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EFFICIENCY OF DOHERTY RF POWER-AMPLIFIER SYSTEMS

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Abstract

A Doherty system combines the outputs of two or more linear RF power amplifiers (PAs) through an impedance-inverting coupler such as a quarter-wave transmission line. At low output levels, the first PA operates linearly, reaching saturation (and maximum efficiency) at some transition voltage below the system peak-output voltage. At higher output levels, the first PA remains saturated and the second PA operates linearly. The instantaneous efficiency and power characteristics of a Doherty system are derived using ideal class-B RF PAs so that the results can easily be scaled for use with real-world PAs. The average efficiency and maximum-efficiency transition points are then determined for a variety of amplitude-modulated signals. The Doherty amplifier can be considerably more efficient than a conventional class-B linear PA. For example, the 28- and 8.9-percent average efficiencies of a class-B PA with Rayleigh-distributed envelopes with 10- and 20-dB peak-to-average ratios are improved to 60 and 48 percent, respectively, by a two-stage Doherty system. The addition of a third stage further improves the efficiencies to 70 and 66 percent, respectively.

Footnote

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1. Introduction

The Doherty technique combines the outputs from two linear RF power amplifiers (PAs) through a transmission-line coupler. The resultant linear RF-amplifier system achieves a significantly higher efficiency (e.g., by a factor of two or three) at outputs below peak-output power (PEP) than does a conventional linear (class-B) RF PA.

The Doherty technique was developed in the 1930s [1, 2] as a more efficient alternative to both conventional amplitude-modulation techniques and Chireix outphasing [3, 4]. Doherty amplifiers continue to be used in a number of medium- and high-power LF and MF vacuum-tube AM transmitters [5 - 9]. They have been considered for use in solid-state MF and HF systems [10, 11] as well as high-power UHF transmitters [12]. Their average efficiency for typical modulation compares favorably with that of pulse-width modulated systems [13 - 16].

Principles of Operation

A simplified block diagram of a two-stage Doherty system is shown in Figure 1. The key elements of the concept are (1) the use of two (or more) PAs and (2) the quarter-wave transmission-line coupler. Optionally, the transmission-line coupler can be replaced by an equivalent impedance-inverting network such as an *L* or *T* network. In addition, the bias may be varied instead of the drive to control PA operation. PAs #1 and #2 are often called the *carrier* and *peaking* amplifiers, respectively.

Both PAs are assumed to be of the push-pull type and/or to contain filters that prevent the generation of signals at harmonics of the carrier frequency. The quarter-wave line on the input to PA #2 is used to compensate for the quarter-cycle phase shift in the line on the output of PA #1. Correct phasing of the two outputs is essential. The active devices in the two PAs are also assumed to have adequate ratings so that breakdown does not occur.

At low output levels, the drive to PA #2 is cut off and PA #1 operates as a linear class-B amplifier. The impedance presented to it by the coupler results in its saturation at a transition point well below the system PEP. In the classical Doherty system, the transition voltage is half of the maximum output voltage. As a result, the maximum amplifier efficiency is achieved at both the transition point and PEP, and the average efficiency for full-carrier AM signals is maximized.

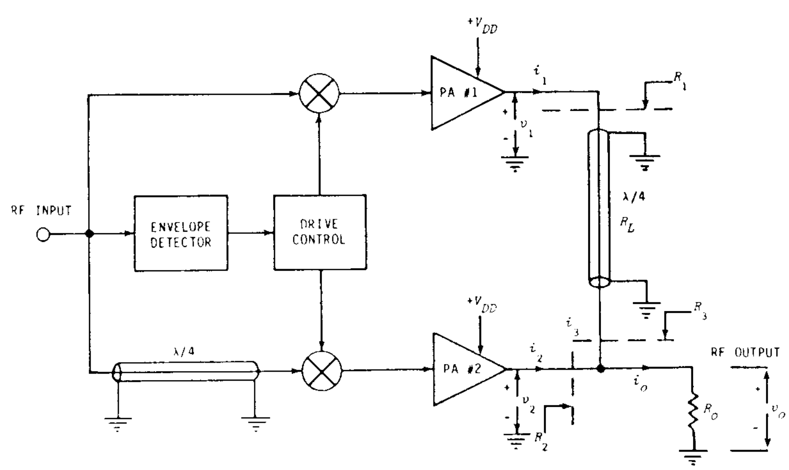

Figure 1. Simplified block diagram of Doherty system.

For output levels above the transition point, PA #2 operates as a linear RF PA and acts as a controlled current source. PA #1 remains saturated, and therefore acts as a voltage source [17, Chapter 13]. Because of the impedance-inversion, the output of the coupler appears to be a current source. Since the load current due to PA #2 increases the RF output voltage above that due to PA #1, the impedance seen by the output end of the coupler is greater than the load impedance and increases with increasing output from PA #2. The impedance-inversion by the coupler therefore presents a decreasing load impedance to PA #1, resulting in increasing output from it as well.

In this medium-power region, the efficiency of PA #1 remains at its maximum value, since PA #1 is saturated. The efficiency of PA #2 increases from half of its maximum value at the transition point to its maximum value at system PEP. As a result, the Doherty system achieves maximum efficiency at both the transition point and system PEP, and remains relatively high in between (Figure 2).

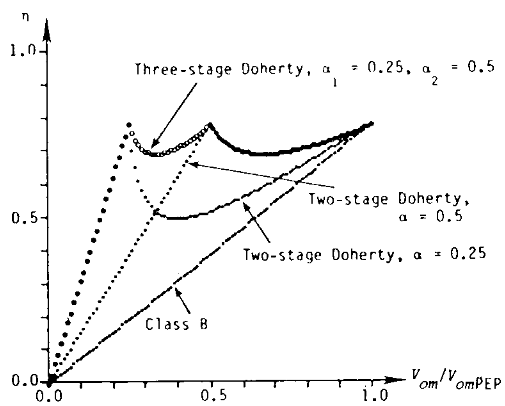

Figure 2. Instantaneous efficiency of typical Doherty systems.

Potential Advantages

There are a number of techniques for implementing high-efficiency RF power amplifiers and for combining RF PAs to increase their efficiency [4, 17 - 19]. Obviously, the Doherty technique is not the best means of increasing the efficiency in all applications. However, the Doherty technique is as effective or more effective than other techniques in a number of applications. The factors that make the Doherty technique of interest include:

- It can be applied in the VHF and UHF regions where it is difficult or impossible to implement intrinsically efficient PAs such as class D or class E.
- Its modulation bandwidth is not restricted by the modulator as in an envelope-elimination-and-restoration system [17 - 19].
- High-power AF amplifiers and modulation transformers are not required.
- Its efficiency is as good or better than that of envelope tracking [17, 18] and outphasing [3, 4] systems.

Naturally, the transmission line coupler limits the use of Doherty amplifiers to small frequency ranges. In addition, the PAs must be able to operate properly with variable load impedances. However, the Doherty system produces real load impedances, in contrast to the highly reactive load impedances produced in an outphasing system.

Objectives and Approach

Previous papers deal only with two-stage Doherty amplifiers and, with some exceptions, all deal only with the classical transition point (half of peak-output voltage). None of the previous papers considers fully the impact of the signal amplitude statistics upon the average efficiency.

This paper has three objectives. First, instantaneous (single-output-amplitude) efficiency and power characteristics are derived for the two-stage Doherty system. Second, these relationships are extended by analogies to multistage Doherty systems. Third, average efficiency and the transition points for maximum efficiency are determined for a number of amplitude-modulated signals.

The subsequent analysis is based upon ideal class-B PAs and a resistive load of nominal value. The efficiency of an ideal class-B PA as well as most real-world linear RF PAs varies linearly with output voltage. Consequently, the results derived here for ideal class-B PAs can easily be scaled to predict the instantaneous and average efficiencies of real-world PAs.

The resistive load of nominal value is a reasonable assumption, as most Doherty systems operate on a fixed frequency and into a well defined antenna. Numerous related practical aspects of Doherty systems (e.g., drive, bias, matching, control, adjustment) are discussed in the literature [5 - 8, 13 - 16].

2. Transmission-Line Coupler

The fundamental relationship governing the operation of the transmission-line coupler is $R_1 R_3 = R_L^2$. Assumption of a lossless line requires conservation of power, hence the current delivered to the load is related to the output voltage of PA #1 by

$$I_{3m} = \frac{V_{1m}}{(R_1 R_3)^{1/2}} = \frac{V_{1m}}{R_L} . \tag{1}$$

The voltage transformation T produced by the coupler is given by

$$T^2 = \frac{V_{1m}^2}{V_{3m}^2} = \frac{R_1}{R_3} = \frac{R_L^2}{R_3^2} . \tag{2}$$

The output current I_{om} is the sum of the outputs of the transmission-line coupler and PA #2, $I_{2m} + I_{3m}$. The *division ratio* is defined by

$$S = I_{3m} / I_{om} . \tag{3}$$

The power output P_o is therefore the sum of

$$P_1 = \frac{V_{om} I_{3m}}{2} = S P_o \tag{4}$$

and

$$P_2 = \frac{V_{om} I_{2m}}{2} = (1 - S) P_o . \tag{5}$$

The impedance seen at the output of the transmission-line coupler is

$$R_3 = \frac{V_{om}}{I_{3m}} = \frac{V_{om}}{S\ I_{om}} = \frac{R_o}{S} \ . \quad (6)$$

Similarly, the impedance seen by PA #2 is

$$R_2 = \frac{R_o}{1 - S} \ . \quad (7)$$

3. Peak-Power Operation

At PEP, both PAs are saturated. The peak-output voltage of the system and of PA #2 is therefore V_{DD}, hence the peak-output power is $P_{oPEP} = V_{DD}^2/2R_o$. The ratio of the two supply voltages defines the coupler transformation ratio; i.e. $V_{DD1} = T\ V_{DD}$. It is most convenient (although not necessary) to set $V_{DD1} = V_{DD}$ so that $T = 1$. Then from (2), and (6),

$$R_1 = R_3 = R_L = \frac{R_o}{\alpha} \ , \quad (8)$$

where α is the power-division ratio at PEP. For the classical Doherty PA, $\alpha = 1/2$, hence $R_L = 2R_o$, and both PAs produce equal output power at system PEP.

The output current is $I_{om} = V_{DD} / R_o$, hence the PA-output currents are $I_{1m} = I_{3m} = \alpha\ I_{om}$ and $I_{2m} = (1 - \alpha)\ I_{om}$. For ideal class-B PAs,

$$I_{dc} = I_{dc1} + I_{dc2} = \frac{2}{\pi}\left[\frac{\alpha\ V_{DD}}{R_o} + \frac{(1-\alpha)\ V_{DD}}{R_o}\right] = \frac{2}{\pi}\frac{V_{DD}}{R_o} \ . \quad (9)$$

The resultant efficiency

$$\eta = \frac{V_{DD}^2/(2\ R_o)}{(2/\pi)(V_{DD}/R_o)} = \frac{\pi}{4} \quad (10)$$

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

4. Low-Power Operation

At low power levels, PA #2 is cutoff and PA #1 is operated as a linear current source. The load impedance presented to PA #1 by the transmission-line coupler is $R_1 = R_L^2 / R_o = R_o / \alpha$. The voltage-transformation ratio is therefore $T^2 = R_1 / R_o = 1 / \alpha$, hence $V_{om} = \alpha\ V_{1m}$, and saturation of PA #1 occurs at $V_{om} = \alpha\ V_{DD}$. The RF-output current delivered by PA #1 is

$$I_{1m} = \frac{I_{om}}{T} = \frac{\alpha\ V_{om}}{R_o} \ . \quad (11)$$

For an ideal class-B PA,

$$I_{dc} = \frac{2}{\pi} I_{1m} = \frac{2}{\pi}\frac{\alpha\ V_{om}}{R_o} \ , \quad (12)$$

hence

$$\eta = \frac{V_{om}^2/(2\ R_o)}{(2/\pi)(\alpha\ V_{DD}\ V_{om}/R_o)} = \frac{\pi}{4\alpha}\frac{V_{om}}{V_{omPEP}} \ . \quad (13)$$

The efficiency is increased from that of a conventional class-B PA by the inverse of the PEP division ratio α.

5. Medium-Power Operation

At medium power levels, PA #1 is saturated and PA #2 is operated as a linear current source. The current delivered to the load from PA #1 (via the transmission-line coupler) is [from (1) and (8)]

$$I_{3m} = \frac{V_{DD}}{R_L} = \frac{\alpha\ V_{DD}}{R_o} \ . \quad (14)$$

Note that I_{3m} is constant in the medium-power region.

From (14), the RF current that must be delivered by PA #2 to produce an output voltage V_{om} is

$$I_{2m} = I_{om} - I_{3m} = \frac{V_{om} - \alpha\ V_{DD}}{R_o} \ . \quad (15)$$

The voltage-transformation ratio for the medium-power region is therefore $T = V_{DD} / V_{om}$, hence the RF current drawn from PA #1 is

$$I_{1m} = \frac{I_{3m}}{T} = \frac{\alpha\ V_{om}}{R_o} \ . \quad (16)$$

For ideal class-B PAs, the total dc-input current is therefore

$$I_{dc} = I_{dc1} + I_{dc2} = \frac{2}{\pi}\frac{(1+\alpha)\ V_{om} - \alpha\ V_{DD}}{R_o} \ . \quad (17)$$

6. Combined Results

The output power is always given by

$$P_o = \frac{V_{om}^2}{2\ R_o} \ . \quad (18)$$

The medium-power equations are accurate at PEP. The RF currents that must be produced by the two PAs are therefore

$$I_{1m} = \frac{\alpha\ V_{om}}{R_o} \quad (19)$$

and

$$I_{2m} = \begin{cases} 0 & , \ 0 < V_{om} < \alpha\ V_{DD} \\ \dfrac{V_{om} - \alpha\ V_{DD}}{R_o} & , \ \alpha\ V_{DD} < V_{om} < V_{DD} \end{cases} \ . \quad (20)$$

For ideal class-B PAs, (19) and (20) can be combined to produce

$$I_{dc} = \begin{cases} \dfrac{2}{\pi}\dfrac{\alpha V_{om}}{R_o}, & 0 < V_{om} < \alpha V_{DD} \\ \dfrac{2}{\pi}\dfrac{(1+\alpha)V_{om} - \alpha V_{DD}}{R_o}, & \alpha V_{DD} < V_{om} < V_{DD} \end{cases} \quad . \qquad (21)$$

The dc input power and efficiency are then

$$P_i = V_{DD}\, I_{dc} \qquad (22)$$

and

$$\eta = P_o / P_i \quad . \qquad (23)$$

Instantaneous-efficiency curves for a Doherty system with two ideal class-B PAs are shown in Figure 2. It is apparent that through selection of α, the instantaneous efficiency can be maximized at any desired value of output voltage. The efficiency at PEP is not degraded, and efficiency remains relatively high between $\alpha\, V_{omPEP}$ and V_{omPEP}.

7. Multistage Doherty Systems

Multistage Doherty systems employ a series connection of PAs through transmission-line couplers. For example, a three-stage system replaces the load R_o in Figure 1 with a transmission-line coupler (impedance R_L^2) that connects PA #2 to PA #3 and load R_o.

The operation of such a system is analogous to that of a two-stage system. In the low-power region, PAs #2 and #3 are cut off and PA #1 operates as a linear current source. In the medium-power region, PA #1 is saturated, PA #2 is a linear current source, and PA #3 is cut off. In the high-power region, PAs #1 and #2 are saturated and together act as a single saturated PA, while PA #3 operates as a linear current source.

If saturation of PAs #1 and #2 are to occur at $\alpha_1 V_{omPEP}$ and $\alpha_2 V_{omPEP}$, respectively, then the required transmission-line impedances are

$$R_{L2} = R_o / \alpha_2 \quad . \qquad (24)$$

and

$$R_{L1} = R_o / (\alpha_1\, \alpha_2) \quad . \qquad (25)$$

8. Average Efficiency

Average efficiency [1, 20] is defined as the ratio of the average RF-output power to the average dc-input power; i.e.,

$$\eta_{AVG} = P_{oAVG} \,/\, P_{iAVG} \quad . \qquad (26)$$

The average powers are determined by integrating the instantaneous powers weighted by the envelope probability-density function (p.d.f.) over the range of envelope values:

$$P_{oAVG} = (1/2) \int_0^{V_{omPEP}} V_{om}^2\, p(V_{om})\, dV_{om} \qquad (27)$$

and

$$P_{iAVG} = \int_0^{V_{omPEP}} P_i(V_{om})\, p(V_{om})\, dV_{om} \quad . \qquad (28)$$

A number of useful p.d.f.s are defined in [20]. For the uniform p.d.f., the dc input power and maximum-efficiency values of ξ, α_1, and α_2 can be determined analytically. However, for the other p.d.f.s, the evaluation is most readily accomplished numerically.

Selected Signals

Single-sideband suppressed-carrier (SSB/SC) transmitters are commonly tested with a two-tone signal, while full-carrier AM transmitters are commonly tested with a single-tone modulating signal. Some types of amplitude companders are said to produce a nearly uniform amplitude distribution. Quadrature amplitude modulation (QAM) is being used with increasing frequency in data-transmission systems because of its ability to pack a large number of bits into a single data symbol. All of these selected signals have relatively low peak-to-average ratios.

The average efficiency of a two-stage Doherty system with the four selected signals is shown in Figure 3 as a function of the transition ratio α. The maximum average efficiency attainable with both two- and three-stage systems as well as the corresponding average efficiency for a class-B PA are given in Table 1. For these signals, a two-stage system makes a noticeable improvement in average efficiency over class-B but a three-stage system makes only a small additional improvement.

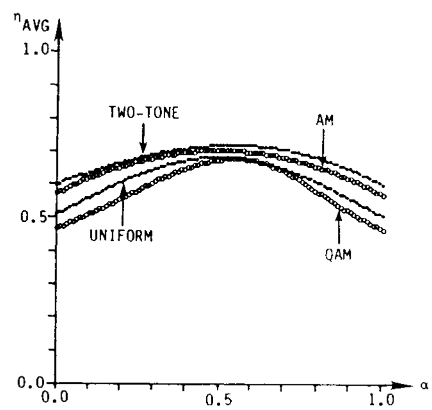

Figure 3. Average efficiency of two-stage Doherty system with selected signals.

Multicarrier and SSB/SC Voice

The envelope of bandlimited Gaussian noise has a Rayleigh distribution [20]. The envelope of the sum of a large number of independent RF carriers (with either FM or AM) also tends to have a Rayleigh distribution. The average efficiency of a two-stage Doherty system with Rayleigh-envelope is shown in Figure 4 for peak-to-average ratios of 5, 10, 15, and 20 dB. The maximum average efficiency (obtained with proper choice of α) is shown in Figure 5 for peak-to-average ratios from 5 to 20 dB. Average-efficiency contours for a three-stage Doherty system with $\xi = 10$ are shown in Figure 6.

For $\xi = 5$ dB, the improvements are similar to those obtained with the four selected signals. However, the improvement in average efficiency becomes much more significant as the peak-to-average ratio increases (Figure 5). For example, at $\xi = 10$ dB, the 28-

Signal	ξ, dB	Class B	Two-stage Doherty max η_{AVG}	α	Three-stage Doherty max η_{AVG}	α_1	α_2
Two-tone S	3.0	0.614	0.732	0.54	0.760	0.36	0.71
AM	4.3	0.587	0.719	0.50	0.753	0.32	0.68
Uniform	4.8	0.524	0.698	0.50	0.744	0.33	0.66
QAM	4.8	0.501	0.697	0.54	0.747	0.39	0.67
Rayleigh	5.0	0.455	0.679	0.47	0.736	0.33	0.62
Rayleigh	6.0	0.423	0.666	0.45	0.730	0.32	0.60
Rayleigh	7.0	0.387	0.650	0.43	0.723	0.30	0.57
Rayleigh	8.0	0.350	0.633	0.41	0.715	0.28	0.54
Rayleigh	9.0	0.314	0.616	0.38	0.708	0.26	0.51
Rayleigh	10.0	0.280	0.600	0.36	0.700	0.24	0.48
Rayleigh	11.0	0.250	0.584	0.33	0.694	0.22	0.44
Rayleigh	12.0	0.223	0.569	0.31	0.688	0.20	0.41
Rayleigh	13.0	0.198	0.556	0.28	0.683	0.18	0.37
Rayleigh	14.0	0.177	0.543	0.26	0.678	0.16	0.34
Rayleigh	15.0	0.158	0.532	0.24	0.674	0.15	0.32
Rayleigh	16.0	0.140	0.521	0.22	0.670	0.14	0.29
Rayleigh	17.0	0.125	0.510	0.20	0.666	0.12	0.26
Rayleigh	18.0	0.112	0.501	0.19	0.666	0.12	0.26
Rayleigh	19.0	0.099	0.492	0.17	0.660	0.10	0.22
Rayleigh	20.0	0.089	0.483	0.16	0.657	0.09	0.20
Laplacian	5.0	0.401	0.640	0.40	0.714	0.25	0.57
Laplacian	6.0	0.386	0.632	0.39	0.710	0.24	0.55
Laplacian	7.0	0.369	0.622	0.38	0.705	0.23	0.54
Laplacian	8.0	0.350	0.612	0.37	0.699	0.22	0.53
Laplacian	9.0	0.330	0.600	0.35	0.693	0.21	0.51
Laplacian	10.0	0.308	0.587	0.34	0.686	0.20	0.49
Laplacian	11.0	0.286	0.573	0.32	0.678	0.19	0.47
Laplacian	12.0	0.263	0.558	0.31	0.670	0.18	0.45
Laplacian	13.0	0.240	0.542	0.29	0.661	0.17	0.43
Laplacian	14.0	0.217	0.525	0.28	0.651	0.16	0.41
Laplacian	15.0	0.195	0.508	0.26	0.642	0.15	0.39
Laplacian	16.0	0.175	0.491	0.25	0.633	0.14	0.37
Laplacian	17.0	0.157	0.475	0.23	0.624	0.13	0.35
Laplacian	18.0	0.140	0.459	0.22	0.615	0.12	0.32
Laplacian	19.0	0.125	0.444	0.20	0.607	0.11	0.30
Laplacian	20.0	0.111	0.430	0.19	0.600	0.10	0.28
Guassian AM	5.0	0.478	0.690	0.50	0.741	0.36	0.65
Guassian AM	10.0	0.431	0.690	0.50	0.745	0.38	0.62
Guassian AM	15.0	0.405	0.710	0.50	0.760	0.41	0.59
Guassian AM	20.0	0.397	0.735	0.50	0.772	0.44	0.56
Laplacian AM	5.0	0.455	0.695	0.50	0.743	0.38	0.62
Laplacian AM	10.0	0.425	0.702	0.50	0.748	0.40	0.60
Laplacian AM	15.0	0.405	0.720	0.50	0.760	0.43	0.58
Laplacian AM	20.0	0.397	0.741	0.50	0.771	0.45	0.56

Table 1. Maximum average efficiencies and corresponding transition ratios.

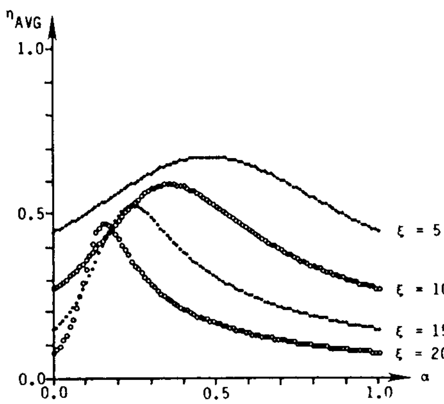

Figure 4. Average efficiency of two-stage Doherty system with Rayleigh-envelope signals.

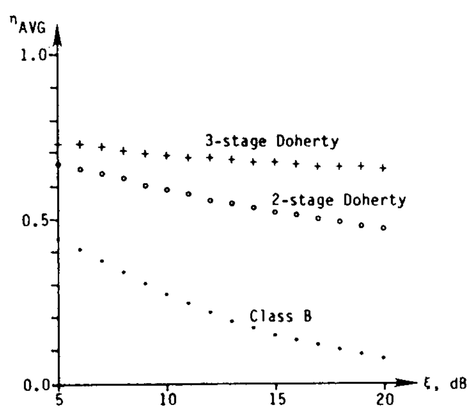

Figure 5. Maximum average efficiency for Rayleigh envelope.

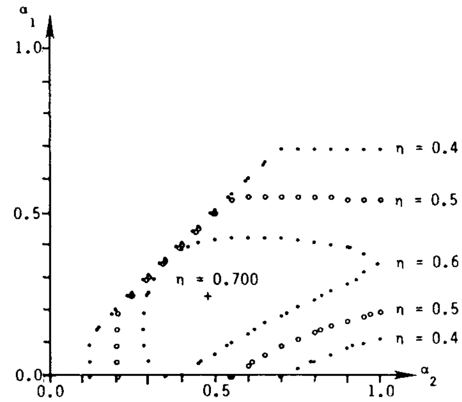

Figure 6. Average-efficiency contours for three-stage Doherty system with Rayleigh signal, ξ = 10 dB.

percent average efficiency of a single-voltage PA is increased to 60 percent by two-stage Doherty and to 70 percent by three-stage Doherty. For ξ = 20 dB, the average efficiency is increased from a meager 8.9 percent to 48 and 66 percent by two- and three-stage systems, respectively. Note that the effect of the transition voltage increases as the peak-to-average ratio increases.

The envelope of an SSB/SC signal produced by speech has a Laplacian (one-sided exponential) distribution. The average efficiency as a function of transition voltage is shown in Figure 7 for Laplacian-envelope signals with peak-to-average ratios of 5, 10, 15, and 20 dB. The maximum attainable average efficiency as a function of peak-to-average ratio is shown in Figure 8 and values of α are given in Table 1.

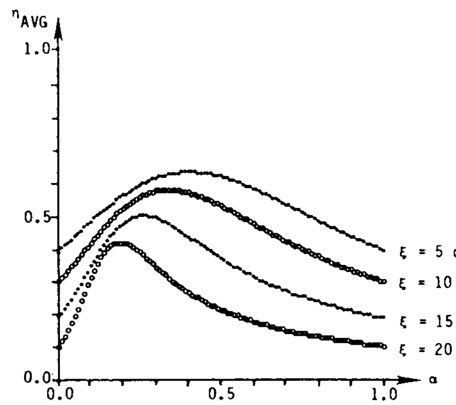

Figure 7. Average efficiency of two-stage Doherty system with Laplacian-envelope signals.

The average-efficiency characteristics for a Laplacian envelope are similar to those for a Rayleigh envelope. For a typical 10-dB peak-to-average ratio, the 30.8 percent efficiency of class B is increased to 58.7 percent by a two-stage Doherty system, and to 68.6 percent by a three-stage Doherty system.

Amplitude Modulation

The modulating signals for full-carrier AM typically have either Gaussian distributions (corresponding to music or the sum of a variety of sounds) or Laplacian distributions (corresponding to speech). The average-efficiency curves for two-stage systems with these two signals are shown in Figures 9 and 10 for several modulation peak-to-average ratios.

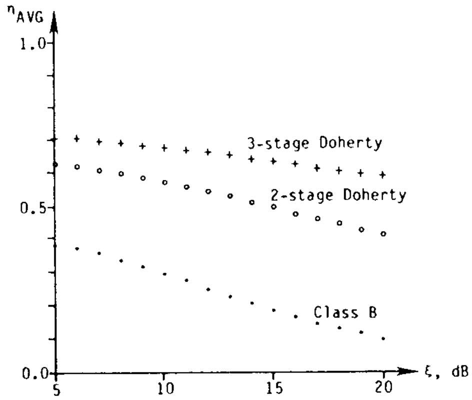

Figure 8. Maximum average efficiency for Laplacian envelope.

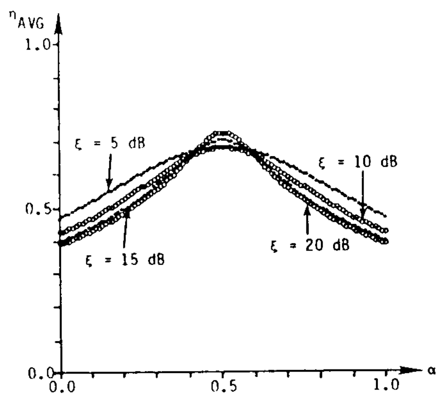

Figure 9. Average efficiency of two-stage Doherty system with Gaussian-AM signals.

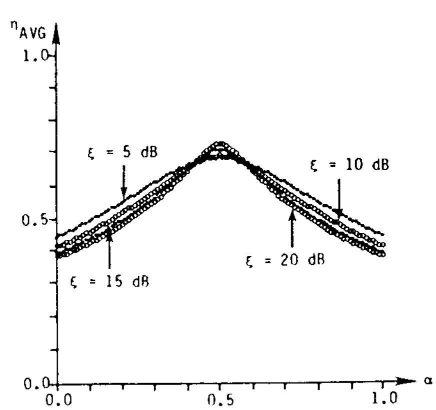

Figure 10. Average efficiency of two-stage Doherty system with Laplacian-AM signals.

The maximum average efficiencies and the corresponding transition voltages are given in Table 1. Since the RF peak-to-average ratio for these signals is relatively low, their average-efficiency characteristics are similar to those of the selected signals.

It is interesting to note that the maximum average efficiency of the two-stage system is achieved with the classical Doherty configuration ($\alpha = 0.5$) for all Guassian-AM signals as well as the single-tone AM and uniform signals. It can be shown that $\alpha = 0.5$ maximizes the efficiency of a two-stage system for any signal whose p.d.f. is symmetrical about $V_{omPEP}/2$. The classical Doherty configuration is therefore the optimum two-stage system for all full-carrier AM signals.

9. Conclusions

The instantaneous-efficiency relationships for two-stage Doherty-PA systems with ideal class-B PAs have been derived. The relationships for three-stage systems have been obtained by analogy. These relationships have been used to calculate the average dc-to-RF power-conversion efficiency of the systems for a variety of amplitude-modulated signals.

The Doherty system can produce a significant increase in efficiency (hence significant decreases in power consumption and heat dissipation) for virtually all signals. The three-stage Doherty system can improve efficiency of the system to nearly the PEP efficiency of the individual PAs, even when the peak-to-average ratio of the signal is large. While the efficiency of a system with real PAs is not as high as that with ideal PAs, the relative improvement in efficiency should be approximately the same.

Many new systems that operate in the UHF and microwave range (e.g., ACSB land-mobile and mobile-satellite repeaters) require a linear RF power amplifier. In these frequency bands, the frequency of operation is usually fixed and the transmission-line couplers are readily implemented in printed-circuit form. The Doherty RF power-amplifier system is therefore an important candidate technology when transmitter efficiency, power consumption, and/or heat dissipation are of interest to the designer.

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