GREEN MOUNTAIN
RADIO RESEARCH LLC

1183 Jonquil Lane, Boone, Iowa 50036 USA Telephone: +1 (515) 275-2141 Email: fraab@gmrr.biz

REPRINT

TP84-2

F. H. Raab, "Efficiency of outphasing power-amplifier systems," *IEEE Trans. Commun*., vol. COM-33, no. 10, pp. 1094 - 1099, Oct. 1985.

Efficiency of Outphasing RF Power-Amplifier Systems

FREDERICK H. RAAB, SENIOR MEMBER, IEEE

Abstract—The outphasing technique (LINC) combines two nonlinear RF power amplifiers into a linear RF power-amplifier (PA) system. The two PA's are driven with signals of different phases, and the phases are controlled so that the addition of the PA outputs produces a system output of the desired amplitude. However, the resultant time-varying impedances presented to the PA's alter their dc power consumption and efficiency. Power and efficiency characteristics are derived for both simple (transformer-coupler) and Chireix (transmission-line-coupler with shunt reactance) outphasing systems using saturated class-B PA's. Simple outphasing systems have the efficiency characteristic of a linear class-B PA. Through proper selection of the shunt reactance, the efficiency of a Chireix outphasing system can be maximized at a specific output amplitude. The average efficiency with various amplitude-modulated signals is determined as a function of shunt reactance. Selecting the shunt reactance to fit the signal can improve efficiency by as much as a factor of 2.

I. INTRODUCTION

OUTPHASING power-amplifier (PA) systems were first developed during the 1930's [1], [2] to improve both the efficiency and linearity of AM-broadcast transmitters. They were used commercially in the RCA "ampliphase" transmitters, and have recently been rediscovered for several applications ranging from high-efficiency low-frequency transmitters [3] to linear microwave transmitters [4]. Recent papers for VHF and microwave applications generally refer to "outphasing" as "LINC," an acronym for "linear amplification using nonlinear components."

Efficiency (the ratio of RF-output power to dc-input power) is an important parameter that enables comparison and selection of PA's, as well as determination of their requirements for supporting circuitry (batteries, power supplies, heat sinks, etc.). Outphasing causes the PA-load impedance (hence, efficiency for most PA's) to vary with the amplitude of the output signal. However, none of the recent papers addresses the impact of outphasing upon PA efficiency. The early papers [1], [2] give some attention to efficiency but use graphical techniques and deal only with unmodulated carriers.

The objective of this paper is to determine both the instantaneous (CW) and average (modulated) efficiency of both simple- and Chireix (transmission-line coupler) outphasing PA systems. The efficiency of the system is, of course, dependent upon the specific efficiency characteristics of the individual RF power amplifiers. However, the efficiency of most class-B and class-C PA's is approximately linearly proportional to signal amplitude. This paper therefore assumes the characteristics of ideal class-B power amplifiers. The results can be easily scaled to obtain approximate predictions of the performance with most other RF PA's.

Paper approved by the Editor for Computer Communication of the IEEE Communications Society. Manuscript received October 24, 1984; revised May 9, 1985.

The author is with Green Mountain Radio Research Company, Winooski, VT 05404.

II. PRINCIPLES OF OPERATION

A simple outphasing PA system is shown in Fig. 1. For simplicity, the input signal is an amplitude-modulated cosine carrier. The control/drive circuits generate two sinewave signals with phases of $+\phi_m$ and $-\phi_m$, as shown in Fig. 2. These two signals are then amplified and added to produce the system-output signal. The peak output is obtained with $\phi_m = \pi/2 = 90°$, which causes the two PA outputs to add in phase. Zero output is obtained with $\phi_m = 0$, which causes the two PA outputs to cancel each other. Intermediate values of ϕ_m produce intermediate values of the amplitude (envelope) of the output signal.

By inspection of Fig. 2, the outputs of the two power amplifiers can be written in phasor form as

$$V_1 = (V_{om\text{PEP}}/2)(\sin\phi_m - j\cos\phi_m) \tag{1}$$

and

$$V_2 = (V_{om\text{PEP}}/2)(-\sin\phi_m - j\cos\phi_m) \tag{2}$$

where $V_{om\text{PEP}}$ represents the amplitude of the output cosinewave at peak envelope power. The transformer coupler differences these two signals to produce the output

$$V_o = V_1 - V_2 = V_{om\text{PEP}} \sin\phi_m. \tag{3}$$

It is therefore necessary that

$$\phi_m = \arcsin(V_o/V_{om\text{PEP}}); \tag{4}$$

i.e., the phase deviation ϕ_m must be the inverse sine of the normalized signal envelope.

The inverse-sine phase modulation required for an outphasing PA system can be produced by several techniques, including nonlinear modulation [5], phaselock/feedback [6]–[8], and processing of the I and Q components of the input [9]. To amplify signals with phase modulation, the control circuit ("component separator") must generate two sinewaves with phase deviation $\pm\phi_m$ from the instantaneous phase of the input signal.

III. INSTANTANEOUS EFFICIENCY OF SIMPLE-OUTPHASING SYSTEM

The simple outphasing PA system of Fig. 1 can use any power amplifier that acts as a voltage source. Suitable PA's therefore include highly efficient class-D (switching-mode) amplifiers [10, ch. 14] as well as class-A, B, and C amplifiers driven into saturation [10, ch. 13]. Power amplifiers that do not behave as perfect voltage sources can also be used if envelope feedback [10, ch. 16] is added.

Outphasing produces time-varying load impedances at the outputs of the individual power amplifiers. Since the effect of impedance variation depends upon the type of PA, the efficiency characteristics of an outphasing system also depend upon the type of PA. Calculation of a specific efficiency characteristic naturally requires knowledge of the characteristics of the specific PA's used. However, some general observations can be made.

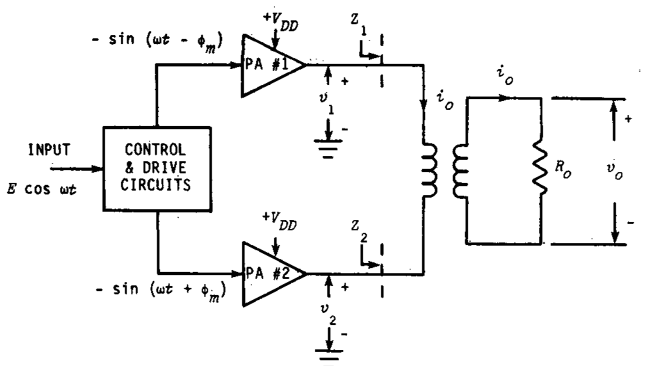

Fig. 1. Simple outphasing system.

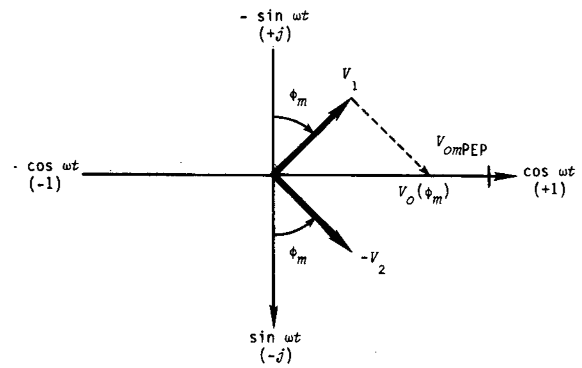

Fig. 2. Phase relationships.

Class-A PA's

Class-A PA's have constant dc input current and, hence, constant dc power consumption as well. The efficiency of an outphasing system with class-A PA's is therefore the same as that of a linear class-A PA.

Class-D PA's

The dc input current of a voltage-switching class-D PA varies with the output power if saturation and switching losses are neglected. Therefore, to a first approximation, an outphasing system employing class-D PA's achieves the high, nearly constant efficiency possible with those PA's. A VLF transmitter that employs outphasing and class-D PA's is described in [3].

Saturating Class-B and Class-C PA's

In class-B PA's, the dc input current varies linearly with the RF-output current. For class-C PA's, the variation of input current with RF-output current is approximately linear in many cases. This characteristic can therefore be used to obtain an efficiency characteristic that is at least approximately applicable to a large number of power amplifiers used in the VHF to microwave bands.

The system RF output current and, hence, the RF output currents of the PA's are

$$I_{1m} = I_{2m} = I_{om} = V_{om}/R_o. \tag{5}$$

The dc current consumed by an ideal class-B PA is directly proportional to its RF output current; hence, from [10],

$$I_{dc_1} = I_{1m}/\pi = I_{om}/\pi = \frac{V_{om}}{\pi R_o}. \tag{6}$$

The dc input power is therefore

$$P_i = V_{DD} \cdot 2I_{dc_1} = \frac{2}{\pi} \frac{V_{DD} V_{om}}{R_o}. \tag{7}$$

Since

$$P_o = V_{om}^2/(2R_o) \tag{8}$$

the instantaneous efficiency of an outphasing system with class-B PA's is

$$\eta = \frac{P_o}{P_i} = \frac{\pi}{4} \frac{V_{om}}{V_{DD}}. \tag{9}$$

While the individual PA's are driven into saturation, the system-efficiency characteristic is the same as that of a linear class-B PA.

IV. Instantaneous Efficiency of Chireix-Outphasing System

Simple outphasing is quite satisfactory for class-D PA's whose efficiency remains high regardless of the load impedance. For saturating class-B and class-C PA's, the efficiency at lower output voltages can be considerably improved by the Chireix system (Fig. 3), which adds transmission-line couplers and shunt reactances. The operation of this system is most readily analyzed by starting at the load and working toward the PA's.

Impedances

The peak RF-output current is related to the peak RF-output voltage by

$$I_{om\text{PEP}} = V_{om\text{PEP}}/R_o. \tag{10}$$

By analogy to (1) and (2), the current phasors I_5 and I_6 must be

$$I_5 = \frac{V_{om\text{PEP}}}{2R_o} (\sin \phi_m - j \cos \phi_m) \tag{11}$$

and

$$I_6 = \frac{V_{om\text{PEP}}}{2R_o} (\sin \phi_m + j \cos \phi_m). \tag{12}$$

The corresponding impedances are therefore

$$Z_5 = \frac{V_{om}}{I_5} = \frac{2R_o V_{om}}{V_{om\text{PEP}}} \cdot \frac{1}{\sin \phi_m - j \cos \phi_m} \tag{13}$$

$$= 2R_0(V_{om}/V_{om\text{PEP}})(\sin \phi_m + j \cos \phi_m) \tag{14}$$

and

$$Z_6 = 2R_o(V_{om}/V_{om\text{PEP}})(\sin \phi_m - j \cos \phi_m). \tag{15}$$

The transmission-line coupler transforms impedance according to

$$Z_3 Z_5 = R_L^2 \tag{16}$$

and hence, the admittance Y_3 is

$$Y_3 = \frac{Z_5}{R_L^2} = \frac{2R_o}{R_L^2} \frac{V_{om}}{V_{om\text{PEP}}} (\sin \phi_m + j \cos \phi_m). \tag{17}$$

Similarly,

$$Y_4 = \frac{Z_6}{R_L^2} = \frac{2R_o}{R_L^2} \frac{V_{om}}{V_{om\text{PEP}}} (\sin \phi_m - j \cos \phi_m). \tag{18}$$

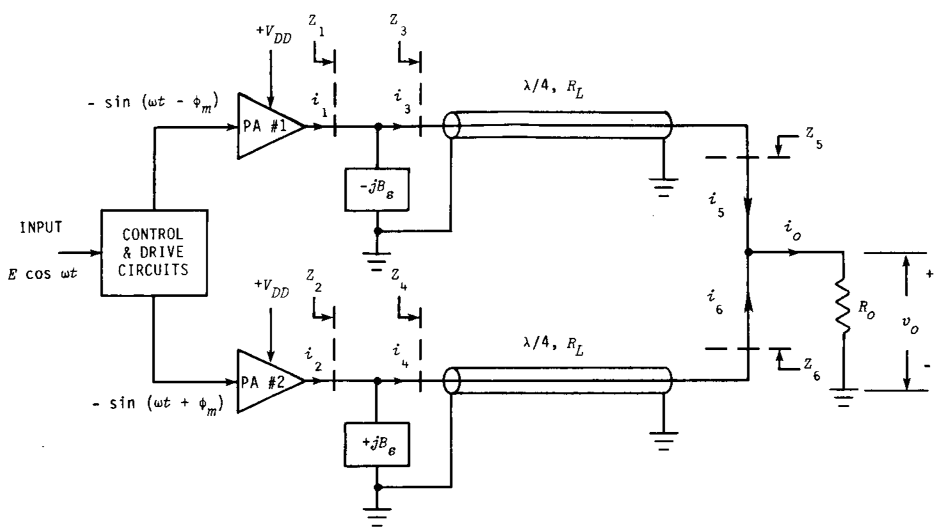

Fig. 3. Chireix-outphasing system.

Fig. 4 shows the magnitude, real, and imaginary parts of the admittance as functions of the normalized output voltage.

The magnitudes of the PA load impedances Z_1 and Z_2 increase to infinity as the system output decreases to zero. However, it is apparent that the PA's are subject to highly reactive loads for most output amplitudes. The effect of the reactive loads can be somewhat mitigated by the addition of shunt susceptances $-B_s$ and $+B_s$, as shown in Fig. 3. The resultant PA-load admittances are

$$Y_1 = Y_3 - jB_s = G_1 + jB_1 \tag{19}$$

and

$$Y_2 = Y_3 + jB_s = G_1 - jB_1. \tag{20}$$

The conductance and susceptance in (19) and (20) are

$$G_1 = \frac{2R_o}{R_L{}^2} \frac{V_{om}}{V_{om\text{PEP}}} \sin \phi_m = \frac{2R_o}{R_L{}^2} \left(\frac{V_{om}}{V_{om\text{PEP}}} \right)^2 \tag{21}$$

and

$$B_1 = \frac{2R_o}{R_L} \left(\frac{V_{om}}{V_{om\text{PEP}}} \cos \phi_m - B_s' \right) \tag{22}$$

$$= \frac{2R_o}{R_L} \left\{ \frac{V_{om}}{V_{om\text{PEP}}} \left[1 - \left(\frac{V_{om}}{V_{om\text{PEP}}} \right)^2 \right]^{1/2} - B_s' \right\} \tag{23}$$

where the normalized shunt susceptance is

$$B_s' = \frac{R_L}{2R_o} B_s. \tag{24}$$

Note that the reactance (susceptance) can be zeroed at one specific output amplitude by setting

$$B_s' = \frac{V_{om}}{V_{om\text{PEP}}} \left[1 - \left(\frac{V_{om}}{V_{om\text{PEP}}} \right)^2 \right]^{1/2}. \tag{25}$$

Output Power

The voltage transformation T produced by the transmission-line coupler is defined by

$$Z_3 = T^2 Z_5. \tag{26}$$

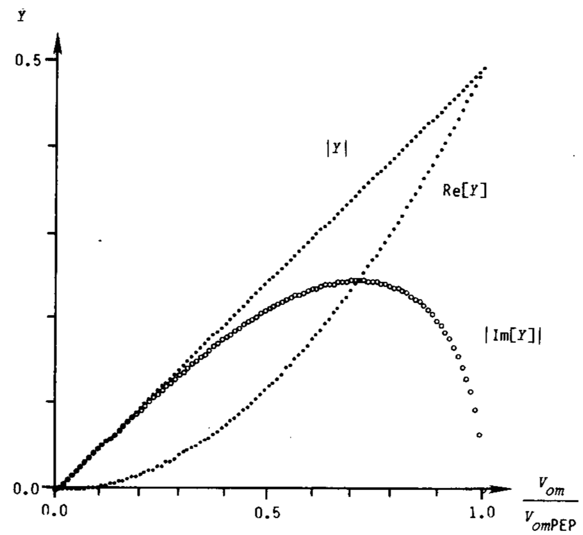

Fig. 4. Drain admittance of Chireix-outphasing PA with $B_s = 0$. Normalization: $R_0 = 1$, $R_L = 2$.

From (16),

$$T = R_L / Z_5. \tag{27}$$

The voltage required at the output of PA number 1 is therefore

$$V_1 = TV_{om} = \frac{R_L}{2R_o} V_{om\text{PEP}} (\sin \phi_m - j \cos \phi_m). \tag{28}$$

For saturated class-B or class-C PA's, the maximum output voltage is supply voltage V_{DD}; hence

$$V_1 = V_{DD} \sin \phi_m - j \cos \phi_m) \tag{29}$$

and by analogy

$$V_2 = V_{DD} (\sin \phi_m + j \cos \phi_m). \tag{30}$$

Note that the required phase relationship is the same as that for simple outphasing (Fig. 2).

From comparison of (28) and (29), the peak-output voltage is

$$V_{om\text{PEP}} = \frac{2R_o}{R_L} V_{DD} \tag{31}$$

and hence, the peak-output power is

$$P_{o\mathrm{PEP}} = \frac{V_{DD}^2}{2R_o(R_L/2R_o)^2}. \tag{32}$$

Note the impedance-inverting effect of the transmission-line transformer; increasing load impedance *increases* output power.

The phasor magnitude I_3 of the current that flows into the upper transmission-line coupler is

$$I_3 = V_1 Y_3 = I_5/T = \frac{2R_o}{R_L} \frac{V_{om} V_{DD}}{V_{om\mathrm{PEP}}} = \frac{V_{om}}{R_L} \tag{33}$$

and hence, the power output from PA number 1 is

$$P_1 = \frac{1}{2} \operatorname{Re}[V_1 I_3] = \frac{1}{2}\left(V_{DD} \frac{V_{om}}{V_{om\mathrm{PEP}}}\right)\left(\frac{V_{om}}{R_L}\right) = \frac{V_{om}^2}{4R_o} = \frac{1}{2} P_o. \tag{34}$$

Therefore, both power amplifiers contribute equal output power at all output amplitudes.

Instantaneous Efficiency

The RF output current from PA number 1 is

$$I_1 = V_1 Y_1. \tag{35}$$

For an ideal class-B PA, the dc input current is

$$I_{\mathrm{dc}_1} = \frac{2}{\pi} |I_1| = \frac{2}{\pi} V_{DD} |Y_1| \tag{36}$$

and hence, the *system* dc-input power is

$$P_i = 2V_{DD} I_{\mathrm{dc}_1} = \frac{4}{\pi} V_{DD}^2 |Y_1|. \tag{37}$$

The resultant efficiency and dc-power-input curves are shown in Fig. 5 for $B_s' = 0$, 0.1, and 0.2.

The case of $B_s = 0$ is of special interest. From (17)

$$|Y_1| = \frac{2R_o}{R_L^2} \frac{V_{om}}{V_{om\mathrm{PEP}}}. \tag{38}$$

Substitution of this and (31) into (37) produces

$$P_i = \frac{4}{\pi} \frac{V_{om\mathrm{PEP}} V_{om}}{2R_o}. \tag{39}$$

The resultant efficiency is

$$\eta = \frac{\pi}{4} \frac{V_{om}}{V_{om\mathrm{PEP}}} \tag{40}$$

which is the same as that of an ideal class-B PA.

Another case of special interest occurs when the combination of output amplitude and shunt susceptance B_s produces a purely resistive load at the PA's. For this condition,

$$|Y_1| = |G_1| = \frac{2R_o}{R_L^2}\left(\frac{V_{om}}{V_{om\mathrm{PEP}}}\right)^2. \tag{41}$$

Hence,

$$P_i = \frac{4}{\pi} \frac{V_{om}^2}{2R_o} \tag{42}$$

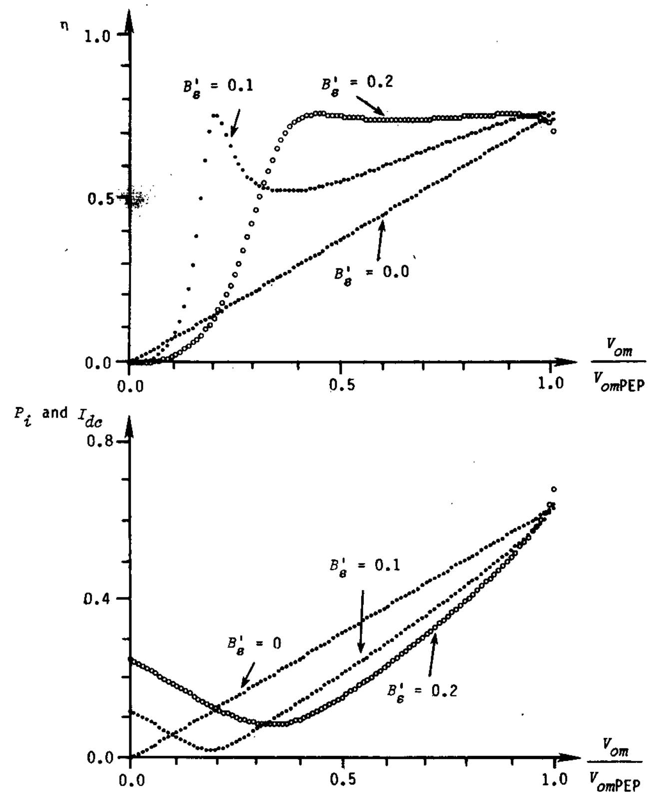

Fig. 5. Instantaneous efficiency and input power of Chireix-outphasing PA.

and

$$\eta = \frac{\pi}{4}.$$

It is therefore possible to select B_s to cause the system to achieve maximum efficiency at any single amplitude output.

V. Average Efficiency

From Fig. 5, it is apparent that the selection of a particular value of B_s increases the efficiency at some output voltages but decreases it at others. Calculation of the average efficiency is therefore necessary to determine and to optimize the performance of a Chireix-outphasing system used with amplitude-modulated signals. The average efficiency is the ratio of the average RF-output power to the average dc-input power, and is computed as described in the Appendix and [11].

The average efficiencies for two-tone, single-tone AM, uniform, and infinitely packed QAM signals are shown in Fig. 6 as functions of shunt susceptance B_s'; the maximum average efficiencies and corresponding values of B_s' are shown in Table I. The two-tone and single-tone AM signal are the familiar deterministic signals used to test power amplifiers. The uniform-amplitude-distribution signal represents the limiting case of amplitude-companded voice signals. The infinitely packed QAM signal is similarly the limiting case for QAM signals. In all four cases, a small improvement over class B (Table I) is achieved and the value of B_s' is not especially critical.

Rayleigh-distributed envelopes are encountered when amplifying band-limited Gaussian noise or a large number of independent carriers. Laplacian (or exponentially) distributed envelopes are produced by single-sideband suppressed-carrier (SSB/SC) modulation by voice signals. The average efficiencies for truncated-Rayleigh-envelope signals and truncated-Laplacian-envelope of various peak-to-average ra-

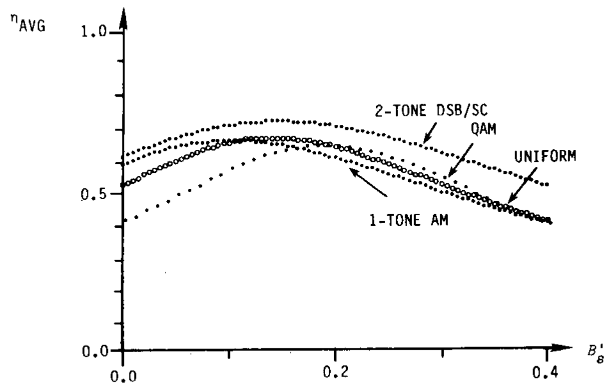

Fig. 6. Average efficiency, selected signals.

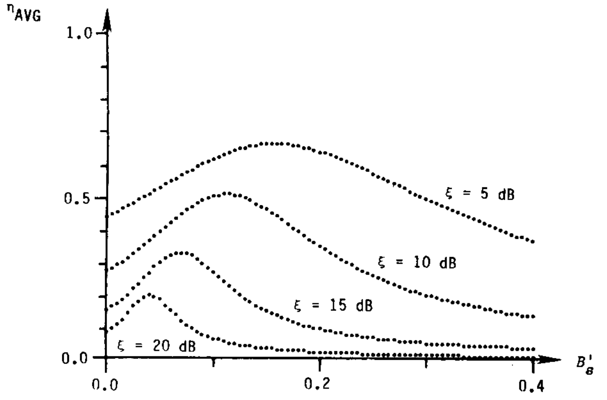

Fig. 7. Average efficiency, Rayleigh envelope.

TABLE I
MAXIMUM AVERAGE EFFICIENCY AND CORRESPONDING SHUNT

SIGNAL	ξ, dB	η_{AVG} class B	max η_{AVG} Chireix	B_s'
Two-tone SSB/SC	3.0	0.614	0.724	0.145
Single-tone AM	4.3	0.587	0.662	0.101
Uniform	4.8	0.524	0.672	0.139
Infinitely packed QAM	4.8	0.484	0.721	0.185
Rayleigh	5.0	0.455	0.684	0.157
Rayleigh	6.0	0.423	0.661	0.149
Rayleigh	7.0	0.387	0.632	0.140
Rayleigh	8.0	0.350	0.598	0.131
Rayleigh	9.0	0.314	0.560	0.121
Rayleigh	10.0	0.280	0.521	0.111
Rayleigh	11.0	0.250	0.482	0.102
Rayleigh	12.0	0.223	0.444	0.093
Rayleigh	13.0	0.198	0.407	0.084
Rayleigh	14.0	0.177	0.372	0.076
Rayleigh	15.0	0.158	0.338	0.069
Rayleigh	16.0	0.140	0.307	0.062
Rayleigh	17.0	0.125	0.278	0.056
Rayleigh	18.0	0.112	0.251	0.050
Rayleigh	19.0	0.099	0.226	0.045
Rayleigh	20.0	0.089	0.203	0.040
Laplacian	5.0	0.401	0.535	0.090
Laplacian	6.0	0.386	0.516	0.085
Laplacian	7.0	0.369	0.496	0.080
Laplacian	8.0	0.350	0.473	0.075
Laplacian	9.0	0.330	0.448	0.070
Laplacian	10.0	0.308	0.421	0.065
Laplacian	11.0	0.286	0.393	0.060
Laplacian	12.0	0.263	0.363	0.055
Laplacian	13.0	0.240	0.333	0.050
Laplacian	14.0	0.217	0.303	0.045
Laplacian	15.0	0.195	0.274	0.040
Laplacian	16.0	0.175	0.247	0.035
Laplacian	17.0	0.157	0.222	0.035
Laplacian	18.0	0.140	0.199	0.030
Laplacian	19.0	0.125	0.177	0.025
Laplacian	20.0	0.111	0.159	0.025
Gaussian AM	5.0	0.478	0.692	0.165
Gaussian AM	10.0	0.431	0.731	0.189
Gaussian AM	15.0	0.405	0.767	0.205
Gaussian AM	20.0	0.397	0.780	0.213
Laplacian AM	5.0	0.455	0.706	0.180
Laplacian AM	10.0	0.425	0.736	0.195
Laplacian AM	15.0	0.405	0.765	0.205
Laplacian AM	20.0	0.397	0.779	0.215

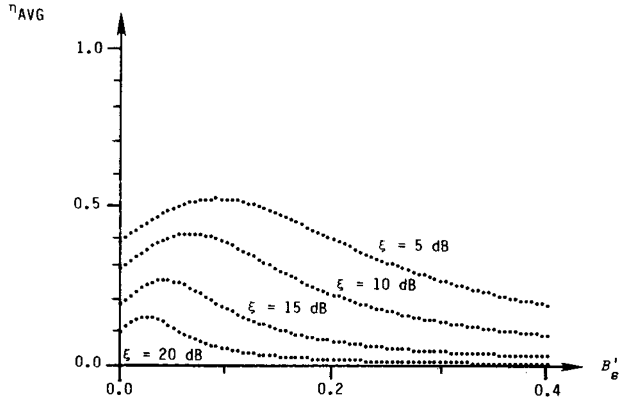

Fig. 8. Average efficiency, Laplacian envelope.

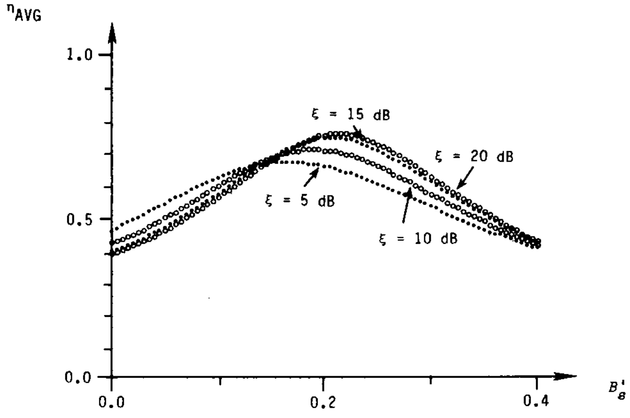

Fig. 9. Average efficiency, Gaussian AM.

tios (ξ) are shown in Figs. 7 and 8, respectively. Considerable improvement over class-B amplification is possible, but the selection of an appropriate value of B_s' is somewhat more critical (Table I).

Fig. 9 depicts the effect of B_s' upon the average efficiency with full-carrier AM signals with truncated Gaussian modulation of various peak-to-average ratios. Some improvement over class B is achieved and the value of B_s' is not critical. The curves for full-carrier AM with Laplacian modulation are similar.

VI. CONCLUSIONS

The power and efficiency characteristics of outphasing RF power-amplifier systems have been derived for ideal class-B RF PA modules. The results can be scaled to predict the efficiency for most real class-B and class-C PA's.

The efficiency characteristic of a simple outphasing system has been shown to be that of a linear class-B PA. Thus, while simple outphasing allows the implementation of a linear PA system from nonlinear PA modules, it does not improve efficiency.

The efficiency of a Chireix outphasing system can be maximized at a specific output-signal amplitude by proper selection of the shunt reactance. The average efficiencies for various amplitude-modulated signals were determined as functions of the shunt reactance. Improvements in efficiency by up to a factor of 2 over that of an ideal class-B PA were shown to be possible by selecting the shunt reactance to match the signal.

Naturally, factors other than efficiency must also be considered in the selection of a power-amplifier system. Three additional factors for outphasing systems are the complexity of the phase-modulation (component separation) circuits, the complexity of the coupler, and the sensitivity of the RF PA modules to the wide range of load impedances.

APPENDIX

COMPUTATION OF AVERAGE EFFICIENCY

The peak envelope power is

$$P_{o\mathrm{PEP}} = V_{om\mathrm{PEP}}^2/2R_o. \tag{A.1}$$

The average output power is

$$P_{o\mathrm{AVG}} = P_{o\mathrm{PEP}} \int_0^1 V^2 p(V)\, dV \tag{A.2}$$

where

$$V = V_{om}/V_{om\mathrm{PEP}} \tag{A.3}$$

and $p(V)$ is the envelope probability-density function. For an ideal class-B PA, the average dc-input power is

$$P_{i\mathrm{AVG}} = (4/\pi) P_{o\mathrm{PEP}} \int_0^1 V p(V)\, dV. \tag{A.4}$$

The envelope probability-density functions used in this paper are listed below for the interval $0 \le V < 1$. Outside that interval, $p(V) = 0$. The tails of the Rayleigh, Laplacian, and Gaussian densities that extend outside the interval of integration can be ignored with negligible error for the peak-to-average ratios of interest.

Two-tone SSB/SC:

$$p(V) = (2/\pi)(1 - V^2)^{-1/2}. \tag{A.5}$$

Single-tone AM:

$$p(V) = (2/\pi)[1 - (2V - 1)^2]^{-1/2}. \tag{A.6}$$

Uniform:

$$p(V) = 1. \tag{A.7}$$

Infinitely packed QAM:

$$p(V) = \begin{cases} \pi V, & 0 \leqslant V \leqslant 1/2 \\ \pi V - 4V \arctan\, 2V^2 - 1, & 1/2 < V < 1 \end{cases}. \tag{A.8}$$

Rayleigh:

$$p(V) = 2V\xi \exp\,(-V^2\xi) \tag{A.9}$$

with peak-to-average ratio

$$\xi = P_{o\mathrm{PEP}}/P_{o\mathrm{AVG}}. \tag{A.10}$$

Laplacian:

$$p(V) = (2\xi)^{1/2} \exp\,[-(2\xi)^{1/2} V] \tag{A.11}$$

with peak-to-average ratio given by (A.10).

Gaussian-AM:

$$p(V) = (2\xi/\pi)^{1/2} \exp\,[-2\xi(V - 1/2)^2] \tag{A.12}$$

with modulation peak-to-average ratio

$$\xi = P_{m\mathrm{PEP}}/P_{m\mathrm{AVG}}. \tag{A.13}$$

Laplacian AM:

$$p(V) = (2\xi)^{1/2} \exp\,[-2(2\xi)^{1/2}(V - 1/2)] \tag{A.14}$$

with modulation peak-to-average ratio given by (A.13).

REFERENCES

[1] H. Chireix, "High power outphasing modulation," *Proc. IRE,* vol. 23, pp. 1370–1392, Nov. 1935.

[2] L. F. Gaudernack, "A phase-opposition system of amplitude modulation," *Proc. IRE,* vol. 26, pp. 983–1008, Aug. 1938.

[3] R. Hammond and J. Henry, "High power vector summation switching power amplifier development," in *Proc. IEEE Power Electron. Specialists Conf. (PESC),* Boulder, CO, June 1981, pp. 267–272.

[4] D. C. Cox, "Linear amplification with nonlinear components," *IEEE Trans. Commun.,* vol. COM-22, pp. 1942–1945, Dec. 1974.

[5] D. Zur Heiden, "Principle of a phase-constant low-distortion amplitude modulation system for transistorized transmitters," *Nachrichtentech Z.,* vol. 12, pp. 608–612, 1970.

[6] D. C. Cox and R. P. Leck, "Component signal separation and recombination for linear amplification using nonlinear components," *IEEE Trans. Commun.,* vol. COM-23, pp. 1281–1287, Nov. 1975.

[7] ——, "A VHF implementation of a LINC amplifier," *IEEE Trans. Commun.,* vol. COM-24, pp. 1018–1022, Sept. 1976.

[8] A. J. Rustako, Jr. and Y. S. Yeh, "A wide-band phase-feedback inverse-sine phase modulator with application toward a LINC amplifier," *IEEE Trans. Commun.,* vol. COM-24, pp. 1139–1143, Oct. 1976.

[9] L. Couch and J. L. Walker, "A VHF LINC amplifier," in *Proc. IEEE SOUTHEASTCON '82,* Destin, FL, Apr. 4–7, 1982, pp. 122–125.

[10] H. L. Krauss, C. W. Bostian, and F. H. Raab, *Solid State Radio Engineering.* New York: Wiley, 1980.

[11] F. H. Raab, "The average efficiency of power amplifiers," to be presented at RF Technol. Expo '86, Anaheim, CA, Jan. 1986.

★

Frederick H. Raab (S'66–M'72–SM'80) was born in Fort Crook, NE, on February 4, 1946. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University, Ames, in 1968, 1970, and 1972, respectively.

Since founding Green Mountain Radio Research, Winooski, VT, in 1980, he has been involved in RF power-amplifier design and simulation, target transfer using GPS and JTIDS, adaptive noise cancellation, proximity warning, VLF propagation prediction, spacecraft rendezvous/docking systems, and in-plant training seminars. From 1975 to 1980, he was with Polhemus Navigation Sciences, Inc. and was involved with terrestrial use of Loran-C, trapped-miner location systems, and special-purpose position-finding systems. From 1971 to 1975 he was with Cincinnati Electronics and was involved in using OMEGA and GPS for search and rescue and transmitter design. He is coauthor of *Solid State Radio Engineering* (New York: Wiley, 1980), has authored or coauthored over 30 technical papers, and holds four patents.

Dr. Raab is a member of the Institute of Navigation, the International Omega Association, the Wild Goose Association, the Canadian Aeronautics and Space Institute, Eta Kappa Nu, and Sigma Xi.