Meaningful Measurements of Power Amplifier Efficiency

Without a frame of reference, a test measurement has little meaning. A motor vehicle that supplies 21 MPG (Miles Per Gallon) may be extremely efficient or embarrassingly inefficient depending on if it is a two-person sports car or an 18 wheel truck, what load it is carrying, if the measurement is made in city traffic or highway usage, etc, etc. A frame of reference is critical to understanding the context of a measurement – and in discerning what it means and what it does not mean.

Power Amplifier Operation in Practice

Power Amplifiers (PA) operating in a typical cellular network environment, observing 4G, 5G standards, are using Orthogonal Frequency Division Multiplexing (OFDM). As seen in the table below, their typical efficiency would be 10%. [1]

Wireless Technology	Wireless Standard	PAR (dB)	Typical PA Efficiency (%)
TDMA	GSM	0	60
TDMA	NADC	3	20
Multicarrier	Any	10+	10[a]
CDMA	CDMA2000 or UMTS	10–12	10[a]
OFDM	LTE or WiMax	10–13	10[a]

PA, power amplifiers; *PAR*, peak to average ratios.
[a] In order to achieve required linearity and meet adjacent channel spectral emission requirements, the PAs often included "feed forward compensation," which involved using analog techniques to cancel PA output distortion, improving linearity.

Orthogonal Frequency Division Multiplexing (OFDM) has many technical advantages for its use as the backbone of cellular networks. Three significant attributes, relative to OFDM, impact the frame of reference for determining power amplifier efficiency:

(1) Measurement of PAs – Power-Added Efficiency (PAE) versus Drain Efficiency (DE),
(2) peak to average ratio (PAPR sometimes abbreviated PAR), and
(3) dynamic range.

(1) A Tale of Two Measurements: Power-Added Efficiency (PAE) vs Drain Efficiency (DE). By any measurement approach, efficiency is a figure-of-merit which describes how well a device converts one energy source to another. For RF power amplifiers there are two approaches in practice.

<u>Power-Added Efficiency</u> takes into account the RF power added to the device input. In this sense, PAE is therefore an all-inclusive measurement. (PAE = 100* (Pout-in)/Pdc).

<u>Drain Efficiency</u> describes a shortcut measurement process where Power out is expressed as a ratio to the primary point where DC power is supplied, the transistor drain. (D efficiency = Pout/Pdc). However, this shortcut does not consider how much power is used by the amplifier and consequently, however easier Drain efficiency is to measure, it will always provide an inaccurate and higher measure of efficiency due to neglecting one of the energy sources.

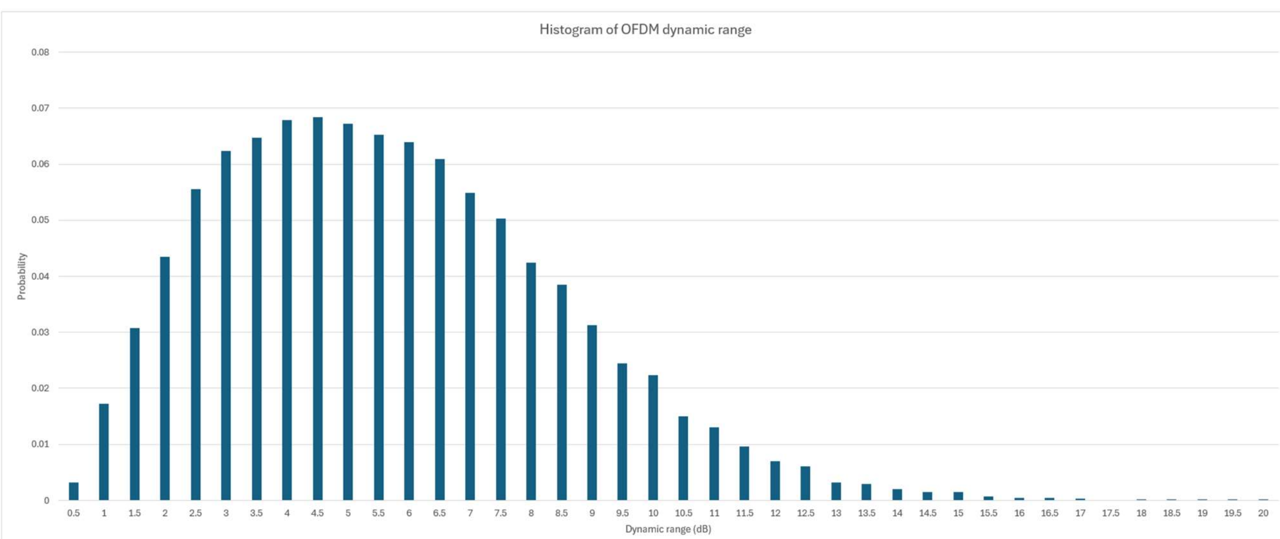
As might be imagined, some researchers and manufacturers prefer Drain Efficiency as it is always higher than the PAE. As a rule of thumb, Power-Added Efficiency PAE is usually 50 to 80% of the Drain Efficiency. Those interested in accuracy use PAE.

(2) Peak to Average Ratio (PAPR). Signal power is not constant but rather it fluctuates with time intermittently reaching very large values. This variability is described as "peak to average ratio". Herein lies the problem: a large PAPR requires the linear transmit amplification circuits to operate over a wide power range. This is both costly and inefficient as OFDM (and CDMA as well) have inherently high PAPR values.

(3) Dynamic Range – Paving the Path for Inefficient Power Amplifiers. The Dynamic Range is the ratio of the largest measurable signal to the lowest measurable signal. In telecommunications practice, the combination of different signals with different phase and frequency in OFDM systems creates large dynamic ranges. *As a characteristic*, these large ranges have a high PAPR (discussed above). Such signals amplified by a nonlinear PA, will result in signal clipping and nonlinear distortion. This causes out-of-band distortion, violating the spectrum emission mask (SEM), disrupting other adjacent channels, and creating unwanted radiation. For the cellular system this means poor coverage, dropped calls, and low quality of service. To avoid the preceding problems, wireless systems assure linearity by operating power amplifiers (PAs) with a large back-off (BO) voltage. This results in dramatically lowering PA efficiency and poorer cell coverage. This describes the devil's dilemma: respectable efficiency at the expense of poorly amplified signal quality, or quality amplified signals at the expense of poor efficiency.

How PA Efficiency is Measured… Or Not

In practice, designers often apply a back-off voltage to part of the dynamic range and condemn the rest of the dynamic range to a much lower efficiency. An example might best portray that. Consider the signal representation of the Dynamic Range of 20 dB. As we know from the above discussion, it is not just one signal but thousands of signals with different phases and frequencies, different peak amplitudes, that we must represent all at once, because we are going to measure a precise point of power amplifier output. We resolve this many-to-one representation via a probability density function, depicted below.



The figure above [2] shows a collection of 40 entries across the bottom corresponding to the 20 dB dynamic range, and shown on the left is the associated probability for each entry. This figure statistically matches the Rayleigh distribution which governs OFDM signals with high PAPR values.[3 4 5]

Examining the statistical distribution across the dynamic range above, one thing should stand out as being abundantly clear: The **measurement** of any point on that distribution **is meaningful only** if that point is included **as an average**. It is meaningless to compare the measurement of one point on that distribution for device-A and then compare that to a single point measurement for device-B. Only comparing the probabilistic average of the two devices provides a meaningful comparison.

More to the point, when there are thousands of different signals being amplified across the dynamic range, the only sensible way to describe efficiency is not pick a specific value, but rather to represent the statistical average value. Only in this way does one arrive at a statistically valid representation of efficiency. That representation is the sum of the probabilistic weighted efficiency values otherwise known as the **efficiency average value**.

The intent here is to walk through a detailed example of how power efficiency is measured and presented. As an example, consider mapping some physical measurements to the probability curve to calculate the probabilistic value of each efficiency and thereby arrive at the weighted average efficiency. This illustration uses data, figures, and quotations from a recent paper presenting measured data on a Doherty Power Amplifier design. [6] That paper, Ref 6, is, "Symmetrical Load Modulated Balanced Power Amplifier With Asymmetrical Output Coupling for Load Modulation Continuum."

The authors note (page 2324) that

> "It should be clearly noted from Fig. 14 that the transducer power gain of this demonstrator (4.6–6.6 dB at PEP) is very low. This causes the power-added efficiency (PAE) to be much lower (34–46% at 10-dB PBO, 30–42% at PEP) than the drain efficiency reported above."

So the authors are aware of, acknowledge, and cite numbers for the differences between PAE (Power Added Efficiency) and DE (Drain Efficiency) efficiencies. This corroborates the PAE discussion above. However, sadly, most of the data they present in the Ref 6 are still DE measurements and therefore present higher efficiencies than the more accurate PAE numbers.

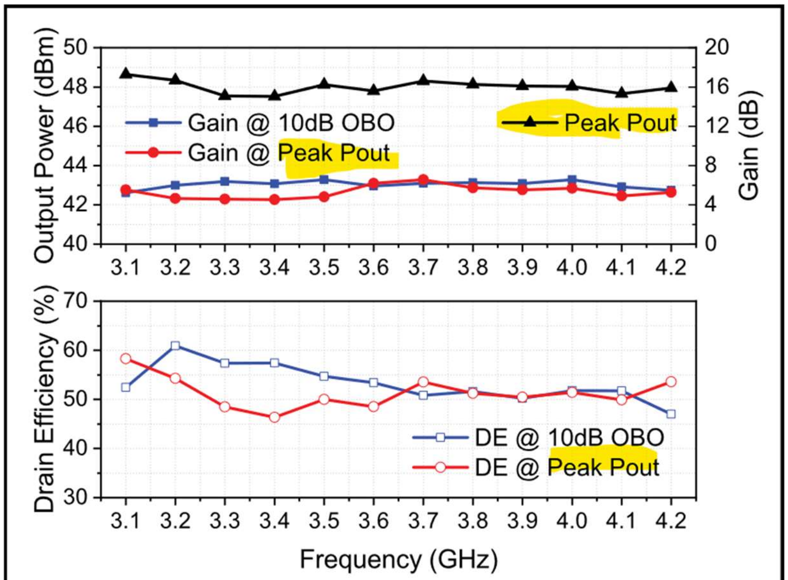


Fig. 14. Measured drain efficiency and gain versus frequency at peak output power and at 10-dB output back-off.

Looking at the Table 14 which they reference in the above quotation …

Note that they are plotting only one single point for each efficiency (one for each different frequency) and that these points correspond to peak points. This means comparing numbers within the same paper may be fine, but taking this efficiency as a measurement to compare to other devices is not meaningful.

The authors present their efficiency numbers in Figure 13 (a) shown at the right. Taking the 20dB dynamic range from the probability density function above and laying that in the center of Output power range of Fig 13 (a) covers a 20dB range from 26.5 dB to 46.5 dB. The corresponding values of DE for 3.1 GHz for this range spans from 13% to 57%. These numbers are presented in the table below with the corresponding other entries.

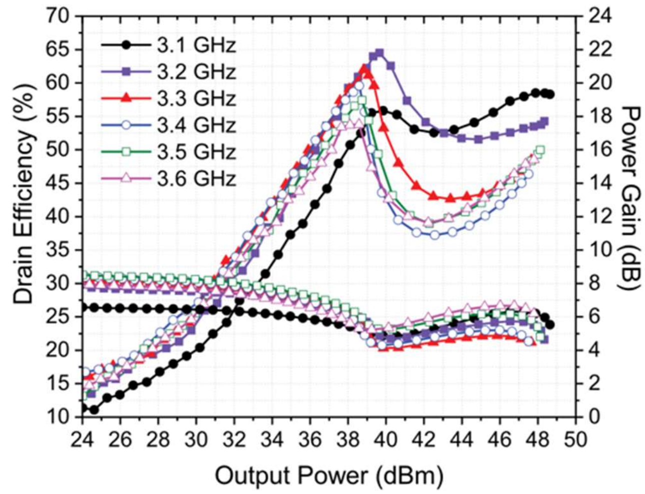


Fig. 13.(a) Measured drain efficiency and gain of the LMBA versus output power. (a) 3.1–3.6 GHz and (b) 3.7–4.2 GHz.

<- Dervived Parameters* ->		<- Fig 13a -> 3.1 Ghz	< --------- Calculated Parameters ---------->		
Power dB	**% of Probability Density Value ***	**DE** Drain eff	**Weighted Efficiency =% Prob*DE**	**PAE =0.8* DE**	**With DPD = 0.8*PAE**
0.5	0.32%	0.130	0.04%	0.03%	0.03%
1.0	1.73%	0.150	0.26%	0.21%	0.17%
1.5	3.08%	0.155	0.48%	0.38%	0.31%
2.0	4.35%	0.160	0.70%	0.56%	0.45%
2.5	5.56%	0.170	0.94%	0.76%	0.60%
3.0	6.23%	0.175	1.09%	0.87%	0.70%
3.5	6.48%	0.180	1.17%	0.93%	0.75%
4.0	6.79%	0.200	1.36%	1.09%	0.87%
4.5	6.84%	0.210	1.44%	1.15%	0.92%
5.0	6.73%	0.200	1.35%	1.08%	0.86%
5.5	6.52%	0.224	1.46%	1.17%	0.94%
6.0	6.40%	0.260	1.66%	1.33%	1.06%
6.5	6.09%	0.270	1.64%	1.32%	1.05%
7.0	5.49%	0.290	1.59%	1.27%	1.02%
7.5	5.03%	0.310	1.56%	1.25%	1.00%
8.0	4.24%	0.325	1.38%	1.10%	0.88%
8.5	3.85%	0.335	1.29%	1.03%	0.82%
9.0	3.12%	0.370	1.16%	0.92%	0.74%
9.5	2.45%	0.380	0.93%	0.75%	0.60%
10.0	2.24%	0.400	0.90%	0.72%	0.57%
10.5	1.50%	0.425	0.64%	0.51%	0.41%
11.0	1.30%	0.440	0.57%	0.46%	0.37%
11.5	0.96%	0.475	0.45%	0.36%	0.29%
12.0	0.70%	0.500	0.35%	0.28%	0.22%
12.5	0.61%	0.520	0.32%	0.25%	0.20%
13.0	0.32%	0.530	0.17%	0.14%	0.11%
13.5	0.30%	0.570	0.17%	0.14%	0.11%
14.0	0.20%	0.560	0.11%	0.09%	0.07%
14.5	0.15%	0.550	0.08%	0.07%	0.05%
15.0	0.14%	0.540	0.08%	0.06%	0.05%
15.5	0.07%	0.530	0.04%	0.03%	0.02%
16.0	0.04%	0.520	0.02%	0.02%	0.01%
16.5	0.04%	0.525	0.02%	0.02%	0.01%
17.0	0.03%	0.525	0.02%	0.01%	0.01%
17.5	0.01%	0.528	0.00%	0.00%	0.00%
18.0	0.02%	0.530	0.01%	0.01%	0.01%
18.5	0.01%	0.535	0.01%	0.01%	0.01%
19.0	0.01%	0.540	0.01%	0.01%	0.01%
19.5	0.02%	0.550	0.01%	0.01%	0.01%
20.0	0.01%	0.570	0.01%	0.01%	0.01%
	100.00%		25.48%	20.38%	16.31%
	Total		Total = Average Weighted Efficiency or **Avg Efficiency**	**Average PAE**	**Average PAE with DPD**
	*** Note:** OFDM Envelope probability for 20 dB Dynamic range, calculated for 2048 Sub-carriers and 16-QAM				

There are 40 row entries in the table to the left corresponding to 0.5 increments in the dynamic range from 0 to 20dB. The DE efficiencies from the table are shown followed by the calculated parameters.

The **average DE efficiency** across the dynamic range for this example is 25.48%. This is substantially less than the “49 to 63%“ peak performance numbers that were offered as efficiency.

On pages 2324 and 2323 the Ref 6 presents its measured PAE and DE efficiencies respectively. As a ratio (34/47 and 46/61) the PAE is 72.3% to 75.4 % of the DE. Conforming to the rule of thumb, the calculations in the table to the left use a more forgiving 80% ratio. This causes the **average PAE** to reduce the DE to 20.38%.

Adding **digital predistortion (DPD)** to the signal processing also **diminishes the PAE** by another 20% to a result of 16.31%.

Two additional publications which present Doherty power amplifier measurement data are now considered: (i) Ref 7: An Efficient Broadband Symmetrical Doherty Power Amplifier With Extended Back-Off Range [7] and, (ii) ref 8: A high-efficiency Doherty Power Amplifier for wireless base stations [8]. Taking the measurement graphs from each paper and applying the Rayleigh probabilistic density function above, yields the following tables below…

REF 7 – GRAPH & TABLE

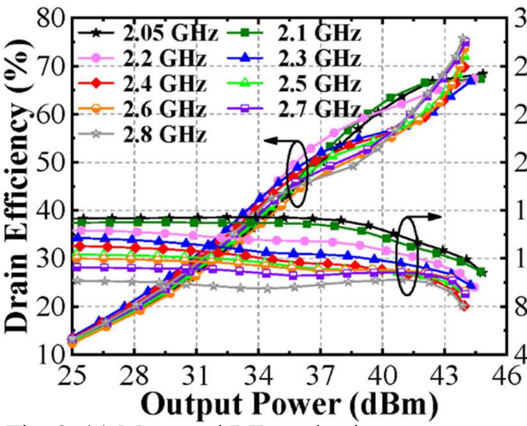


Fig. 8. (a) Measured DEs and gains versus output power.

<- Dervived Parameters* ->		<- Fig 8a -> 2.05 Ghz	< --------- Calculated Parameters ----------->		
Power dB	**% of Probability Density Value ***	**DE** Drain eff	**Weighted Efficiency =% Prob*DE**	**PAE =0.8* DE**	**With DPD = 0.8*PAE**
0.5	0.32%	0.120	0.04%	0.03%	0.02%
1.0	1.73%	0.130	0.22%	0.18%	0.14%
1.5	3.08%	0.150	0.46%	0.37%	0.30%
2.0	4.35%	0.160	0.70%	0.56%	0.45%
2.5	5.56%	0.170	0.94%	0.76%	0.60%
3.0	6.23%	0.180	1.12%	0.90%	0.72%
3.5	6.48%	0.195	1.26%	1.01%	0.81%
4.0	6.79%	0.200	1.36%	1.09%	0.87%
4.5	6.84%	0.210	1.44%	1.15%	0.92%
5.0	6.73%	0.220	1.48%	1.18%	0.95%
5.5	6.52%	0.230	1.50%	1.20%	0.96%
6.0	6.40%	0.260	1.66%	1.33%	1.06%
6.5	6.09%	0.270	1.64%	1.32%	1.05%
7.0	5.49%	0.300	1.65%	1.32%	1.05%
7.5	5.03%	0.350	1.76%	1.41%	1.13%
8.0	4.24%	0.360	1.53%	1.22%	0.98%
8.5	3.85%	0.380	1.46%	1.17%	0.94%
9.0	3.12%	0.390	1.22%	0.97%	0.78%
9.5	2.45%	0.400	0.98%	0.78%	0.63%
10.0	2.24%	0.410	0.92%	0.74%	0.59%
10.5	1.50%	0.420	0.63%	0.50%	0.40%
11.0	1.30%	0.430	0.56%	0.45%	0.36%
11.5	0.96%	0.450	0.43%	0.34%	0.28%
12.0	0.70%	0.500	0.35%	0.28%	0.22%
12.5	0.61%	0.520	0.32%	0.25%	0.20%
13.0	0.32%	0.530	0.17%	0.14%	0.11%
13.5	0.30%	0.550	0.17%	0.13%	0.11%
14.0	0.20%	0.580	0.12%	0.09%	0.07%
14.5	0.15%	0.590	0.09%	0.07%	0.06%
15.0	0.14%	0.600	0.09%	0.07%	0.06%
15.5	0.07%	0.620	0.04%	0.04%	0.03%
16.0	0.04%	0.620	0.02%	0.02%	0.02%
16.5	0.04%	0.640	0.03%	0.02%	0.02%
17.0	0.03%	0.650	0.02%	0.02%	0.01%
17.5	0.01%	0.660	0.00%	0.00%	0.00%
18.0	0.02%	0.665	0.01%	0.01%	0.01%
18.5	0.01%	0.670	0.01%	0.01%	0.01%
19.0	0.01%	0.675	0.01%	0.01%	0.01%
19.5	0.02%	0.680	0.01%	0.01%	0.01%
20.0	0.01%	0.690	0.01%	0.01%	0.01%
	100.00%		26.44%	21.15%	16.92%
	Total		Total = Average Weighted Efficiency or **Avg Efficiency**	**Average PAE**	**Average PAE with DPD**
	*** Note:** OFDM Envelope probability for 20 dB Dynamic range, calculated for 2048 Sub-carriers and 16-QAM				

REF 8 – GRAPH & TABLE

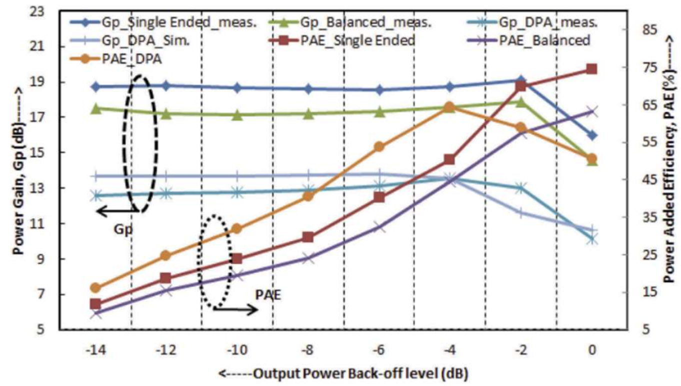


Figure 12. DPA CW performance comparison (measured and simulated power gain) with single-ended, balanced topologies (measured PAE).

<- Dervived Parameters* ->		<- Fig 12 ->	< --- Calculated Parameters --->	
Power dB	**% of Probability Density Value ***	**PAE**	**Weighted Efficiency = % Prob*PAE**	**With DPD = 0.8*PAE**
0.5	0.32%	0.050	0.02%	0.01%
1.0	1.73%	0.050	0.09%	0.07%
1.5	3.08%	0.055	0.17%	0.14%
2.0	4.35%	0.060	0.26%	0.21%
2.5	5.56%	0.065	0.36%	0.29%
3.0	6.23%	0.070	0.44%	0.35%
3.5	6.48%	0.075	0.49%	0.39%
4.0	6.79%	0.080	0.54%	0.43%
4.5	6.84%	0.085	0.58%	0.46%
5.0	6.73%	0.090	0.61%	0.48%
5.5	6.52%	0.095	0.62%	0.50%
6.0	6.40%	0.100	0.64%	0.51%
6.5	6.09%	0.120	0.73%	0.58%
7.0	5.49%	0.150	0.82%	0.66%
7.5	5.03%	0.160	0.80%	0.64%
8.0	4.24%	0.200	0.85%	0.68%
8.5	3.85%	0.210	0.81%	0.65%
9.0	3.12%	0.220	0.69%	0.55%
9.5	2.45%	0.230	0.56%	0.45%
10.0	2.24%	0.250	0.56%	0.45%
10.5	1.50%	0.260	0.39%	0.31%
11.0	1.30%	0.270	0.35%	0.28%
11.5	0.96%	0.280	0.27%	0.21%
12.0	0.70%	0.300	0.21%	0.17%
12.5	0.61%	0.330	0.20%	0.16%
13.0	0.32%	0.350	0.11%	0.09%
13.5	0.30%	0.370	0.11%	0.09%
14.0	0.20%	0.400	0.08%	0.06%
14.5	0.15%	0.430	0.07%	0.05%
15.0	0.14%	0.450	0.06%	0.05%
15.5	0.07%	0.480	0.03%	0.03%
16.0	0.04%	0.500	0.02%	0.02%
16.5	0.04%	0.550	0.02%	0.02%
17.0	0.03%	0.600	0.02%	0.02%
17.5	0.01%	0.650	0.00%	0.00%
18.0	0.02%	0.700	0.01%	0.01%
18.5	0.01%	0.720	0.01%	0.01%
19.0	0.01%	0.730	0.01%	0.01%
19.5	0.02%	0.740	0.01%	0.01%
20.0	0.01%	0.750	0.01%	0.01%
	100.00%		12.65%	10.12%
	Total		Total = Average Weighted Efficiency or **Avg Efficiency**	**Average PAE**
	*** Note:** OFDM Envelope probability for 20 dB Dynamic range, calculated for 2048 Sub-carriers and 16-QAM			

Regarding Ref 7 and Figure 8 above left and right respectively, consider the **average PAE efficiency** and Ref 7 results. Ref 7 is not incorrect. It's perspective on the measured results is much like a silhouette view. It offers a one dimensional perspective by focusing on 9 different frequency measurements at two discreet points! – the backoff point and the point of maximum power input. To wit: from Ref 7 abstract:

> "DPA exhibits drain efficiency of 40%–49% at 9 dB output back-off level and 66%–76% at saturation with a maximum output power"

However, the transmitted signals are amplified across the entire dynamic range, not at only two points. A more meaningful discussion of efficiency would address all the points – not only two. A more colorful, accurate, and complete picture, rather than a silhouette, is to use the average PAE shown in the above table.

Comparing Industry and QDA Measurements

From the analysis above, it is now possible to consolidate results into a comparison table. Back in 2021, the first paper [9] describing a specific QDA application, provided details on the average PAE efficiency – as well as comparable numbers available at that time. This was in Table 4 reproduced below for convenience.

TABLE 4. Measurement summary and comparison with other architectures found in the literature.

		This Work	RFIC'20 [32]		TCASI'20 [33]	JSSC'16 [34]	JSSC'15 [35]	ISSCC'17 [36]		MWCL'14 [37]	ISSCC'10 [38]	ISSCC'10 [39]
	Freq. (MHz)	**880**	28000		2400	3710	1900	4900/5900		16500	60000	60000
	BW (MHZ)	**0.25**	4000		10	1000	20	160		N.A.	N.A.	N.A.
	Technology	**Discrete**	22 nm FDSOI		45 nm CMOS	65 nm CMOS	40 nm CMOS	55 nm CMOS 180 nm SOI		180 nm BiCMOS	90 nm CMOS	65 nm CMOS
	Architecture	**QDA**	TRX front end module		Multi-mode outphasing	Class G mixed-signal Doherty PA	Dual-mode Doherty PA	Doherty PA		2-stage cascode and Wilkinson divider/combiner	2-stage PA and Wilkinson divider/combiner	N-way differential power combiner (transformer)
	Supply (V)	**12.3/3.2**	2.4/0.8		2.4	3	1.5	3.3		2.4	1.8	0.9/1.0
PA	Gain (dB)	**9.8/14.35**	30		N.A.	N.A.	N.A.	26		34.5	26.1	18.9/19.2
PA	PAE (%)	**63.4 (9 dB BO)**	8.7 (6 dB BO)		25.3 (6 dB BO DE SLO) 32.9 (6 dB BO DE AMO)	37.0 (6 dB BO DE)	25.5 (6 dB BO)	N.A.		N.A.	N.A.	N.A.
PA	PAE (%)	**69.7****	21.5**		49.2** (DE)	40.2** (DE)	34**	N.A.		17	10.5**	10.8/11.1**
SYSTEM	Signal Modulation	**16 QAM**	64 QAM	256 QAM	64 QAM LTE	16 QAM	16 QAM LTE	MCS 9	MCS 11	N.A.	N.A.	N.A.
SYSTEM	Data Rate (MHz)	**2**	2400	800	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
SYSTEM	EVM (dB)	**-27**	-25	-30	-39.4 (SLO) -25.2 (AMO)	-24	-23	-35	-38	N.A.	N.A.	N.A.
SYSTEM	Pout (dBm)	**21.8***	11.13*	10.1*	31.6**	26.7**	28**	20.3	18.3	18.3	14.5**	17.6 (PSAT)
SYSTEM	PAE (%)	**31.3***	9.7*	8.3*	N.A.	N.A.	N.A.	12***	10***	N.A.	N.A.	N.A.

* Average value, ** Maximum value, *** At the desired P_{out} value, N.A. not available, DE: Drain Efficiency, SLO: Single Level Outphasing, AMO: Asymmetric Multilevel Outphasing, BO: Backoff, MCS: Multilevel Coded Spreading Symbols.

Updating these results and including all the papers discussed herein, we offer the following summary.

Event or Cited Source	Year	Architecture	Average PAE Measured Efficiency	Average PAE Simulated Efficiency	PEAK Single Point Efficiency	Bandwidth	Carrier Frequency	Pout
Ref #8: A High-Efficiency Doherty Power Amplifier for Wireless Base Stations. International Journal of Electronics Letters	2020	Doherty	12.65%	…	75.00%	60 MHz	1960 MHz	40 dBm
Ref #9: A Novel Highly-Efficient Amplification Scheme for Wireless Communications in a CathLab Environment	2021	**QDA**	31.3% **	33.60%	59.50%	.25 MHz	880 MHz	21.8 dBm
Ref #6: Symmetrical Load Modulated Balanced Power Amplifier With Asymmetrical Output Coupling for Load Modulation Continuum	2022	Doherty / DPD	20.38%	…	57.00%	1100 MHz	3.1 GHz	48 dBm
Event 1: Filmed Laboratory Demonstration	2023	**QDA**	51.1% **	54.60%	70.60%	20 MHz 1 MHZ	5.25 GHz	36 dBm
Ref #7: An Efficient Broadband Symmetrical Doherty Power Amplifier With Extended Back-Off Range	2023	Doherty / DPD	26.44%	…	69.00%	20 MHz	2.05 GHz	43-44 dBm
Event 2: QDA Evaluation Kits August 2024	2024 (August)	**QDA**	TBD AUGUST 2024	71.50%	TBD AUGUST 2024	80 MHz	3.6 GHz	23 dBm (handset) 43-46 dBm (base station)
** these figures, as shown, reflect a further limitation of the combiner average efficiency								

A figure of merit, such as the power efficiency of a power amplifier, needs to be meaningful if one is to compare, plan and build on the results it provides. The industry practice of conveniently measuring at the BackOff point or the peak power output is limited at best. The more rigorous practice of using the PAE measurement calculation and applying that across the entire dynamic range, is too often avoided as it tends to reward the additional work required by providing lower overall performance numbers. Although lower, it is more complete as well as more accurate – and unlike the alternative it's useful to compare alternatives.

The Peak Single Point Efficiency numbers in the table above convey exactly what the name says. Often it is measured as Drain Efficiency, sometimes as PAE efficiency, sometimes measured at the back off point, sometimes measured at the peak power point. Simply said: it is just a highpoint number. This is equivalent to looking at an automobile fuel consumption gage after cresting a hill and traveling downhill, thinking. "I'm really getting high MPG now." True, but it is not indicative of anything predictable.

The average PAE efficiencies in yellow above are accurate representations of efficiency and may be compared from system to system.

Conclusion

Considerable effort has been devoted to documenting an accurate way to measure and account for efficiency. To what end? Until now the telecom industry has had no motive to measure the entire dynamic range of amplifier operation because no amplifying solution worked well over that range. The advent of QDA changes that. QDA's higher overall efficiency necessitates the need for average efficiency measurement so that alternative solutions may be compared. In the words of Lord Kelvin, "If you can not measure it, you can not improve it."

Since the 1930s there have been substantial architecture and technology improvements on power amplifiers, including Doherty Amplifiers, envelope tracking, pre-distortion, LINC Linear Amplification with Non Linear Control, EER Envelope Elimination & Restore, and mode switching. Although each has provided some measure of improvement, each has also been found wanting – either in performance, or limitations, or both These techniques have sometimes increased cost, had distortion and bandwidth effects, but certainly been responsible for doubling amplifier efficiency from 10% to 20%. Doubling performance is always an impressive gain. The impact of QDA is to thrust efficiency to above 50% - and this is done without other negative performance or cost impacts.

Beyond impacting measurement requirements, QDA's beneficial impact to manufacturers is intense:

- In mobile phones QDA's efficiency dramatically increases battery life, allowing the addition of new applications, marketing advantages, and substantially less heat generation.
- In base stations QDA efficiency reduces high power amplifier electricity needs by more than half. This reduces costs through less heat dissipation, less metal in the RRUs (Remote Radio Units), substantially less electricity consumption, less required air cooling.

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[1] Michael Parker, *Digital Signal Processing,* Second Edition 2017 Elsevier Inc., Cambridge, UK 414 pgs.

[2] **NOTE:** The 20 dB dynamic range histogram was computed for 2048 OFDM subcarriers with 16-QAM, using more than 1000 K samples to assure statistical significance for all probabilities. The value of 20dB is appropriate as it is the dynamic range that base stations and handsets manage at present. The 5G specs allow the number of effective subcarriers to a maximum of 3300 subcarriers which corresponds to a dynamic range of 23.9 dB.

[3] https://www.zuj.edu.jo/conferences/ICIT09/PaperList/Papers/Image%20and%20Signal%20Processing/489.pdf
Aburakhia, Sulaiman & Badran, Ehab & Mohamed, Darwish. (2009). Distribution of the PAPR for Real-Valued OFDM Signals. 2. 10.13140/2.1.1212.7680

[4] An overview of peak-to-average power ratio reduction schemes for OFDM signals

Wang, Luqing & Tellambura, Chintha. (2006). An Overview of Peak-to-Average Power Ratio Reduction Techniques for OFDM Systems. 840 - 845. 10.1109/ISSPIT.2006.27091

[5] An approximation for the distribution of the peak-to-average power ratio in carrier-aggregated OFDM signals using level crossing rate analysis

Issa, Mariam & Ajami, Abdel Karim & Artail, Hassan & Nasser, Youssef. (2017). An approximation for the distribution of the peak-to-average power ratio in carrier-aggregated OFDM signals using level crossing rate analysis. 1-8. 10.1109/WiMOB.2017.8115794

[6] https://ieeexplore.ieee.org/document/9712870

P. Saad and R. Hou, "Symmetrical Load Modulated Balanced Power Amplifier With Asymmetrical Output Coupling for Load Modulation Continuum," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 4, pp. 2315-2327, April 2022, doi: 10.1109/TMTT.2022.3147843

[7] https://ieeexplore.ieee.org/document/9971742

J. R. Zhang, S. Y. Zheng and N. Yang, "An Efficient Broadband Symmetrical Doherty Power Amplifier With Extended Back-Off Range," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 4, pp. 1316-1320, April 2023, doi: 10.1109/TCSII.2022.3227045

[8] https://www.researchgate.net/publication/339038366_A_High Efficiency_Doherty_Power_Amplifier_for_Wireless_Base_Stations

Panda, Ajit & Patro, Saroj. (2020). A High-Efficiency Doherty Power Amplifier for Wireless Base Stations. International Journal of Electronics Letters. 9. 10.1080/21681724.2020.1726478

[9] https://ieeexplore.ieee.org/document/9449894

P. Viegas *et al*., "A Novel Highly-Efficient Amplification Scheme for Wireless Communications in a CathLab Environment," in *IEEE Access*, vol. 9, pp. 87520-87530, 2021, doi: 10.1109/ACCESS.2021.3087966