Power Amplifiers for 5G Transmitters

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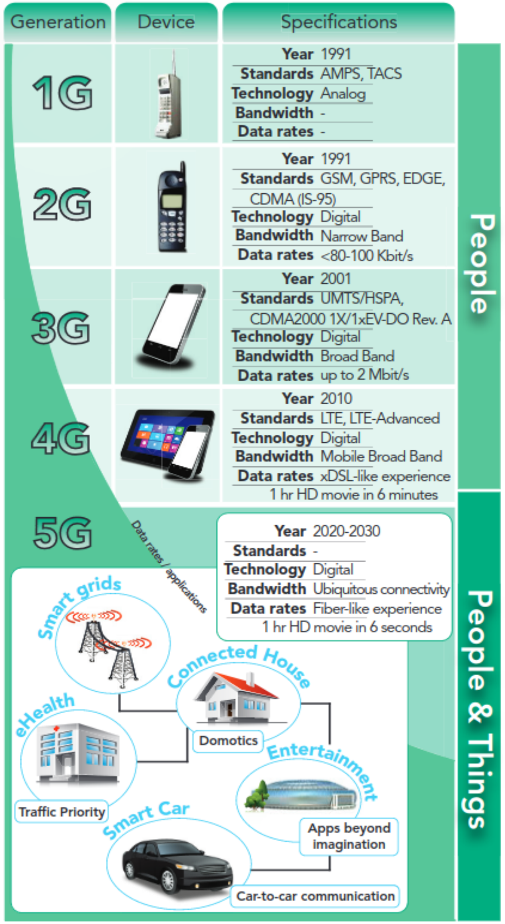
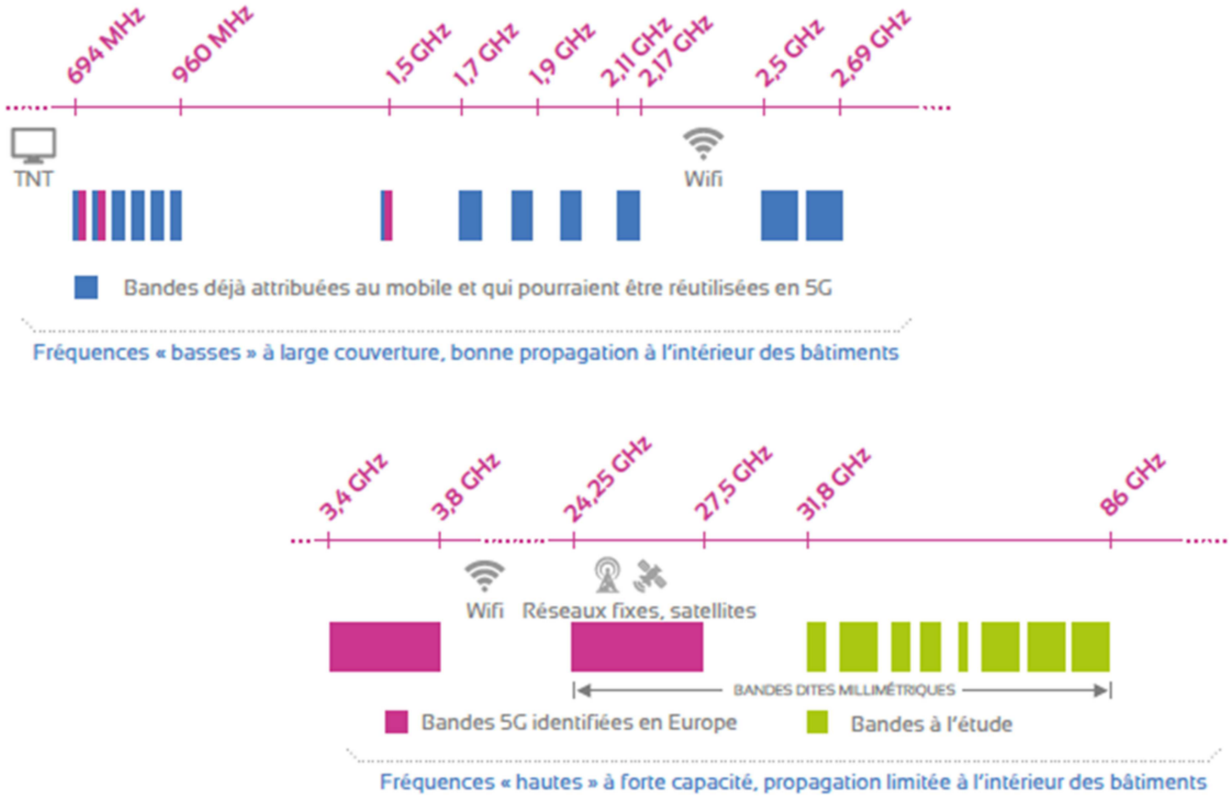
Outline

- Introduction (5G Context)
- PA fundamentals
- Chalenges and Opportunities

5G Frequency Spectrum



Test Strategies for 5G NR, Anritsu



Evaluation de l'exposition du public aux ondes électromagnétiques 5G, Volet 1 : présentation générale de la 5G, Juillet 2019, ANFR.

Power Cost

OBSERVATOIRE DU DEPLOIEMENT DES RESEAUX MOBILES
Métropole, RESULTATS AU 1 ER JANVIER 2024
https://www.anfr.fr

Base Stations in France

5G – 43673 (With permission)
4G - 57947 (Operating)
3G - 57455 (Operating)
2G - 39714 (Operating)

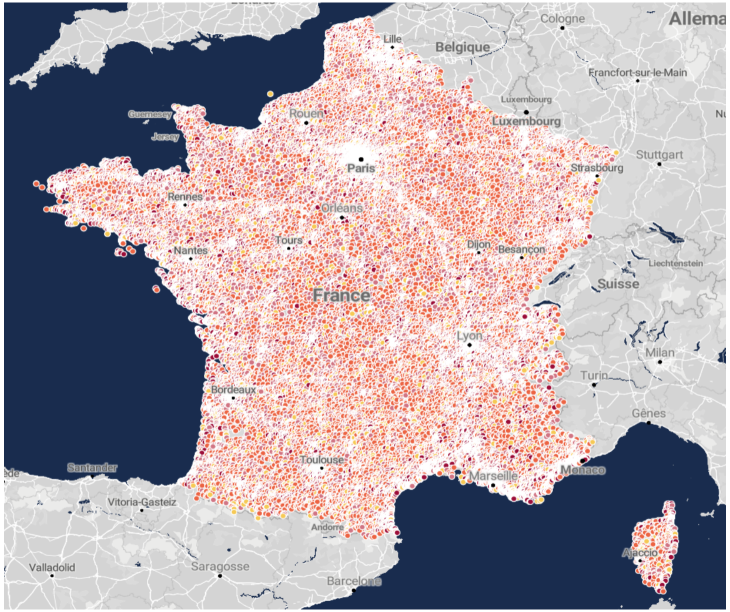
198789
x 2.5 kW

~ 500 MW

Very roughly

"...Ainsi, selon l'Arcep, une antenne 5G peut consommer jusqu'à 19 kilowatts quand une antenne 4G se contente de 7 kilowatts..."

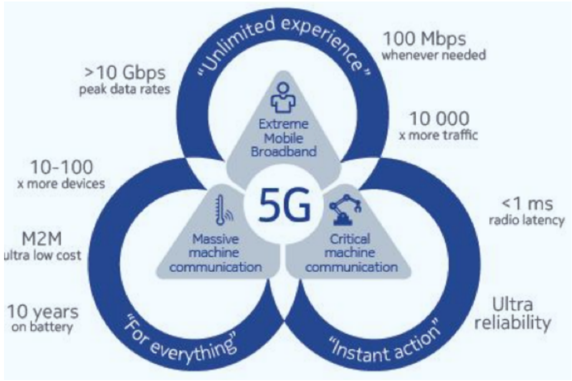
La 5G est-elle soluble dans la sobriété, CNRSlejournal.fr (https://lejournal.cnrs.fr/articles/la-5g-est-elle-soluble-dans-la-sobriete)



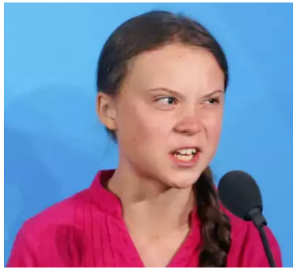
https://www.ariase.com/mobile/carte-antennes

https://www.anfr.fr
https://www.arcep.fr/cartes-et-donnees/nos-cartes/deploiement-5g/observatoire-du-deploiement-5g-decembre-2023.html

The Future (and present) is “Green”



How dare!



Maybe better PA designs can help

- Most of the energy spent in a transceiver occurs on the PA
- PAs are less than 50 % energy efficient in average
- Every single TX antenna has a PA driving it

Large room for improvements

High Speed
(mmW)

Devices and Design

Better PAs

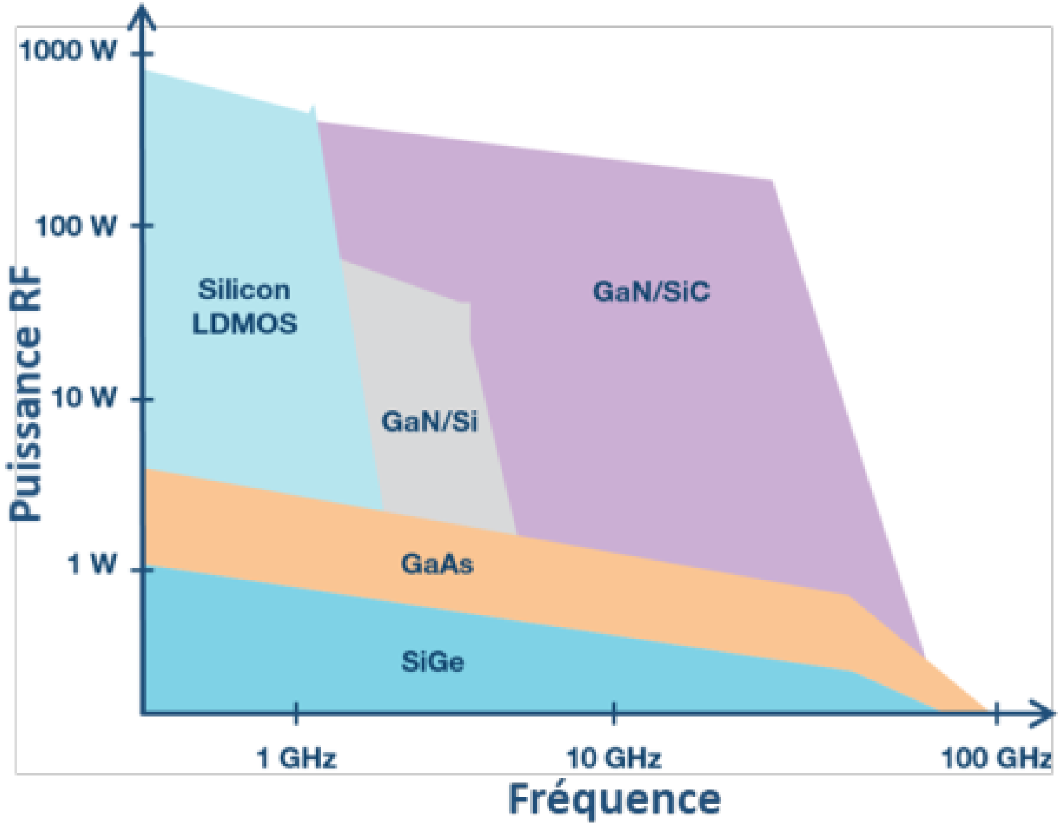
Design
(heavy integration)

Process and Design

Lower Cost
(More Users and Services)

Lower Energy Consumption
(More Connected Devices
and ecofriendly too)

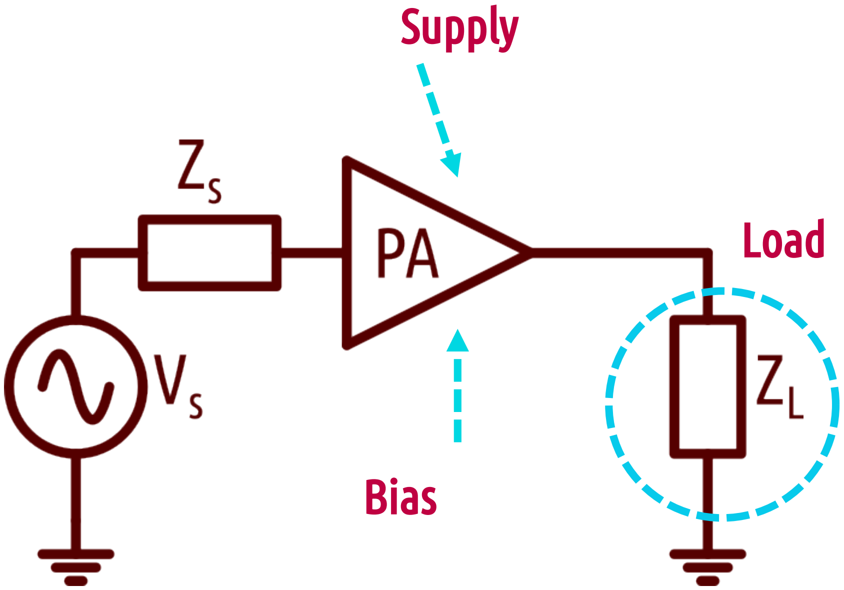
Power x Frequency (devices)



PA fundamentals

Core Definitions

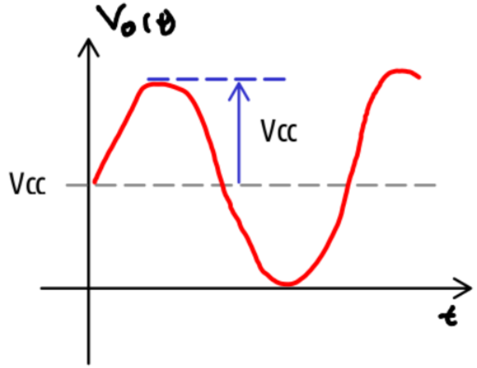
- In a RF transmitter, the Power Amplifier (PA) is used to drive the antenna.
- PA main specifications:
  - Load Power
  - Linearity
  - Efficiency

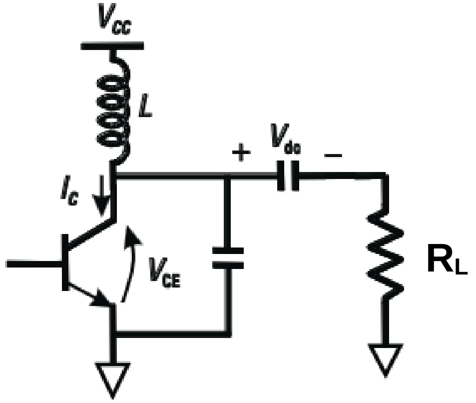


Power Capability

- The main objective when designing a PA is to deliver a certain amount of power to a load. This is largely dependent on load and source voltage.
- For a given power supply VCC and a given load RL, the power capacity of the PA is defined by:

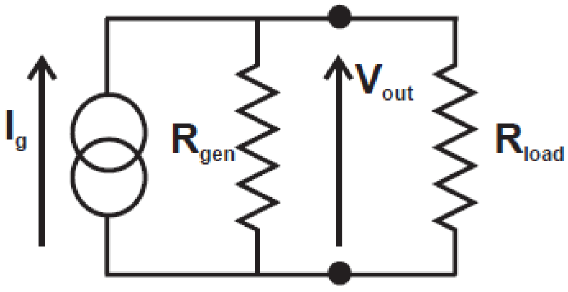
$$P = \frac{V_{CC}^2}{2R_L}$$

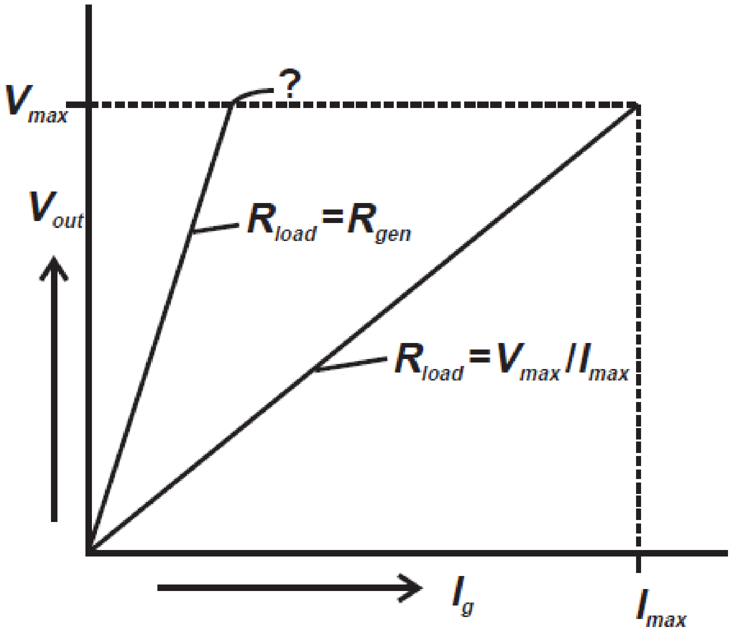




Optimum Load

- Conjugate matching may not be a good choice
- Loadline perhaps is better





Is Rgen is of the same order of Ropt, better use:

$$\frac{R_{gen} \cdot R_{opt}}{R_{gen} + R_{opt}} = \frac{V_{max}}{I_{max}}$$

Drain Efficiency

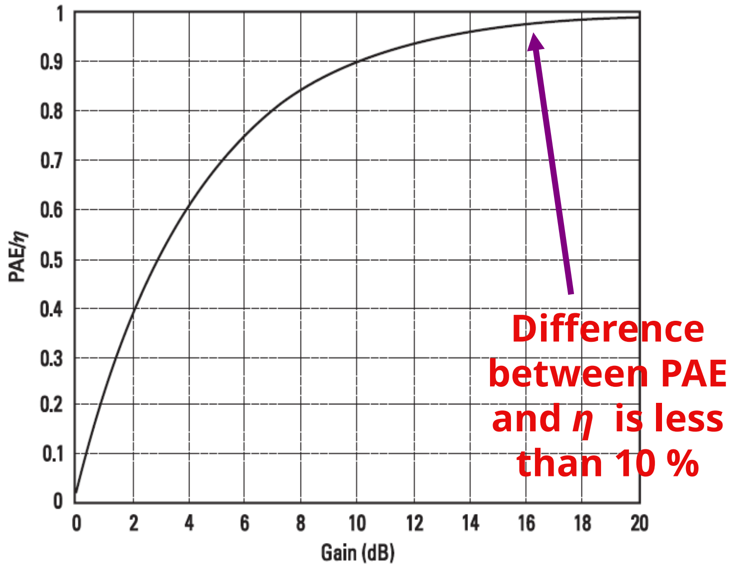
- dc-RF efficiency (η):
- Measures how efficient is the conversion between source power and load power:

$$\eta = \frac{P_{RL}}{P_{DC}}$$

Power Added Efficiency

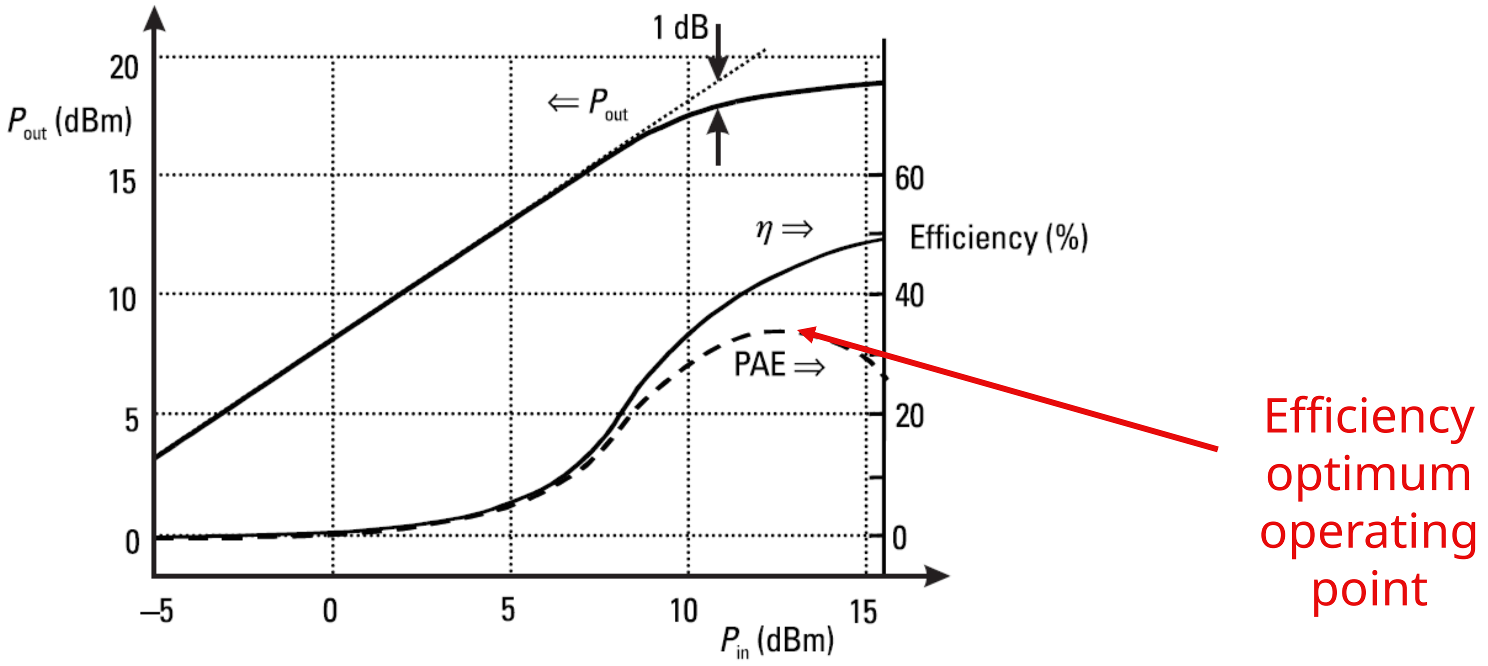
- Power-added efficiency (PAE) incorporates the RF-drive power by subtracting it from the output.

$$PAE = \frac{P_{RL} - P_{\text{IN}}}{P_{DC}} = \frac{P_{RL} - \frac{P_{RL}}{G}}{P_{DC}} = \eta\left(1 - \frac{1}{G}\right)$$

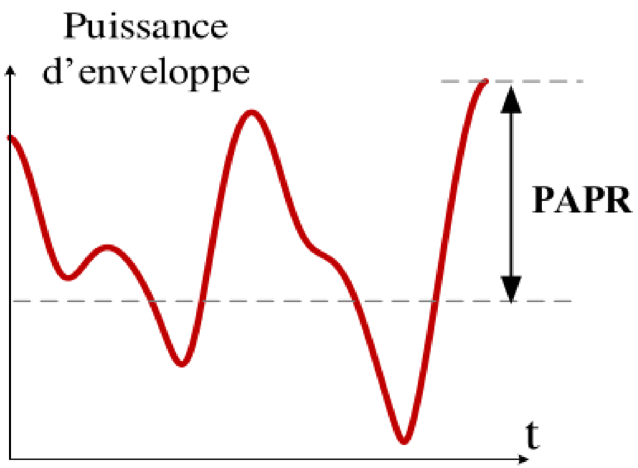


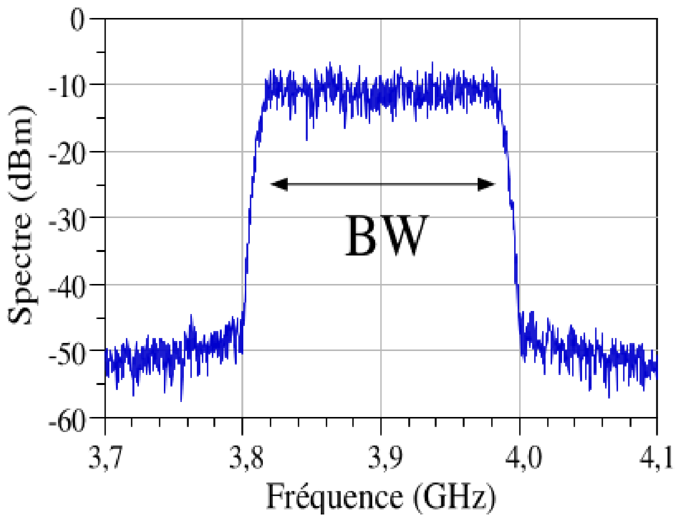
PAE x Pin

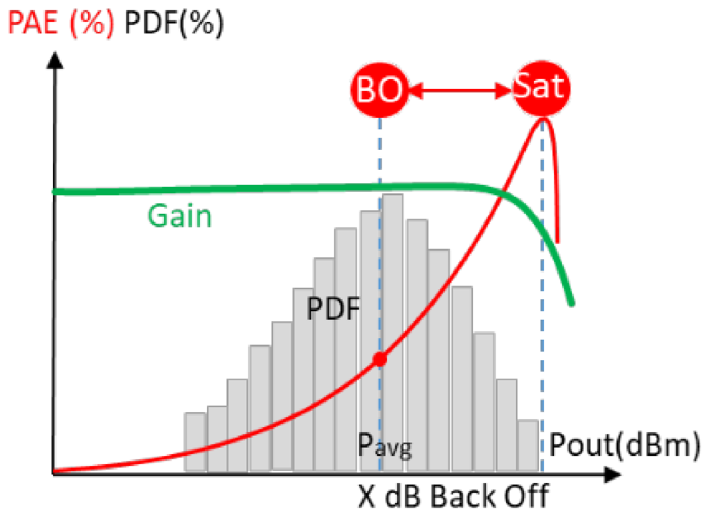
- The maximum value of PAE occurs in the saturation range



Modulated Signal Characteristics

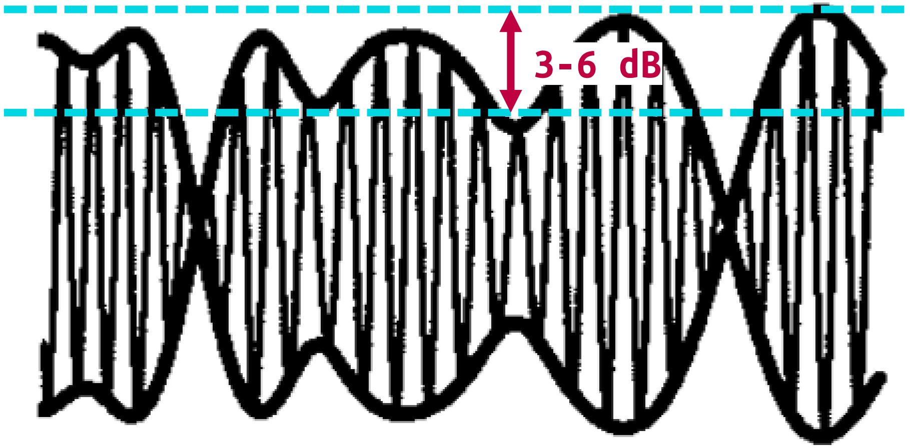




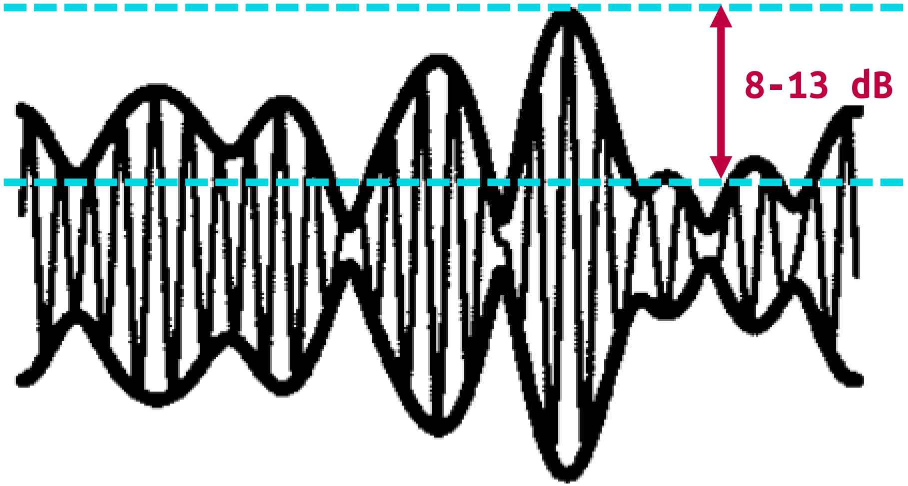


K. H. Joao, Dispositifs intégrés à très haute efficacité pour la gestion de l'énergie dans les émetteurs de télécommunications de 5ème génération (5G), Thèse de doctorat, École doctorale Sciences et Ingénierie (Limoges ; 2022).

Peak-to-Average Power (PAPR)



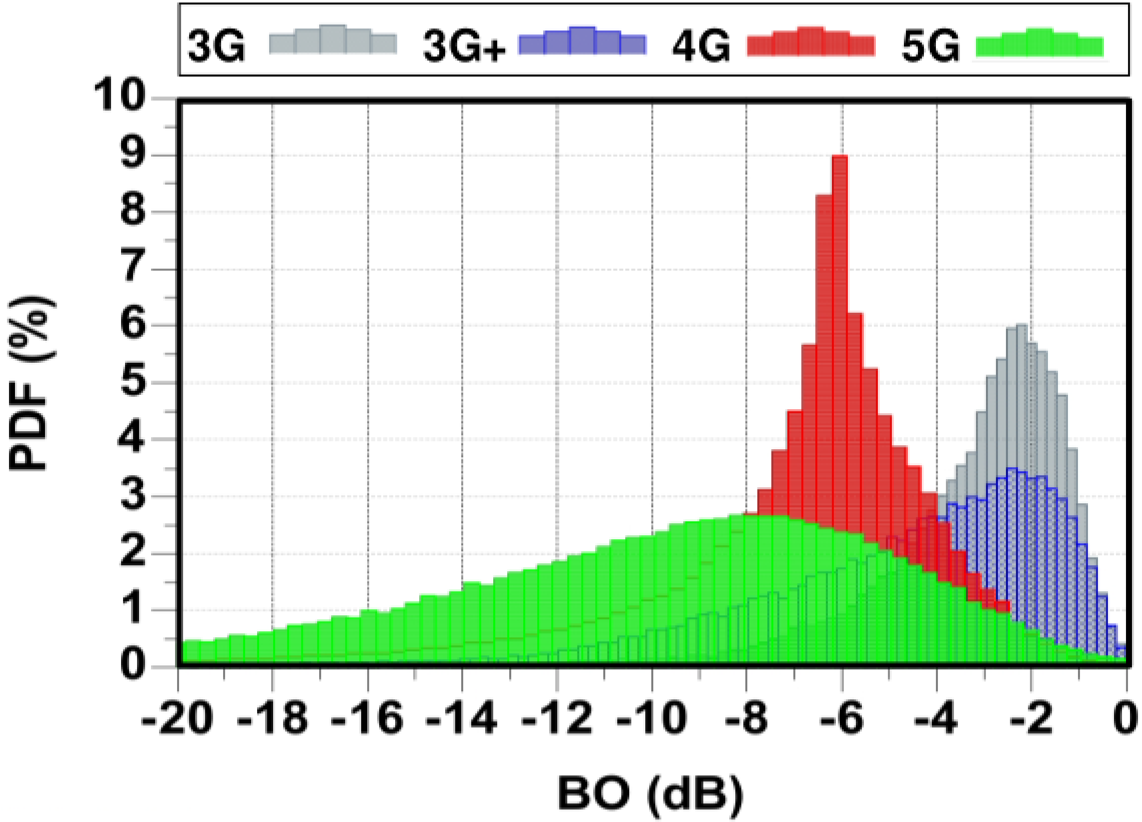
Shaped-pulse data
(QPSK, QAM, CDMA)



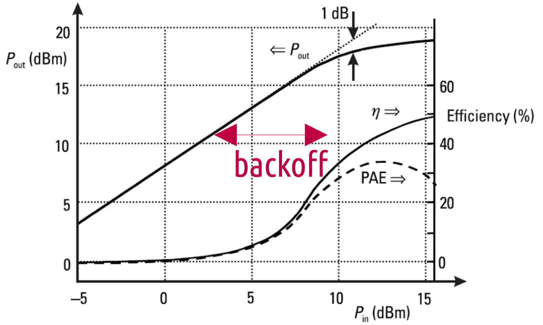
Multi-Carrier
(OFDM)

F. H. Raab et al., "Power amplifiers and transmitters for RF and microwave," in IEEE Transactions on Microwave Theory and Techniques, vol. 50, no. 3, pp. 814-826, March 2002, doi: 10.1109/22.989965.

Back-off requirements

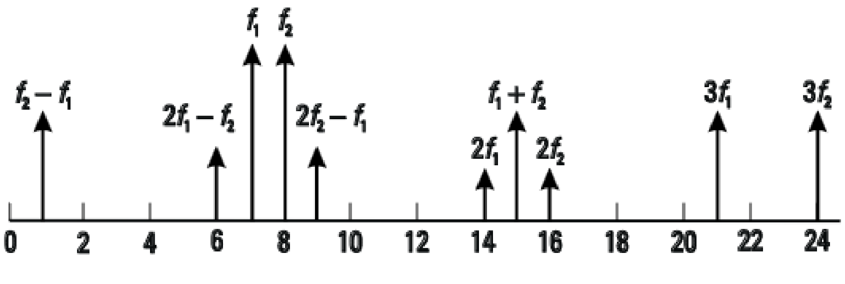


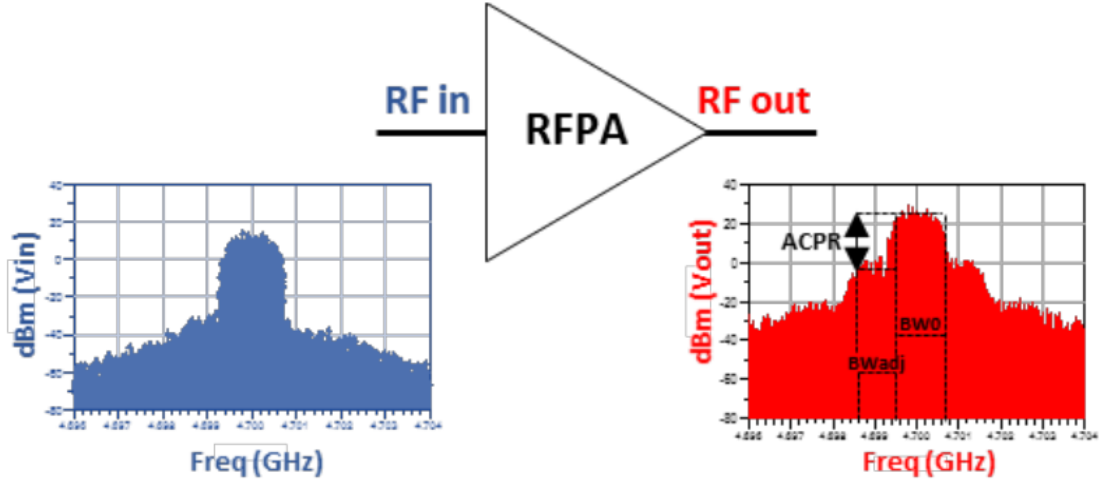
3G : REL 99
3G+ : HSUPA
LTE : DFTs-OFDM
5G : CP-OFDM



Adjacent Channel issues

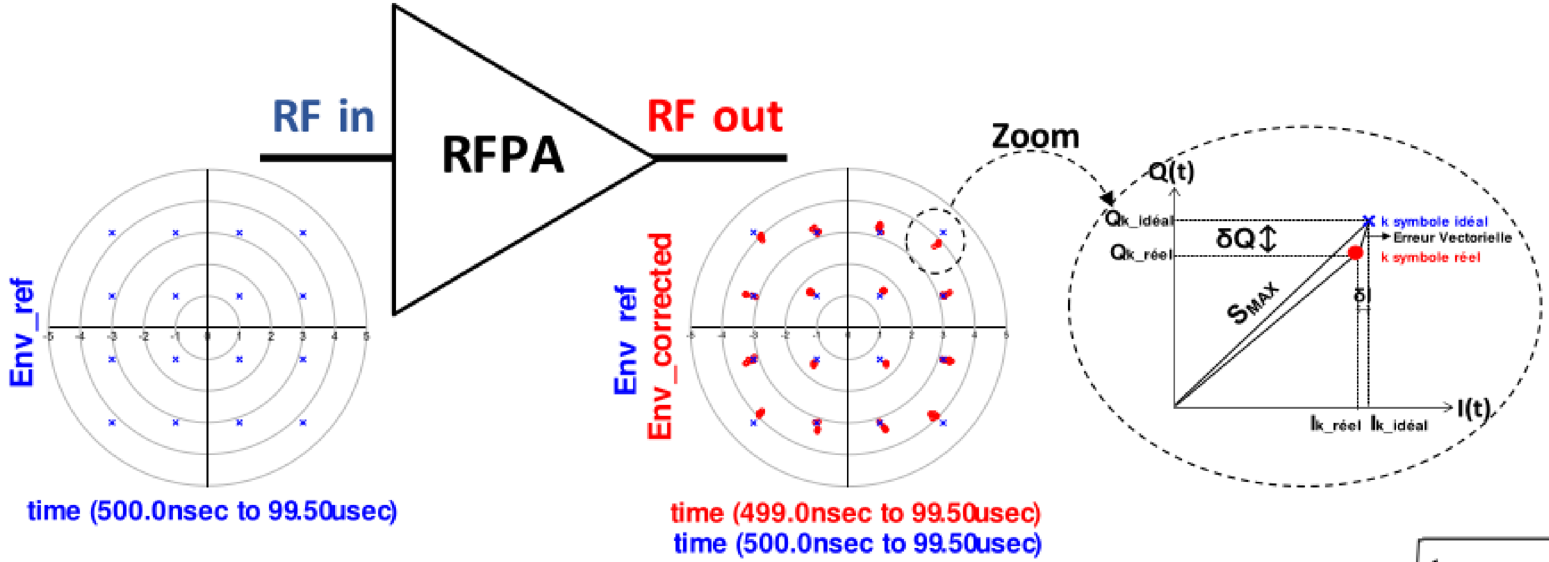
- Nonlinearities cause spectral regrowth
- Adjacent channel power ratio (ACPR) compares the power in an adjacent channel to that of the signal





EVM (Error Vector Magnitude)

- Expected EVM levels for 5G are less than 5% for 64QAM modulation and less than 3% for 256QAM

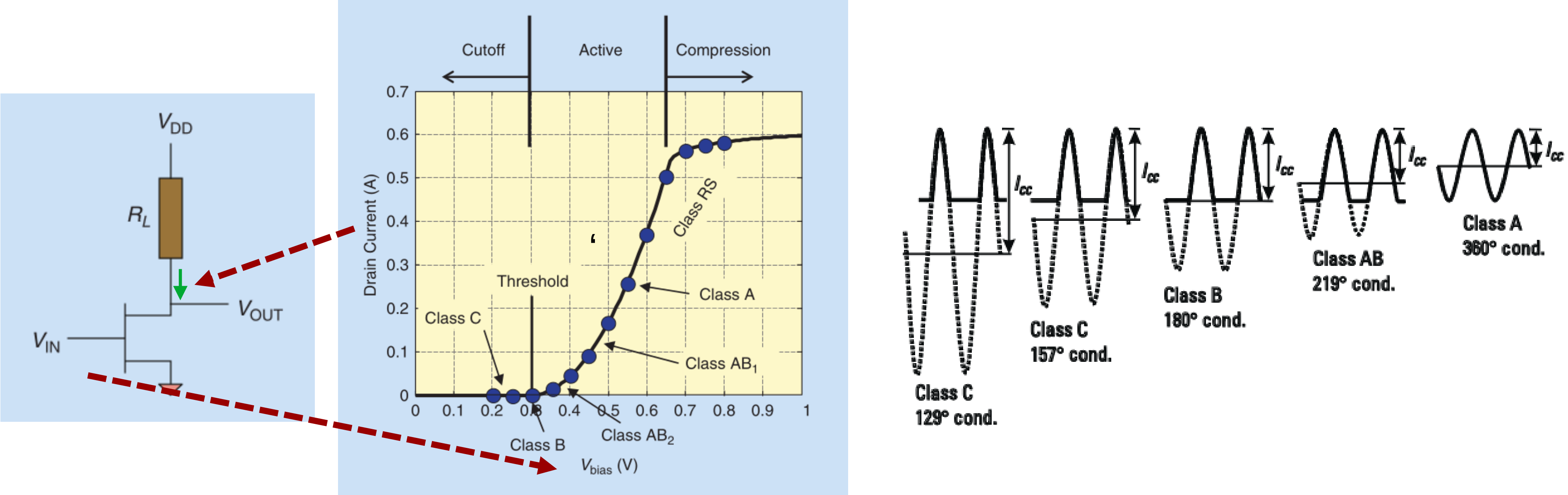


$$EVM(\%) = \sqrt{\frac{\frac{1}{N} \cdot \Sigma_{i=1}^{N} (\delta I_i^2 + \delta Q_i^2)}{S_{MAX}^{2}}} \times 100\%$$

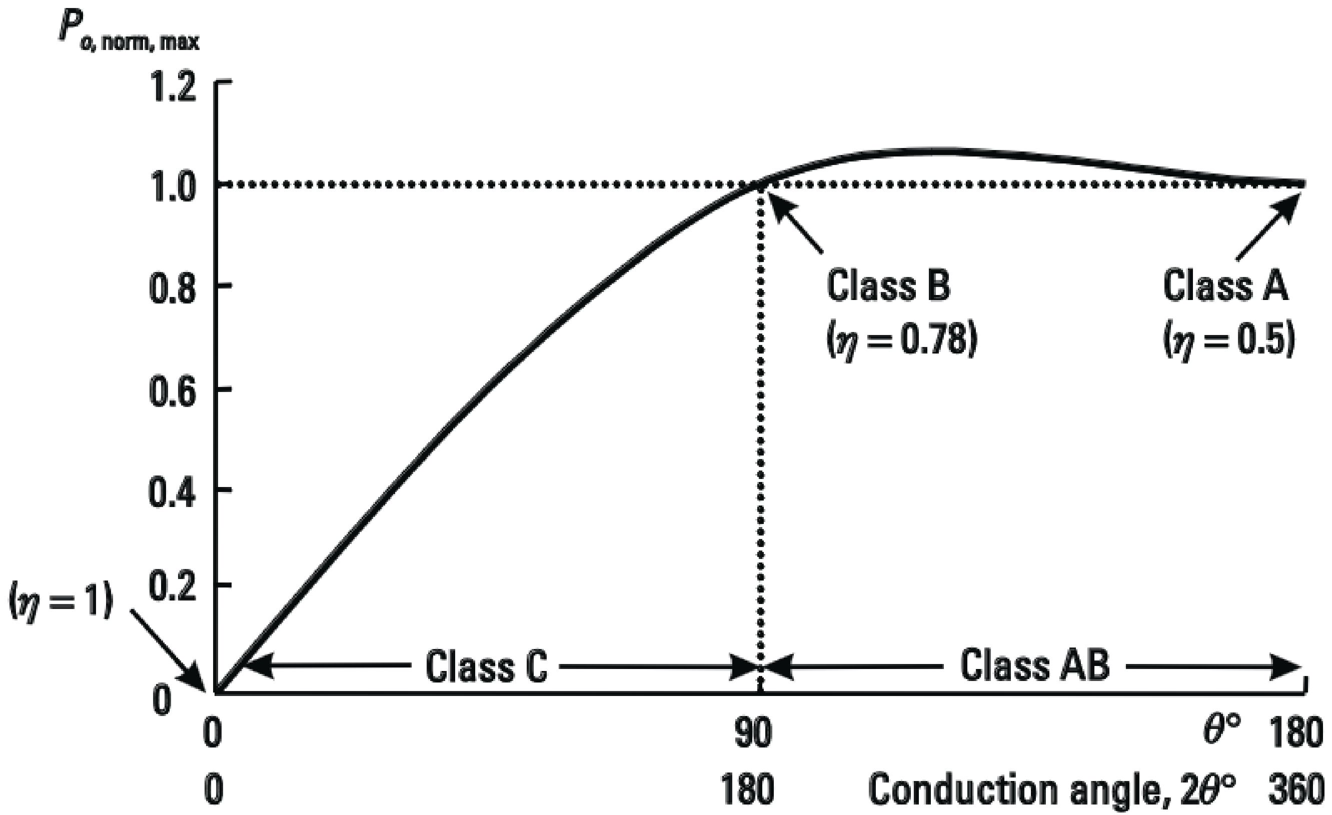
K. H. Joao, Dispositifs intégrés à très haute efficacité pour la gestion de l'énergie dans les émetteurs de télécommunications de 5ème génération (5G), Thèse de doctorat, École doctorale Sciences et Ingénierie (Limoges ; 2022).

Basic amplifier classes (Bias)

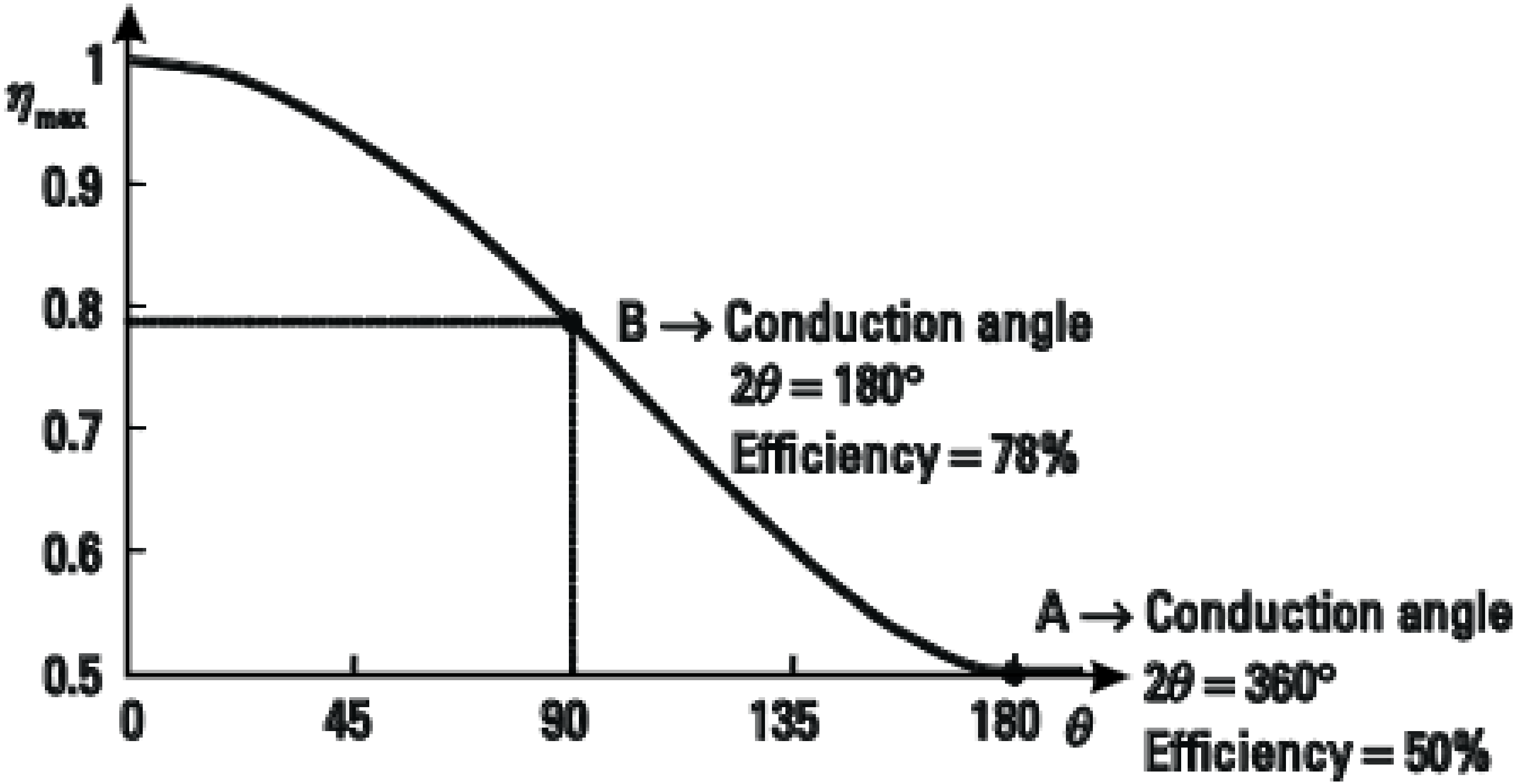
- The basic PA classes are defined as function of the drain/collector current “shape” (or conduction angle)



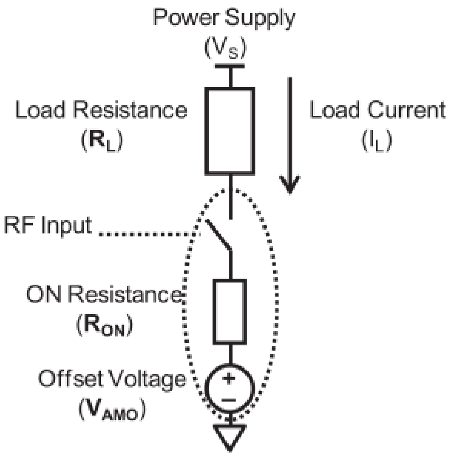
Output power x conduction angle



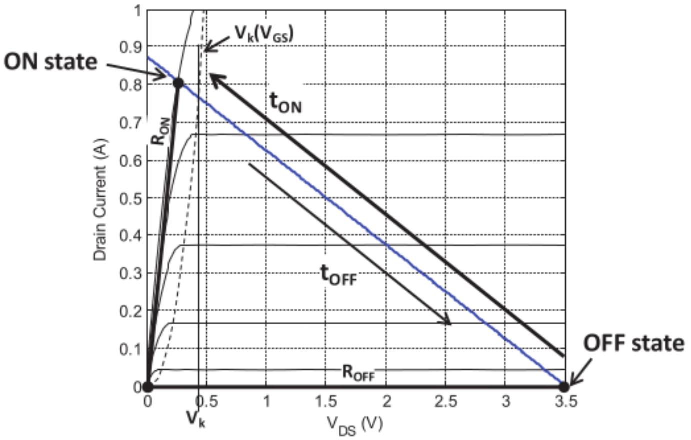
Efficiency x conduction angle



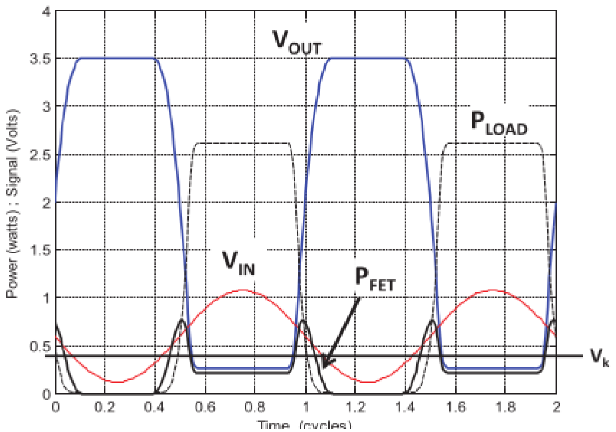
Switching amplifiers



Circuit model



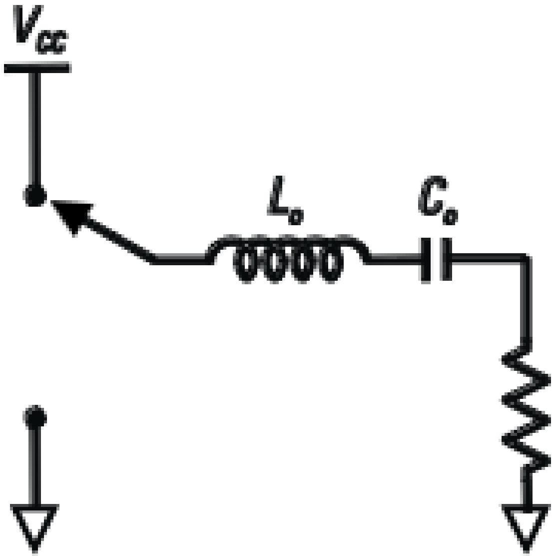
Transistor
Operating Point

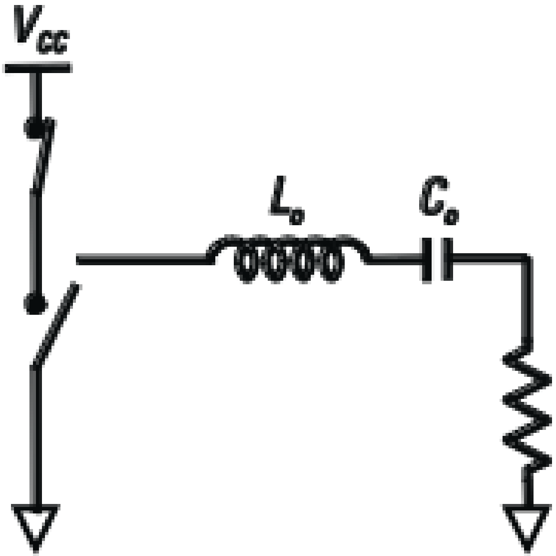


Power

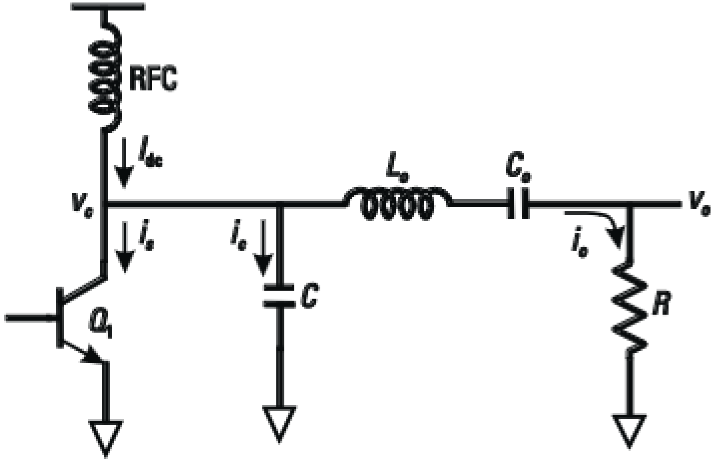
Switched amplifiers

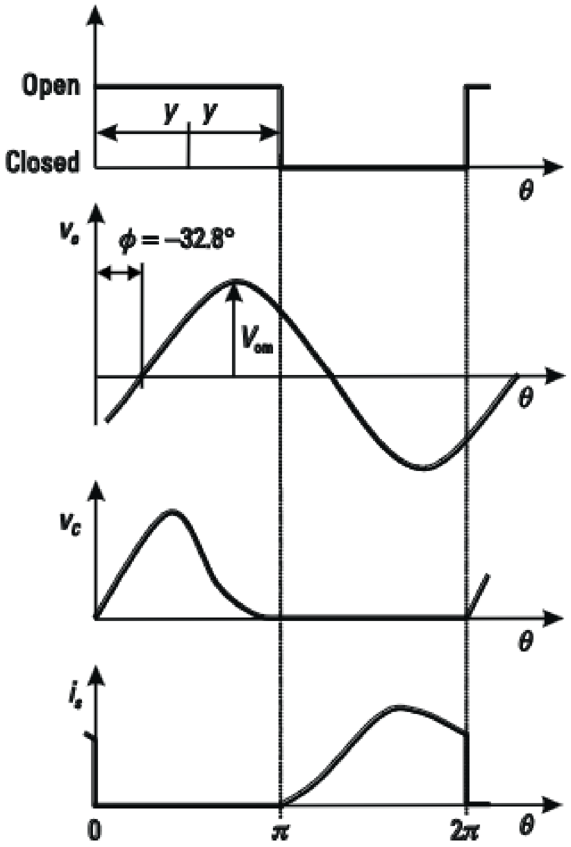
- Class D



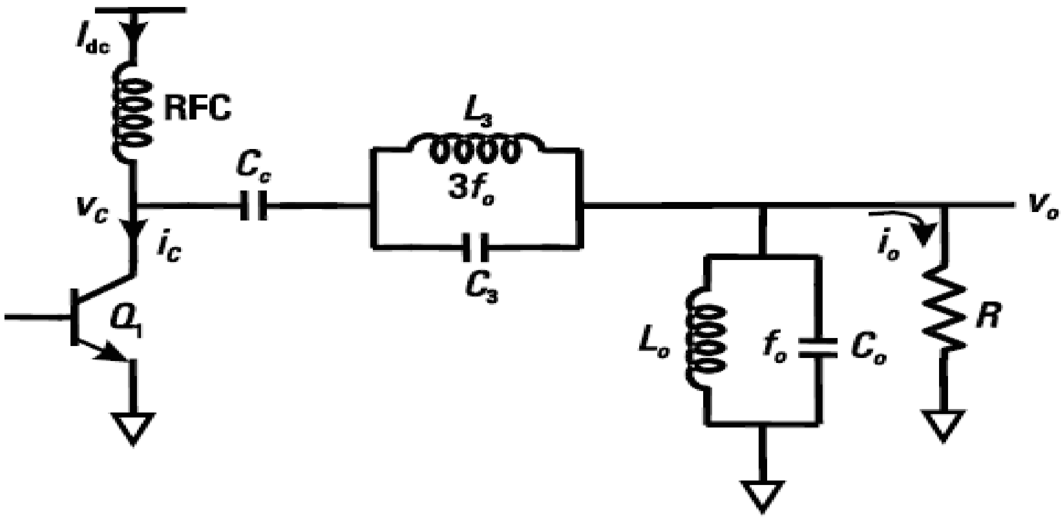


Class E

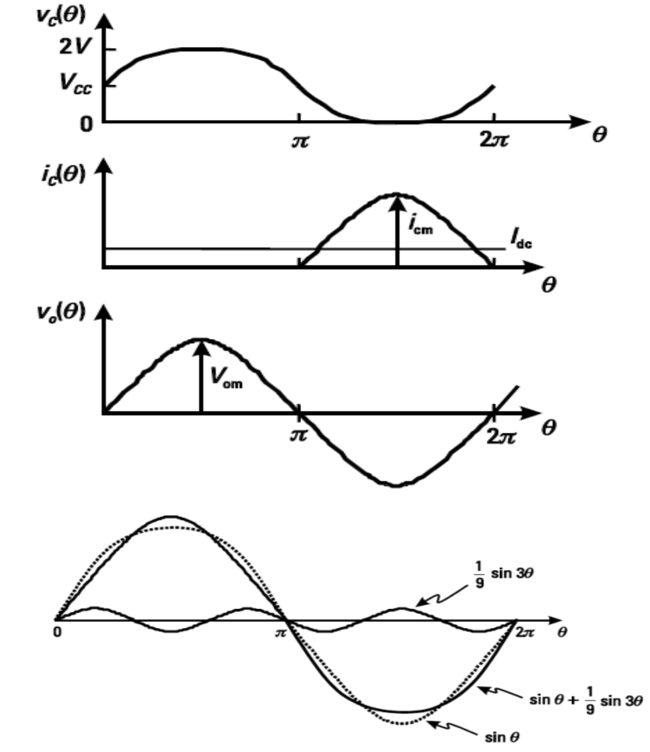

RFC
I_{dc}
v_c
i_s
i_c
L_o
C_o
v_o
i_o
C
R
Q_1


Open
Closed
y
y
θ
v_o
$\phi = -32.8°$
V_{om}
θ
v_C
θ
i_s
0
π
2π
θ

Class F



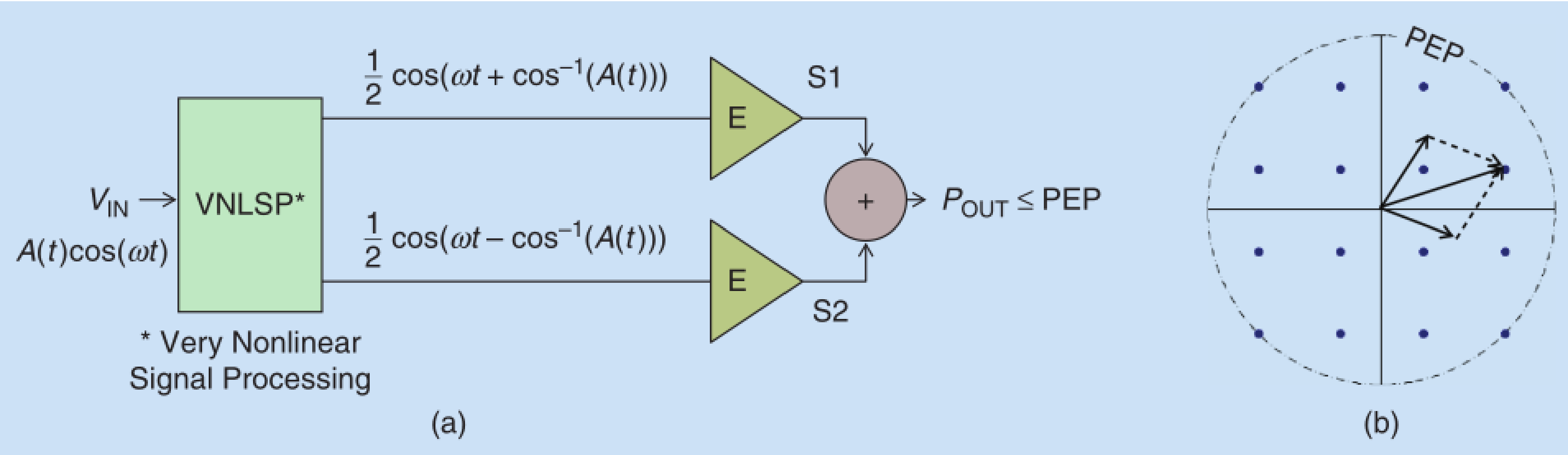
I_{dc}
RFC
L_3
$3f_o$
C_c
v_C
i_C
C_3
Q_1
L_o
f_o
C_o
i_o
R
v_o



$v_c(\theta)$
$2V$
V_{cc}
0
π
2π
θ
$i_c(\theta)$
i_{cm}
I_{dc}
θ
$v_o(\theta)$
V_{om}
π
2π
θ
$\frac{1}{9}\sin 3\theta$
0
π
2π
θ
$\sin\theta + \frac{1}{9}\sin 3\theta$
$\sin\theta$

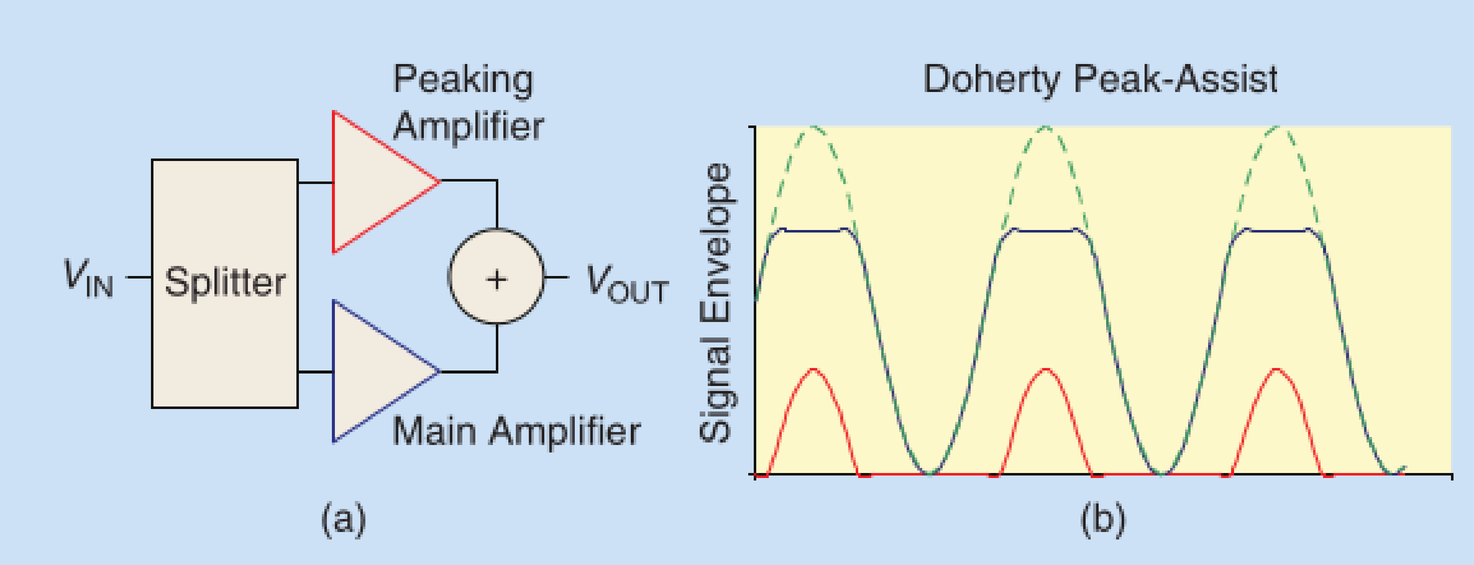
Outphasing amplifiers

- Two amplifiers are combined at their highest energy efficiency (i.e., in power saturation) at all times. Variations in the input signal magnitude are converted into a phase shift. between the two amplifier drive signals, such that the vector summation of their output signals yields the intended output magnitude.

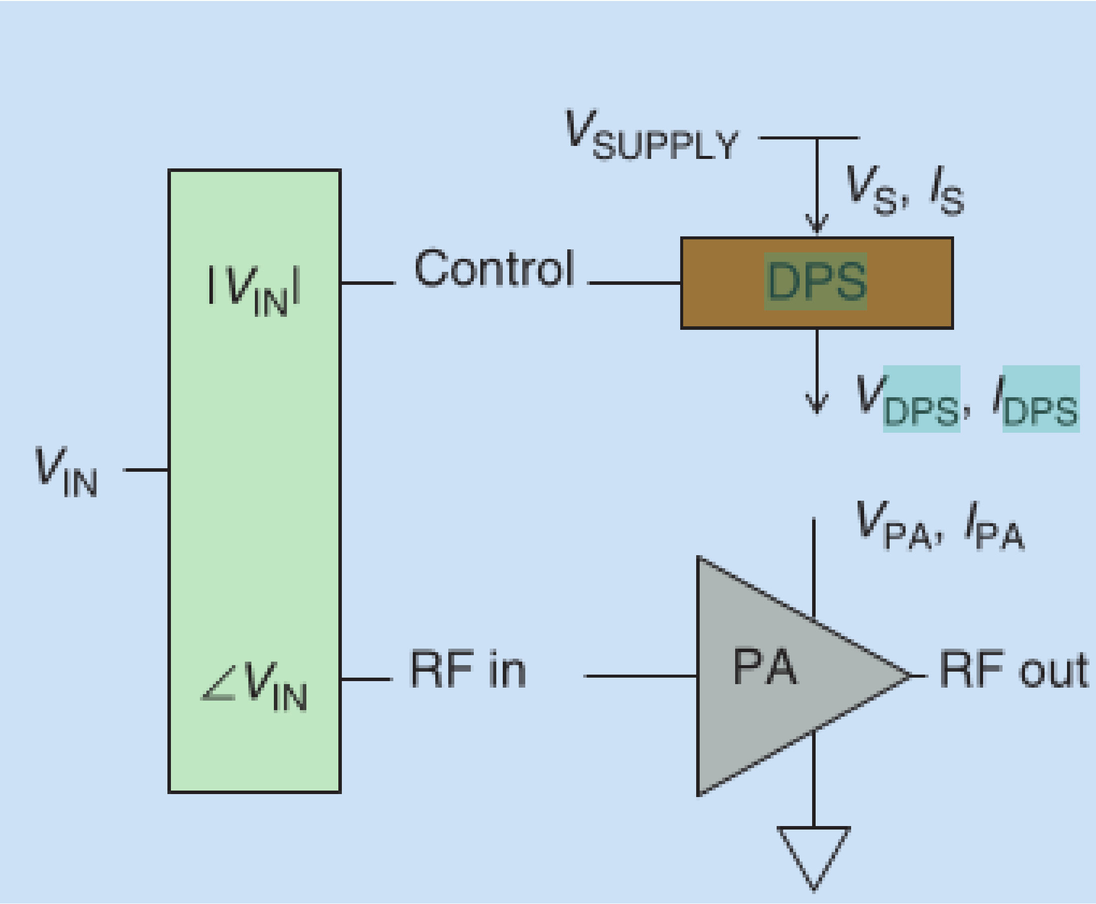


Doherty Amplifier

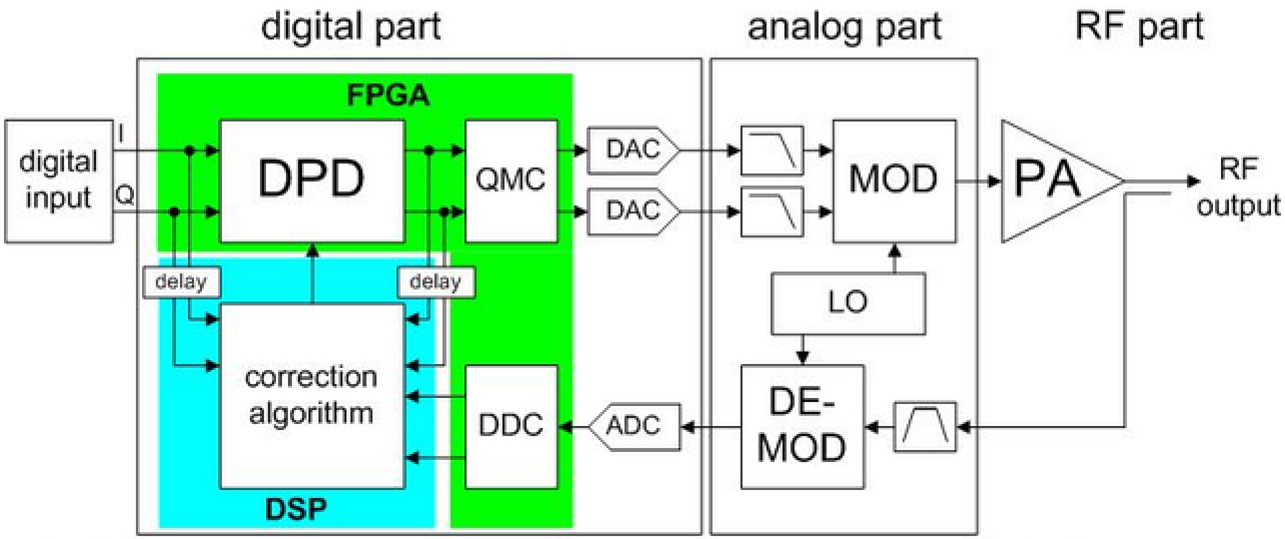
- It uses two amplifiers: one is always ON (normally a class AB or B amplifier) and the other (class C) is turned on for higher levels of the envelope.



Envelope Tracking PA



Digital Pre-Distortion

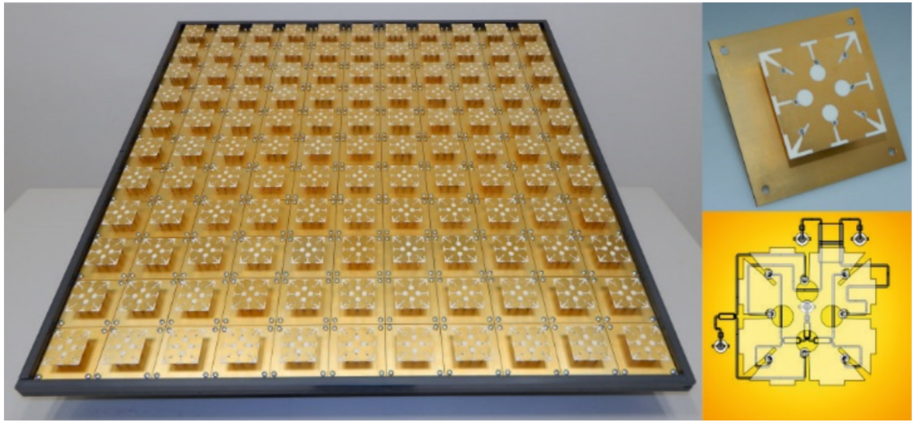


DPD: digital predistorter
QMC: quadrature modulation compensator
DDC: digital down converter
DAC: digital to analog converter
ADC: analog to digital converter
MOD: modulator (frequency up converter)
DEMOD: demodulator (frequency down converter)
PA: power amplifier

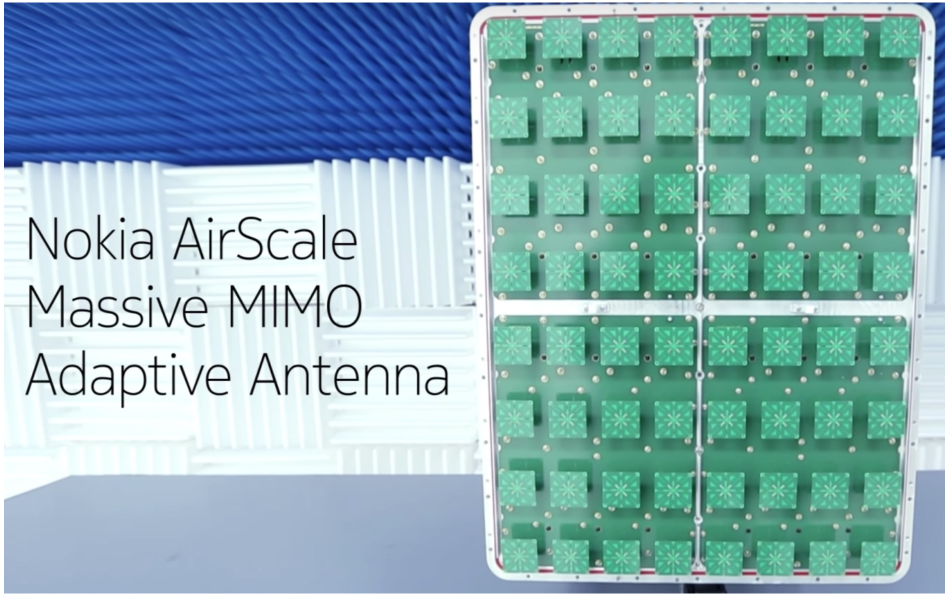
http://mmic.postech.ac.kr/Homepage/poweramp/digital_predistortion_linearization.htm

State-of-the art (Addressing Opportunities and Chalenges)

5G mMIMO



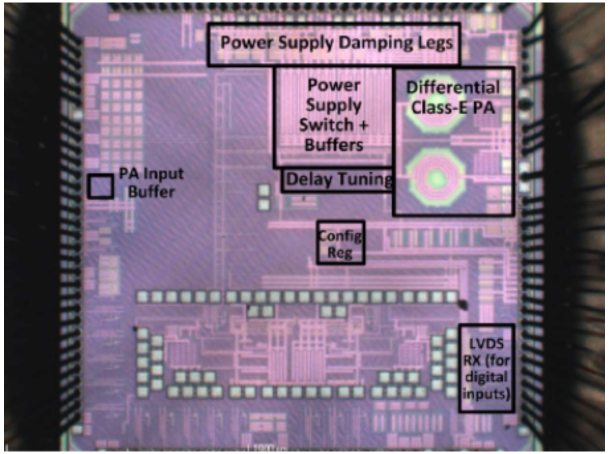
N. L. Johannsen, N. Peitzmeier, P. A. Hoeher and D. Manteuffel, "On the Feasibility of Multi-Mode Antennas in UWB and IoT Applications below 10 GHz," in IEEE Communications Magazine, vol. 58, no. 3, pp. 69-75, March 2020, doi:10.1109/MCOM.001.1900429

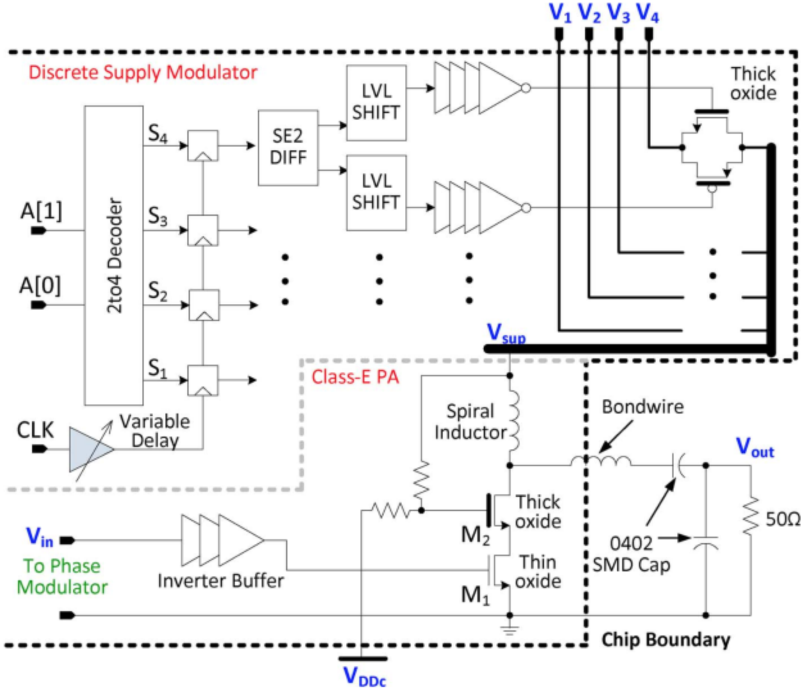


IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 47, NO. 10, OCTOBER 2012

A 2.4-GHz, 27-dBm Asymmetric Multilevel Outphasing Power Amplifier in 65-nm CMOS

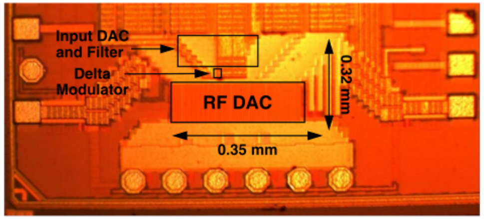
Philip A. Godoy, *Member, IEEE*, SungWon Chung, *Student Member, IEEE*,
Taylor W. Barton, *Student Member, IEEE*, David J. Perreault, *Senior Member, IEEE*, and
Joel L. Dawson, *Member, IEEE*





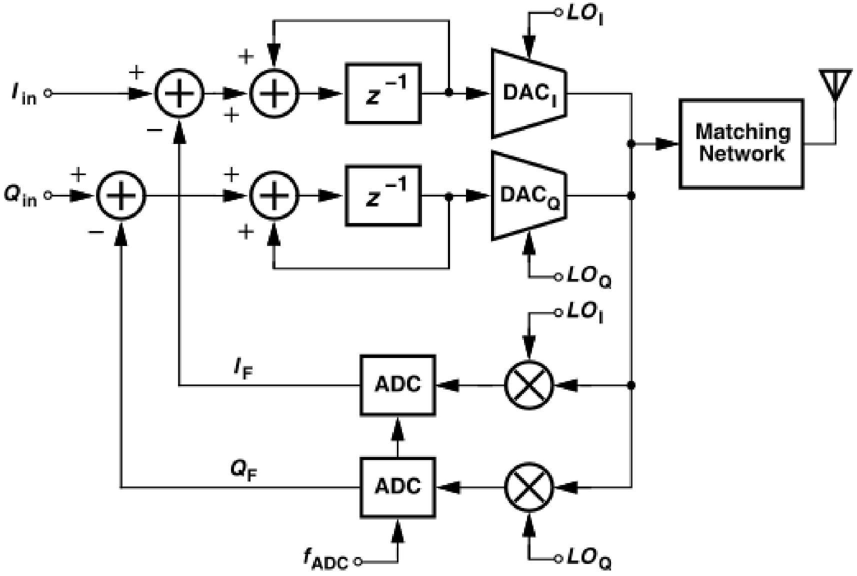
System Architecture	Tech.	Carrier Freq	Bandwidth	Modulation	PAPR	Peak P_{out}	Avg P_{out}	Peak PAE	Avg PAE
AMO [This Work]	65 nm	2.4 GHz	20 MHz	OFDM	7.5 dB	27.7 dBm	20.2 dBm	45.1%	27.6%
Switched-cap PA [37]	90 nm	2.25 GHz	20 MHz	OFDM	7.5 dB	25.2 dBm	17.7 dBm	45.0%	27.0%
Class-AB [38]	90 nm	2.5 GHz	10 MHz	WiMAX	7.0 dB	32.0 dBm	25.0 dBm	48.0%	25.0%
Class-AB [39]	65 nm	2.442 GHz	20 MHz	OFDM	5.9 dB	28.3 dBm	22.4 dBm	35.3%†	23.2%†
Class-G Polar [15]	130 nm	2.0 GHz	20 MHz	OFDM	9.7 dB	29.3 dBm	19.6 dBm	69.0%	22.6%
Outphasing [8]	32 nm	2.4 GHz	20 MHz	OFDM	5.8 dB	25.3 dBm	19.6 dBm	35.0%	21.8%
Inverse Class-D [40]	65 nm	2.25 GHz	20 MHz	OFDM	7.8 dB	21.8 dBm	14.0 dBm	44.2%†	18.0%†
Outphasing [41]	45 nm	2.4 GHz	20 MHz	OFDM	6.7 dB	31.5 dBm	24.8 dBm	27.0%	16.0%

IEEE JOURNAL OF SOLID-STATE CIRCUITS



A Digital RF Transmitter With Background Nonlinearity Correction

Seyed-Mehrdad Babamir, *Student Member, IEEE*, and Behzad Razavi, *Fellow, IEEE*

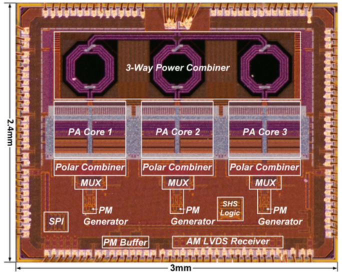


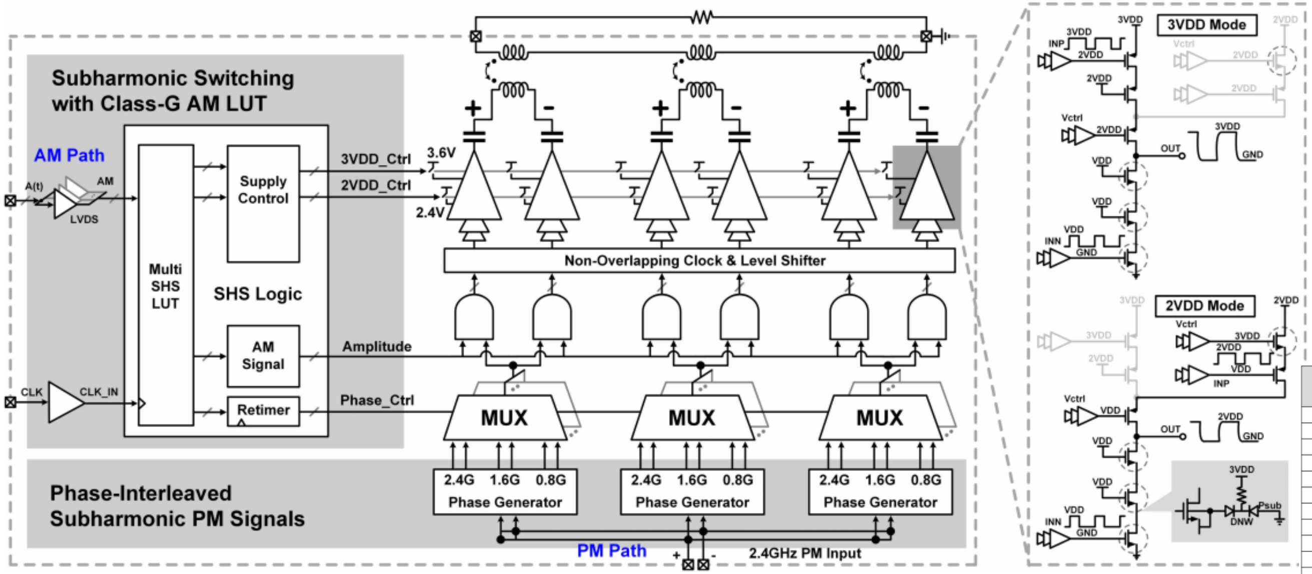
Reference	[41]	[42]	[43]	[44]	This Work
Frequency (GHz)	1.95	1.98	1.88	0.8	2
P_{out} (dBm)	28	28	29.8	22.9	24.1
PAE (%)	39[1]	35.1	40.8	26.1	50[5]
Supply (V)	1.2/3.7	3.4	3.4	1.2/2.4	1/1.8
Output Matching	ext. tuner[2]	off-chip	IPD die	on-chip	off-chip
Standard	WCDMA	WCDMA	WCDMA	WiFi	WCDMA
ACPR (dBc)	-41/-52	-42/NA	-36/-50	N/A	-35/-45
EVM (%)	7[3]	N/A	3.5	5.4[4]	4.7
RXBN (dBc/Hz)	N/A	N/A	N/A	N/A	-150
Technology	90–nm CMOS	CMOS/GaAs hybrid	153–nm CMOS	55–nm CMOS	28–nm CMOS
Calibration	None	None	None	Foreground	Background

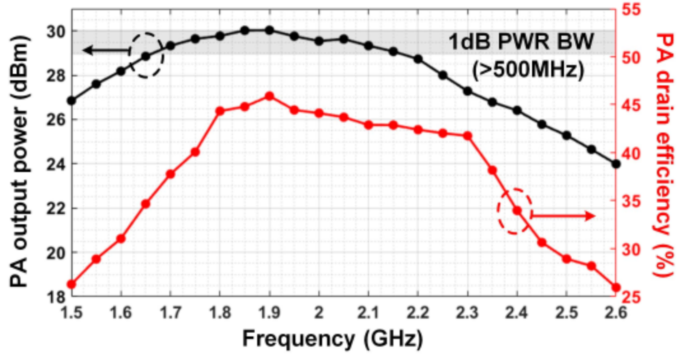
1 PAE is obtained without output matching loss
2 This work uses on-chip balun but external tuner as load
3 For 20-MHz 16-QAM LTE uplink signal
4 For 20-MHz 64-QAM WLAN, using off-chip predistortion
5 System efficiency including power of all the building blocks

A Watt-Level Phase-Interleaved Multi-Subharmonic Switching Digital Power Amplifier

Aoyang Zhang, *Student Member, IEEE*, and Mike Shuo-Wei Chen, *Senior Member, IEEE*





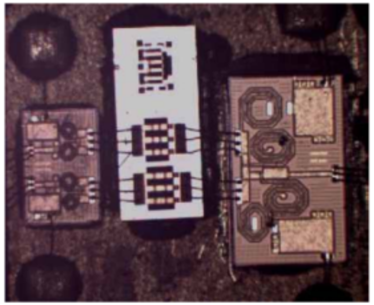


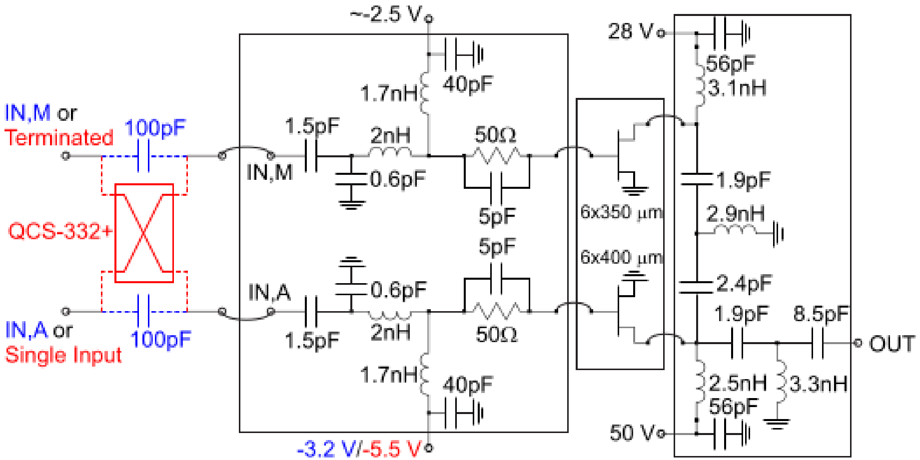
Specifications		This work		[36] D. Cousinard ISSCC 2017	[37] V. Vorapipat ISSCC 2017	[38] S. Hu ISSCC 2015	[39] K. Onizuka ISSCC 2013	[40] P. A. Godoy JSSC 2012	[11] S. Yoo JSSC 2019	[41] R. Bhat JSSC 2017	[42] W Tai JSSC 2012
Architecture		Watt Level SHS PA		CMOS PAs with Efficiency Enhancement Techniques					CMOS PAs with Watt Level Output Power		
Process	[nm]	65		28	45	65	65	65	65	65	45
Frequency	[GHz]	1.9	2.2	2.45	3.5	3.71	1.8	2.4	2.2	2.2	2.4
Max P_{out}	[dBm]	**30**	**28.7**	28.2	25.3	26.7	27.2	27.7	30.1	30.3	31.5
Peak DE	[%]	**45.9**	**42.4**	39	30.4‡	40.2	30	45.1‡	37‡	34‡	27‡
-3.5 dB DE	[%]	**41.3**	**36.1**	33*	26‡, *	32.5*	24‡, *	39‡, *	30‡, *	24‡, *	22‡, *
-7 dB DE	[%]	**35.3**	**30.8**	23*	23‡, *	35*	19‡, *	37‡, *	25‡, *	18‡, *	17‡, *
-9.5 dB DE	[%]	**32.2**	**27.3**	18*	19‡, *	31.5*	14‡, *	24‡, *	17‡, *	14‡, *	14‡, *
-12 dB DE	[%]	**24.2**	**20.7**	14*	17.4‡	26.2	9‡, *	22‡, *	12‡, *	9‡, *	12‡, *
PAPR	dB	7.2		5.7	6.3	5.8	5.9	7.5	7.6	6.5	6.7
Average DE	[%]	**31.4†**		30	24‡	28.8	18‡	27.6‡	18.3‡	16‡	16‡
Power Supply	[V]	2.4/3.6		2.2	1.2/2.4	3/1.65	3.3	2.5/1.8/ 1.35/0.85	2.5/1.2	2.6	2.4
EVM	[dB]	-24.7†		-25	-35.8	-24	-22	-31.4	-40.3	-30	-25
Modulation		16QAM OFDM 5MHz		64QAM OFDM 20MHz	256QAM OFDM 20MHz	16QAM SC 1MHz	64QAM OFDM 20MHz	64QAM OFDM 20MHz	256QAM SC 20MHz	64QAM SC 1.4MHz	64QAM OFDM 20MHz
Matching Network		On-Chip		On-Chip	On-Chip	On-Chip	On-Chip	Off-Chip	On-Chip	On-Chip	On-Chip
PBO Efficiency Enhancement Tech		Multi-SHS /Class-G		Polar/PWM	Doherty/ Class-G	Doherty/ Class-G	Supply Switching	AMO	IQ Shared/ Class-G	-	Current Switching

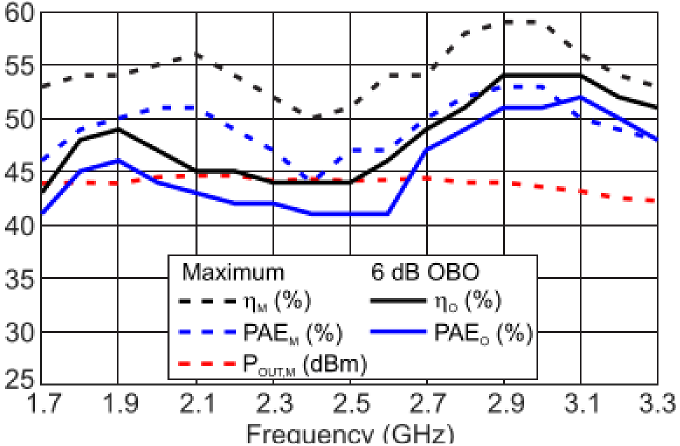
IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 29, NO. 5, MAY 2019

A 1.8–3.2-GHz Doherty Power Amplifier in Quasi-MMIC Technology

Roberto Quaglia, *Member, IEEE*, Mark D. Greene, Matthew J. Poulton, and Steve C. Cripps, *Life Fellow, IEEE*

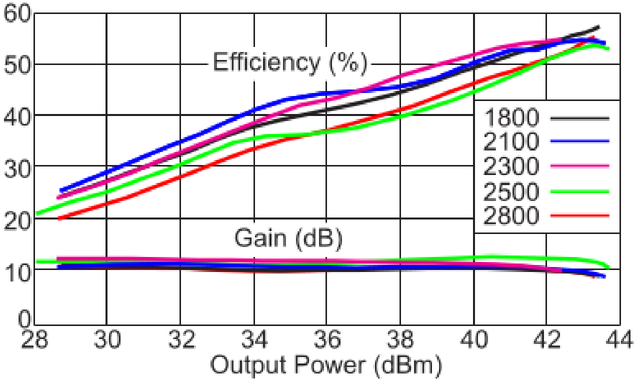






COMPARISON WITH PREVIOUSLY PUBLISHED DOHERTY PA ICS

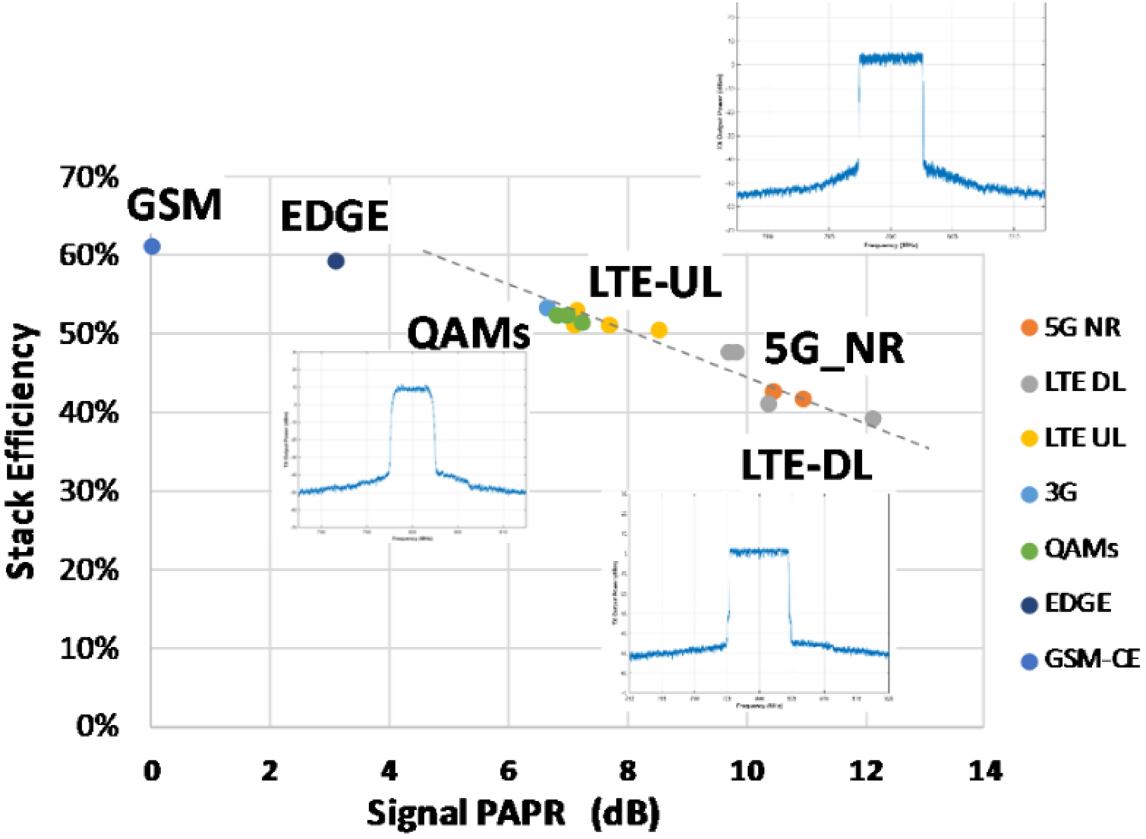
Ref.	Freq. (GHz)	$P_{OUT,MAX}$ (dBm)	η_{SAT} (%)	η_{OBO} (%)	OBO (dB)	Gain (dB)
[3]	2.14	40.5	60	52	7.1	16
[4]	2.14	41.2	57	43	4.7	20
[5]	0.75–0.77	39	46	37	7.2	46
[6]	2.1–2.7	41	n.a.	46	7.2	12
[7]	2.655	42.2	n.a.	47	7.1	31
[8]	2.6	45	n.a.	45	6	28
[9]	1.7–2.7	40.2	42	37	6	12
[10]	2.6	44	63	52	6.5	18
D.I.	**1.8–3.2**	**42.0**	**52**	**38**	**6**	**9**
S.I.	**1.8–3.2**	**41.4**	**43**	**36**	**6**	**9**

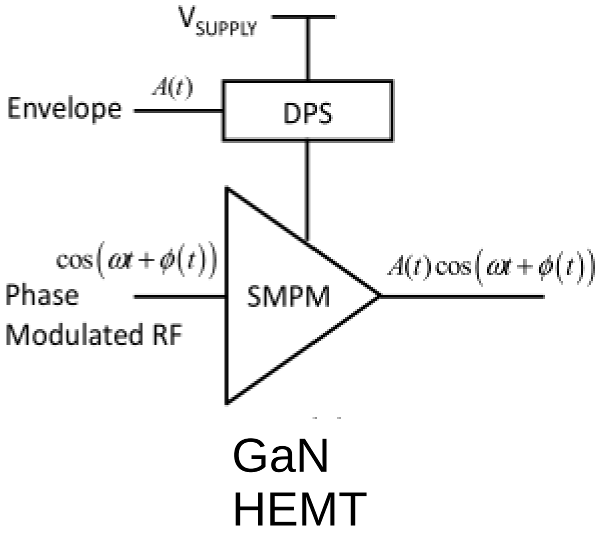


5G New-Radio Transmitter Exceeding 40% Modulated Efficiency

E. McCune, Q. Diduck, W. Godycki, M. Mohiuddin

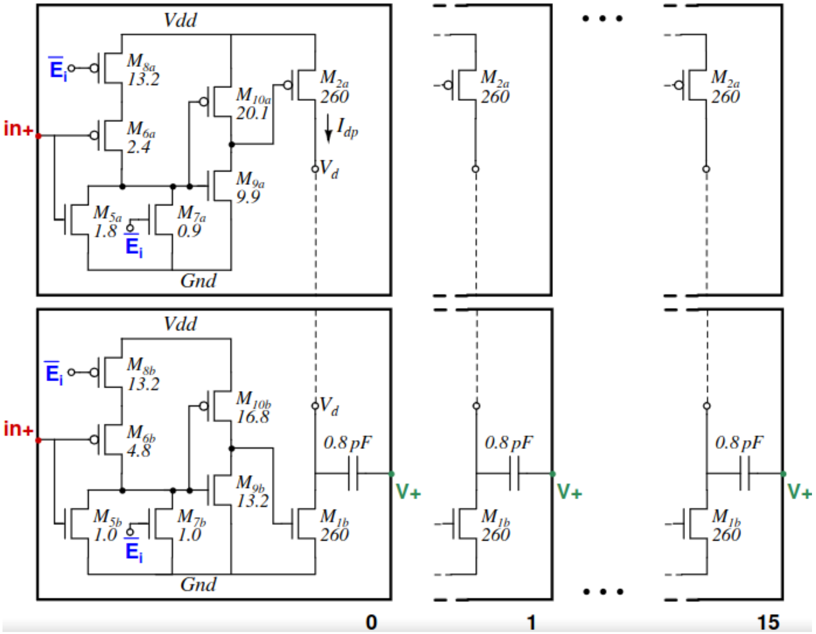
Eridan Communications



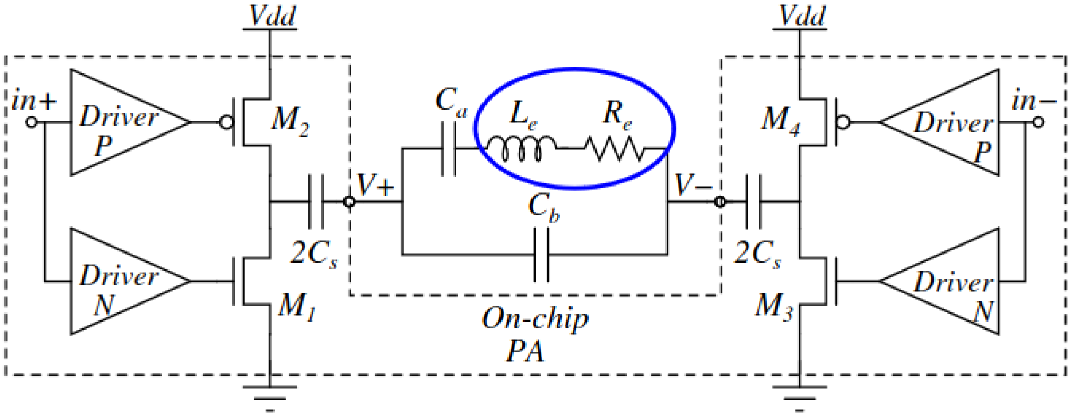


A 25-dBm 1-GHz Power Amplifier Integrated in CMOS 180nm for Wireless Power Transferring

Fabian L. Cabrera, and F. Rangel de Sousa
fabian.l.c@ieee.org, rangel@ieee.org



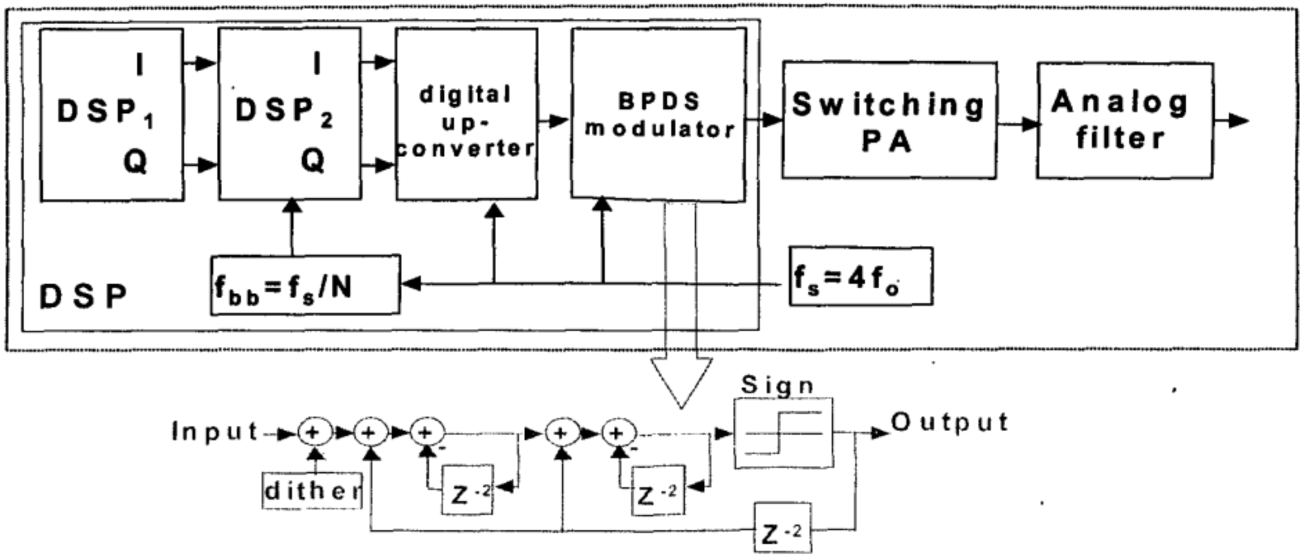
24.2 dBm with 48.1% efficiency at the 986 MHz frequency

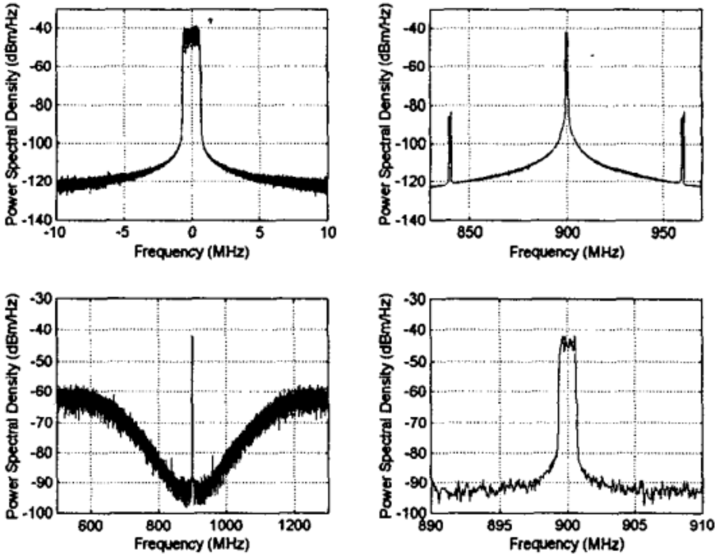


Digital Generation of RF Signals for Wireless Communications With Band-Pass Delta-Sigma Modulation

J. Keyzer, J. Hinrichs, A. Metzger, M. Iwamoto, I. Galton, and P. Asbeck

University of California, San Diego, La Jolla, CA 92093-0407





Thank you

Fernando.rangel@lip6.fr
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