Multimode RF power amplifier in mobile broadband modules

Master of Science Thesis

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Master Thesis

MULTIMODE RF POWER AMPLIFIER IN MOBILE BROADBAND MODULES

A trial to embed GSM and WCDMA in the same single line-up device

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Abstract

Mobile broadband modules offer high-quality connectivity for business customers. Cost and size are the key factors in their design. This thesis work presents a cheap and small solution concerning the radio transmission area: a multimode power amplifier. The intent of this project is to understand the limitations in embedding two telecommunication standards in the same device.

The first chapter creates a scenario for this work, introducing which the key factors are. In the second chapter, a theoretical study of the issue is reported, firstly defining the boundary problems and then gradually shifting toward designing a PA. The third chapter has been developed taking the PA as a black box and deciding how it should work to satisfy the telecommunication standard requirements. Product implementation is in the fourth chapter, in which CAD work is reported step by step. The fifth chapter presents the test bench and some measurements. Conclusions and comments are finally summarized, as well as some tips for the future development on multimode power amplifiers.

Contents

Terminology

ACLR	Adjacent Channel Leakage Ratio
ADS	Advanced Design System
BER	Bit Error Rate
BJT	Bipolar Junction Transistor
CMOS	Complementary Metal Oxide Semiconductor
CORDIC	for COordinate Rotation DIgital Computer
DCS	Digital Cellular System
DSP	Digital Signal Processing
DUT	Device Under Test
EDGE	Enhanced Data rates for GSM Evolution
GaAs	Gallium Arsenide
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile communications
HBT	Heterojunction Bipolar Transistor
MAG	Maximum Available Gain
MEMS	Micro Electro-Mechanical Systems
MSG	Maximum Stable Gain
PA	Power Amplifier
PAE	Power Added Efficiency
PAR	Peak to Average Ratio
PCB	Printed Circuit Board
PCS	Personal Communications Service

pHEMT	Pseudomorphic High-Electron Mobility Transistor
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RRC	Root Raised Cosine
SRRC	Square Root Raised Cosine
UMTS	Universal Mobile Telecommunication System
VCO	Voltage Controlled Oscillator
WCDMA	Wideband Code Division Multiple Access

1 Introduction

Wireless devices have by now become needful everyday life. Their diffusion is in full growth and it is provided by many competitors, so as to push all the markets, sooner or later, towards the condition of mass-market. In these commercial environments, products have almost similar performances but not the same impact on customers. This happens because purchasers represent a big number; therefore companies try to focus their attention mainly on some key factors. Research of alternative solutions is always well accepted to reach cost and size reduction of portable modules.

1.1 Background

The power amplifier represents the most power consuming device in RF wireless applications. It increases the power of a modulated signal source before being radiated by transmitter antenna. Its design is critical, as it has always been based on reaching the trade-off between linearity and efficiency.

RF PA design is different depending on which telecommunication standard is used. This usually results in space and money consuming. In fact, when operating in a multimode and multiband platform, several power amplifiers are used, lowering the process efficiency. The feasibility of a single device that is able to work for different transmission standards is therefore under discussion in this thesis.

1.2 Aims

The goal of this work is to achieve a single line-up RF power amplifier that operates for GSM/EDGE and WCDMA technology. The device should be able to satisfy the main 3GPP requirements and result in an efficient solution for both cost and size. The purpose of this research work consists also in identifying limitations of the mentioned multimode processes, as well as proposing new solutions for the future.

2 Theory

The first part of this section gives the possibility to comprehend the apparent antithesis between GSM and WCDMA signals [1]. Their digital modulations are therefore described, focusing the attention on various and constant envelope signals differences. The second part instead is based on the fundamental things to know when designing a PA, spotlighting the theoretical backgrounds that concern the matching network choice.

2.1 Digital modulations

Modulation technique has consequences on the nature of transmitting signal. Shifting the frequency from baseband to radiofrequencies is a non-linear process, resulting in phase and amplitude distortions with respect to the original waveform. Explaining mathematical theory behind this process is not a part of this report, but it is possible to recap the main effects of widely used modulation classes in RF telecommunications. Tab. 2.1 [2] contains some features and comments about the constellations shown in Fig. 2.1.

Modulation name	**GMSK**	**8PSK**	**QPSK**
Telecommunication standard	GSM	EDGE	WCDMA
Amplitude shift	No	Yes	Yes
Filtering type	Gaussian	RRC	SRRC
Bit per symbol	2	3	2
Spectral efficiency	Great	High	Lower
PAR	Low	Higher	High
Non-linear mode	Yes	No	No

Table 2.1: *Widely used digital modulations for RF transmitters.*

The represented parameters show the main differences among the transmitted signals. Amplitude modulation represents anyway the biggest trouble to deal with. It does not happen in GSM because the Gaussian filter is not sharp, so it keeps the waveform envelope practically constant. PSK modulations, instead, have amplitude variations in shifting from one symbol to another, so they need a pulse shaping filter to improve their spectral efficiencies. The most important result of the previous considerations is that EDGE and WCDMA signals require a linear amplification because otherwise they could suffer from a BER worsening.

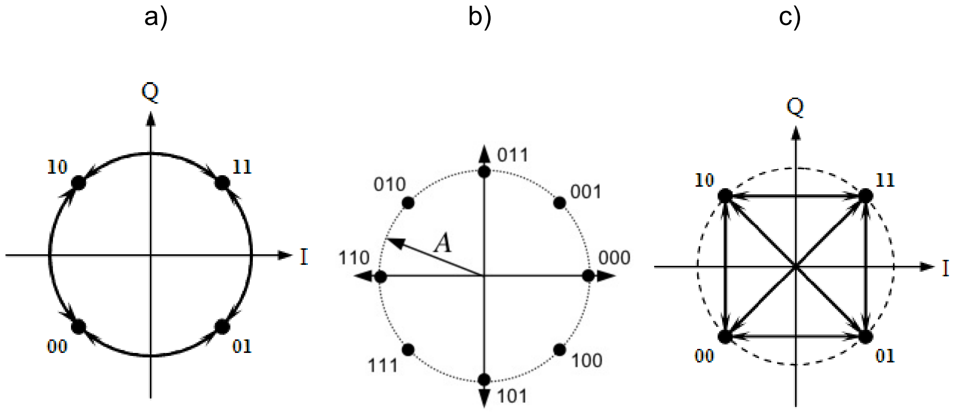


Figure 2.1: *Constellation plot for a) GMSK b) 8PSK c) QPSK.*

It would be easier to amplify always a constant amplitude signal since linearity is not required and an efficiency enhancement can therefore be obtained. This is the concept behind polar modulation technique.

2.1.1 Polar transmitters

These transmitters use a second-level modulation that operates separately on the amplitude and phase components of the signal, as shown in Fig 2.2. It is possible to describe it with the following steps [3]:

- Baseband DSP elaborates data and move them to high frequency;
- The RF signal is then shifted into its amplitude and phase components;
- The phase signal drives a VCO in order to provide the input for the first active device;

- The amplitude signal controls the supply voltage of the final stage PA, modulating its the drain (or collector) voltage;
- The output envelope is controlled by the amplitude component, while phase one controls the DC value.

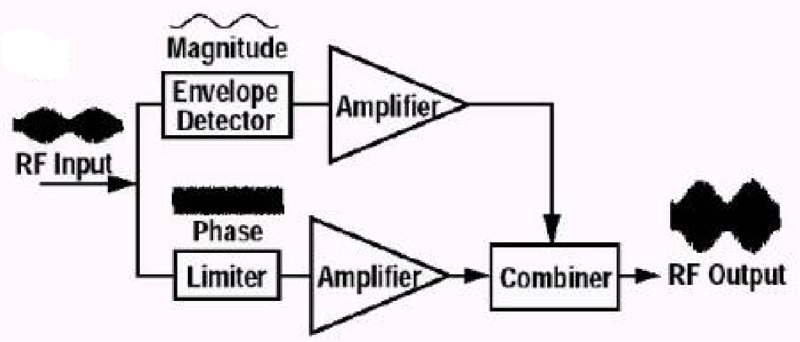


Figure 2.2: *Polar modulation process scheme [3].*

This scheme has brought module design to reach an integration of GSM and EDGE in a single line-up PA. Anyway, it is more difficult to extend this step to WCDMA mostly because a non-linear algorithm (CORDIC type) and a spectral efficiency worsening can make the PAR too wide for reaching specifications. There also problems concerning the duplexer insertion loss and the large power control dynamic range.

Indeed, this solution is not the right way to develop a multimode power amplifier with the present technology. Other design possibilities have therefore to be taken into account.

2.2 Operation frequency bands

GSM and WCDMA work on different frequencies. 3GPP has attributed 14 bands to both the standards [4] [5], each of them with a certain extent and application area. The most common and used bandwidths are shown in Tab. 2.2.

GSM	Uplink frequency bands (MHz)	WCDMA	Uplink frequency bands (MHz)
GSM 850 GSM 900	824.0 – 849.0 880.0 – 915.0	Band V Band VIII	824.0 – 849.0 880.0 – 915.0
DCS 1800 PCS 1900	1710.0 – 1785.0 1850.0 – 1910.0	Band IV Band I	1710.0 – 1755.0 1920.0 – 1980.0

***Table 2.2:** Main operation frequency bands for GSM and WCDMA.*

2.3 Power amplifier general design

2.3.1 Schematic

A general single-stage RF PA has the configuration represented in Fig. 2.3. The transistor represents the active device that converts DC power provided by the biasing networks into RF power to increase the input signal level. The matching networks have the job of transforming the input impedance to the output. They are usually obtained by a procedure called conjugated matching.

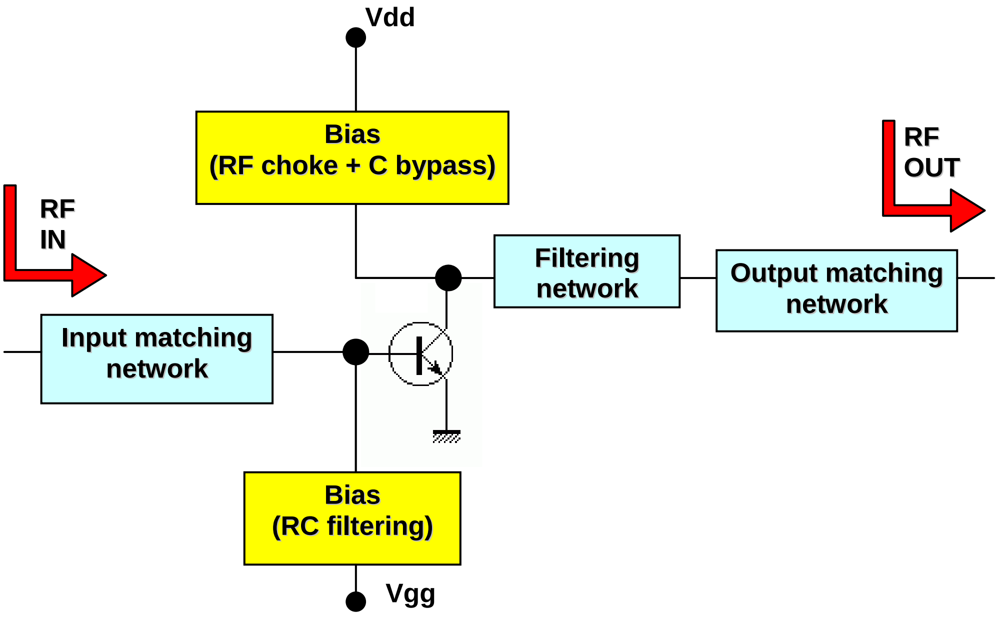


***Figure 2.3:** Power Amplifier general representation*

2.3.2 Active device selection

There are some criteria to be considered for choosing the proper transistor family for a RF PA. Power capability, gain, efficiency and power supply range are the most discriminating factors in the active device selection step.

The trade-off between size and cost reduction seems to favour CMOS research and development. The large integration capability of these devices makes it appropriate for the targeted application. Digital performances of these transistors are further better than those of other technologies. Unfortunately, there are still lots of troubles with RF applications, even if shrinking gate length is leading, nowadays, to a remarkable headway [6]. Probably CMOS modules will be an ace in the hole when technology embeds also the PA in the DSP chip [7].

GaAs transistors are probably the best choice presently on the market. They do not have those difficulties to reach linearity and efficiency requirements. Moreover, they are ready to satisfy tighter and tighter demands from mobile handset manufacturers concerning the next generation of wireless platforms. The most used processes belonging to this category are pHEMT and HBT.

Pseudomorphic HEMT technology is based on a heterostructure FET, since the transistor includes a junction of different band gap materials, offering better high frequency performances and elevated gain. HBT, on the other hand, is a BJT that works with a heterojunction instead of a PN one, resulting in lower on-resistance and improved efficiency. Both the families are based on band gap mismatching between AlGaAs and GaAs. Other combinations are still under development, but it has not been possible to find the right trade-off between cost, performances, requirements and yield production [8].

There is a possibility to mix these two technologies into one: placing the HBT structure atop the pHEMT layers (shown in Fig. 2.4), giving nature to E-pHEMT transistors, where E stays for *enhanced.* The area that is shared by them works as a sub-collector for HBT and a protective cap for pHEMT. In this way it is possible to minimize cost and maximize yield, with the same performance as the stand alone devices [9]. There is no added complexity, but availability of discrete packaged components should be evaluated.

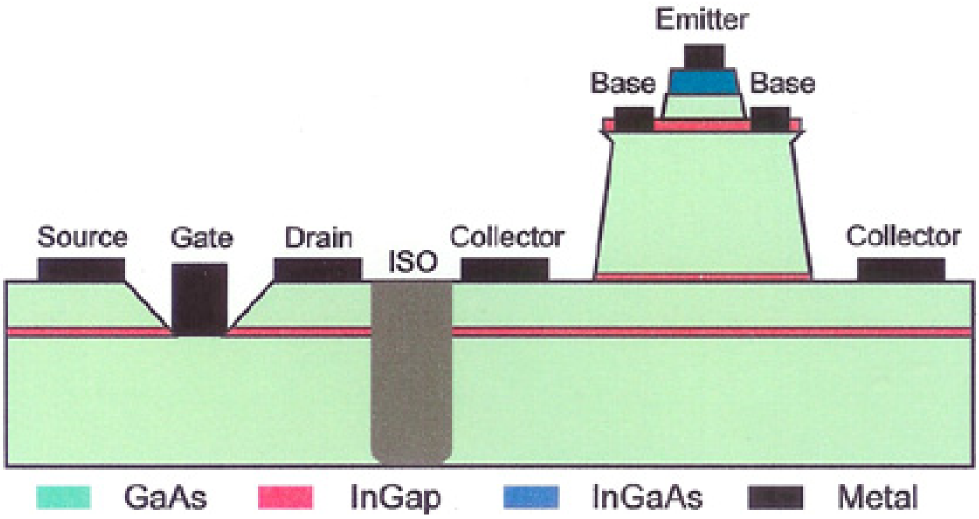


Figure 2.4: *Enhanced mode pHEMT epitaxial structure [9].*

2.3.3 Matching networks

The goal of impedance matching in a RF PA design is to deliver maximum power to the output. This condition is linked to a lot of other parameters, mostly concerning linearity and efficiency issues.

The simplest kind of matching network is a single L-transformer. This structure has two just two components, that surely provide less filtering properties, but a narrow band response.

Other topologies are Π-type and T-type matching circuits, described roughly in Tab. 2.3. They enlarge the frequency band behaviour but they also introduce more phase delay. This can involve the need of phase compensation. A multimode and a multiband approach probably leads to more complicated topologies. Attention should be focused on number of components used in order to preserve money and space on the PCB.

	Π-type	T-type
Output Matching	Class B with sinusoidal drain voltage Class E	High power PA Class F for high impedances
Input/Inter-stage Matching	Easy to handle transistor capacitances	Widely used
Level of Harmonic Suppression	High	Significant

Table 2.3: *Features of fundamental matching network configurations.*

There is also another consideration to take into account: the different targets of the two networks. If the input matching is needed to minimize the return loss, bringing the correspondent reflection coefficient to the centre of the Smith Chart, the output network defines instead PA features and behaviour, so it is a tougher process to realize.

Anyway, most of all the projects are focused on maximization of the output power, high-linearity or lowest current consumption. To achieve these kinds of characteristics, the reflection coefficient should be moved to other areas of the Smith Chart. There is a measurement method, called Load-Pull [10], which produces constant level curves for one of the already mentioned parameters (Fig. 2.5). In this way, the designer is able to understand how to move the output impedance on the Smith Chart in order to realize a certain performance.

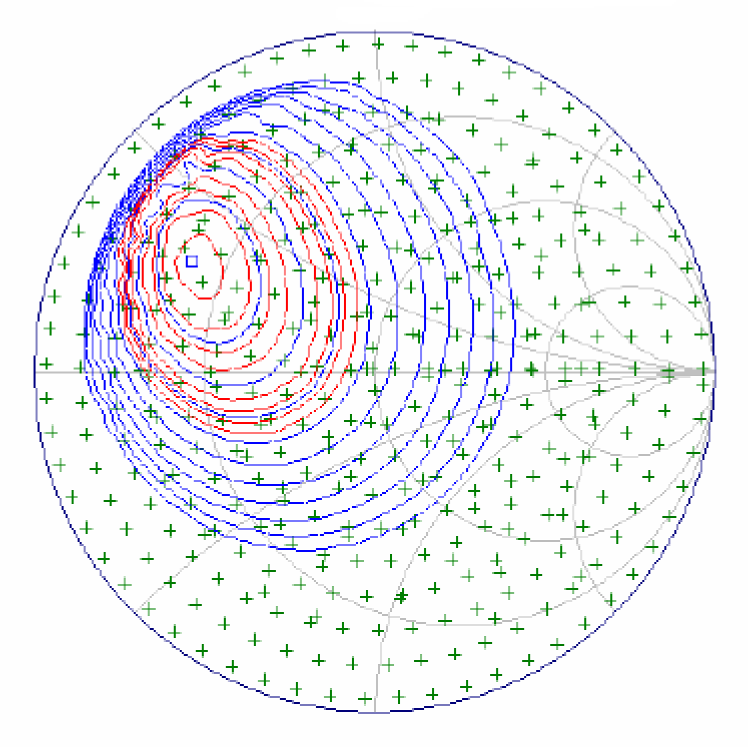


***Figure 2.5:** Load-pull curves example.*

Unfortunately, there are fewer and fewer companies that produce high-performance single transistor. Most of them prefer to sell directly the integrated circuit, reducing their fabrication costs. Software large signal characterizations for discrete transistors are not often available, therefore penalizing design choices.

2.3.4 PA biasing

Biasing networks are required to supply the PA with DC power. Usually they comprehend a current mirror stage that is useful for the performances stability with temperature. Besides, some passive elements are needed.

As concerns, firstly, drain (collector) polarization, an inductive coupling to feed the transistor (usually called RF choke inductor) is used to cut RF interferences from the DC supply voltage. By-pass capacitors are instead used to provide a direct AC path to ground and, consequently, to absorb possible current peaks.

Gate (base) biasing corresponds, on the other hand, to control the PA working class. Some drawbacks could anyway happen in a multistage PA since this feeding system provides coupling path between input and output. This leads to distortion. The simplest solution to avoid these boredoms is to low-pass filtering the supply gate voltage, so that AC components cannot create interferences [11].

2.3.5 Optimum load

The optimum load is the one that maximizes the output power in a PA design. It is exactly defined as the ratio of its output voltage and current fundamental harmonics. This value depends on how long the transistor is kept on, so on its circulation angle α (defined between 0 and 2π).

However, while the fundamental frequency voltage is fixed at the drain biasing (that is usually half the maximum drain-source voltage), on the other hand the current component is linked to α and it is defined as [12]:

$$I_L(f_0) = \frac{I_P}{\pi}\frac{\alpha - \sin(\alpha)}{1-\cos(\alpha/2)} \tag{2.1}$$

The current I_P is the peak load current and it is the half of the peak drain current, as seen from the waveforms in Fig. 2.6. The maximum value of the drain current depends on the transistor limitations and it is usually measured when V_{DS} reaches the so called “knee voltage” value.

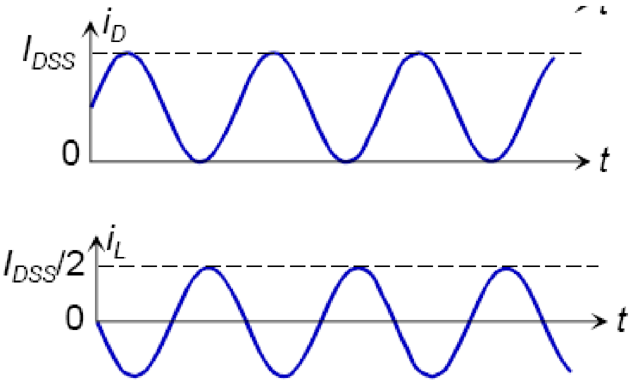


Figure 2.6: *Drain and Load current waveforms. I_{DSS} is the device saturation current [12].*

The definition of optimum load resistance can thus be expressed through the following formula [12]:

$$\begin{aligned} R_{LO} &= \frac{V_L(f_0)}{I_L(f_0)} = \\ &= V_{DD}\cdot\left[\frac{I_P}{\pi}\frac{\alpha-\sin(\alpha)}{1-\cos(\alpha/2)}\right]^{-1} = \\ &= \frac{2\pi V_{DD}}{I_{DSS}}\cdot\frac{1-\cos(\alpha/2)}{\alpha-\sin(\alpha)} \end{aligned} \tag{2.2}$$

3 Issue

Having introduced some theoretical background, it is possible to describe the working structure of this report. The idea is based on switching the working class of the multimode PA depending on the selected standard.

3.1 Target

GSM and WCDMA standards represent the past and the future of wireless mobile communications. Nowadays, they are often both used in the same platforms, providing a wideband approach in voice and data transmissions. As illustrated in Fig. 3.1 for a mobile phone, for instance, there are several power amplifiers on the PCB, even two for the same transmission mode.

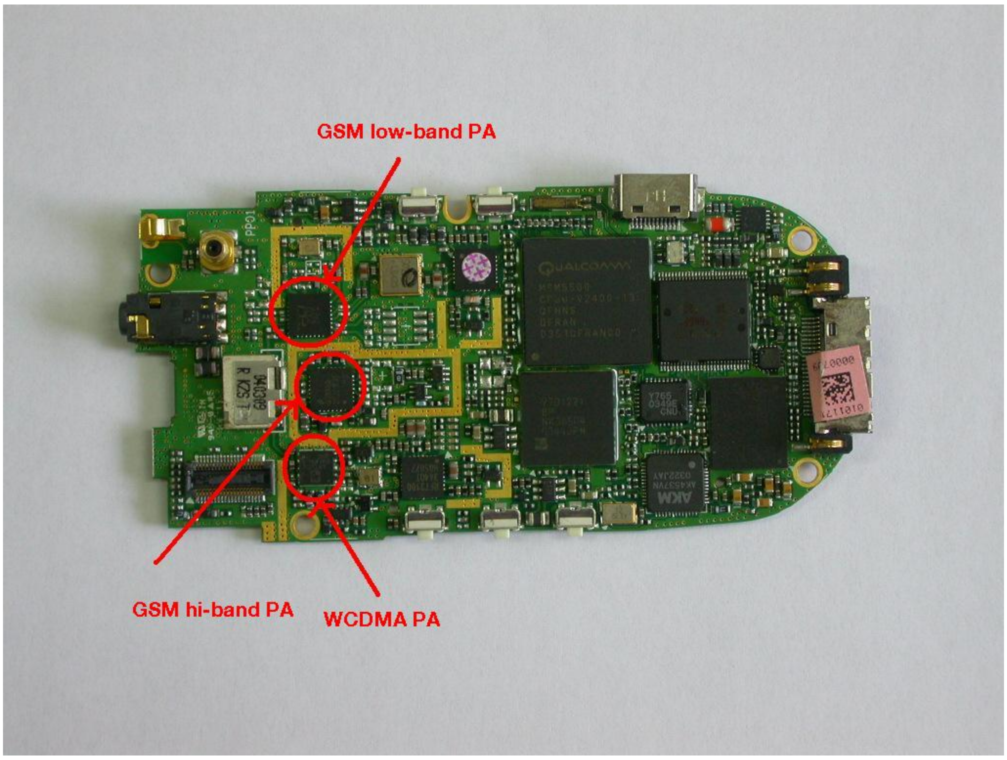


Figure 3.1: *Mobile phone PCB from upper view.*

Reducing the number of chips for power amplification should be the defining strategy in mobile broadband modules. The purpose of this project is to set up a RF multimode and multiband single-stage single line-up PA. The device is meant to work for all the bands namely UMTS-FDD I, UMTS-FDD IV, GSM DCS 1800 and GSM PCS 1900.

3.2 Requirements

To start with a design, the main specifications are studied. The 3GPP has defined parameters and conditions to fulfil these requirements. Tab. 3.1, 3.2 and 3.3 summarize the main parameters that are measured when working with the transmission side of the mobile stations. It is not part of the job of the RF PA designer to check and verify all the listed values. Reported data [4] [5] concern frequency bands that are contemplated in this project.

GSM – DCS 1800								
Parameter	3GPP Specification							
Maximum output power	36 dBm ± 2.5 dB (DCS 1800)							
Modulation and wideband noise RF spectrum	**Power level (dBm)**	**Frequency offset from the carrier (kHz)**						
		100	200	250	400	≥ 600 and < 1800	≥ 1800 and < 6000	≥ 6000
		Maximum level measured (dB)						
	≥ 36	+0,5	-30	-33	-60	-60	-71	-79
	34	+0,5	-30	-33	-60	-60	-69	-77
	32	+0,5	-30	-33	-60	-60	-67	-75
	30	+0,5	-30	-33	-60	-60	-65	-73
	28	+0,5	-30	-33	-60	-60	-63	-71
	26	+0,5	-30	-33	-60	-60	-61	-69
	≤ 24	+0,5	-30	-33	-60	-60	-59	-67
Switching transients RF spectrum	**Power level (dBm)**	**Frequency offset from the carrier (kHz)**						
		400	600	1200	1800			
		Maximum level measured (dBm)						
	39	-21	-26	-32	-36			
	≤ 37	-23	-26	-32	-36			

***Table 3.1:** Main 3GPP requirements for a DCS 1800 PA [4].*

<table>
<tr><th colspan="2">GSM – PCS 1900</th></tr>
<tr><th>Parameter</th><th>3GPP Specification</th></tr>
<tr><td>Maximum output power</td><td>33 dBm ± 2.5 dB</td></tr>
<tr><td>Modulation and wideband noise RF spectrum</td><td>
<table>
<tr><th>Power level (dBm)</th><th colspan="7">Frequency offset from the carrier (kHz)</th></tr>
<tr><td></td><td>100</td><td>200</td><td>250</td><td>400</td><td>≥ 600 and < 1800</td><td>≥ 1800 and < 6000</td><td>≥ 6000</td></tr>
<tr><td></td><td colspan="7">Maximum level measured (dB)</td></tr>
<tr><td>≥ 33</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-68</td></tr>
<tr><td>32</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-67</td></tr>
<tr><td>30</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-65</td></tr>
<tr><td>28</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-63</td></tr>
<tr><td>26</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-61</td></tr>
<tr><td>≤ 24</td><td>+0,5</td><td>-30</td><td>-33</td><td>-60</td><td>-60</td><td>-60</td><td>-59</td></tr>
</table>
</td></tr>
<tr><td>Switching transients RF spectrum</td><td>
<table>
<tr><th>Power level (dBm)</th><th colspan="4">Frequency offset from the carrier (kHz)</th></tr>
<tr><td></td><td>400</td><td>600</td><td>1200</td><td>1800</td></tr>
<tr><td></td><td colspan="4">Maximum level measured (dBm)</td></tr>
<tr><td>39</td><td>-21</td><td>-26</td><td>-32</td><td>-36</td></tr>
<tr><td>≤ 37</td><td>-23</td><td>-26</td><td>-32</td><td>-36</td></tr>
</table>
</td></tr>
</table>

Table 3.2: *Main 3GPP requirements for a PCS 1900 PA [4].*

<table>
<tr><th colspan="2">WCDMA – UMTS band I, IV</th></tr>
<tr><td>Parameter</td><td>3GPP Specification</td></tr>
<tr><td>Maximum output power</td><td>24 dBm +1/-3 dB</td></tr>
<tr><td>Adjacent Channel Leakage Ratio</td><td><table>
<tr><th>Frequency shift respect to fundamental channel</th><th>ACLR limit</th></tr>
<tr><td>+ 5 MHz or - 5 MHz</td><td>33 dB</td></tr>
<tr><td>+ 10 MHz or - 10 MHz</td><td>43 dB</td></tr>
</table></td></tr>
<tr><td>Error Vector Magnitude</td><td><table>
<tr><th>16QAM modulation</th><th>EVM limit</th></tr>
<tr><td>Yes</td><td>14.5%</td></tr>
<tr><td>No</td><td>17%</td></tr>
</table></td></tr>
<tr><td>Transmit Intermodulation</td><td><table>
<tr><th>Interference Signal Frequency Offset</th><td>5MHz</td><td>10MHz</td></tr>
<tr><th>Interference CW Signal Level</th><td colspan="2">-40dBc</td></tr>
<tr><th>Intermodulation Product</th><td>-31dBc</td><td>-41dBc</td></tr>
</table></td></tr>
</table>

Table 3.3: *Main 3GPP requirements for a WCDMA PA [5].*

3.3 Power driving

The characteristic curve of a PA is represented in Fig. 3.2 with its 1 dB compression point. The latter is the input power level for which the gain has decreased by 1dB with respect to its linear portion. It can also be viewed as the barrier between the linear and saturation zones. The idea of this report is based on coupling WCDMA and GSM/EDGE respectively in one of these areas.

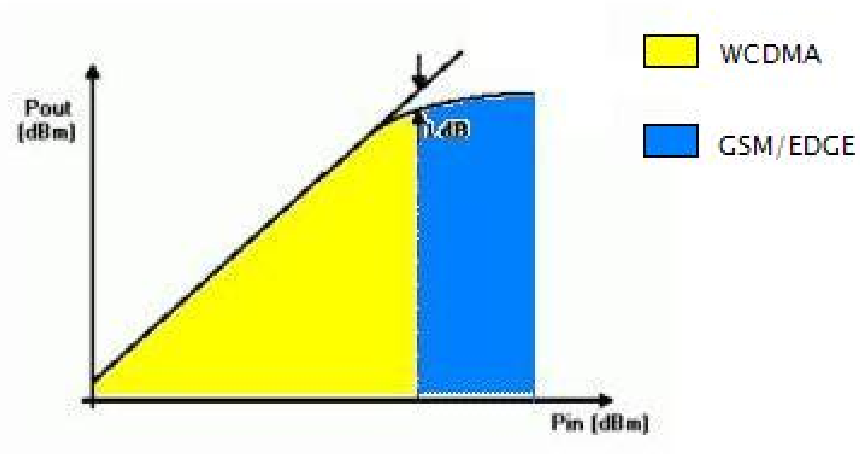


Figure 3.2: *Characteristic power curve of a PA.*

3.3.1 Linear zone

There is no harmonic term added from the PA function. This means that in this area theoretically there is no spectral regrowth in the output spectrum.

WCDMA signal has tough specifications regarding linearity parameters (ACLR, EVM). Moreover it has a high PAR due to non-constant amplitude modulation. For this reason it could be thought that this signal has to have an input power inside this range.

3.3.2 Saturation zone

When the fundamental gain starts to decrease, other harmonics begin to grow, as the PA transfer function can be viewed as a power series. The output power reaches a saturation value in correspondence to this non-linear region.

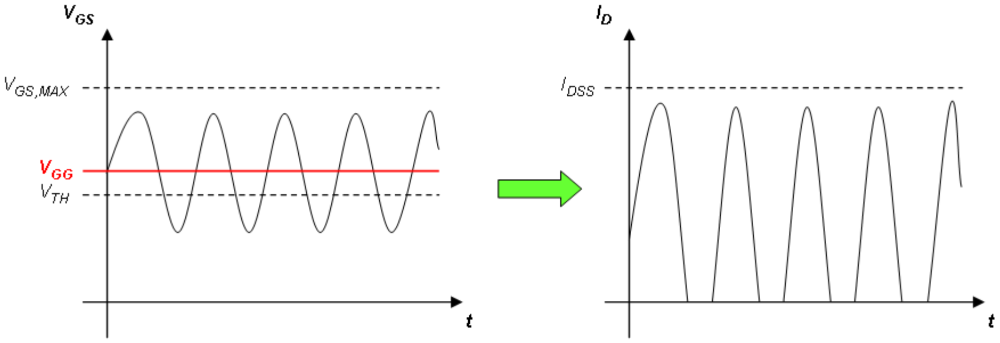
The GSM signal has a constant amplitude modulation. Also EDGE waveform can be characterized in the same way since most of the modern transmitters use polar modulation technique. This kind of behaviour allows pushing the working point into the saturation zone, leading to high-efficiency achievement.

3.4 Working class

Maximum output power levels are different from WCDMA to GSM/EDGE. For this reason, not only the input RF power has consequences on the transmitted signal, but also, and most of all, the working class to which the PA belongs. This design choice has big impact on linearity and efficiency demanded by 3GPP standards.

The multimode PA designed in this project has the same network topology for both the telecommunication standards. Anyway, gate polarization value conditions the device working class. The operation idea is based on switching the biasing that could bring the multimode PA to shift from one condition to another. Practically, the aim is to make the WCDMA signal work in class AB and the GSM in overdriven class AB, as illustrated in Fig. 3.3.

WCDMA operation mode



GSM operation mode

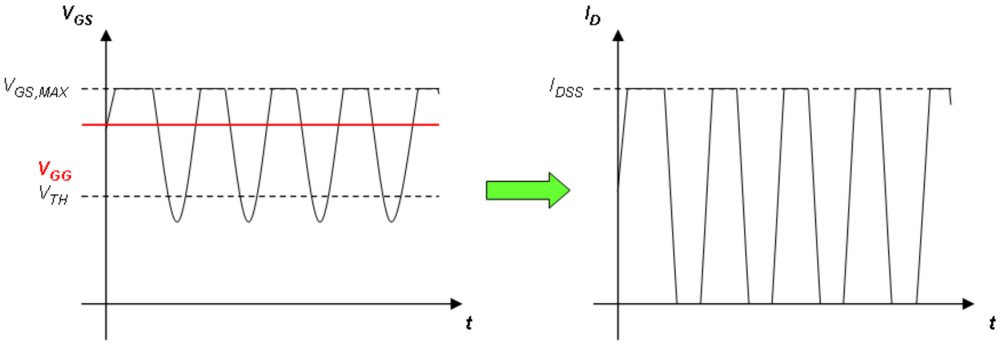


Figure 3.3: *Gate voltage and drain current in a class AB (upper) and overdriven class AB (lower) PA.*

The gate voltage for WCDMA should be close to the threshold value since it corresponds to a trade-off between current consumption and ACLR value.

On the other hand, GSM needs a drain current that is as close as possible to a square wave (like inverse class F behaviour, Fig 3.4). This is done to achieve a high-efficiency PA. Pushing the gate polarization toward its maximum value would ensure a not that distorted waveform and a better overlapping between drain current and voltage [13].

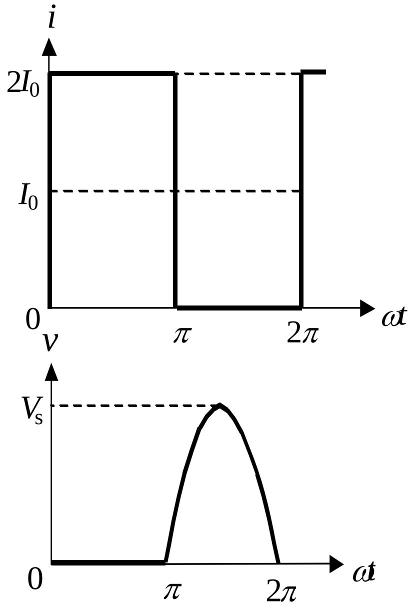


Figure 3.4: *Drain current and voltage waveforms in an inverse class F PA.*

4 Design and simulations

A first practical approach is analyzed inside this chapter. This step was realized through ADS 2008 from © Agilent Technologies, a CAD for designing RF and Microwave circuits. Simulations are included, focusing the attention on fundamental gain, RF spectrum, output power and PAE.

4.1 Active device

The basic device that performs power amplification is a transistor. Its research was based on some of the requirements listed in section 3.2. Nowadays markets push companies toward ICs development and therefore to create always less discrete transistors. For this reason, just few devices could be considered interesting for this project. In Tab. 4.1, a list of these transistors is reported.

The spotlighted ATF-501P8 from © Avago Technologies has been chosen for this work. The main reasons are:

- Efficient process;
- Positive gate voltage;
- High gain;
- Test conditions;
- Availability of ADS large signal model.

The latter is the mathematical characterization of the transistor and also the first requirement to start the CAD design.

4.2 Design

4.2.1 Working point

Characterization of the starting point in a general PA design derives from project theory. The situation can be better understood by plotting the characteristic curve of the device (Fig. 4.1). The graph contains the dependence of drain current on drain supply voltage. The drawn load lines are the borders of this report, because it has been decided before to polarize the transistor in class AB, so between them.

It is seen that the threshold gate voltage V_{TH} is approximately the same as the one given in the data sheet (reported in Tab. 4.1).

It is possible to calculate the optimum load impedance. It has been decided to use a circulation angle of 3π/2, (it actually corresponds to V_{GS} = 0.5V, while V_{TH} = 0.33V and V_{GSmax} = 0.67V). Moreover, the saturation drain current I_{DSS} can be instead found from the I-V plot, while the drain voltage is fixed for this project to 3.4 V.

Applying (2.2):

$$R_{LO} = \frac{2\pi \cdot 3.4V}{400mA} \cdot \frac{1-\cos(3\pi/4)}{3\pi/2-\sin(3\pi/2)} \cong 24.5\Omega \tag{4.1}$$

Company		**WJ**	**Excelics**	**Aeroflex**	**CEL**
Device ID		FP31QF	EPA480C-180F	MMA709	NE5520379A
Process		HFET	HFET	HBT	LD-MOSFET
Size		6x6 mmq	15x9 mmq	3x3 mmq	5.7x5.7 mmq
Gain (dB)		16÷14	20÷18	13÷11	9÷7
1dB output power (dBm)		34÷33.5	36÷34	34÷33	33÷31
Noise Figure		4÷4.6		6÷6.5	
Breakdown voltage (V)			12	14.5	20
Pinch-off voltage (V)		-2	-1		1
Test conditions	Vds (V)	9	8	7	3.2
	Idq (ma)	450	600	700	750

Company		**Sirenza**	**RFMD**	**Triquint**	**Avago**
Device ID		SPB-2026Z	RF3809	TGF4118-EPU	ATF-501P8
Process		HBT	HBT	HFET	E-pHEMT
Size		4.57x4.45 mmq	5.93x3.81 mmq	0.9x2 mmq	2x2 mmq
Gain (dB)		15÷13.5	12.5÷10.5	15÷13	16.5÷15
1dB output power (dBm)		32÷34	34÷32.5	33÷34	29÷30
Noise Figure		5.2			1
Breakdown voltage (V)		7	9	12	7
Pinch-off voltage (V)				-1.85	0.33
Test conditions	Vds (V)	5	8	8	4.5
	Idq (ma)	445	750	1.69	280

Table 4.1: *Some of discrete transistors for a multimode application and their main characteristics.*

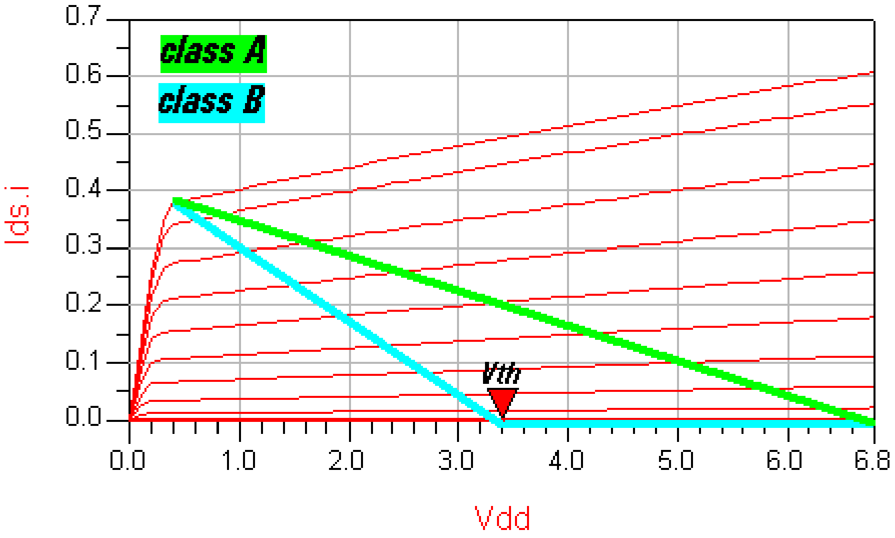


Figure 4.1: *PA characteristic curve with load lines for class A and B.*

4.2.2 Stabilization

This multimode power amplifier is a two-port device and it surely needs to be stable in order to provide the defined gain. Usually the latter is a function that goes down with the increase of frequency, amplifying spectral components in the lower band more, as shown in Fig. 4.2. *TGain* is the transducer gain, so the one measured from the RF input to the RF output port, while *MAG* represents the maximum available gain, which can be reached through a simultaneous impedance matching of the device. The two markers point out the gain at the interested bandwidth.

The stability condition can be measured through two frequency dependent parameters: the stability factor K and the stability measure B. They are expressed throughout the following formulas [14]:

$$K = \frac{1 - |S_{22}|^2 - |S_{11}|^2 + |\Delta s|^2}{2|S_{21}S_{12}|} > 1$$

$$B = 1 - |S_{22}|^2 + |S_{11}|^2 - |\Delta s|^2 > 0 \qquad (4.2)$$

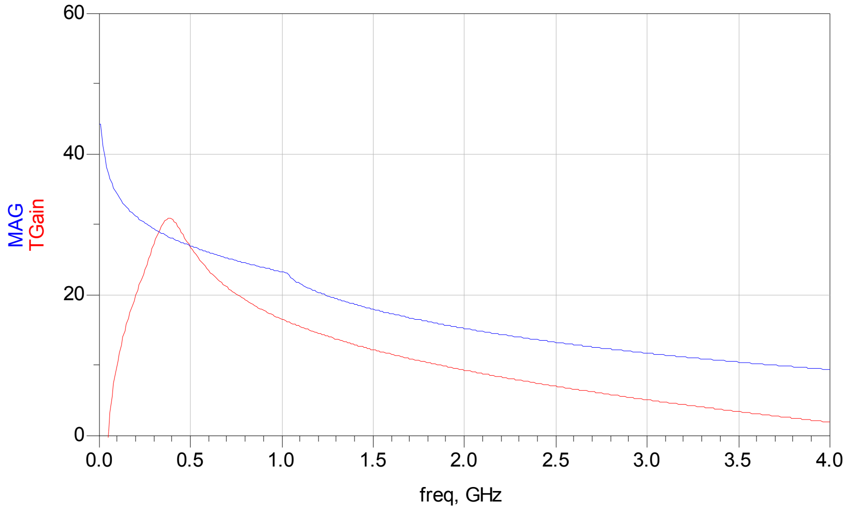


***Figure 4.2:** Gain vs. Frequency in a PA.*

From Fig. 4.3, it is seen that these conditions are not satisfied. It is predictable that at lower frequencies the PA be unstable since the corresponding maximum gain is really high[1]. Low-band stabilization is therefore required.

This step has been implemented through the insertion of a dissipative network that brings down the low frequency gain. For this purpose, a small resistor has been placed in series with the gate. The result of this operation is reported in Fig. 4.4. It is important to notice that stabilization does not have to take the in-band gain down.

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[1] Usually the MAG is infinite for low frequencies without stabilization. The graph, instead, plots a finite value. That happens because ADS replace the MAG, when infinite, with MSG, which is defined at the border of stability circles.

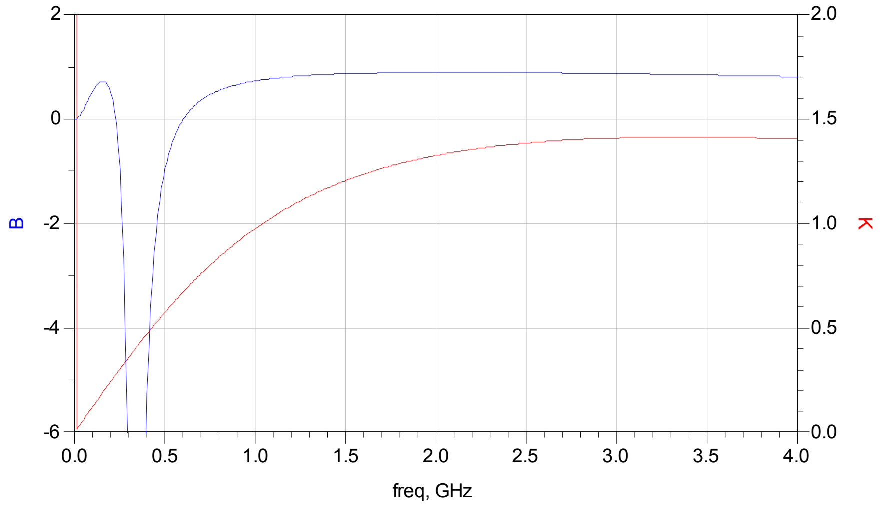

Figure 4.3: *Stability vs. Frequency in a PA.*

4.2.3 Output filtering design

The selected working class for the multimode PA is AB. That means that amplification is not that linear. To reduce distortion effects, usually an LC resonator is used. This multimode PA filtering design is the same as the inverse class F behaviour. In addition to the fundamental resonator, there is another one that activates itself with the second harmonic; in this way, efficiency is improved. A series capacitor is added to block the DC component from the output. This network is illustrated in Fig. 4.5.

The values are found solving the following equations:

$$\begin{gathered}\frac{1}{jw_0 C_{BLOCK}} + \frac{jw_0 L_2}{1 - w_0^2 L_2 C_2} = 0 \\ \frac{1}{j(3w_0) C_{BLOCK}} + \frac{j(3w_0) L_2}{1 - (3w_0)^2 L_2 C_2} + \frac{j(3w_0) L_1}{1 - (3w_0)^2 L_1 C_1} = 0\end{gathered} \tag{4.3}$$

L_1 and C_1 define the fundamental frequency resonator, L_2 and C_2 the second harmonic one, C_{BLOCK} represents the series DC block capacitor while w_0 is the fundamental angle frequency.

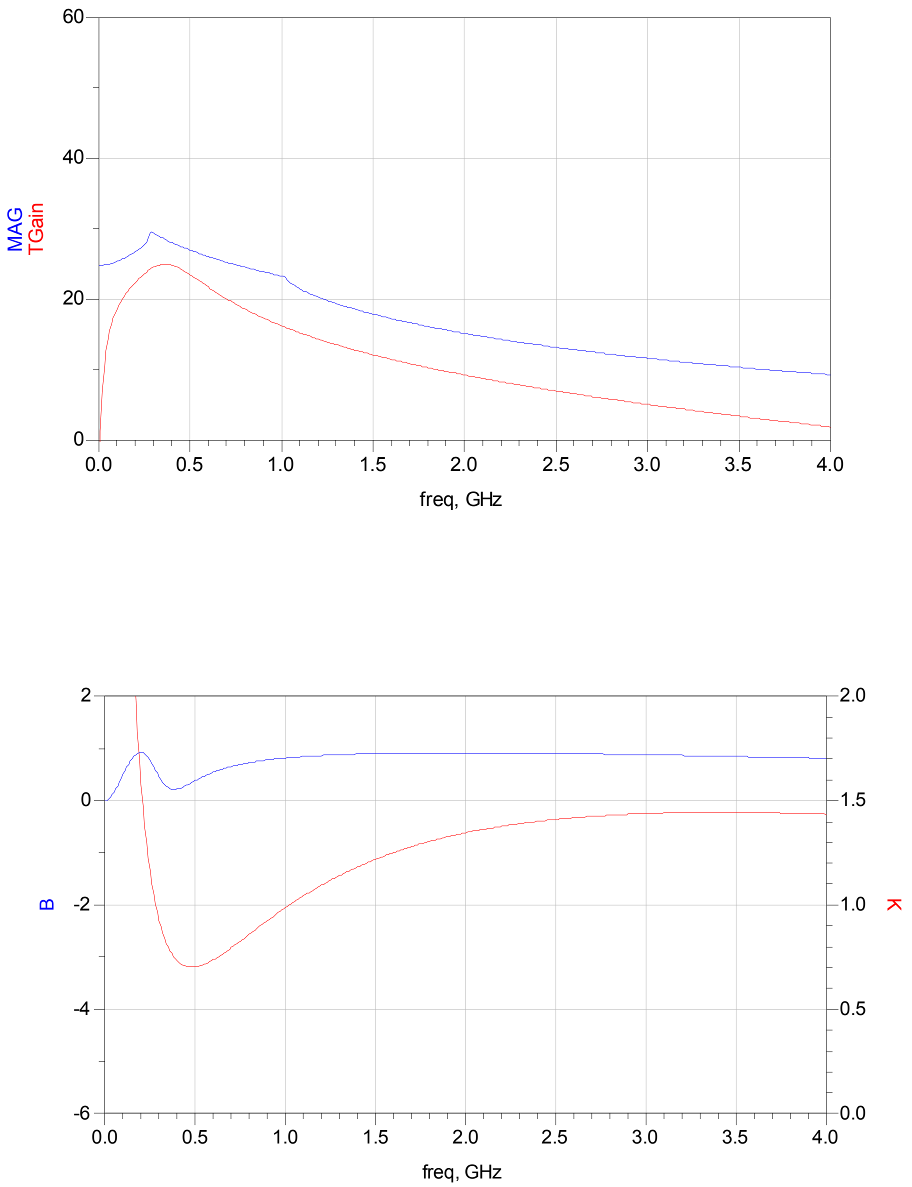

Figure 4.4: *Stabilization resistor effects on Gain, K and B.*

The first equation brings the fundamental frequency component to the load impedance. The second one establishes the third harmonic down to ground, in order to cut it from the drain voltage waveform, as shown previously in Fig. 3.4. Unfortunately, for any Q relative to this circuit, the second equation gives no solution.

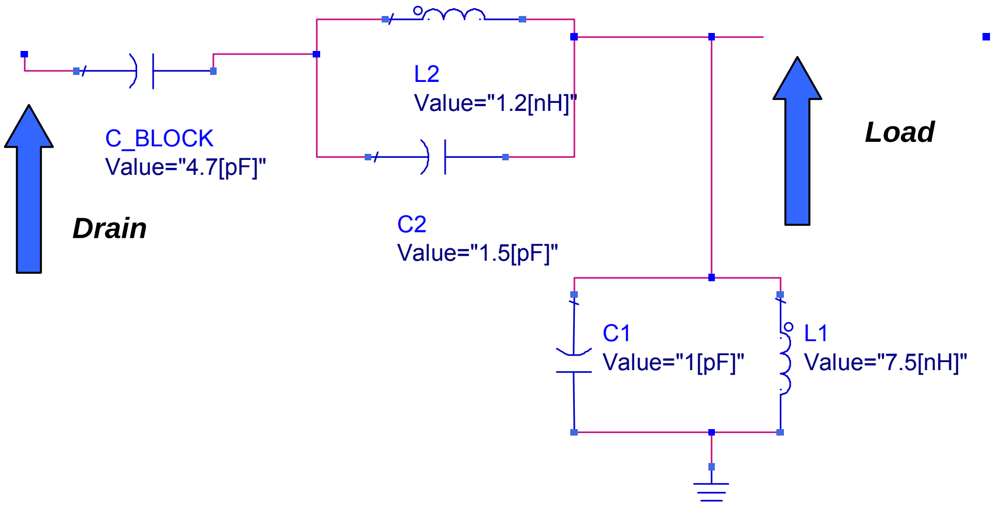

Figure 4.5: *Filtering network.*

The criterion that has been adopted to implement this network is to start from the second harmonic resonator; to choose the smallest available inductor value (and consequently the capacitor that tunes the desired frequency) and finally to find the value of *C_BLOCK* from the first equation, which says that $C\_BLOCK = 3C_2$. The fundamental parallel resonator is chosen trying to achieve small impedance at $3w_0$ and also to preserve the gain. C_1 and L_1 values are obtained through a trade-off process, so this is why they could be subject to some changes depending on simulations results.

4.2.4 Matching networks

The last step to create a working PA is the matching networks implementation. This process is usually quite complicated because it has to be done simultaneously between the device input and output; in fact, the two correspondent reflection coefficients depend on each other.

The multimode PA presented in this work uses lumped components instead of the distributed ones (microstrip or stripline components) since working frequencies correspond to a too long wavelength and, consequently, to too long transmission lines for the size of the PCB.

After several attempts and optimizations, it has been possible to create two matching networks. The input configuration, shown in Fig. 4.6, is focused on return loss maximization. The output components (Fig 4.7) provide load impedance that is a compromise between GSM and WCDMA.

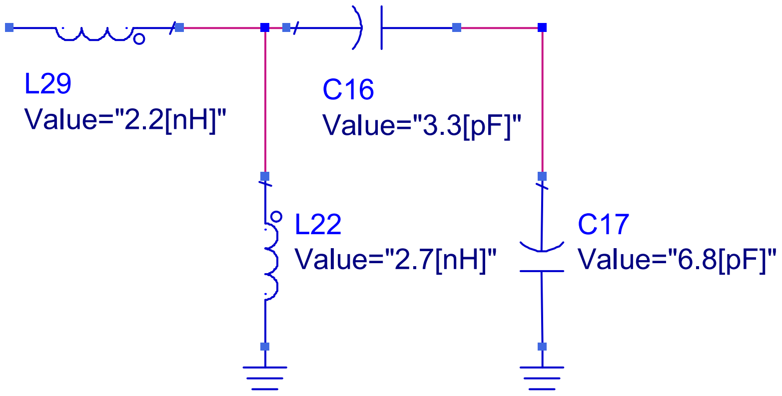

Figure 4.6: *Input matching network.*

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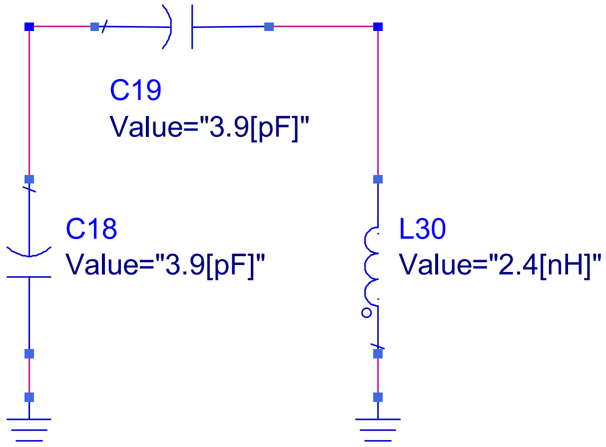

Figure 4.7: *Output matching network.*

4.2.5 Small signal S-Parameters

Matching networks components values have been determined thanks to small signal S-parameters simulations. Attention has been focused on S_{21}, which corresponds to PA transducer gain, and on reflective coefficients S_{11} (input) and S_{22} (output).

Since the project frequency bandwidth is quite wide (270 MHz), the first purpose of matching has been not to lose gain with respect to the MAG whose effects are reported in Fig. 4.8.

This desired frequency behaviour can shape setting some goals on PA reflection coefficients. S_{11} should be as close as possible to the centre of Smith Chart, in order to have a small return loss, as shown in Fig. 4.9. In the same picture S_{22} should be a trade-off between parameters that are successively measured through simulations, which are described in the next paragraph.

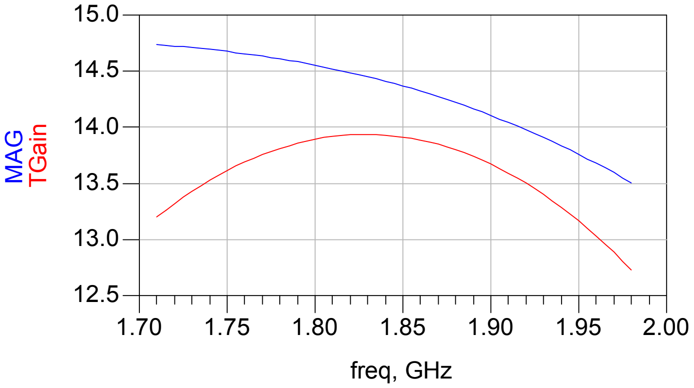

Figure 4.8: *Multimode PA small signal S_{21} respect to MAG, expressed in dB.*

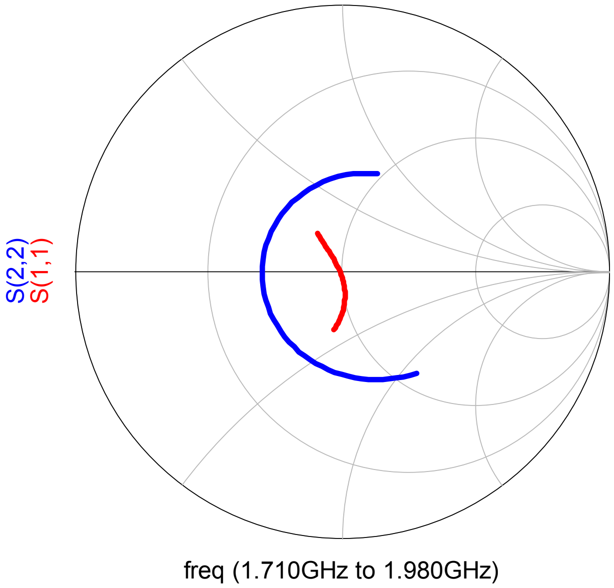

Figure 4.9: *Input and output reflection coefficients on the Smith Chart*

4.3 Simulations

Before implementing a circuit, its performances should always be estimated roughly. The following simulations have been performed for both the GSM/EDGE and the WCDMA mode using a harmonic balance setup and a proper 3GPP modulated RF power source.

4.3.1 Measured parameters

The parameters that have to be considered and plotted are:

- P_{OUT} versus P_{IN};
- Drain current and voltage waveforms;
- Output spectrum;
- Supply DC current;
- PAE (Power Added Efficiency)[2].

Other parameters like ACLR, EVM, and PAR for WCDMA as well as transient and modulation spectrum for GSM have not been the subject of simulations. ADS gives the possibility to evaluate the mentioned parameters, but just if the device under test comprehends also a DSP chip.

All the plots and tables are reported in the appendix.

4.3.2 PCB model

The target of simulations is to foresee the device real behaviour in order to design consequently the best outline, tuning the components value. To achieve the best match with reality, the schematic has to take into account also non-ideality of the PCB. There are two main factors that influence the multimode PA characteristics:

- Microstrip paths that link passive components, transistor and connectors;
- Soldering pads.

At RF frequencies, both these two elements require an ADS model that could simulate their behaviour. Fig. 4.10 represents, for instance, a 1.3 nH inductor on a FR-4 PCB. The component library already contains parasitic resistances and capacitances of the passive element.

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[2] The Power Added Efficiency is defined as the difference between the output and the input power at the fundamental frequency, divided by the DC power provided to the PA. In simple words, it represents the amount of DC power that is converted into RF gain.

To characterize PCB effects, a substrate model has to be added to the ADS schematic. In this work, a 4 layers PCB has been produced. Only the layer on the top is used for the signal propagation, while the others represent the ground planes. Tab. 4.2 shows the main parameters in the substrate model template with their correspondent values.

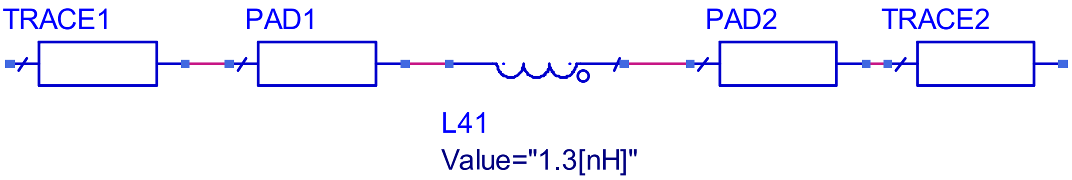

Figure 4.10: *PCB effects on a 1.3 nH inductor.*

Layer No.	1	2	3	4
Layer Type	Signal	Ground	Ground	Ground
Dielectric Constant	4.6	4.6	4.6	
Substrate Height (mm)	0.18	0.4	0.18	
Dielectric Loss Tangent	0.015	0.015	0.015	
Layer Thickness (mm)	0.035	0.035	0.035	0.035
Conductivity (S/m)	6e+07	6e+07	6e+07	6e+07

Table 4.2: *Four Layers FR-4 PCB characterization.*

5 Measurements

A first practical approach is analyzed inside this chapter. When all the components are mounted on the PCB, a measurement bench can be set up. Different variables have to be swept in order to characterize the device performances. Descriptions of how to measure the desired features are reported in 3GPP requirements.

5.1 Test bench

The test bench for the multimode PA is shown in Fig. 5.1. The voltage generator feeds the transistor and measures the current consumption. The RF input is provided by a signal generator that operates up to 6 GHz. This instrument is usually already set to 3GPP standards. A linear preamplifier then rises up the signal level to provide the desired output power. The spectrum analyzer receives the output signal. Observed data can be eventually compared with the specifications.

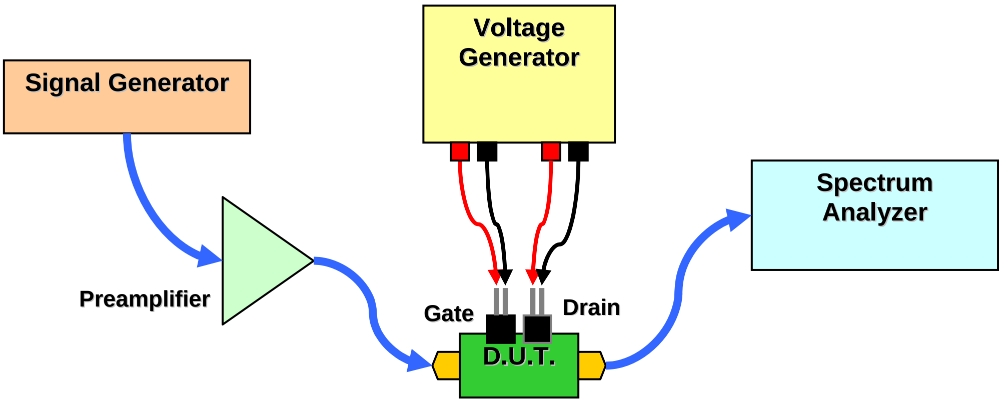

Figure 5.1: *The device under test set up.*

5.2 Characteristics

The most important parameters to be measured are the current consumption, the ACLR (only for WCDMA), the output power and RF spectrums.

The current consumption is an expression of the device efficiency and it can be read on the voltage generator. It does not have a 3GPP specification, but it is obvious that it has to be as low as possible.

The ACLR measures the linearity of the WCDMA PA since it depends on the output power that ends up in transmission channels adjacent to the used one. This phenomenon is due to the spectral regrowth [15].

The PA has to work with different output power levels. For this reason, this parameter is usually swept so to observe different achieved performances.

RF spectrum is studied in order to control out-of-band emissions. For WCDMA this parameter is not so relevant, while in GSM it is useful to measure both the spectrum due to modulation and the one due to switching transients.

5.3 Results

Measurements have been performed sweeping transmission channels (frequency) and the RF input power. The DUT is able to reach a maximum of 29 dBm at the output, which is not enough for GSM specifications. For this reason, it has been thought to make measurements as if the device was capable of driving up to 24 dBm. Obtained data has therefore been associated to a 5 dB higher output power level.

Moreover, gate voltage dynamic biasing was not realizable over all the range. The device has been too sensitive to values smaller than 0.51-0,53V, creating several disturbances in large frequency spans.

5.3.1 Output Power

The multimode PA has been tested with 3 different input power levels when transmitting in WCDMA mode: 0, 8 and 12 dBm, as shown in Fig. 5.2. It is possible to see that the gain is between 10 and 11 dB, since the PA still works in an almost linear zone.

In GSM mode, output power is represented in Fig. 5.3. There is a 7 dB gain since the active device is working in saturation. Only the maximum output power has been measured since it corresponds to the best efficiency.

5.3.2 Current consumption

WCDMA and GSM efficiency measurements are reported in Fig. 5.4 and Fig. 5.5. The current increases when the gate voltage and the input power increase too. Shifting the biasing by 100 mV allows pushing down the current by 200 mA.

5.3.3 ACLR

Linearity in WCDMA is relative to ACLR (or ACPR) measurements. The latter have been performed both in the adjacent channels (5 MHz from the central frequency) and in the alternate ones (10 MHz distance). This parameter is linked directly to the gate voltage. The latter adjusts the time in which the transistor is on. Consequently, a low V_{GG} makes the linearity decrease. Results are reported with Fig. from 5.6 to 5.9.

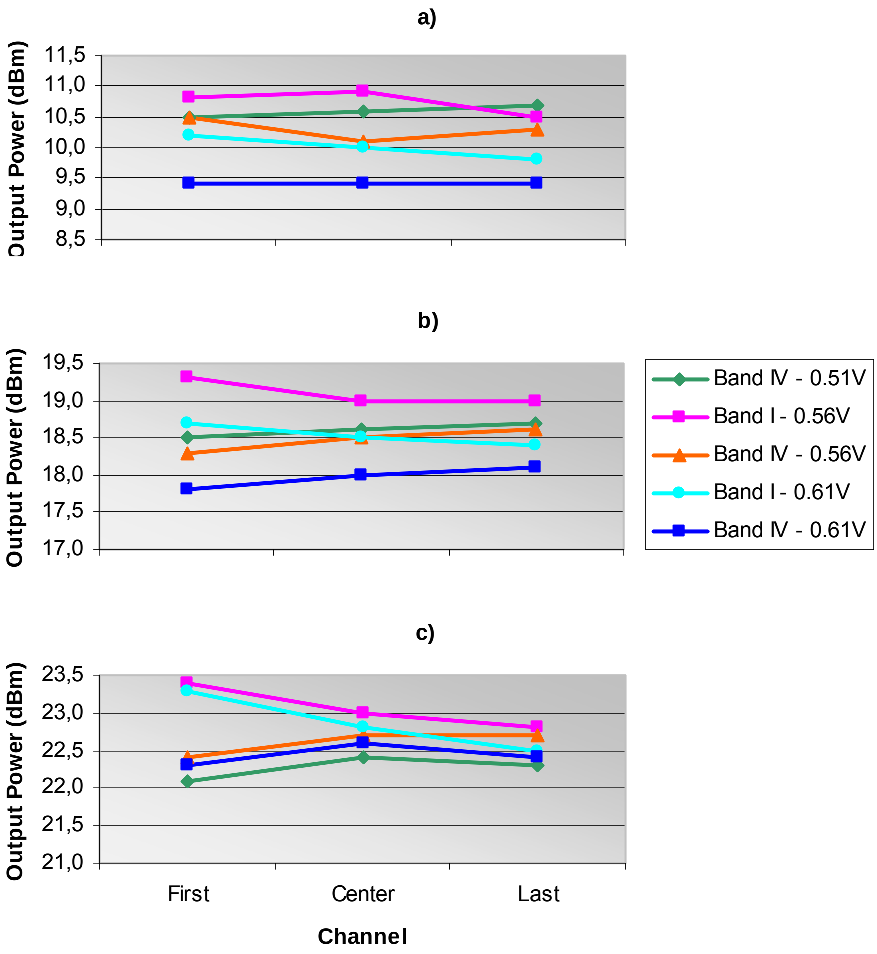

Figure 5.2: *Output Power in WCDMA mode when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

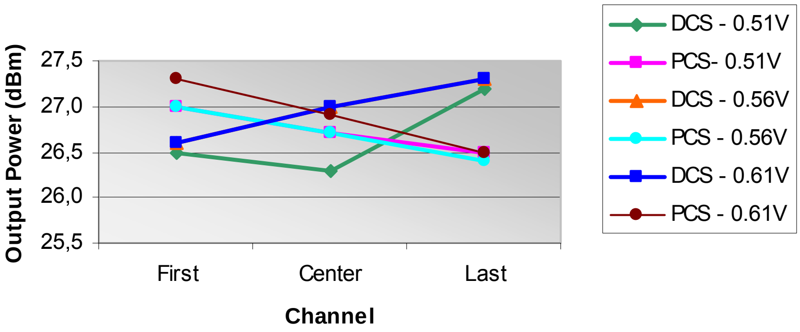

Figure 5.3: *Output Power in GSM mode when Input Power is 20 dBm.*

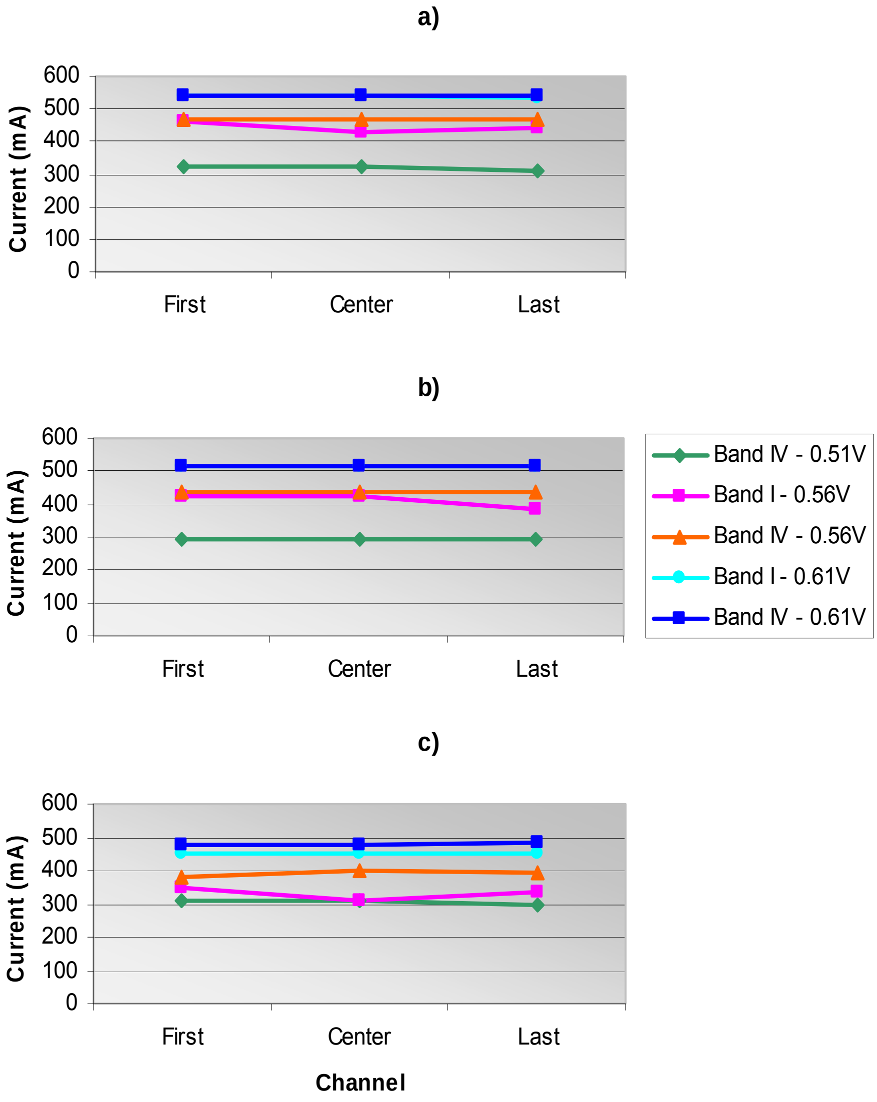

Figure 5.4: *Current consumption in WCDMA mode when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

5.3.4 RF spectrum

In GSM mode, switching and modulation spectrums have to be measured in order to check if the burst does not interfere with other channels. In Fig. 5.10 and 5.11 data are represented with respect to the frequency spacing from fundamental frequency. Tests have been performed at maximum power level since it represents the limiting condition for linearity. However, there are no problems to reach requirements in this case.

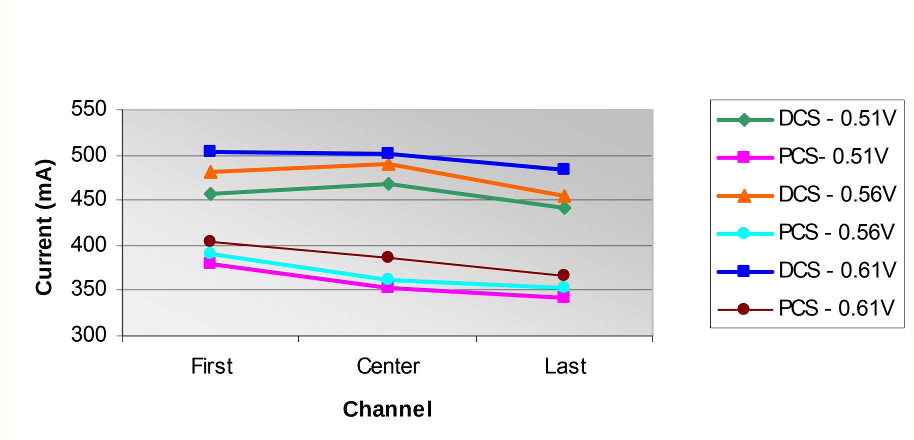

Figure 5.5: *Current consumption in GSM mode when Input Power is 20 dBm.*

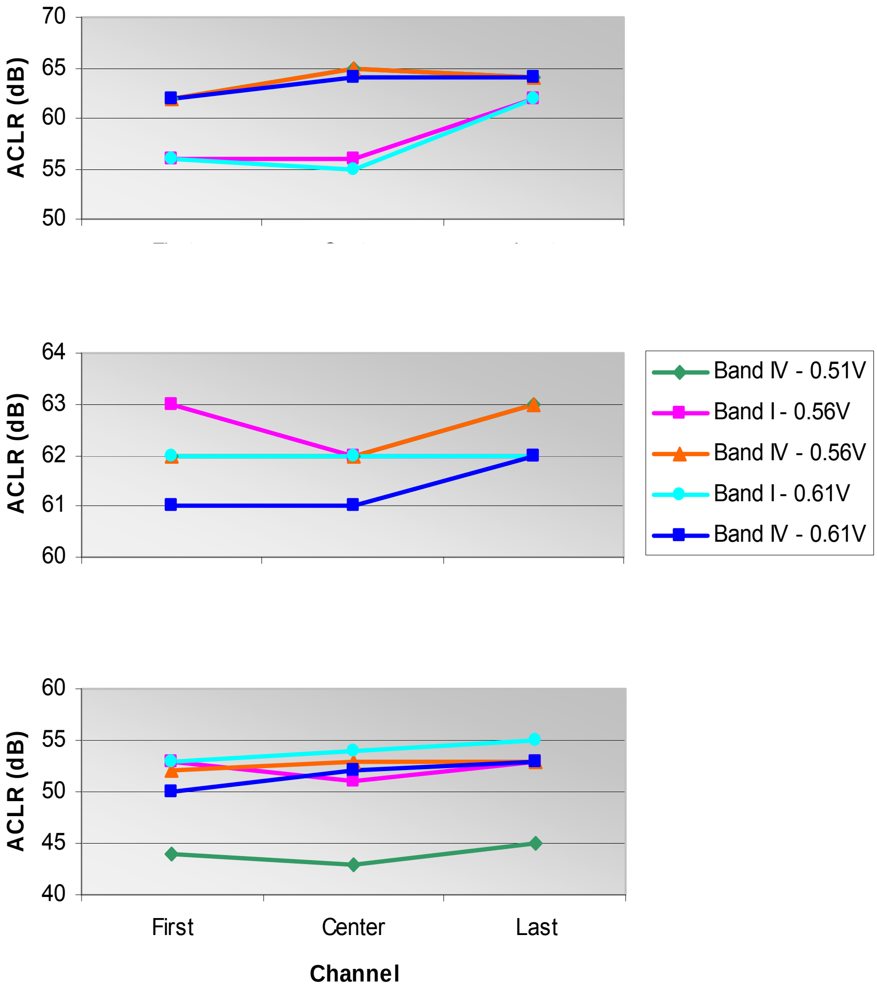

Figure 5.6: *ACLR at -10 MHz when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

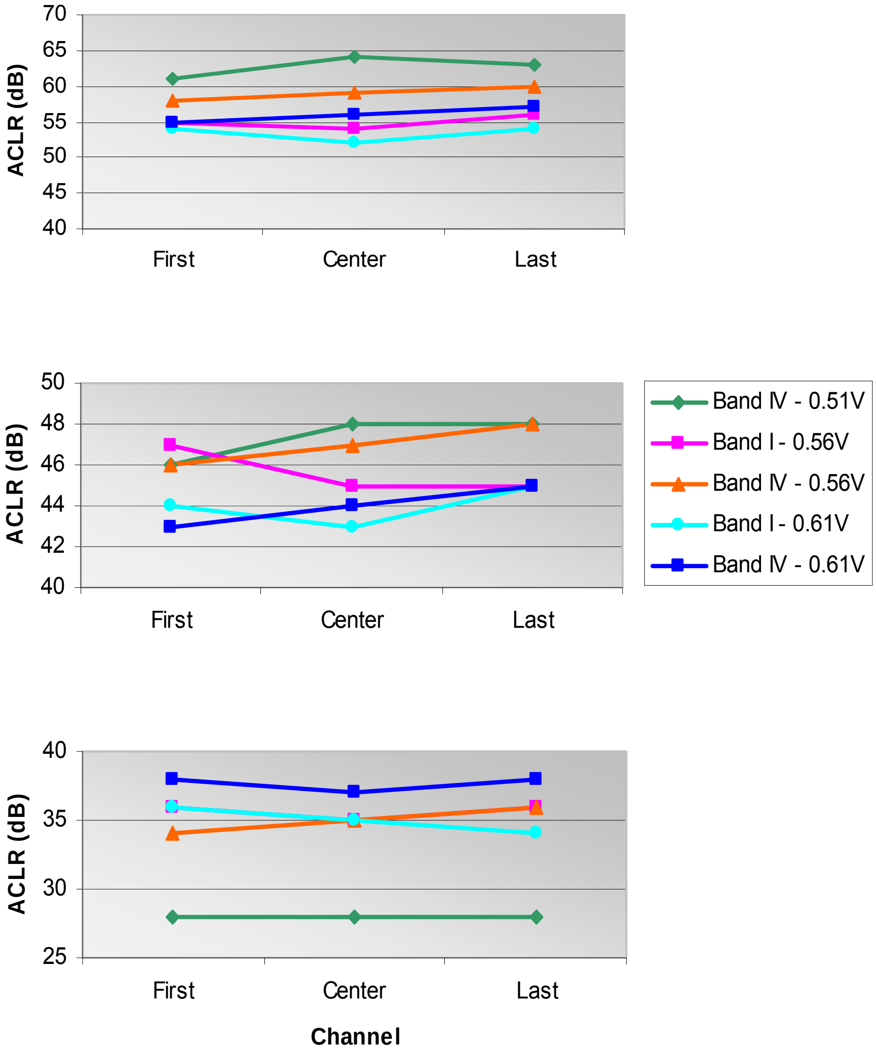

Figure 5.7: *ACLR at -5 MHz when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

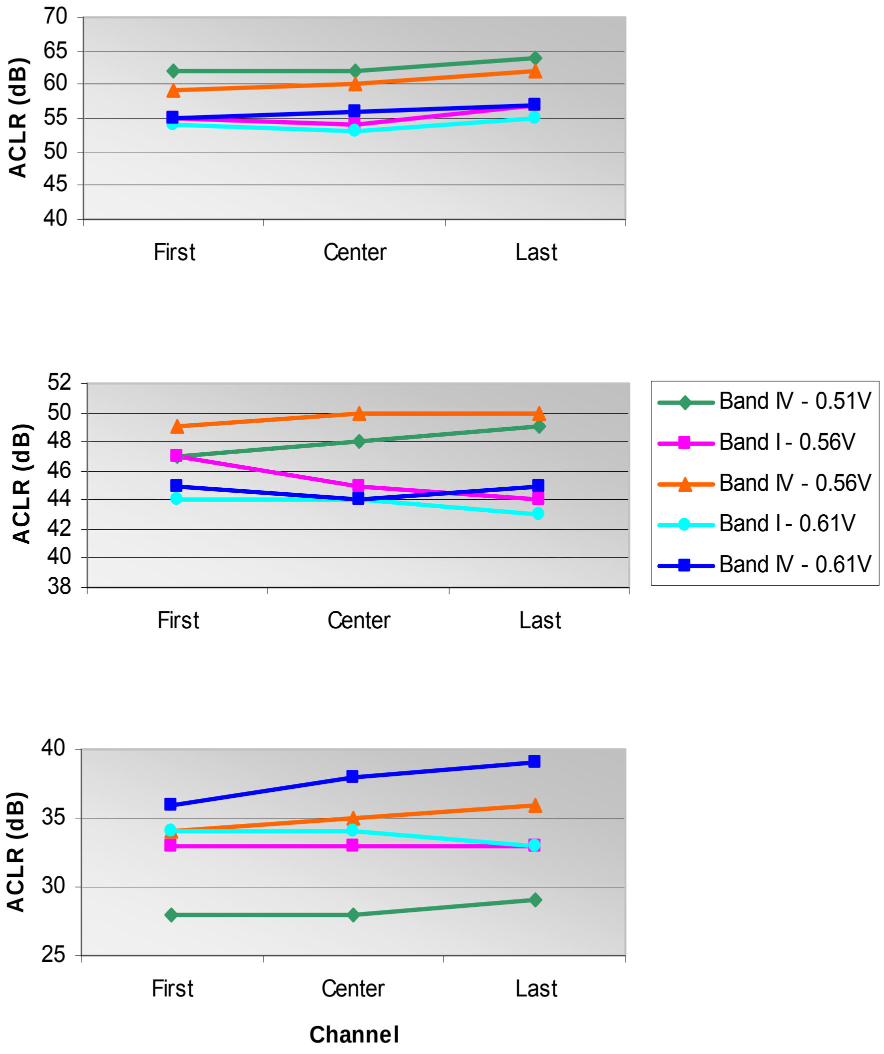

Figure 5.8: *ACLR at +5 MHz when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

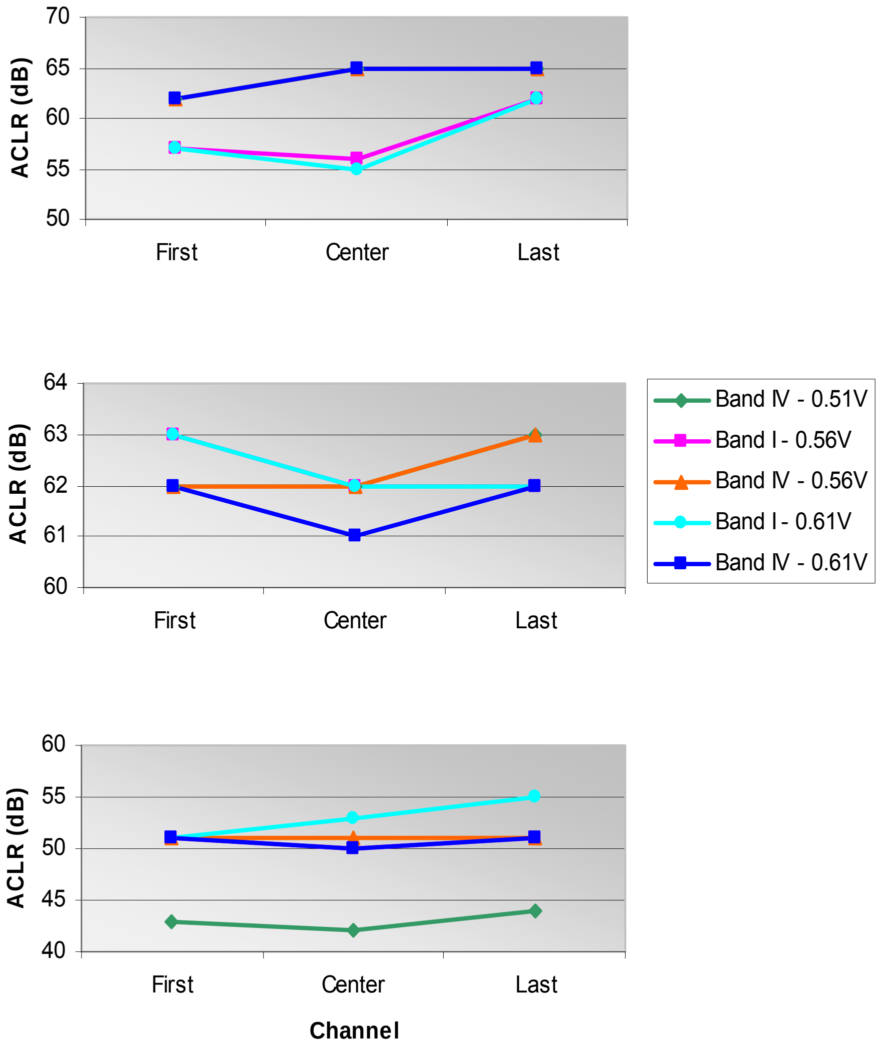

Figure 5.9: *ACLR at +10 MHz when Input Power is a) 0 dBm; b) 8 dBm; c) 12 dBm.*

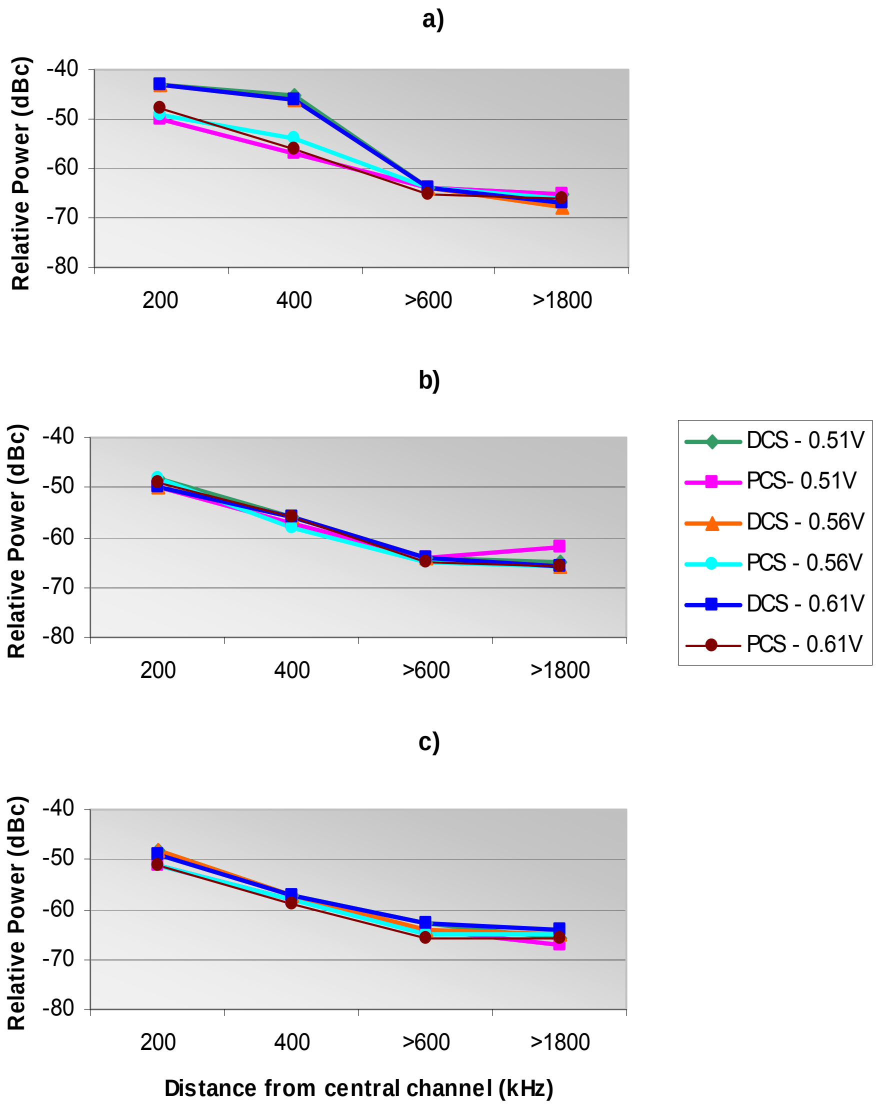

Figure 5.10: *Modulation Spectrum when transmitting in a) first b) central c) last bandwidth channel.*

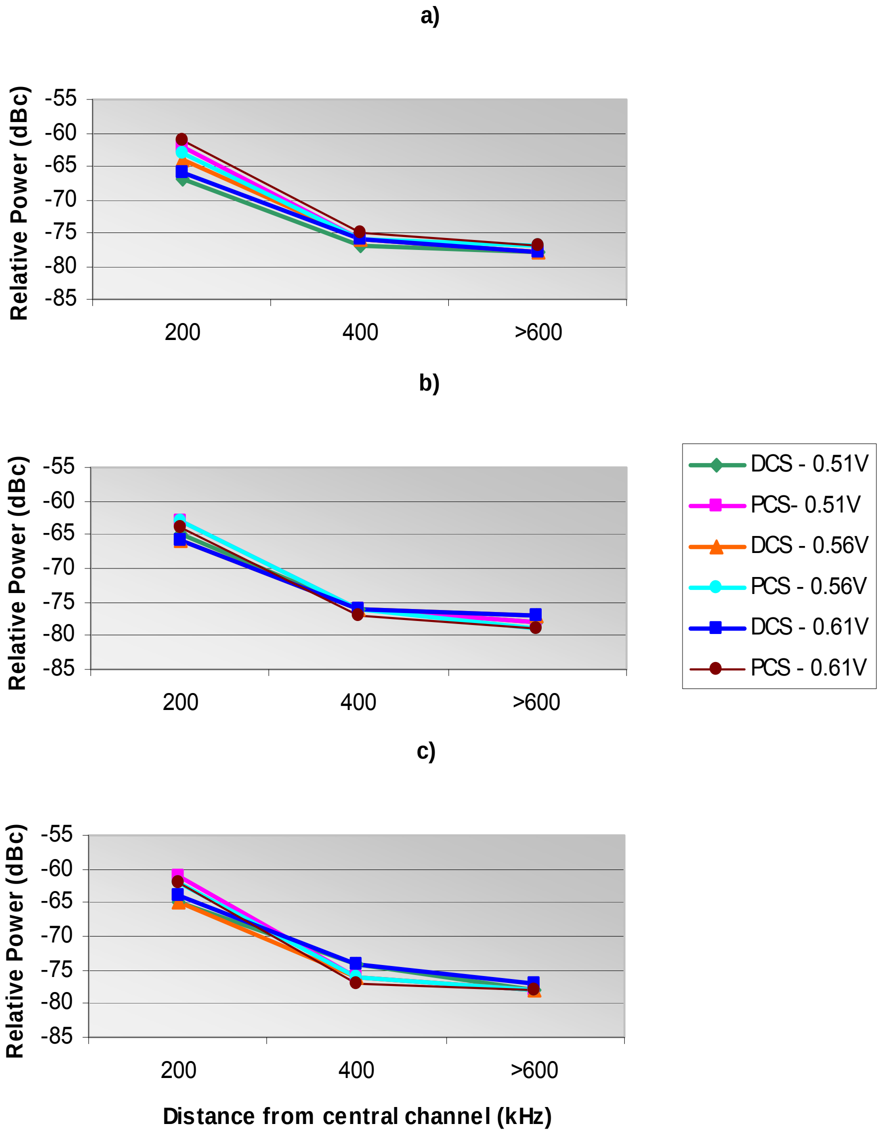

Figure 5.11: *Switching Spectrum when transmitting in a) first b) central c) last bandwidth channel.*

5.4 Considerations

Multimode PA performances are eventually compared with those of two different PA modules by © Skyworks Solutions, Inc: a Quad-Band PA module for GSM/GPRS and a Band I PA module for WCDMA/HSDPA. From the Tab. 5.1 and 5.2 it is seen that 3GPP performances are approximately the same if we consider the 5 dB power step between the Multimode PA and the single-mode SKY7736 and SKY77182.

5.4.1 Efficiency

Anyway, efficiency reduction represents a real problem. As already seen from simulations, the filtering network does not seem to be so efficient for such a large bandwidth. All the parasitic PCB effects increases the phase variation along the bandwidth in question, as it is seen from Fig. 4.9.

The PAE measured values are not the same of simulations. This depends on output power 2 dB loss respect to simulated data. However, it is not possible to obtain a higher efficiency since the transistor is not able to deliver more than 29 dBm. The PAE depends directly on the output power, and for this reason it cannot be higher that approximately 40%.

DCS 1800	**PAE (%)**	**Output Power (dBm)**	**Modulation Spectrum**	**Switching Spectrum**
Simulated	42	29	-	-
Multimode PA	29	27.2	OK	OK
SKY77336	48	33	OK	OK

PCS 1900	**PAE (%)**	**Output Power (dBm)**	**Modulation Spectrum**	**Switching Spectrum**
Simulated	49	28.6	-	-
Multimode PA	31	27	OK	OK
SKY77336	53	33	OK	OK

Table 5.1: *Comparison between simulations, measurements and Quad Band SKYWORKS module for GSM.*

5.4.2 Gate voltage biasing

Moreover, the efficiency for WCDMA is limited by the small dynamic range of the gate voltage. The values reported in the appendix could not be reached since the PA started apparently to oscillate. Some replicas appeared close to the fundamental frequency spectrum, increasing noise floor level. In this way it has not been possible to measure the DUT performances.

This behaviour can be due to a particular sensitivity of device to low currents polarization but also to the lack of a temperature stabilization circuit. When polarizing with a voltage close to the threshold value, the device get closer to the class B situation, in which the PA is on for just half of a hypothetical sinusoidal period. In these conditions, harmonics are added to the output and linearity requirements gets usually tougher to be reached.

UMTS band I	**PAE (%)**	**Output Power (dBm)**	**ACLR @ 5 MHz**	**ACLR @ 10 MHz**
Simulated	40	23.8	-	-
Multimode PA	18	23	36	52
SKY77336	39	28	36	48

Table 5.2: *Comparison between simulations, measurements and SKYWORKS module for WCDMA.*

6 Conclusions

The single stage single line-up multimode PA is able to reach 3GPP requirements at environment temperature, for different power levels and gate voltages. The optimum polarization depends on the input power and on the communication standard in use.

Linearity specifications have been reached without big problems. The preamplifier used in the test bench is not an ideal device, leading to slight worsening performances.

The current consumption is quite high, when compared to simulations. This happens especially in WCDMA, where it has been needed to drive the transistor with high gate voltages, achieving a worse efficiency. In GSM, instead, considerable troubles have been experiences by absorbed current uniformity on all the bandwidth.

Simulation results are different from what has been measured. Even though the models for path and pads are quite accurate, there are still some losses or some impedance mismatching, probably due to connector or to imperfect soldering. Anyway, with an IC realization of this device, the model could be more accurate and even the matching could lead to better performances.

It should be said that the design is based on a model with simple discrete components and on a general theory consideration. For this reason, there are some obvious limitations in approaching a wideband matching. The minimum number of passive elements has been used, in order to keep the overall size smaller and to reduce microstrip paths on the board. However, this outline does not push the device into particular enhancements regarding radio characteristics.

Anyway, the device works and overdriving the PA in GSM could be considered a simple technique. Some more attentions should be focused on the matching networks. There are some structures like MEMS that could develop tunable matching networks [16] [17] and, consequently, can push the market to digital control of PA. The standard mode could be controlled through a dynamic biasing and dynamic impedance network on just one single-line up device.

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Appendix

A Simulated plots and tables

DCS 1800 (@ 1747.5 MHz)

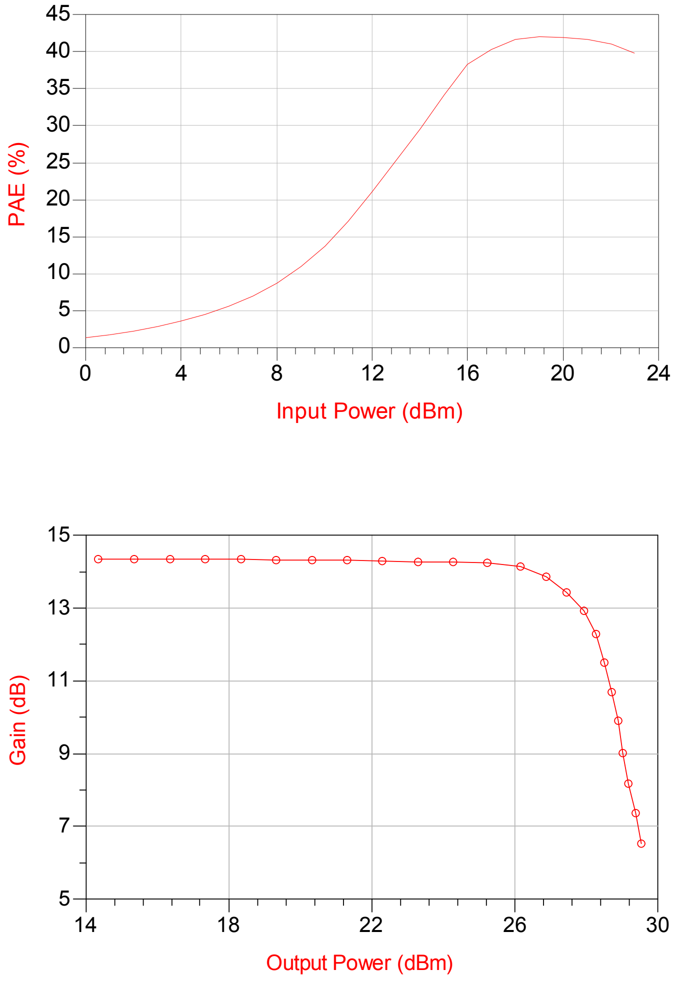

Figure 0.1: *Simulated PAE and Gain for DCS 1800.*

Gate Voltage (V)	PAE (%)	Output Power (dBm)	Second Harmonic (dBm)	Third Harmonic (dBm)
0.6	42	29	-10	-1

Table 0.1: *Simulation parameters for DCS 1800.*

PCS 1900 (@ 1880 MHz)

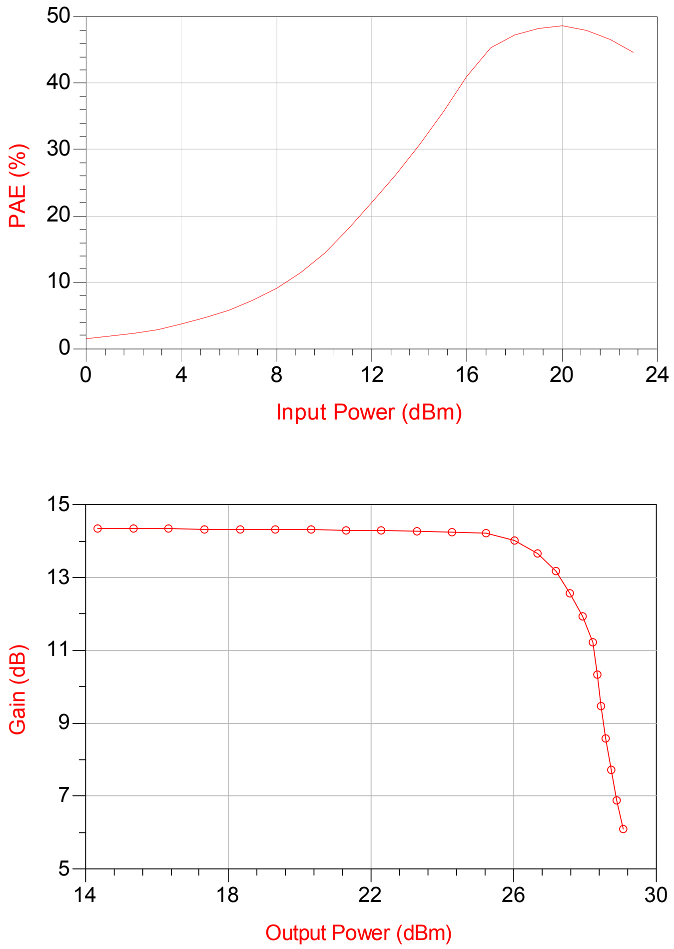

Figure 0.2: *Simulated PAE and Gain for PCS 1900.*

Gate Voltage (V)	**PAE (%)**	**Output Power (dBm)**	**Second Harmonic (dBm)**	**Third Harmonic (dBm)**
0.59	49	28.6	-7.8	-1.5

Table 0.2: *Simulation parameters for PCS 1900.*

UMTS band IV (@1732.5 MHz)

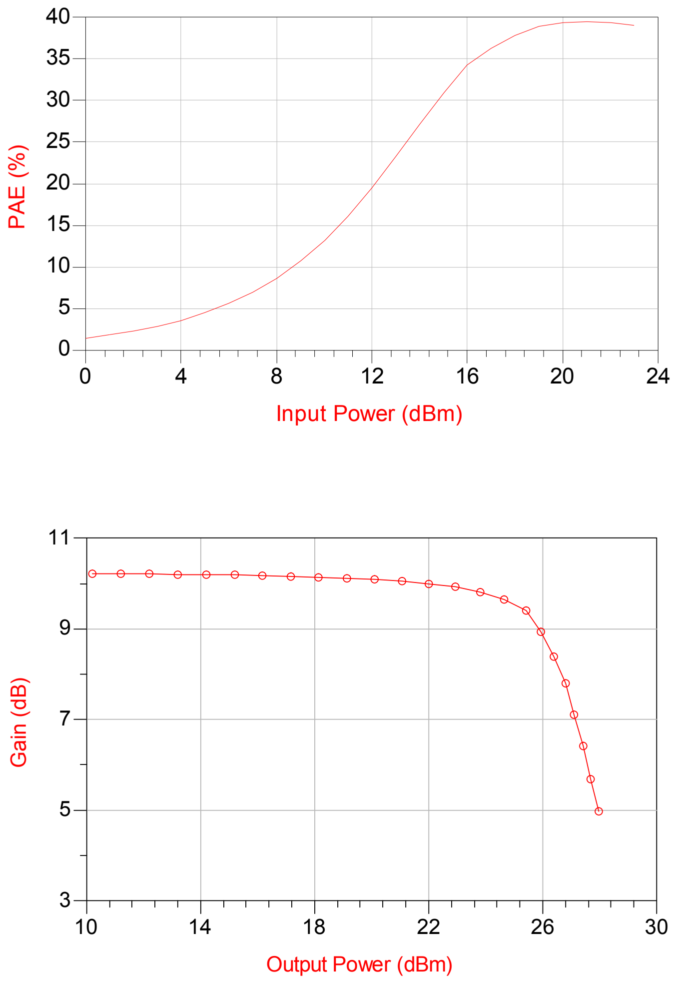

Figure 0.3: *Simulated PAE and Gain for UMTS band IV.*

Gate Voltage (V)	**PAE (%)**	**Output Power (dBm)**	**Second Harmonic (dBm)**	**Third Harmonic (dBm)**
0.41	27	23.8	-25.7	-9.5

Table 0.3: *Simulation parameters for UMTS band IV.*

UMTS band I (@1950 MHz)

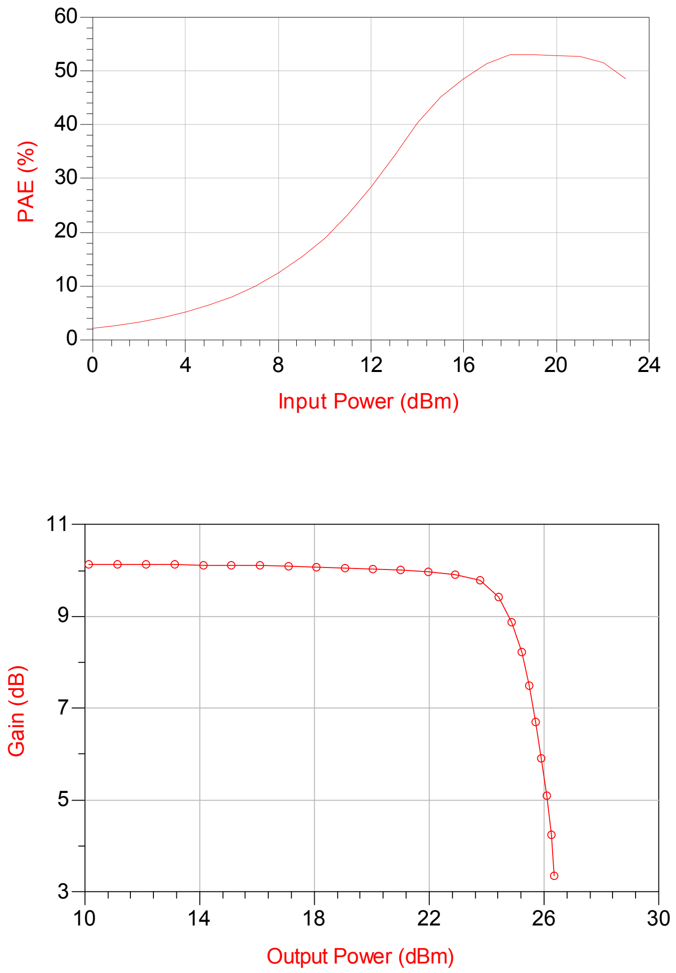

Figure 0.4: *Simulated PAE and Gain for UMTS band I.*

Gate Voltage (V)	**PAE (%)**	**Output Power (dBm)**	**Second Harmonic (dBm)**	**Third Harmonic (dBm)**
0.36	40	23.8	-17.1	-24.2

Table 0.4: *Simulation parameters for UMTS band I.*