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Optimizing the Perennial Doherty Power Amplifier

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The Doherty power amplifier (PA), invented almost 100 years ago, is used in an increasing number of radio transmitter applications to improve energy efficiency, with numerous ways to build the PA. This article begins with an overview of linearization and efficiency enhancement and, against that backdrop, highlights the associated challenges and some of the numerous solutions. Finally, there is an alternative design flow, illustrated with a case study providing insight into the design and how to achieve the best performance-cost compromise.

LINEARIZATION TECHNIQUES

The four key technical performance parameters in a transmit (Tx) RF front-end (RFFE) are the efficiency, output power, linearity and bandwidth. The latter three are often dictated by system requirements, such as a communications standard. The former, (energy) efficiency, is the differentiator. All other performance parameters being equal, a higher efficiency for a front-end is preferred.

Devices used in the RFFE have imperfect linearity characteristics, preventing them from being fully utilized merely as drop-in components. The linearity of a Tx RFFE can be improved by implementing a linearization scheme. Typically, this will increase the raw cost of a Tx RFFE, trading that for a combination of efficiency, linearity and output power improvement. Numerous linearization methods have been published, stretching back at least to the feedforward[1] and feedback[2] patents. Arguably, the use of nonlinear predistortion dates similarly to the invention of companding.[3] These schemes may be classified according to their modus operandi (see ***Figure 1*** and ***Table 1***).[4] One way of dividing the linearization pie is to identify whether a scheme predicts or extracts its unwanted signal and whether that unwanted correc-

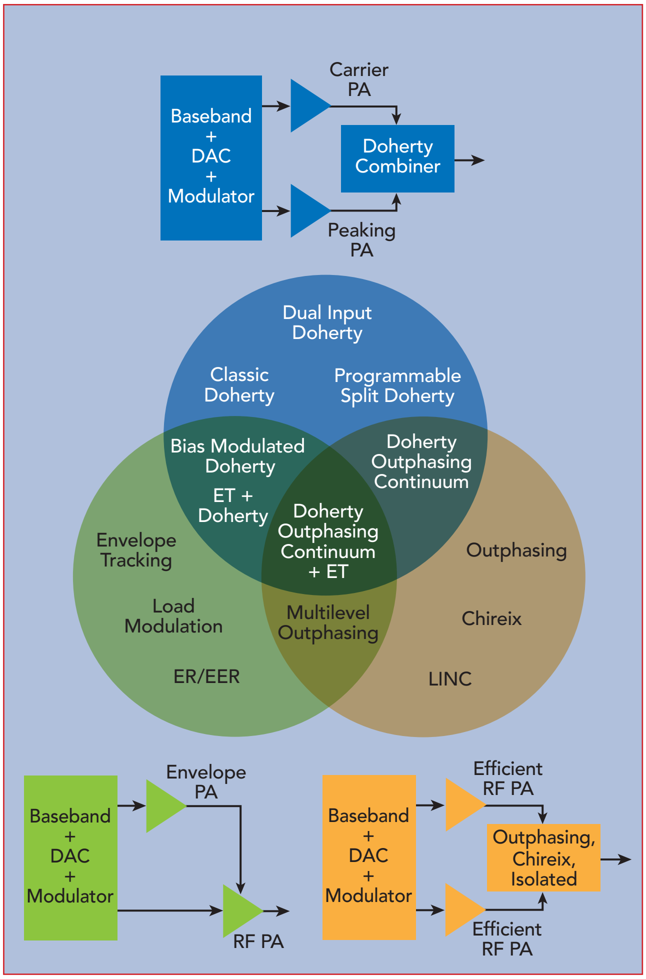

Fig. 1 **Amplifier linearization options using post-source, predicted/synthesized composition schemes.**

TABLE 1

AMPLIFIER LINEARIZATION METHODS

		Impediment Generation	
		Predicted/ Synthesized	**Measured/Extracted**
Correction Location	**Pre-Source**	Digital Predistortion	Cartesian Feedback
		Analog Predistortion	Polar Feedback
	Post-Source	Analog Post-Distortion	Feedforward
		Composition Schemes	Fixed Filtering (e.g., Bandpass)

tion is applied before or after its creation. Classification is useful to understand the general properties and identify the best approach for the application.

Feedforward is an example of a measured, post-correction scheme; feedback is a measured, pre-correction scheme; and predistortion is a predicted, pre-correction scheme. Predictive schemes rely on the unwanted signal being generated, which can potentially be onerous in wider band and lower power systems for digital predistortion (DPD). On the other hand, predictive schemes do not require that distortion exists and can, potentially, eliminate distortion completely.

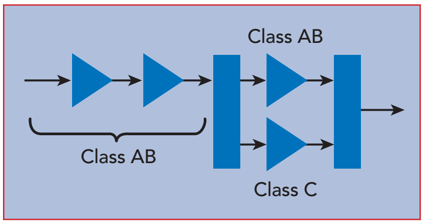

Fig. 2 Simplest implementation of the Doherty amplifier.

Missing from these examples is a whole class of linearization techniques using predictive post-correction. This family of techniques has also been heavily researched and documented over the last 100 years. Outphasing,[5] envelope[6] and Doherty[7] transmitters, along with their hybrids by Choi,[8] Andersson[9] and Chung[10] are examples of such techniques, except they have been primarily marketed for efficiency enhancement rather than as linearization techniques. In their purest forms, envelope and outphasing schemes construct their signals from efficiently generated, nonlinear components, using multiplication and summing of their paths, respectively. A Doherty comprises a reference path, referred to as the "main" or "carrier," and an efficiency path, named the "peaking" or "auxiliary." A more comprehensive mathematical analysis of the Doherty design is beyond the scope of this article and is available in a plurality of texts. For further information, the reader is especially referred to Cripps.[11]

DOHERTY IMPLEMENTATIONS

Arguably, the most common and often quickest starting point for a Doherty amplifier design is the "zeroth embodiment" (see ***Figure 2***), comprising a

- Fixed RF input to the final stage power splitter.
- Main and auxiliary amplifiers, differently biased (e.g., using class AB and class C).
- Doherty combiner made from a quarter-wavelength transmission line.

In most applications, this architecture does not provide sufficient power gain—at least not from a single, final stage—and additional gain stages are cascaded ahead of the power splitter. Criticism of this most commonly used implementation include

- No method for compensating gain and phase variations in any domain after the design is frozen.
- Both the efficiency and output power are traded-off because of the bias class. In effect, the class C bias, an open loop analog circuit, is driving this.
- Efficiency enhancement is limited to a single stage. With a multistage cascade, this limits the performance improvement, especially as gain diminishes at higher frequencies.

From another perspective, the Doherty engine is an open loop scheme, with several key functional mechanisms derived from the bias points of the transistors. Once the other variables are defined (e.g.,

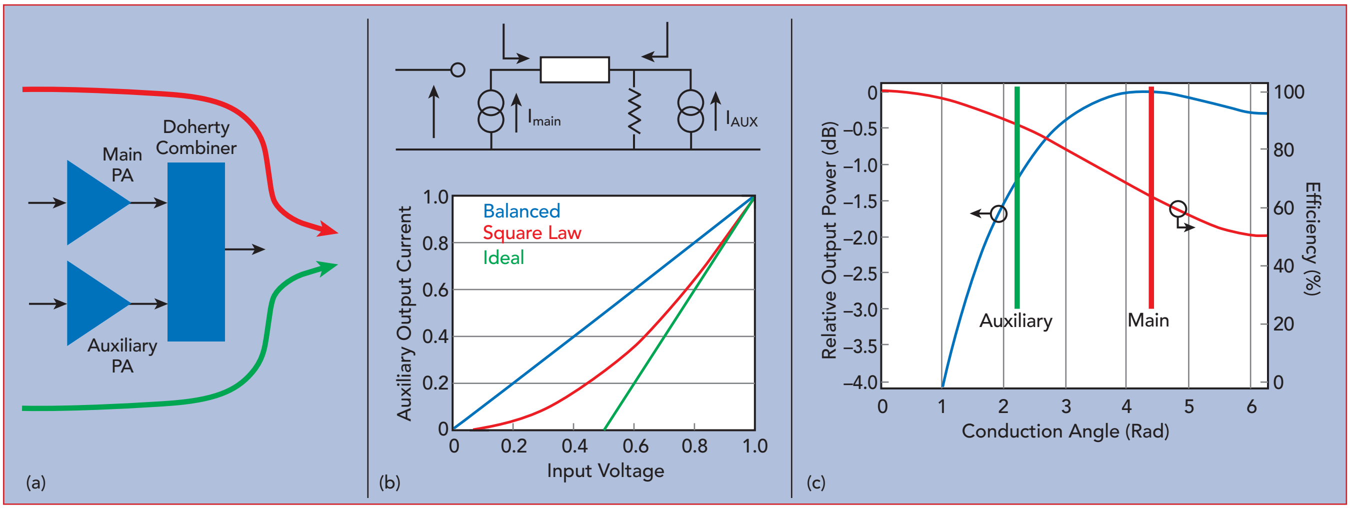

Fig. 3 Doherty amplifier challenges: combiner amplitude and phase matching (a), auxiliary amplifier current response (b) and power-efficiency trade-off (c).

phase offsets, splitter design, etc.), only one or two handles are provided, upon which multiple critical adjustments rely.

Challenges

One of the ways the Doherty improves efficiency is load modulation. The engine that drives that is the difference in output currents, sourced into the combiner from two or more amplifiers. Since the engine can only approximate the Doherty operation, the challenge for the designer is to enable the engine to approximate it with the best, but still appropriate, cost-performance paradigm. Some of the potential hindrances or impediments to Doherty performance are 1) the amplitude and phase matching of the signals incident to the combining node, especially over frequency (see ***Figure 3a***). Deviation from the ideal degrades efficiency and output power. Potentially, this can be more destructive, as the devices are intentionally not isolated, with the efficiency enhancement relying on their mutual interaction through the combiner. 2) Ideally, the auxiliary path of the Doherty engine exhibits a dog leg or hockey stick characteristic (see ***Figure 3b***). Failure to achieve the ideal is often the primary reason for not realizing the famous efficiency saddle point. As the characteristic tends from the ideal to a linear response, the Doherty amplifier increasingly behaves like its quadrature-balanced relative—albeit with a non-isolated combiner—especially its efficiency performance. 3) The commonly used "differential biasing" of the main and auxiliary operating in class AB and class C, respectively, forces the output power and efficiency of both amplifiers to be degraded (see ***Figure 3c***). As Cripps showed,[11] the continuum of quasi-linear amplifier classes from A to C, which theoretically operate with sinusoidal voltages across their sources, varies their respective maximum output power and efficiency characteristics. At the same time, if biasing is used to create the difference engine, as is the case in the classical Doherty embodiment, there is intrinsically a trade-off between output power and efficiency. Simultaneously, differential biasing increases the Doherty effect, yet decreases the achievable performance.

VARIANTS AND IMPROVEMENTS

The following variations on the basic concept may be more appropriate for some applications and, with the classical implementation, offer the designer performance and flexibility options.

- Multiple gain stages inside the Doherty splitter and combiner.
- N-way Doherty.
- Intentionally dispersive splitter.
- Programmable splitter.
- Bias modulation.
- Supply modulation, i.e., adding a third efficiency enhancement technique to the two leveraged by Doherty.
- Envelope shaping.
- Digital Doherty.

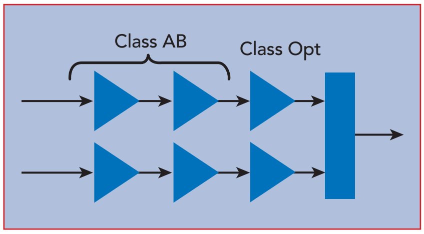

Fig. 4 Digital Doherty amplifier, where the main and auxiliary amplifier operating class is digitally controlled.

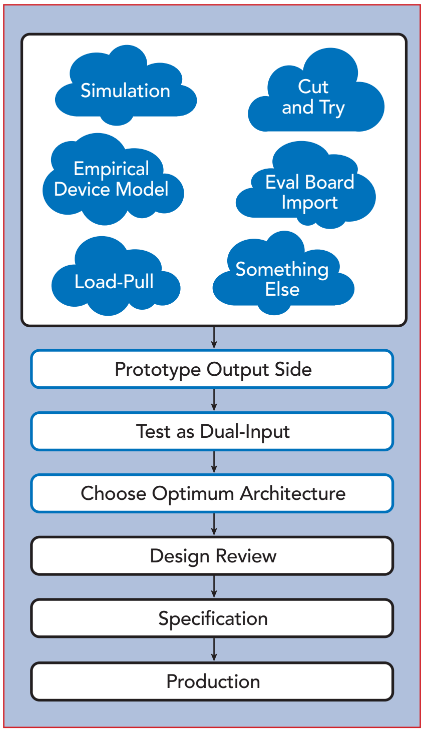

Fig. 5 Measurement-aided design flow for a digital Doherty amplifier.

In addition to the different architectures available to the designer, three points in the product life cycle allow adjustments. During the design phase, the design parameters can be modified, recognizing the parameters will be passed to production as fixed values (e.g., the input splitter design). During production, the parameters may be modified or tuned, typically based on measured data, and then frozen or fixed through programming. One example is the nominal bias voltage used to generate the target bias current in the devices. Once the equipment is deployed in the field, parameters may be updated, either continuously or at specific times, either open or closed loop. Open loop concepts rely on sufficiently predictable behaviors, while closed loop concepts might require built-in measurement and control. One example is circuitry for temperature compensation. These product life cycle options provide a plurality of solutions with no "best" solution. It is just as important for the designer to be aware of the manufacturing and supply capabilities following the design as the design challenges and trade-offs made during the design phase.

At the opposite end of the solution spectrum from the zeroth embodiment is the digital Doherty (see ***Figure 4***). This architecture is characterized by an input split which stretches back into the digital domain, prior to the digital-to-analog conversion. The ability to apply digital signal processing to the signal applied to both amplifier paths potentially gives unsurpassed performance from a set of RF hardware. Compared to the standard Doherty implementation, the digital version can achieve 60 percent greater output power, 20 percent more efficiency and 50 percent more bandwidth without degrading predictive, pre-correction linearity.[12]

MEASUREMENT-AIDED DESIGN FLOW

To optimize any Doherty design, it is advisable to build simulation environments that correlate well with the design, to understand trends and sensitivities. The simulation enables a significant part of the

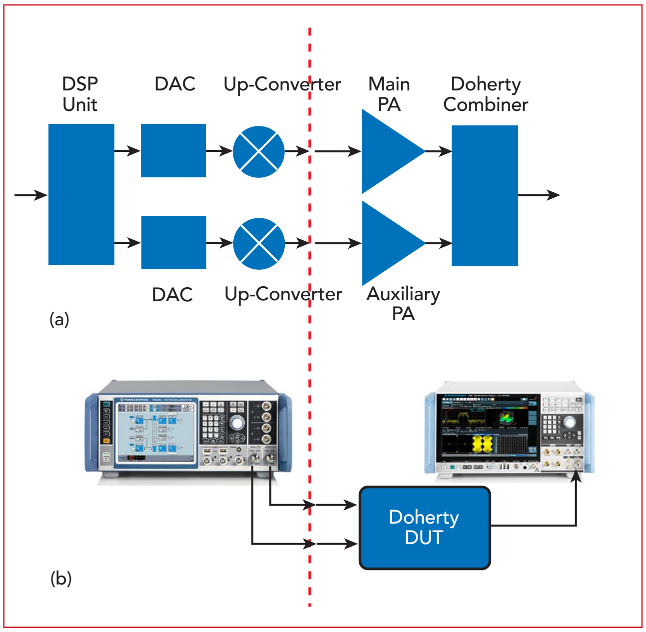

Fig. 6 **Simplified block diagram (a) and hardware setup (b) for designing a digital Doherty amplifier.**

development to be covered quickly. Inputs to the first step might include load-pull data or models for the candidate devices, a theoretical study of the combiner and matching network responses, evaluation boards with measured data or other empirical data. Building on this starting point, the design flow can be supplemented with measurement-aided design (see ***Figure 5***).

For the digital Doherty, the starting point for this approach is a Doherty comprising two input ports, input and output matching networks, active devices, bias networks and the Doherty combiner (see ***Figure 6***). Measuring the prototype Doherty as a dual-input device provides greater insight into the performance limitations, trade-offs and reproducibility expected in a production environment. Critical to the test set-up are two signal paths, whose signals may be varied relative to each other. In addition to applying precise, stable and repeatable amplitude and phase offsets to the signals, it is advantageous to be able to apply nonlinear shaping to at least one of the signal paths.

The measurement algorithm may be rapid or more exhaustive, programmed to seek the optimum values for desired parameters or configured to characterize a wide range of parameters. In a simple case, the designer may want to confirm the best-case quantities and their relative amplitude and phase balance values. More complicated, a detailed sweep to enable a sensitivity analysis or rigorous solution space search may be warranted. The post-processing of these measurements can be as simple or sophisticated as the user wishes.

CASE STUDY

To demonstrate the design flow and achievable results, a digital Doherty PA for a 3.5 GHz, 5G New Radio (NR) base station was designed using a single stage unmatched GaN power transistor, the Qorvo® TQP0103. A dual-path R&S®SMW200A vector signal generator provided the two input signals to drive the GaN am-

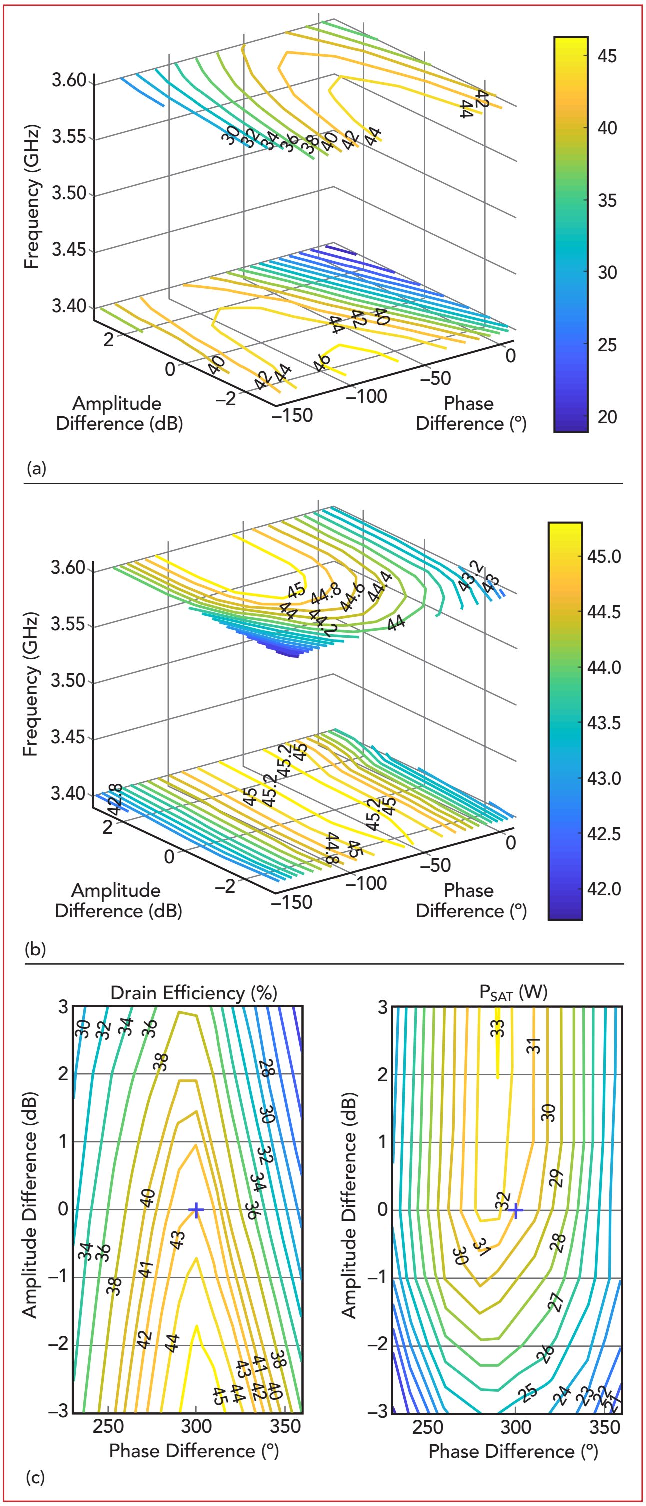

Fig. 7 **Dual-input Doherty in linear operation: measured efficiency at 35.5 dBm (a), saturated power (b) and worst-case efficiency and power (c).**

plifier. For measurement of dependent quantities, the single RF output of the amplifier was connected to an R&S®FSW Signal Analyzer. DC power for the devices was sourced from an R&S®HMP power supply, which measured the DC power consumption. The amplifier was stimulated using differentially linear and nonlinear signals, the former sweeping the input power, ampli-

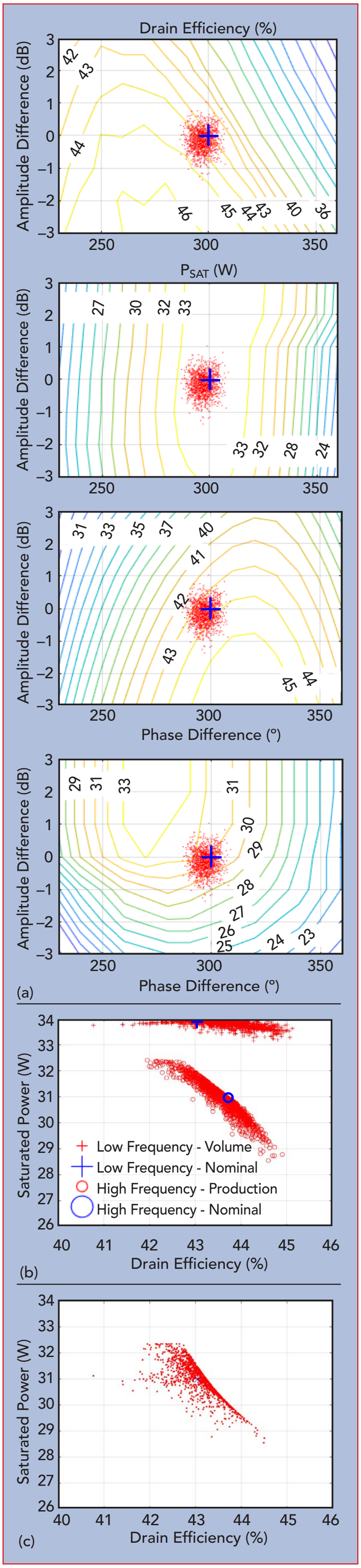

Fig. 8 Gain and phase variation of a population of split digital Doherty amplifiers with a fixed RF input (a), saturated power and efficiency using a look-up concept (b) and cumulative, worst-case production distribution (c).

tude and phase. The nonlinear tests used a variable shaping function, amplitude dependent, at two frequencies. Output power, output peak-to-average power ratio, adjacent channel leakage ratio (ACLR) and current consumption were measured, and the measurement results were analyzed using MATLAB®.[13]

Analyzing the linear measurements, efficiency at a specified power level and saturated power were plotted versus the amplitude and phase differences (see ***Figure 7***), with the worst-case efficiency and output power shown in Figure 7c. In the basic Doherty embodiment, a quasi-constant amplitude/phase split is chosen for the operating frequency. The efficiency and saturated power for these amplitude/phase values can be determined by extracting the worst-case performance at the test frequencies.

Selecting a nominal amplitude/phase split, a perturbation representing the natural variation in production may be added to the evaluation. Using a look-up table, the bulk effect of these part-to-part variations can be observed, as shown in ***Figure 8***. Figure 8a shows the drain efficiency and saturated output power at two frequencies, Figure 8b shows the estimated production spread of saturated output power and drain efficiency versus the nominal values for the same two frequencies. Figure 8c shows the cumulative production spread, aggregating the results from the two frequencies. Paradoxically, in this case, most of the part-to-part variation is in the target variable, efficiency.

By adopting an alternative approach to the input splitter design, this variation can be reduced. Using a dispersive input splitter design, meaning using different amplitude and phase differences at the two design frequencies, advantageously enables the stacked contour plots shown in Figure 8a to, in effect, slide over one another. Using the same part-to-part variation data with this dispersive splitter design yields a better result (see ***Figure 9***), with a higher mean efficiency and lower standard deviation.

By directly generating signals for the two amplifier inputs in the digital domain, the deficiencies of the Doherty amplifier are significantly reduced. Additionally, the simple part-to-part amplitude/phase variations shown in the linear example may be eliminated. To illustrate this, albeit not exhaustively, the auxiliary path was programmed with a square law shaping function applied to both the amplitude and phase, with the phase "start" and "end" values—the phase with zero and maximum input amplitude—varied randomly. With a common bias for the two amplifiers, only a trade-off between output power and efficiency remains, rather than those and the Doherty difference engine magnitude.

To establish a baseline, driving the commonly biased amplifiers with a linearly differential signal enabled the equivalent "balanced" performance to be ascertained: the available saturated output power in this mode was 0.5 dB higher than the differential biased case (12 percent higher power). That represents the "cost" of operating the Doherty engine using differential bias points. The scatter plot of random shaping functions applied to the auxiliary path yields the locus of performance shown in ***Figure 10***, reflecting the distributions of average power versus efficiency and peak envelope power (PEP) versus average power. The saturated output power is 1.7 dB higher than the conventional Doherty amplifier (48 percent higher power), suggesting that 1.2 dB of the improvement (32 percent) is from better amplitude/phase matching of the signal paths.

The 1.7 dB improvement in saturated output means the amplifier may be operated at that increased output power without compromising headroom, and the increase in average power is associated with a 5 point increase in efficiency (from 44 to 49 percent). Alternatively, devices with 48 percent smaller periphery may be used to achieve the original target output power. Taking into account the expected part-to-part variation, this reduction in device periphery might be reduced further.

CONCLUSION

Significant improvements in Doherty performance can be achieved by addressing the input side of the design. The use of either an intentionally dispersive or programmable input split can improve performance, especially considering manufacturing distributions. According to peer reviewed research,[12] the digital Doherty with nonlinear input splitting or shaping can achieve 60 percent more output power, 20 percent more efficiency and 50 percent greater bandwidth without any degradation in predictive linearization. The case study described in this article achieved 47 percent higher output power and 11 percent greater efficiency over a fixed bandwidth.

A measurement-aided methodology for extracting and understanding possible improvements was demonstrated. While efficiency and saturated power served as examples, they do represent the two most important parameters in most Doherty designs. Regardless of which Doherty architecture is used, this design methodology provides more detailed and rigorous insight and improves both time-to-market and the cost-specification paradigm.■

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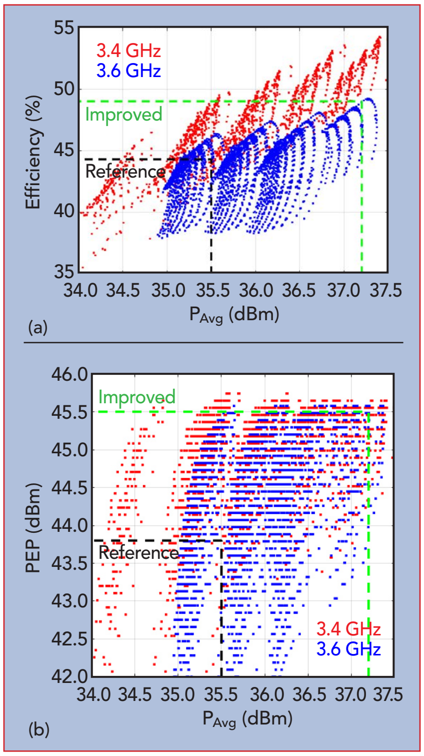

Fig. 10 Efficiency vs. average output power (a) and PEP vs. average output power (b) for a dual-input Doherty amplifier using with square-law shaping and randomized phase.

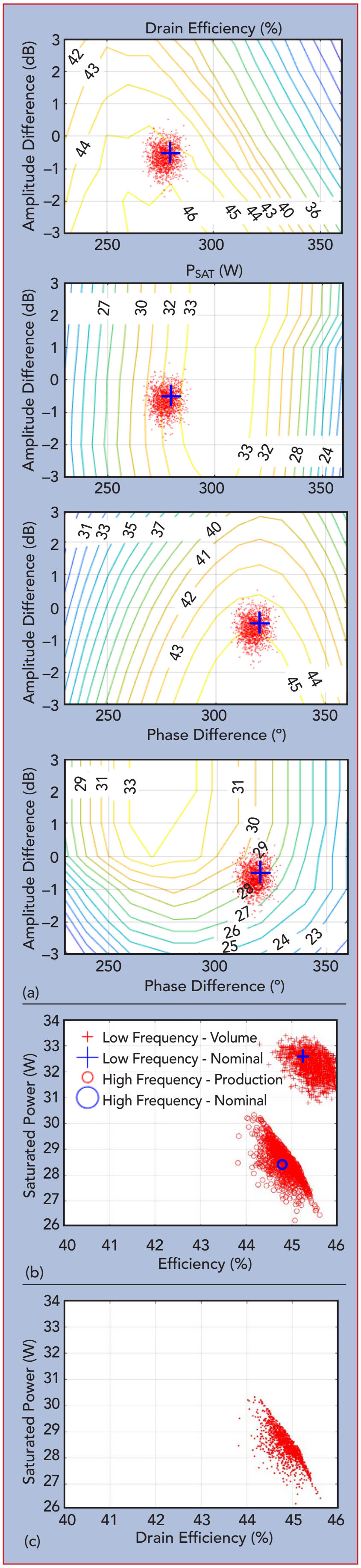

Fig. 9 Digital Doherty amplifier population using a dispersive input split: gain and phase variation (a), saturated power and efficiency (b) and cumulative, worst-case production distribution (c).