System-based RF Amplifier Design

Proper transceiver design depends upon a solid understanding of the performance parameters and trade-offs of RF amplifiers

Glossary of acronyms

ACLR — Adjacent Channel Leakage Power Ratio
ACP — Adjacent Channel Performance
ACPR — Adjacent Channel Power Ratio
AlGaAs — Aluminum Gallium Arsenide
e-PHEMT — enhancement Mode Pseudomorphic High Electron Mobility Transistor
EVM — Error Vector Magnitude
GaAs — Gallium Arsenide
GaAsFET — Gallium Arsenide Field-Effect Transistor
HBP — Heterojunction Bipolar Transistor
HEMP — High Electron Mobility Transistor
HFET — Heterostructure Field-Effect Transistor
Idss — drain current at zero gate voltage
IF — Intermediate Frequency
InGaP — Indium Gallium Phosphide
IS-95A — the first CDMA cellular standard
I-V — Current-Voltage
LFOM — Linear Figure of Merit
LO — Local Oscillator
MESFET — Metal Demiconductor Field-Effect Transistor
MMIC — Monolithic Microwave Integrated Circuit
MTTF — Mean Time to Failure
OIP3 — Output Third-Order Intercept Point
P1dB — 1 dB Compression Point
PA — Power Amplifier
PAE — Power Added Efficiency
R-C — Resistor-Capacitor
RX — Receive
SiGe — Silicon Germanium
TX — Transmit

A multitude of system requirements must be considered when choosing an optimal amplifier from the many devices available in the marketplace. Since early days when only GaAsFET and silicon bipolar technologies were available, amplifier choices have significantly increased for the RF designer. This article discusses performance trade-offs among GaAs MESFET, InGaP HBT and GaAs HFET technologies targeted at wireless and wireline basestation driver amplifier applications. Measured ACPR and PAE performance is shown for 0.5, 1 and 2 W amplifiers utilizing the various process technologies.

In a standard basestation transmitter application, various RF amplifiers can be placed in three categories: small-signal buffer amplifier stages, driver amplifier stages and power amplifier stages (see Figure 1). Although driver amplifier stage applications are the main focus, key parameters are fundamentally similar for RF designers looking to choose a device to amplify a signal.

Small-signal RF performance, such as gain and return loss, is what most engineers look for with an RF amplifier — especially for the small-signal amplifier stages. Following that, and depending on where the amplifier is used in the chain and whether the amplifier is used in the RX/TX path, device linearity, compression and noise figure are the key parameters.

For digital radio applications, linearity can be described as spectral regrowth of the modulated (as ACPR, ACLR or EVM) signal rather than the traditional figure of merit with OIP3, which is ideally independent of the output signal level. Because these characterizations depend on the signal output power level, graphs with respect to output power are often shown on suppliers' datasheets rather than a direct numerical value.

Other RF performance parameters that designers often consider are the device's operational bandwidth, gain flatness across the frequency of operation, RF stability, the amplifier's performance over temperature and, depending on the application, PAE. All other things being equal, subtle considerations designers often make are with the reliability of device (also known as MTTF) and the ease of designing or matching with the device.

With cost-reduction design cycles becoming shorter and shorter, the devices' price competitiveness becomes important — especially with the purchasing engineer.

Among subtle factors engineers can consider to lower the overall cost of the system is the feasibility to reuse the same amplifier in other parts of the system chain. For example, a high linearity device with low noise figure performance can be used in both the RX and TX chains. Another aspect affecting the overall system cost is parts count. Certain amplifier configurations are fairly complex and may require many external components to properly bias and tune.

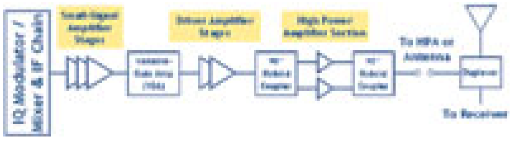

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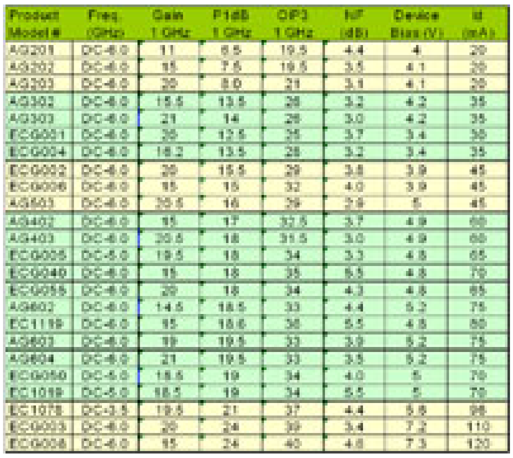
Figure 1. Simplified basestation transmitter block diagram.



Product Model #	Freq. (GHz)	Gain 1 GHz	P1dB 1 GHz	OIP3 1 GHz	NF (dB)	Device Bias (V)	Id (mA)
AG201	DC-6.0	11	6.5	19.5	4.4	4	20
AG202	DC-6.0	15	7.5	19.5	3.5	4.1	20
AG203	DC-6.0	20	8.0	21	3.1	4.1	20
AG302	DC-6.0	15.5	13.5	26	3.2	4.2	35
AG303	DC-6.0	21	14	26	3.0	4.2	35
ECG001	DC-6.0	20	12.5	25	3.7	3.4	30
ECG004	DC-6.0	16.2	13.5	28	3.2	3.4	35
ECG002	DC-6.0	20	15.5	29	3.8	3.9	45
ECG006	DC-6.0	15	15	32	4.0	3.9	45
AG503	DC-6.0	20.5	16	29	2.9	5	45
AG402	DC-6.0	15	17	32.5	3.7	4.9	60
AG403	DC-6.0	20.5	18	31.5	3.0	4.9	60
ECG005	DC-5.0	19.5	18	34	3.3	4.8	65
ECG040	DC-6.0	15	18	35	5.5	4.8	70
ECG055	DC-6.0	20	18	34	4.3	4.8	65
AG602	DC-6.0	14.5	18.5	33	4.4	5.2	75
EC1119	DC-6.0	15	18.6	36	5.5	4.8	80
AG603	DC-6.0	19	19.5	33	3.9	5.2	75
AG604	DC-6.0	21	19.5	33	3.5	5.2	75
ECG050	DC-5.0	18.5	19	34	4.0	5	70
EC1019	DC-5.0	18.5	19	34	5.5	5	70
EC1078	DC-3.5	19.5	21	37	4.4	5.8	98
ECG003	DC-6.0	20	24	39	3.4	7.2	110
ECG008	DC-6.0	15	24	40	4.6	7.3	120

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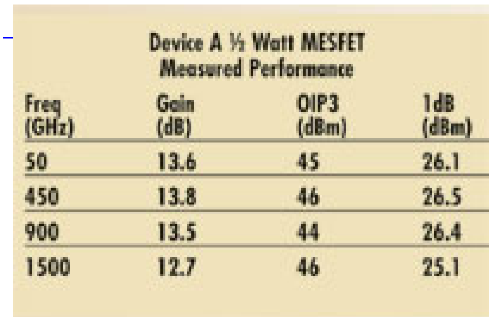
Figure 2. InGaP HBT gain blocks.

Small-signal Amplifier Stages

The small-signal buffer amplifier stages in the RF, IF, TX & LO sections of a system are the simplest amplifiers for designers to consider in the design of their system. Darlington-pair HBT gain blocks are probably the most common devices. They are designed internally using resistive matching and thus are inherently broadband and easy to use.

Because gain blocks are simple, designers have a wide variety of choices from various suppliers, including many process technologies: SiGe, AlGaAs or InGaP HBTs. HBTs were initially pushed into the market using AlGaAs technology, but many engineers have steered away from using AlGaAs because of reliability concerns. SiGe and InGaP HBTs are the process technologies of choice, from price competitiveness and reliability standpoints. Unfortunately, for higher power applications, increased power densities force SiGe HBTs to operate on the borderline limits of reliability and RF stability.



Device A ½ Watt MESFET Measured Performance

Freq (GHz)	Gain (dB)	OIP3 (dBm)	1dB (dBm)
50	13.6	45	26.1
450	13.8	46	26.5
900	13.5	44	26.4
1500	12.7	46	25.1

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Figure 3.

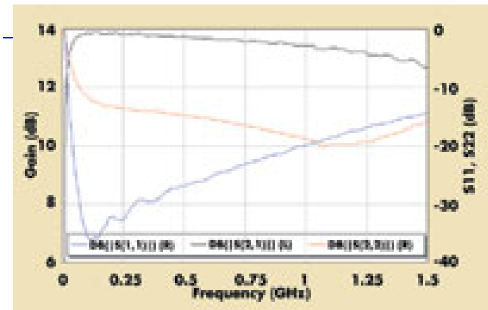

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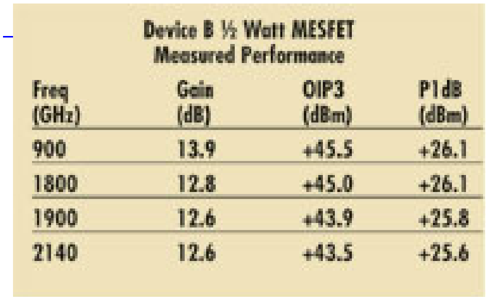
Figure 4. Device A small-signal performance.

Although SiGe HBTs are price-competitive for low-power applications, InGaP HBTs offer increased reliability and flexibility for higher-power applications. Figure 2 lists gain blocks with respect to increasing compression levels.

GaAs MESFETs for Driver Amplifiers

RF designers looking for driver amplifier stages in a transmit application with compression levels between 20 to 33 dBm also look for similar RF characteristics as with the small-signal amplifiers, such as gain, return loss, OIP3 and P1dB. Because of the larger power requirements though, Darlington-pair gain blocks are unsuitable and are not available for these applications. Designers have choices between MMIC and discrete devices of various competing technologies: GaAs MESFET, GaAs HBT, InGaP HBT, GaAs HFET, GaAs HEMT and e-PHEMT, for example. The following information gives some details about performance characterizations of InGaP HBT, GaAs HFET and InGaP HBT process.



Device B ½ Watt MESFET
Measured Performance

Freq (GHz)	Gain (dB)	OIP3 (dBm)	P1dB (dBm)
900	13.9	+45.5	+26.1
1800	12.8	+45.0	+26.1
1900	12.6	+43.9	+25.8
2140	12.6	+43.5	+25.6

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Figure 5.

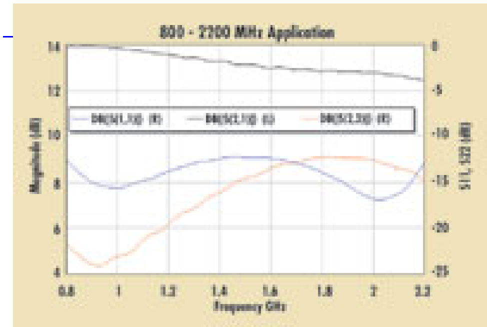

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Figure 6. Device B small-signal performance.

A key feature of MESFET amplifiers is their suitability for broadband amplifier designs. Operational bandwidths greater than five octaves can be achieved with few external matching circuit components. Flat performance across the 50 to 1500 MHz bandwidth with high linearity (see Figures 3 and 4) can be achieved, as can unique circuit design for all three major mobile infrastructure frequency bands at 900 MHz, 1900 MHz and 2140 MHz with a 0.5 W driver amplifier. Performance charts and values are shown in Figures 5 and 6.

Manufacturers have optimized processes for driver applications where high linearity is required. Suppression of intermodulation products of multi-tone signals allows for high LFOM values. Designers often use this figure of merit to measure the amplifier's linearity efficiency. The LFOM is defined as the difference in OIP3 and the P1dB. Typical values for other process technologies are around 10 dB for HEMTs and 15 dB for HBTs. Optimization achieved with MESFET technology allows for the optimal required load impedance for linearity and compression at 50Ω while concurrently keeping the output load impedance of the amplifiers around 50Ω. Thus from a designer's standpoint, output return losses better than 14 dB can be achieved and do not require any additional external matching to optimize for return loss, linearity or compression.

Device C ½ Watt HFET performance.

Frequency (GHz)	Gain (dB)	OIP3 (dBm)	P1dB (dBm)
150	13.9	+32	+26.8
350	13.9	+41	+26.6
550	13.9	+40	+26.4
750	13.9	+40	+26.4

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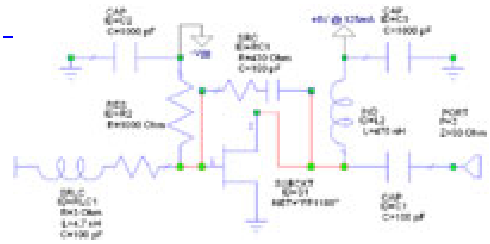

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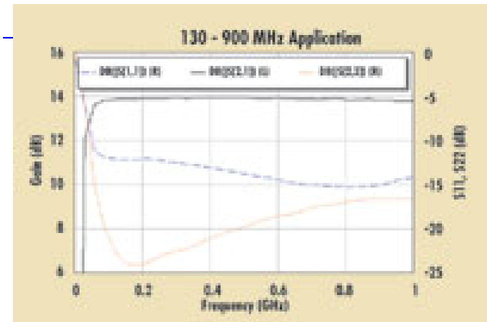
GaAs HFETs for Driver, PA Stages

GaAs HFETs are also widely used for driver or power amplifier applications. HFET I-V characteristics offer the ability to achieve higher power levels than MESFETs with higher P1dB efficiency. High breakdown voltages make this process technology ideal for designs operating under large signal conditions such as output power stages for ultra-small repeater applications. But similar to other depletion-mode FET devices, HFETs require a negative power supply. In addition, HFETs offer slightly lower LFOMs compared to MESFET devices. This translates into slightly lower OIP3 values for HFET devices with comparable compression values than for devices from other process technologies. Details presented further on show that the ACP performance for wireless basestation or repeater applications is about the same or better than devices from other process technologies.



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Comparison of RF and DC Parameters for Various ½ Watt Amplifiers at 900 MHz

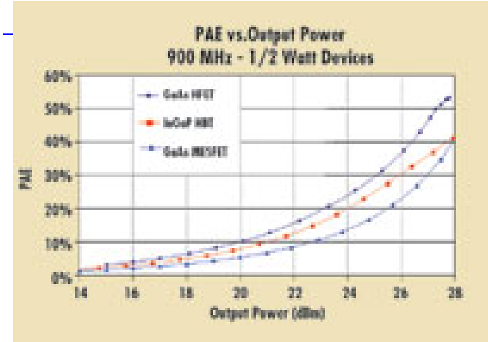
Type	MESFET	HFET	HBT
Gain (dB)	13.9	17.5	17.5
NF (dB)	3.1	2.7	7
P1dB (dBm)	+27	+27.4	+28.7
OIP3 (dBm)	+46	+40	+43
Bias Voltage	+9 V	+8 V, −VG	+5 V
Pdiss (W)	1.8	1	1.25
P1dB Efficiency	28%	55%	59%
Bandwidth	Wideband	Narrowband	Narrowband
Effective BW @ 1GHz	400 MHz	100 MHz	100 MHz

[10]

Similar to MESFET devices, HFETs can easily be tuned for broadband applications. As shown in Figure 8, only two input matching components along with a feedback R-C network are required to design a broadband VHF amplifier from 130 to 900 MHz with less than 0.1 dB gain flatness.

InGaP HBTs for Driver, PA stages

Operation of devices using GaAs MESFET and HFET technologies for driver amplifier applications above 0.5 W require biasing voltages above 8 V. Thus the use of these types of devices can sometimes be undesirable for designers constrained to +5 V regulators in their system. InGaP HBT devices resolve this problem by operating directly from a +5 V rail while offering designers high power-added efficiencies and linearity. In addition, HBT devices often are configured so that designers can set the amplifier bias to optimize Class A or Class AB operation.



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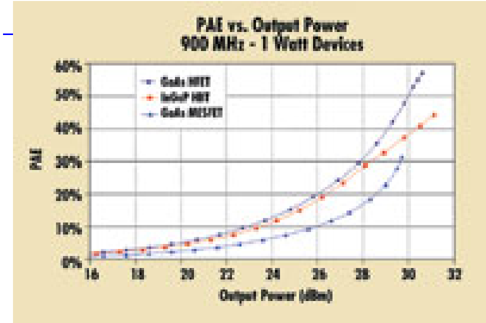

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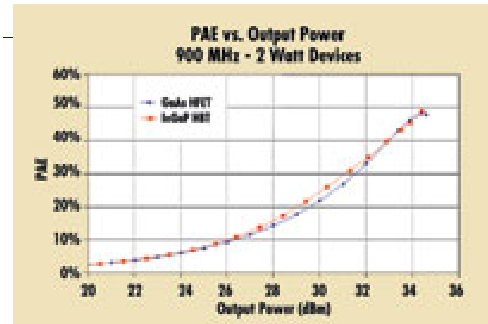
Although similar GaAs HBT technology has been available, reliability limitations have left the primary applications for GaAs HBTs to handsets. Components targeting wireless and wireline basestation infrastructure are often biased on constantly and must be orders of magnitude more reliable. Reliability engineers often define the characteristic as MTTF. Amplifiers having an MTTF exceeding 1 million hours (more than 100 years) at the maximum recommended operating case temperature are now available.



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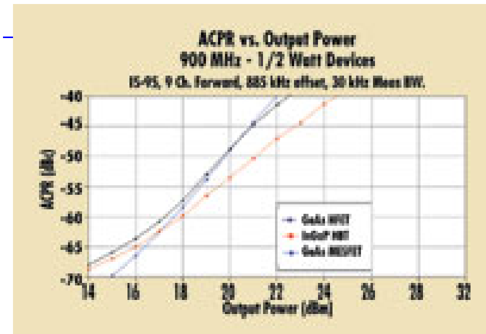

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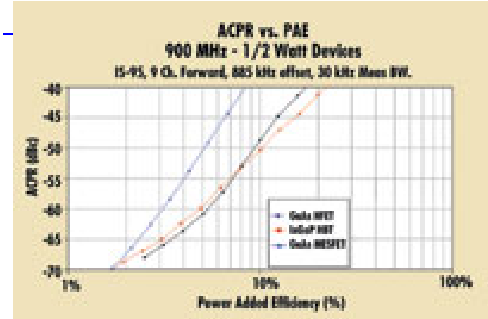
Although HBTs offer several advantages over other process technologies, designers must consider some trade-offs. Often, the optimal load impedance required for maximum linearity and compression is low. It can lead to configuring HBT amplifier output matching without the 14 dB minimum return loss designers often prefer. In addition, the low impedance limits HBT amplifiers to narrowband applications; designs typically are not ideal for bandwidths greater than 100 MHz. Moreover, HBTs have higher noise figures compared to GaAs MESFET and HFET technologies — although that is not a major concern for transmit power applications.



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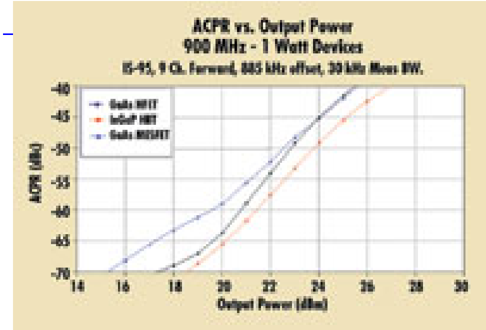

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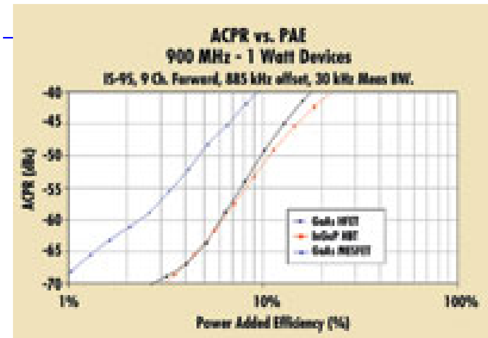
Comparison of Devices From Various Process Technologies

The information presented discusses the benefits and trade-offs that GaAs MESFET, GaAs HFET and InGaP HBTs have to offer. With the understanding that designers have different requirements for their various applications, Figure 10 lists the RF and DC characteristics for 0.5 W devices configured for operation in the cellular band of 900 MHz. As discussed above and as shown in Figure 10, the major performance differences can be seen with the noise figure, OIP3 and P1dB efficiency values between GaAs MESFETs/HFETs and InGaP HBT devices.

Further performance plots for power-added efficiency vs. output power for 0.5, 1 and 2 W amplifiers are shown in Figures 11 to 13. The plots show that HFET and HBTs behave fairly similarly for efficiency, and MESFETs perform slightly worse.



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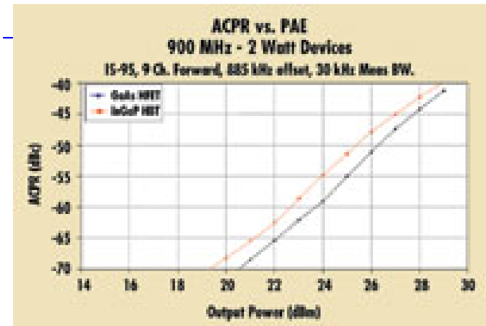

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Finally, Figures 14 through 19 illustrate the true linearity performance for the amplifier used in a realistic system environment. ACPR performance using a standard IS-95A signal is examined in terms of output power and efficiency for various devices ranging in power from 0.5 to 2 W. Figure 14 shows that a designer must also take into account the targeted operating power level when looking for an amplifier with the highest linearity. The acceptable ACPR level within the system for the particular amplifier socket depends on the overall chain analysis. Based on these observations, note that the stated OIP3 values given on amplifiers may not always state true linearity characteristics of how the device performs in a true modulated signal environment.

Summary

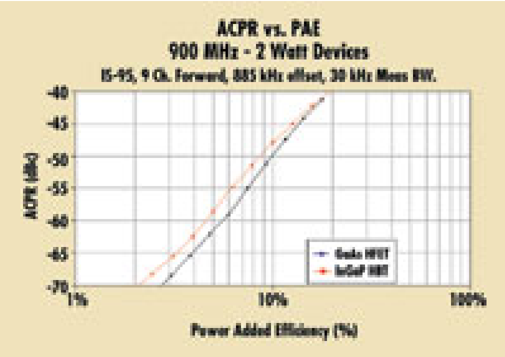

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Figure 19. ACPR vs. PAE Plot (2 W devices)

RF designers have a multitude of options when choosing an RF amplifier. Many RF performance characteristics should be considered that extend past the gain, P1dB and OIP3 parameters typically shown on a datasheet. Modulated signal linearity performance and other subtle characteristics such as ease of use, bandwidth and cost competitiveness can also guide designers in making device and process technology decisions for driver amplifier applications.

WD&D

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By Tuan Nguyen

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