59% and 28% for the OQPSK PDF (square-root raised-cosine (SRRC), $\alpha = 0.4$) and Rayleigh PDFs shown in Fig. 1.

If the PA is operated in back-off, the PDF in Fig. 1 is, in essence, shifted leftward and the average efficiency is reduced even more, as shown in Fig. 3. For an ideal class-B PA, the efficiency with the OQPSK signal is reduced to 19% at a 10-dB back-off and to 6% at a 20-dB back-off. Doherty [5] and Chireix-outphasing [6] transmitters offer improved average efficiency, but only over a limited range of back-off.

III. Kahn Technique

The Kahn envelope elimination and restoration (EER) technique combines a highly efficient, but nonlinear RF PA with a highly efficient envelope amplifier to implement a high-efficiency linear RF power amplifier. In its simplest form, a limiter (Fig. 4) eliminates the envelope, allowing the constant-amplitude phase-modulated carrier to be amplified efficiently by class-C, class-D, class-E, or class-F RF PAs. Amplitude modulation of the final RF PA restores the envelope to the phase-modulated carrier, creating an amplified replica of the input signal.

The basis for EER is the equivalence of any narrow-band signal to simultaneous amplitude (envelope) and phase

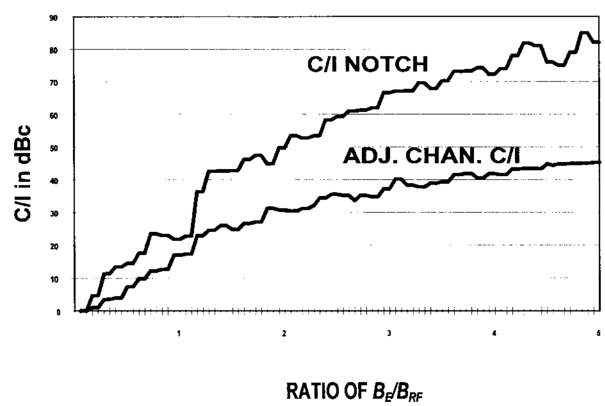


Fig. 5. Variation of NPR and intermodulation distortion (IMD) with envelope bandwidth.

modulations

$$v_{\text{RF}}(t) = E(t)\cos[\omega_c t + \phi(t)] \quad (2)$$
$$= I(t)\cos(\omega_c t) - Q(t)\sin(\omega_c t). \quad (3)$$

The envelope and phase are readily related to the familiar I and Q components (modulations of cosine and sine carriers) used in signal processing [7].

Leonard Kahn [8] developed EER in the 1950s as a means of improving the efficiency of short-wave broadcast transmitters. In contrast to linear amplifiers, a Kahn-technique transmitter operates with high efficiency over a wide dynamic range and, therefore, produces a high average efficiency for a wide range of signals and power (back-off) levels [3], [9]. Previous applications include short-wave broadcast [10], HF/VHF transmitters [7], [11], [12], VHF amateur-satellite repeaters [13], and cellular transmitters [14].

A. Requirements for Linearity

The linearity of an EER transmitter does not depend upon the linearity of its RF-power transistors, but upon the accuracy of reproduction of the input-signal's amplitude and phase information. The RF PA can be operated at full power and

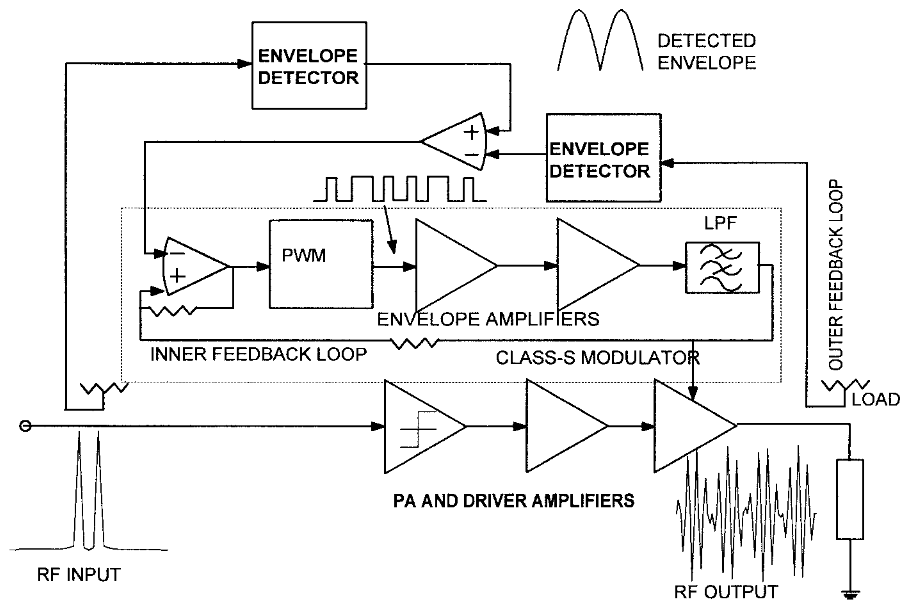


Fig. 6. Block diagram of L-band transmitter.

several decibels into compression and still achieve the specified intermediate modulation (IM) performance. In contrast, other types of PAs must be operated in back-off (with lower power and lower efficiency) in order to achieve the same IM levels.

In addition to the linearity of the class-S modulator and the amplitude-modulation linearity of the RF PA, the two principal factors that affect linearity are the bandwidth B_E of the class-S modulator and the differential delay between the envelope and phase modulation at the final amplifier [15]. Fig. 5 shows the variation with envelope bandwidth B_E of the worst-case noise–power ratio (NPR) and adjacent-channel IM levels for ten simulated signals (the signals are randomly phased tones and occupy nine of ten slots that are evenly spaced in frequency). To keep IM products below -30 dBc (30 dB below the tones), $B_E \geq 1.78\, B_{\mathrm{RF}}$, where B_{RF} is the bandwidth of the RF signal.

B. L-Band Implementation

The L-band transmitter (Fig. 6) ensures high linearity by adding two features to the classical Kahn technique: two envelope-feedback loops and matched envelope detectors. The two feedback loops ensure high linearity in both the class-S modulator and modulation of the RF PA. Matched envelope detectors operating at the same signal levels eliminate distortion caused by nonlinearities in the detectors.

IV. RF PA

The RF PA in a Kahn-technique transmitter is always saturated and, therefore, always operates at maximum efficiency. Hard limiting is performed in the driver amplifier and the drive level to the PA is adjusted to maintain its output 3 dB into saturation for all values of supply voltage V_{DD}.

The RF chain consists of a two-stage monolithic-microwave integrated-circuit (MMIC) driver (developed by Motorola for another application) and a Fujitsu 1415-20 final stage in a microstrip package. Other PA types can be successfully used, but the Fujitsu PA is most conveniently integrated with the driver amplifier and class-S modulator. The driver amplifier employs T.I. GaAs foundry 1/2-μm high field-effect transistors (HFETs) and the PA employs 1/2-μm-epi MESFETs.

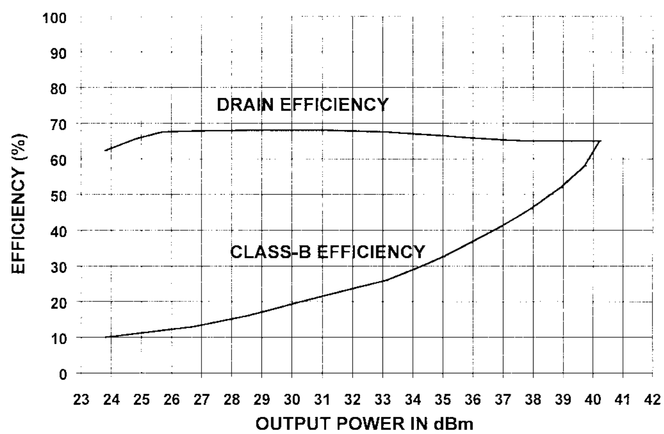


Fig. 7. Instantaneous CW efficiency of RF PA.

The overall linear gain of the transmitter is 37 dB, 12 dB of which is in the output stage. The final stage is biased to class-AB and class-B in order to achieve a flat gain response. Drain-bias voltages of 7 and 10 Vdc are used for the driver and PA, respectively.

The CW efficiency of the PA is 65% at PEP and remains above 60% over an 18-dB dynamic range (Fig. 7). In contrast, the efficiency of a conventional class-B PA with the same PEP efficiency drops to 10% at 18-dB back-off.

V. CLASS-S MODULATOR

A class-S modulator is a switching-mode envelope amplifier, which converts the dc-supply voltage into a time-varying supply voltage that amplitude modulates the RF PA [16].

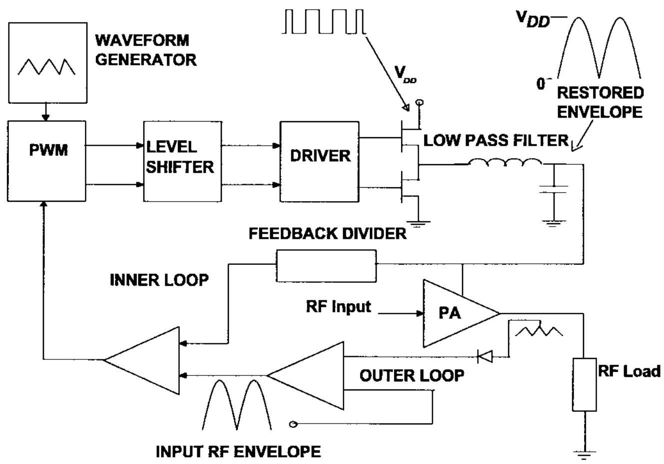


Fig. 8. Block diagram of class-S modulator.

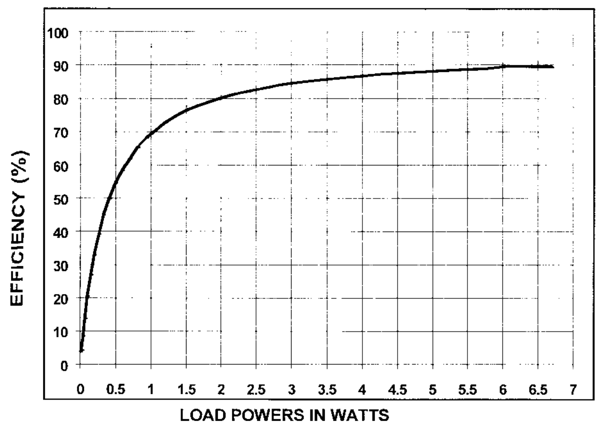


Fig. 9. Efficiency of class-S modulator.

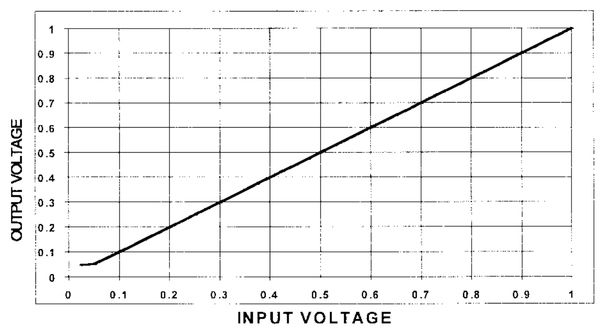


Fig. 10. Transfer function of class-S modulator.

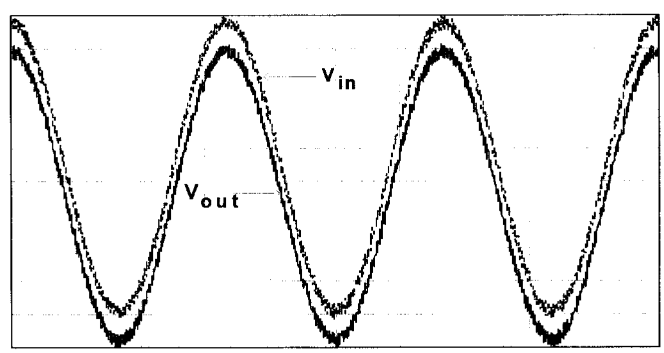


Fig. 11. Input and output of class-S modulator (150 kHz).

Variation of the output voltage is accomplished by varying the pulsewidth. Class-S modulators are ideally 100% efficient.

The closed-loop class-S modulator is similar to a buck-topology dc–dc switching power converter. The major difference is the class-S modulator operates with a variable reference signal (the RF envelope).

The group delay introduced by the low-pass filter at the output of the class-S modulator must be matched in the RF-PA (phase) arm of the Kahn transmitter if IMD products are to be kept to a minimum [15]. Insertion of a delay module in the RF arm [11] is not always practical. In this design, the delay compensation is achieved by using a two-loop feedback system (Fig. 8).

The RF output of the PA is detected and fed back to the outer-loop error amplifier (Fig. 8), which compares the detected signal to the RF-input envelope. The difference between these two signals is amplified to produce an error signal, which is fed to one input of the inner-loop error amplifier. The inner-loop error amplifier feeds its control signal to one input of a high-speed pulsewidth modulator (PWM).

A 3.3-MHz triangle wave drives the other input to the PWM. The resultant output of the PWM is a train of pulses whose width varies with the amplitude of the envelope of the RF input signal. The use of a triangular waveform produces symmetrical double-sided pulsewidth modulation.

The output of the PWM is level-shifted to drive a totem pole arrangement of 16-mm GaAs HFETs, which was designed by Motorola and fabricated by the T.I. GaAs foundry. Three devices are connected in parallel in the upper arm and three more in the lower arm to minimize the "on-state" resistance of the output stage. A two-pole low-pass filter removes the switching frequency and its harmonics to produce the high-level envelope signal.

The efficiency of the class-S modulator operating into a dummy load is 90% at PEP and better than 80% over a 10-dB back-off (Fig. 9). The transfer function of the modulator is virtually a straight line over a 26-dB dynamic range (Fig. 10). The frequency response is essentially flat from dc through 150 kHz. Fig. 11 shows that a 150-kHz sinusoid is reproduced both linearly and with correct timing (offset is added to facilitate visualization).

VI. Transmitter Performance

The average efficiency of the complete EER PA is shown in Fig. 12. The average power-added efficiency for production of a two-tone signal is 57% at PEP and drops to about 35% at 18 dB into back-off. In contrast, a class-B PA that is 65% efficient for CW at PEP is only about 6.5-percent efficient for a two-tone signal 18 dB into back-off.

For a two-tone signal with a 150-kHz RF bandwidth, the IMD levels vary between −30–−39 dBc over the 18-dB range of back-off (Fig. 12). Fig. 13 shows the output spectrum produced by a full-power (43-dBm peak) 50-kb/s QPSK signal with $\alpha = 0.4$ SRRC pulse shaping. The first and second adjacent-channel powers (ACPs) measured in 41.666-kHz bandwidths are −48.1 and −57.3 dBc, respectively.

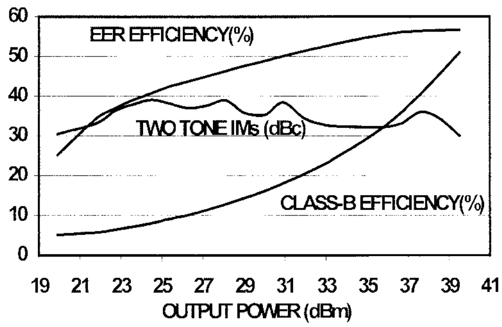


Fig. 12. Measured performance of transmitter.

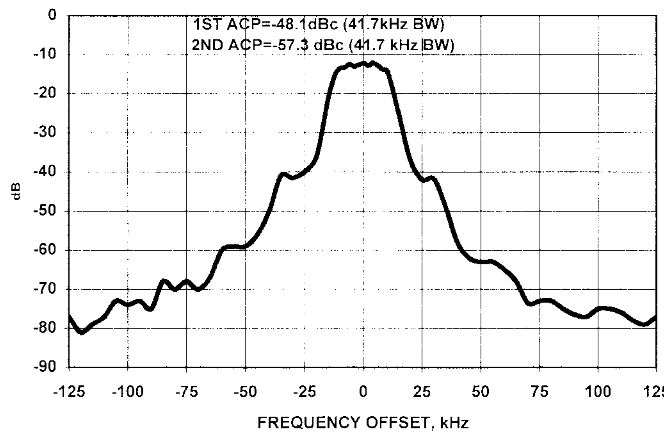


Fig. 13. Output spectrum of transmitter.

VII. Physical Dimensions

The breadboard EER PA consisted of the following three discrete functional stages:

1) MMIC driver amplifier with 25-dB gain;
2) packaged PA with 12-dB gain;
3) class-S modulator.

The class-S modulator is fabricated by wire-bonding chips and occupies a board area of 1.5 in $\times$ 1.5 in. Full integration and packaging of the design will yield a size of approximately 1.35 in $\times$ 1.0 in $\times$ 0.5 in. It appears possible to put all or most (depending upon power) of the signal-processing components into a single integrated circuit (IC) [17].

VIII. Conclusion

The Kahn EER technique dates back from the 1950s. This paper presents the application of today's technology to one of yesterday's techniques. Implementation of a Kahn EER transmitter improves both PA efficiency and linearity. The next step is to employ digital-signal-processing (DSP) technology to replace many of the analog functions presented in this paper.

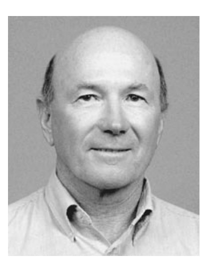
References

[1] L. Sundström and M. Johansson, "Effect of modulation scheme on LINC transmitter power efficiency," *Electron. Lett.*, vol. 30, no. 20, pp. 1643–1644, Sept. 1994.
[2] F. H. Raab, "Average efficiency of power amplifiers," in *Proc. RF Technology Expo. '86*, Anaheim, CA, Jan. 30–Feb. 1, 1986, pp. 374–486.
[3] H. L. Krauss, C. W. Bostian, and F. H. Raab, *Solid State Radio Engineering*. New York: Wiley, 1980.
[4] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2007–2012, Nov. 1997.
[5] F. H. Raab, "Efficiency of Doherty RF-power amplifier systems," *IEEE Trans. Broadcasting*, vol. BC-33, pp. 77–83, Sept. 1987.
[6] F. H. Raab, "Efficiency of outphasing power-amplifier systems," *IEEE Trans. Commun.*, vol. COM-33, pp. 1094–1099, Oct. 1985.
[7] F. H. Raab and D. J. Rupp, "High-efficiency single-sideband HF/VHF transmitter based upon envelope elimination and restoration," in *Proc. 6th Int. Conf. HF Radio Syst. and Tech.*, York, U.K., July 4–7, 1994, pp. 21–25.
[8] L. R. Kahn, "Single sideband transmission by envelope elimination and restoration," *Proc. IRE*, vol. 40, pp. 803–806, July 1952.
[9] J. F. Sevic, "Statistical characterization of RF power amplifier efficiency for wireless communication systems," in *Proc. Wireless Commun. Conf.*, Boulder, CO, Aug. 1997.
[10] B. Weaver, "A new, high efficiency, digital, modulation technique for AM or SSB sound broadcasting applications," in *Proc. Int. Symp. Broadcasting Technol.*, Zhuhai, China, 1991.
[11] F. H. Raab and D. J. Rupp, "High-efficiency single-sideband HF/VHF transmitter for communications and jamming," in *Proc. MILCOM '94*, Ft. Monmouth, NJ, Oct. 2–5, 1994, pp. 880–884.
[12] A. Bateman, P. Kennington, J. P. McGeehan, and M. Beach, "Multimode transceiver design," in *Proc. RF Expo West '94*, San Jose, CA, Mar. 22–24, 1994, pp. 327–331.
[13] K. Meinzer, "A linear transponder for amateur radio satellites," *VHF Commun.*, vol. 7, pp. 42–57, Jan. 1975.
[14] T. Sowlati, Y. Greshishchev, C. Angre, T. Salama, G. Rabjohn, and J. Sitch, "Linear transmitter design using high efficiency class-E power amplifier," in *Proc. Int. Symp. Personal, Indoor, and Mobile Radio Commun.*, Toronto, Canada, Sept. 1995, pp. 1233–1237.
[15] F. H. Raab, "Intermodulation distortion in Kahn-technique transmitters," *IEEE Trans. Microwave Theory Tech*, vol. 44, pp. 2273–2278, Dec. 1996.
[16] F. H. Raab and D. J. Rupp, "Class-S high-efficiency amplitude modulator," *RF Design*, vol. 17, no. 5, pp. 70–74, May 1994.
[17] D. Su and W. McFarland, "An IC for linearizing RF power amplifiers using envelope elimination and restoration," in *Proc. ISSCC'98*, San Francisco, CA, Feb. 5–7, 1998.

Frederick H. Raab (S'66–M'72–SM'80) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University (ISU), Ames, in 1968, 1970, and 1972, respectively.

He is Chief Engineer and Owner of Green Mountain Radio Research, Colchester, VT, a consulting firm which he founded in 1980. He co-authored *Solid State Radio Engineering*, authored or co-authored over 70 technical papers, and holds four patents. He is an extra-class amateur-radio operator W1FR, and has been licensed since 1961. His professional activities include RF power amplifiers, radio transmitters, and radio-communication/navigation systems.

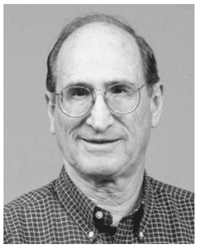
Dr. Raab is a member of HKN, Sigma Xi, AOC, AFCEA, and RCA. He was program chairman of RF Expo East '90, and is co-chairman of the IEEE MTT-S committee 17 on HF–VHF–UHF technology. He received ISU's Professional Achievement Citation in Engineering in 1995.



Bernard E. Sigmon (S'67–M'68–SM'91) received the B.S. and M.S degrees in electrical engineering from the University of South Florida, Tampa.

Since 1976, he has been with Motorola Satellite Communications, Scottsdale, AZ, where he is a Member of the Technical Staff in the Satellite Communications Group.

He is a member of the Motorola Honorary Technical Society SABA, and a Dan Noble Fellow, which is a Motorola honor.



Ronald G. Myers received the B.S. and M.S. degrees in electrical engineering from the University of Missouri at Columbia.

He is a Member of the Technical Staff at Motorola Satellite Communications, Scottsdale, AZ, where he is responsible for the development of high-efficiency power technology and products. Prior to joining Motorola, he held a number of engineering and management positions at Tecnetics, Monsanto, Emerson Electric, and Argonne National Laboratory.

Robert M. Jackson, photograph and biography not available at the time of publication.