A Reconfigurable Power Amplifier for Mobile WIMAX Applications

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Abstract. This paper presents the design of a reconfigurable power amplifier for Mobile WIMAX applications in the user terminal. The amplifier, which operates from 3.4GHz to 3.5GHz, is based on the Doherty technique. This power efficiency enhancement technique is suitable for modern wireless communications systems, as Mobile WIMAX, that present with high peak-to-average power ratio (PAPR) to target high peak data rates while maintaining a trade-off between efficiency and linearity. In addition, reconfigurability in output power levels is added to the design to adapt it to different power scenarios. This work has been carried out in the framework of the CELTIC project MOBILIA, "Mobility Concepts for IMT-Advanced".

Keywords: WIMAX, amplifier, reconfigurable, power efficiency and linearity.

1 Introduction

Nowadays radio link design is targeting high peak data rates for high quality multimedia applications such as video, audio, animation, etc. In order to support these services, larger bandwidths and more complex modulations are required. Present wireless communications systems such as WIMAX, Wi-Fi and LTE employ orthogonal frequency division multiplexing (OFDM) as modulation technique to reach this aim.

OFDM has the ability to cope with severe channel conditions without complex equalization filters. However, an OFDM signal exhibits a high PAPR. In case of WIMAX signals, this value is around 8-10dB. Achieving simultaneously high efficiency and good linearity in power amplifiers design is the most challenging task.

Although typically energy efficiency has not stated as the main design criterion, it has been considered since the power consumption in mobile terminals is an actual bottleneck. The extension of the battery lifetime has been a design goal. One of the main factors involved in the success or failure of a radio technology is the performance of the high power amplifier. GSM uses low cost amplifiers due to the selected modulation, being this fact one of the reasons for its success. For example, LTE has adopted SC-FDMA in the uplink which reduces the PAPR requirement around 2-5dB compared with WIMAX, whilst maintaining OFDM advantages.

RF power amplifier designers are faced with this problem and different power efficiency enhancement techniques has been developed in [1], [2] and [3]. These techniques have been carried out to improve the efficiency of linear power amplifiers,

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especially in the back-off region, where the power amplifier generally operates. Some examples are Envelope Elimination and Restoration (EER), Class F, Doherty and Envelope Tracking.

Most of these techniques involve complex architectures designs, and require the use of external control circuits and signal processing; except the Doherty topology which does not require any additional circuit. A Doherty power amplifier is a promising candidate having the advantage of high power added efficiency (PAE), low cost and simple implementation.

Under these statements, the design of a reconfigurable power amplifier for Mobile WIMAX applications based on the Doherty topology is considered as a demanding goal. The amplifier design is in 3.5GHz band, because it is the main frequency band for Mobile WIMAX applications in Europe. This frequency band covers from 3.4GHz to 3.6GHz. It is divided into uplink band (3400-3500MHz) and downlink band (3500-3600MHz) approximately. The present development has focused on the user terminal, so the design is set to cover the frequency band from 3400MHz to 3500MHz.

Apart from energy efficiency, reconfigurability is another important issue in power amplifiers. This is because potential adjustments in output power levels can lead to strategies using different cell sizes, network topologies, coordination between radio access technologies, etc. Therefore this feature was added to the power amplifier design requirements.

Along this paper, it is presented the design of a reconfigurable power amplifier for Mobile WIMAX, with some partial measured results. The final stage of the development phase will be addressed during the next year of the CELTIC project, MOBILIA.

2 WIMAX Reconfigurable Power Amplifier Design

Combining power efficiency enhancement techniques as the Doherty topology and power reconfigurability is a challenge to improve the battery lifetime in the user terminal. A design using both techniques was developed for Mobile WIMAX applications in 3.5GHz band.

In general, commercial WIMAX transceivers deliver around 0dBm output power, without a power amplifier. This paper has focused on the design of a power amplifier which can deliver up to 23dBm, typical value for mobile terminals, whilst maintaining a back-off not to distort the signal. The expected saturated output power is 30dBm, suitable to reach a trade-off between linearity and energy efficiency. Besides, power reconfigurability is added through an attenuator. The attenuator let the power amplifier be adjusted to different power scenarios and modulation levels. It is important to notice that the back-off will be different depending on the modulation level: QPSK, 16-QAM, or 64-QAM.

Following these requirements, the design presents in the following sections.

2.1 Doherty Amplifier Technique

Doherty technique was developed in 1936 for using in high-power broadcast transmitters [4]. Nowadays, it has found application in wireless communications due to its relative simplicity of implementation. It is an efficient method of using conventional linear amplifiers when operating with envelope-varying signals, such as WIMAX signals which exhibit high PAPR.

The basic concept behind the Doherty technique [5] is to allow one or more amplifiers to operate at their peak envelope power level and hence at maximum efficiency, whilst allowing a final linear amplifier to deal with the modulation peaks.

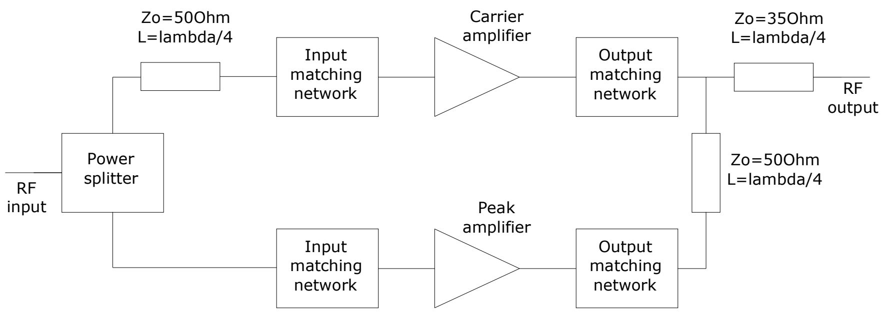


Fig. 1. Classical Doherty amplifier topology

Figure 1 presents a classical Doherty amplifier consisting of two amplifiers, namely the “carrier” and the “peak” amplifiers. These amplifiers are connected in parallel with their outputs joined by a quarter-wave transmission line, which performs impedance transformation. The “peak” amplifier delivers the current when the “carrier” amplifier saturates, thereby reducing the impedance seen at the output of the “carrier” amplifier. Thus, the “carrier” amplifier delivers more current to the load while it is saturated because of the load-pulling effect.

The performance of a two-stage Doherty amplifier can be defined in three ranges. The first one, it is the operation at low power levels, where the “peak” amplifier is shut down and the “carrier” amplifier is operating as a conventional linear amplifier. In the second range, it works at medium power levels and the “carrier” amplifier is saturated and acts as a voltage source; the “peak” amplifier takes over linear operation and acts as a controlled current source. And finally, as it operates at high power levels, both amplifiers are saturated, with the peak output voltage of the complete amplifier being the power supply voltage.

This configuration has a medium complexity, because of the relatively undemanding and low degree of required control. However, its main disadvantage is the narrow bandwidth performance because of the use of $\lambda/4$ transmission lines and the required phase accuracy between the two amplifiers.

As well as classical Doherty topology, some design methods have been studied to improve its performance and reduce its potential disadvantages [6], [7], [8] and [9]. One possibility is the use of individually optimized matching circuits in the “carrier” and the “peak” amplifier. Another method is the properly adjustment of the bias circuit to optimize the linearity and the efficiency. It is to be noted that an inverted Doherty topology can provide better efficiency. The theory indicates that the best efficiency at average envelop power is produced with a load impedance closer to 25Ohm than to 100Ohm. In this topology, the position of “carrier” and “peak” amplifiers are interchanged. Adding compensation lines and shunt capacitors to adjust phase in the circuit can improve linearity too.

Although some of the previously mentioned methods have been employed in this design, additional efforts will be made to improve the performance of the reconfigurable power amplifier.

2.2 Power Reconfigurability

Due to the limited power available in a user terminal, power reconfigurability is suitable to optimize energy resources for new multimedia applications. WIMAX Forum has published mobile radio specifications for WIMAX Release 1.0 [10]. According to these specifications, there are four power classes in WIMAX with different power level ranges from 18dBm to 30dBm approximately. Then adding power reconfigurability with an attenuation range lower than 12dB is an appropriate solution to save energy.

Furthermore, Mobile WIMAX standard incorporates mechanisms that enable subscriber terminals to be active only at certain times as negotiated with the base station. When there is no data to be transmitted or received, the subscriber terminal can move into sleep or idle modes to minimize power consumption. This characteristic will be proper to be implemented as well in the design in order to increase the battery lifetime.

Following these ideas, the power amplifier design incorporates an attenuator to be able to deliver the suitable power in each moment and to minimize power consumption and so extending battery lifetime. This option is adequate because the Doherty amplifier consumes according to its input power and this value can be adjusted through an attenuator combined with a driver amplifier.

Commercial WIMAX transceivers deliver around 0dBm, so about 30dB of gain for the reconfigurable power amplifier design would be enough. A Doherty amplifier using FPD1500SOT89 gets around 11dB of gain, so a driver amplifier in the order of 20dB of gain was selected, HMC326MS8G. This driver provides 22dB of gain and 26dBm of saturated power from a +5V supply voltage. It was optimized to provide greater than 40% PAE and has power down capability to reduce current consumption when the amplifier is not in use.

To adapt the power amplifier to different WIMAX power classes, an attenuator is introduced in the design, HMC540LP3. It is a 4-bit digital attenuator, with a total attenuation of 15dB (1dB LSS).

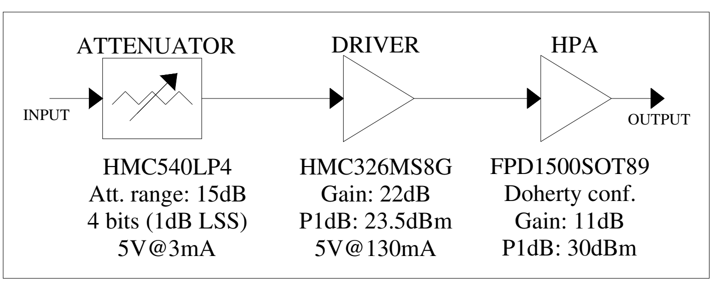


Fig. 2. RF block diagram of the reconfigurable power amplifier for Mobile WIMAX applications

As a result the reconfigurable power amplifier design is composed by a digital attenuator, a driver amplifier and a power amplifier based on the Doherty technique. Its main characteristics are 30dB of gain and 30dBm of output power with 12dB of attenuation range from 3.4GHz to 3.5GHz. Combining these components, the final amplifier is more efficient due to energy saving from Doherty technique and power reconfigurability. The block diagram of the proposed design including the selected components is shown in Figure 2.

Next sections present a detailed analysis of the reconfigurable power amplifier.

2.3 WIMAX Reconfigurable Power Amplifier Analysis

First of all, technical specifications for the amplifier design are stated. The frequency range will cover from 3400 to 3500MHz. Usually, it is the frequency band assigned in European Mobile WIMAX services to user terminals. Apart from that, WIMAX output power is between 18 and 30dBm to cover different power classes into the standard. Generic WIMAX transceivers deliver around 0dBm output power and WIMAX mobile stations typically transmit at 23dBm. Because of that a design with 30dB of gain and about 12dB in power adjustment is an appropriate goal.

In the first stage, a search for WIMAX commercial amplifiers in 3.5GHz band was carried out. In a Doherty amplifier, there are two amplifiers in parallel biased in class-AB and class-C, respectively. To model their performance, a non-linear model is required. Only RFMD, manufacturer of high-performance semiconductor components, provides a non-linear model that fits to the technical specifications, so the selected amplifier was FPD1500SOT89. The manufacturer provides a modeling report for FPD1500 TOM3 and TOM2 models. These models can be used in different microwave simulators and in this case the Advanced Design System (ADS) software was employed. Using these models, it is possible to simulate the full-scale device characteristics such as DC bias, gain, return losses, output power, efficiency (PAE), intermodulation, etc.

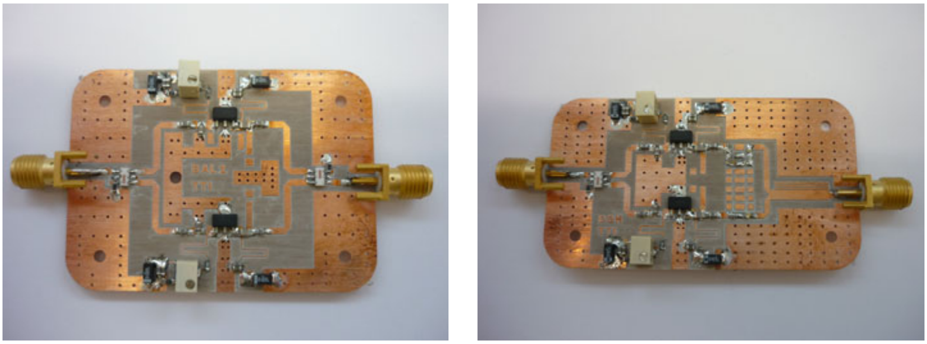
FPD1500SOT89 has 12dB of gain and 27.5dBm at 1dBcompression output power. It is biased by applying +5V and a negative voltage to get 200mA consumption in 3.5GHz band (class-AB).

A preliminary development of a Doherty amplifier using FPD1500SOT89 was carried out. A power splitter is required to separate the input signal into two ways with 90º phase shift. A 3dB 90º hybrid coupler can be used, QCN-45+ from Mini-Circuits. The rest of the circuit is designed using microstrip lines and passive components (capacitors, resistors and potentiometers). To compare Doherty amplifier results, a balanced amplifier was prepared in order to evaluate it in similar conditions.

The balanced amplifier has two amplifiers in parallel biased in class-AB. These amplifiers are combined using a 3dB 90º hybrid coupler at input and output ports.

The Doherty amplifier has two amplifiers in parallel biased in class-AB and class-C, respectively. The class-AB amplifier is biased as mentioned previously and the class-C amplifier is biased by applying +5V and a negative voltage to get 10mA consumption approximately. The main negative voltage in the circuit is -5V. The required negative voltage at the gate of the transistor is adjusted thanks to a potentiometer. In the case of 200mA, the negative voltage is around -0.5V, and it is -1V for 10mA.

In the following figures, photographs of these circuits are presented.



a) b)

Fig. 3. a) Balanced amplifier circuit using FPD1500SOT89 in 3.5 GHz band. b) Doherty amplifier circuit using FPD1500SOT89 in 3.5 GHz band.

The input structure in both circuits is the same, a 3dB 90º hybrid coupler. However, the output way presents some differences. In the balanced amplifier, a 3dB 90º hybrid coupler is employed again, while a λ/4 microstrip line with impedance transformation is used in the Doherty amplifier.

As it is presented in figure 3b), some compensation lines are used to fit phase in the Doherty amplifier in order to improve performance in the 3.5GHz band. This configuration presents a narrow bandwidth and it needs a specific adjustment. In the case of the balanced amplifier, the design has a large bandwidth, but it is not so energy efficient as the Doherty amplifier.

These circuits were measured in a radio frequency laboratory and the results are shown in the next section.

In a final design, the reconfigurable power amplifier will be integrated with a digital attenuator, a driver amplifier and a Doherty amplifier. In this document, only Doherty amplifier results are presented.

3 Performance Analysis

The design of the former amplifiers and the layout of their printed circuit boards were carried out thanks to linear and non-linear simulations realized in ADS. An S-parameters simulation was calculated to optimize the performance in frequency, and a Harmonic Balance simulation was done to improve the power performance. Figures 4 and 5 show the measured results of each amplifier. Both topologies have similar gain with good return losses. Something to be highlighted is that the balanced amplifier has return losses less than -20dB, while the Doherty amplifier has -10dB. The pseudomorphic high electron mobility transistor (pHEMT), FPD1500SOT89, is matched in each case through a shunt capacitor at input and a series capacitor at output to improve return losses.

ADS simulations had already presented return losses less than -20dB in the balanced amplifier from 3.4GHz to 3.5GHz and less than -10dB in the Doherty amplifier.

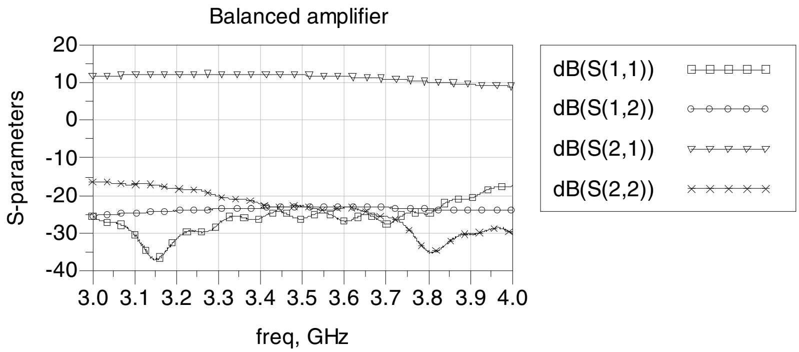


Fig. 4. Measured S-parameters results for the balanced amplifier using FPD1500SOT89

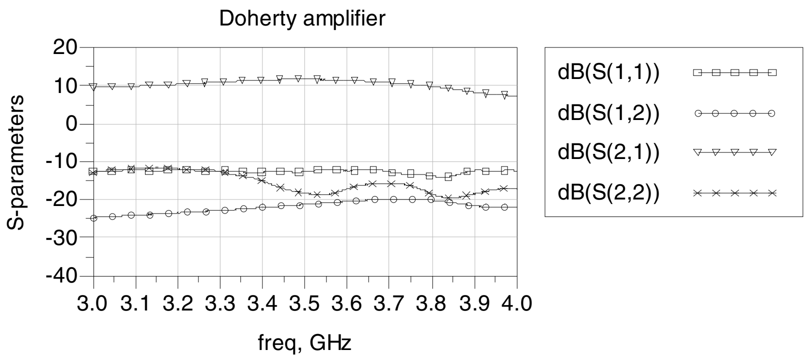


Fig. 5. Measured S-parameters results for the Doherty amplifier using FPD1500SOT89

Power measured results were obtained using an HMC326MS8G evaluation board from Hittite because of the available output power in typical RF generators is not enough to achieve the measurements properly. This driver amplifier, HMC326MS8G, has 22dB of gain and 23.5dBm of output power at 1dB compression. Using this amplifier combined with the balanced amplifier or the Doherty amplifier, it reaches more than 30dB of gain, enough for the reconfigurable power amplifier for Mobile WI-MAX applications.

In the next figures, gain and PAE are presented for the balanced amplifier and the Doherty amplifier. The balanced amplifier gives 29.6dBm of 1dB compression output power and 29.8dBm of saturated output power. Meanwhile, the Doherty amplifier provides a power output of 30dBm at 1dB compression output power and 30.2dBm of saturated output power. Maximum PAE in the Doherty topology is 40% as ADS simulations with TOM3 model presented and afterwards measurements have demonstrated. Both designs have similar gain. The Doherty design has around 0.5dB less gain than the balanced design. However PAE results are much better in the Doherty design compared with the balanced design. For example, for 23dBm output power, which is a typical value in mobile terminals, it is around 4% better. This power consumption improvement extend the battery lifetime which is a significant parameter for users. As size and complexity for both designs are quite similar, Doherty design becomes an interesting solution.

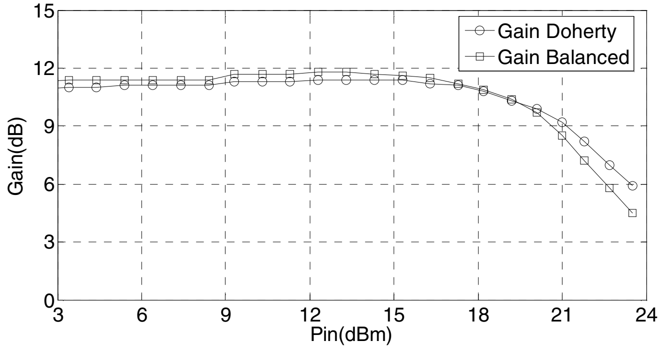


Fig. 6. Gain measurements versus input power for Doherty amplifier and balanced amplifier

Gain results are similar in both topologies and it can be observed than the Doherty amplifier provides higher output power. Besides, it is more efficient than the balanced amplifier as it is presented in Figure 7. Measurements are at 3.4GHz and results are similar from 3.4GHz to 3.5GHz.

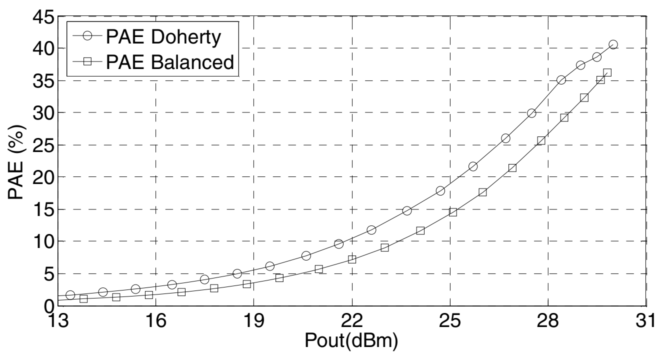


Fig. 7. PAE measurements versus output power for Doherty amplifier and balanced amplifier

In the Doherty design, offset lines were introduced to improve its performance adjusting phase shift between class-AB amplifier and class-C amplifier in 3.5GHz band. Furthermore, different polarization points for class-C amplifier were set to find the best results. Additional activities about this issue will be carried out during the project to find out the appropriate relation between efficiency and linearity.

4 Conclusions

A reconfigurable power amplifier for Mobile WIMAX applications has been designed based on a Doherty configuration. The Doherty amplifier technique can improve energy efficiency through an innovative topology of two parallel amplifiers biased in class-AB and class-C, respectively.

A balanced and a Doherty amplifier were fully developed and measured. Both designs use the same transistor, FPD1500SOT89, which is a high-linearity packaged pHEMT. Measurements show an improvement in PAE for the Doherty amplifier, implying an impact in battery lifetime, which is an important feature in user terminals. This improvement is around 4% of PAE for 23dBm output power, a typical output power in user terminals.

Apart from the Doherty amplifier, a driver amplifier and a digital attenuator is added to the system to integrate a reconfigurable power amplifier to be able to adjust the power to different scenarios. The same output power is not required all the time, it is better to fit the communication according to certain conditions as distance, number of users, quality of service, etc.

Final development and measurements will be carried out during next year of the project MOBILIA.

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