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RF POWER AMPLIFIERS FOR MOBILE COMMUNICATIONS

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Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-5116-6 (HB)
ISBN-13 978-1-4020-5116-6 (HB)
ISBN-10 1-4020-5117-4 (e-book)
ISBN-13 978-1-4020-5117-3 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Printed on acid-free paper

Printed in the Netherlands.

Contents

Preface

Since the early nineties, mobile communication systems have entered our daily life. The main reason for this unprecedented wireless revolution, is the high integration level that can be achieved with CMOS. This allowed the integration of enormous amounts of digital functionality on one single chip. As such, it became feasible to introduce digital coding and digital signal processing in wireless communication systems which resulted in the powerful mobile networks of today. Another reason for the successful wireless development, is the low cost of the user equipment which in turn is due to the low cost of CMOS.

The evolution of mobile communication systems continues and today, telephony, television, internet, e-mail, radio broadcast, . . . are all being merged together. They have become services, rather than stand-alone systems, that users can access through one single mobile device. Putting all this functionality into one small mobile device, at a reasonable cost, requires a higher integration level. For the comfort of the user, it also requires an increased battery lifetime and thus a low power consumption.

Mobile phones and wireless network equipment both require a power amplifier to amplify the radio signal before it can be transmitted through the antenna. The power amplifier should amplify the radio signal to the desired output level, as accurately as possible, but without consuming too much power itself as this would reduce the battery lifetime. In other words, besides the required output power, the power amplifier should have sufficient linearity and a high efficiency.

The overall goal of this work is to provide circuit design techniques that allow the reader to design a power amplifier that (1) meets the output power and linearity requirements of a mobile communication system, (2) has a high efficiency and gain, (3) is integrated in CMOS and (4) requires no expensive off-chip components. To achieve this goal, a theoretical foundation is developed first. It investigates the consequences of CMOS integration with respect to power amplification. Impedance transformation and power combining are crucial to achieve sufficient output power in a low-voltage CMOS technology and is subsequently covered. Combining efficiency and linearity leads to the development of a polar modulation architecture.

To validate the developed theory, two amplifiers were successfully designed, fabricated and measured. The first amplifier is designed for GSM-EDGE in a $0.18\,\mu\mathrm{m}$ CMOS technology and operates at $1.75\,\mathrm{GHz}$. To efficiently amplify the non-constant envelope EDGE signal, a polar modulation architecture was developed. The amplifier achieves a peak output power of $27\,\mathrm{dBm}$ with an overall efficiency of $34\,\%$. When transmitting EDGE signals, the amplifier achieves an overall efficiency of $22\,\%$ at an output power of $23.8\,\mathrm{dBm}$ or $240\,\mathrm{mW}$. The second amplifier is integrated in a $0.13\,\mu\mathrm{m}$ CMOS technology, operates at $2.45\,\mathrm{GHz}$, is fully differential and has a single-ended output. To achieve sufficient output power in the $0.13\,\mu\mathrm{m}$ technology, a lattice-type LC power combining network is integrated on the CMOS chip, that allows the parallel connection of four amplifiers. The amplifier achieves an output power of $23\,\mathrm{dBm}$ with an overall efficiency of $29\,\%$. The power combining network allows for both a discrete power control and an efficiency improvement.

Chapter 1

INTRODUCTION

1.1 Wireless Communication

Wireless and mobile communication systems have become ubiquitous in our daily life and it has changed our society and our way of living in a tremendous way. For sure, the desire for mobility and communication are natural human properties and society is always changing. But it is only recently that the possibilities have taken a steep flight upwards, it is only recently that people are able to *see and hear* things that are not nearby. Thanks to the invention of wireless (radio-)communication in the nineteenth century and television in the twentieth century, humanity has extended its own sensorial capabilities; an unprecedented change.

It is generally accepted that mobile communication was born in 1897, when Guglielmo Marconi gained a patent for his wireless telegraph[1]. In those days, radio-communication was merely transmitting the dots and dashes of the Morse code. Slowly, communication equipment enhanced and radio-communication was used for navigation and to keep contact with ships and airplanes. But still, there was as strong need for new technologies that could manipulate, amplify and decode the weak electronic radio signals.

The invention of the vacuum tube in 1906 by Lee De Forest made it possible to amplify and process the received radio signals. Armstrong was the first to develop radio receivers and is well-known for his invention of the regenerative receiver in 1913 , the invention of the super-heterodyne receiver during World War I and his successful demonstration of frequency modulation in 1933. Although a brilliant radio amateur, Armstrong eventually lost all his patents.

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[1] Nikola Tesla is now credited with having inventing modern radio; the Supreme Court overturned Marconi's patent in 1943 in favor of Tesla.

The invention of the transistor in 1947 by John Bardeen, Walter Brattain and William Shockley resulted in a tremendous size and weight reduction of most electronic equipment and increased the reliability; the *transistor radio* is a nice example of this. Another important technological step was made in 1958, when Jack Kilby invented the integrated circuit. He conceived and built the first electronic circuit in which all of the components, both active and passive, were fabricated in a single piece of semiconductor material half the size of a paper clip. The successful laboratory demonstration of that first simple microchip on September 12, 1958, made history.

Apart from the wireless evolution, the invention of the integrated circuit also enabled engineers to design large digital systems at a relative low cost. This in turn gave rise to a rapid growth of the number of personal computers and a shift from the old telephone systems to digital networks. The Internet, invented in 1973 and laid out in 1983 and the World Wide Web, developed in 1989, were the logical consequences.

Since the introduction of GSM in Europe in 1991, the mobile telephony market is growing rapidly. In 2003, the number of global mobile subscribers exceeded the number of fixed lines for the first time and it is expected that by 2010, there will be over 23 billion individual wireless subscribers worldwide [Deut04]. Besides the mobile phone networks, the development of wireless data networks, like W-LAN and Bluetooth, followed quickly and they became very popular to make a wireless link between all kinds of devices and for wireless internet access.

Today, telephony, television, internet, e-mail, radio broadcast, . . . are all being merged together. They have become services, rather than stand-alone systems, that users can access through one single mobile device. The design of such a single mobile device requires a high level of integration and miniaturization, a low power consumption and a low production cost. This is the point were CMOS pops up.

1.2 CMOS Technology and Scaling

1.2.1 Moore's Law

Device scaling aims to integrate more transistors per unit area. This requires less silicon area for the same functionality and a lower production cost. Gordon Moore has predicted this trend already in 1965 [Moor65]. He observed that the number of transistors on a single chip doubles every year. In 1975, he updated his prediction to once every two years. While originally intended as a rule of thumb in 1965, it has become the guiding principle for the industry to deliver ever-more-powerful semiconductor chips at proportionate decreases in cost. To achieve such high integration levels, the size of each individual transistor has to shrink, and to reduce the cost, the yield has to go up.

In 1962, Steven Hofstein and Fredric Heiman at the RCA research laboratory in Princeton, New Jersey, invented a new family of devices called metal-oxide semiconductor field-effect transistors, or MOSFET. CMOS circuits were invented in 1963 by Frank Wanlass at Fairchild Semiconductor. The first CMOS integrated circuits were made by RCA in 1968 by a group led by Albert Medwin. Since the eighties, CMOS is pre-eminently *the* digital technology of choice. The success of CMOS in the digital semiconductor market has resulted in huge technological investments to shrink the transistors and to increase the production yield. CMOS scaling has followed *Moore's Law* for over 40 years and nowadays, several billions of transistors can be integrated on a single chip. As such, CMOS has also become the cheapest technology available today. Roughly, the cost of a SiGe technology is two to three times the cost of CMOS and GaAs is about five to ten times the cost of CMOS [Jaco].

The influence of Moore's Law on our every day life can not be overestimated. The semiconductor industry is the only industry that achieves a cost reduction every two years. In the 2005 annual report of the Semiconductor Industry Association [SIA05], it is formulated as follows: *"... in 1978, a commercial flight between New York and Paris cost 900 USD and took seven hours. If the principles of Moore's Law were applied to the airline industry, that flight would now cost about a penny and take less than one second ... "* an impressive thought.

1.2.2 RF-CMOS: Moore meets Marconi

The main trigger for the tremendous growth of the mobile phone market, was the introduction of digital coding and signal processing in wireless communications [Reyn03b]. The development and scaling of CMOS allowed the integration of enormous amounts of digital functionality on one single chip. This *digital power* enabled the use of sophisticated modulation schemes, complex demodulation algorithms, high quality error detection and correction, and allowed to obtain high data rate communications.

For a consumer, performance is only one aspect, he or she also wants a low cost mobile device with a high battery lifetime. In other words: low cost and low power consumption. The digital circuitry, typically integrated on one or two CMOS chips, already fulfills this requirement to a great extend. It is only recently that the radio frontend, i.e. the analog interface between the antenna and the digital baseband circuitry, is being integrated in CMOS [Abid04]. For this, it took the persistence of some academic institutions [Stey98] and some pioneering firms [Silb] to prove the feasibility of CMOS design at radio frequencies[2] (RF).

CMOS is a digital technology and was originally not developed for high-frequency or microwave design. It is thanks to the scaling, dictated by Moore's Law, that CMOS became able to operate at GHz frequencies and this triggered researchers to investigate the possibilities to do analog RF design in CMOS. Surely, better RF performance can be achieved with a dedicated RF technology like GaAs, SiGe or InP. However, the real strength of RF-CMOS is the low cost and the possibility to use digital signal processing to improve the performance of the RF frontend. Furthermore, in a highly integrated solution, the signals stay on-chip. Driving off-chip RF components requires more power and makes the system prone to noise pick-up. A highly integrated RF frontend in a CMOS technology thus results in a low power consumption, a better noise immunity and a low cost solution.

A lot of controversy still exists around RF design in CMOS. After all, CMOS can operate at high frequencies, but it is not a dedicated RF or microwave technology. Yet, the cost reduction and high integration level are the main motivations. If extreme high performance is needed, like in military or space applications, no doubt that other technologies are preferable. However, for medium performance applications and especially if low cost and high production volumes are an issue, CMOS is unbeatable. To illustrate this view, figure 1.1 shows a traditional technological view and a market driven view of CMOS, compared to SiGe and GaAs [Jaco]. The operating frequency and performance of CMOS has improved over the last decades; this is the technological view. Today, an entire mobile phone at 1.8 GHz can be integrated in CMOS [Silb] and research is done to integrated circuits at 24 GHz and even 60 GHz in CMOS [Komi04, Doan04]. The market-driven view on the other hand shows for which applications CMOS is of importance. If it has to be cheap and large quantities are required, CMOS is the only viable solution. But of course, the performance has to be met and no doubt that for some applications, CMOS will never be good enough.

1.3 The Research Work

The RF power amplifier is a vital part of any wireless transmitter as it has to amplify the electric radio signal before it can be transmitted through the antenna. Wireless communication systems are of course very broad, submarine communications at 18 kHz are wireless, a microwave link at 60 GHz is also wireless. . . . and yet they both require a power amplifier. However, this

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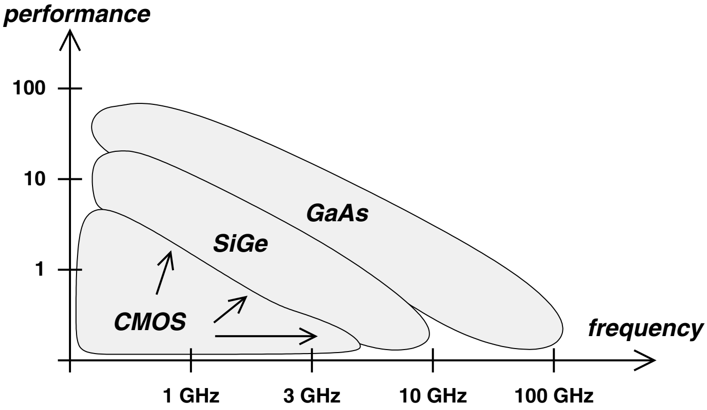
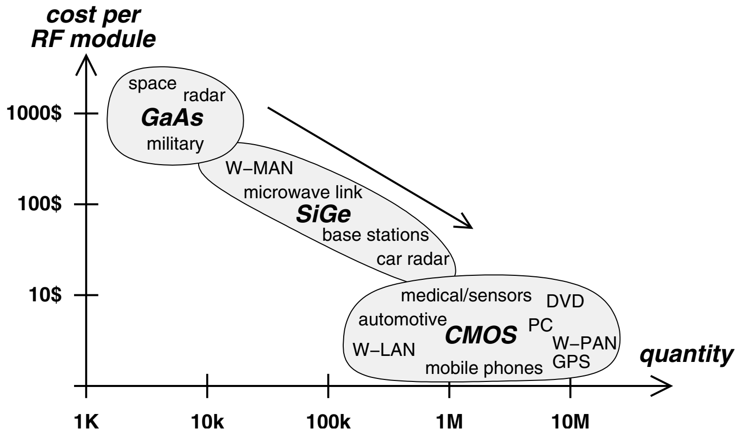
[2] RF stands for Radio Frequencies and is rather general term since radio waves can have frequencies from a few hertz up to several hundreds of gigahertz. However, RF has become a synonym for frequencies roughly above 1 GHz.



(a) technological view



(b) market driven view

Figure 1.1. Position of RF-CMOS compared to SiGe and GaAs.

research is focussed on the design of RF power amplifiers in mobile user devices, like mobile phones.

Four keywords characterize the electrical performance of a power amplifier: *output power*, *efficiency*, *gain* and *linearity*. Output power and linearity are performance figures that are set by the requirements of the wireless system. If these specifications are not met, the power amplifier is useless. This is different for efficiency and gain. A high efficiency and a large gain results in a power amplifier that consumes little power from the battery while amplifying and transmitting radio signals. In other words, these figures are related to the battery lifetime. A higher efficiency gives a longer battery lifetime and thus a longer talk time of the mobile device. The product cost, maybe the most important figure for many customers, is related to the technology in which the amplifier is integrated and the number of external components that are needed to have a functional power amplifier. As said before, CMOS in large volumes undoubtedly has a production cost advantage over competing technologies like SiGe and GaAs.

Several research institutes have already demonstrated the CMOS integration of RF transceivers for mobile telephony, Bluetooth and WLAN. Nowadays, these research efforts become visible in the many commercially available products [Ath, Silb, STM, Axi, Bro, RFMa] and the research focus on RF transceivers in CMOS has shifted to higher frequencies [Komi04, Doan04] and to low power consumption [Otis05].

The integration of power amplifiers in CMOS seems to follow a slightly different story. Although CMOS RF power amplifiers become commercially available [Sila, Axi], many research institutes and companies continue to investigate the possibilities to combine linearity, efficiency and output power in one single CMOS RF power amplifier. Many alternative architectures and approaches exist in literature and, in contrast to integrated receiver architectures, a clear road or solution has not arisen yet.

1.4 Outline of the Work

Combining the previous thoughts, the aim of this work is to develop design techniques for an integrated CMOS RF power amplifier. These techniques should allow the design a CMOS RF power amplifier that meets the output power and linearity requirements of a mobile communication system, that has a high efficiency and gain, that is integrated in CMOS and that requires no expensive off-chip components. The outline of this work is shown in figure 1.2. It is divided in two major parts: *theory* and *implementations*.

- Chapter 2 aims to welcome the reader in the world of power amplification. It gives a general overview of digital modulation and it will introduce some important definitions and figures that characterize a power amplifier. Next, a classification of RF power amplifiers is given together with a discussion on how to combine efficiency and linearity in one power amplifier.

- The aim to achieve both a high efficiency and a high integration level in a low cost CMOS technology is the basic idea that will lead us to chapter 3. It first presents a tool to analyze and design the Class E amplifier with the inclusion of all power losses. The influence of the parasitic capacitances on the transistor sizing is demonstrated with the design tool. Next, the impact of technology scaling, device stacking and the shift towards a higher frequency are investigated. The chapter concludes with some CMOS layout aspects.

- The next problem to tackle is the low supply voltage of current CMOS technologies, and this is covered in chapter 4. First the L-match network is discussed, followed by the lattice-type LC balun network. The latter network allows to achieve a higher output power, can easily be integrated in CMOS and can be merged with the Class E amplifier. The LC balun also allows to implement a discrete form of power control.

- Modern communication systems, like W-LAN and CDMA, allow both amplitude and phase modulation of the RF carrier to increase the datarate of a wireless link. Hence, the amplifier must have sufficient amplitude linearity. Polar modulation of the Class E amplifier allows to combine a high efficiency and a high integration level together with the required linearity and output power specifications. Chapter 5 presents a thorough discussion on polar modulation. The architectural issues and the distortion mechanisms of polar modulation are covered in this chapter and are expanded towards full digital linearization.

The theoretical aspects of this research were also put into practice and resulted in the design, fabrication and measurement of two integrated CMOS RF power amplifiers.

- Chapter 6 will discuss the design, the implementation and the measurement results of a polar modulated power amplifier for the GSM-EDGE mobile phone system. The amplifier is integrated in a 0.18 μm CMOS technology and requires no expensive RF components. First, the system level aspects of EDGE are covered, which leads to the design requirements of the integrated amplifier. The circuit implementation of the RF amplifier and the amplitude modulator are covered and followed by an extensive discussion on the measurement results.

- Chapter 7 will discuss the design, implementation and measurement results of an integrated power amplifier for Bluetooth. The differential amplifier is fully integrated in a 0.13 μm CMOS technology, has a single-ended output and is capable to efficiently control its output power. First, a brief discussion of the Bluetooth system is given and followed by the circuit level implementation issues. The measurement results clearly demonstrate the efficiency improvement of the amplifier.

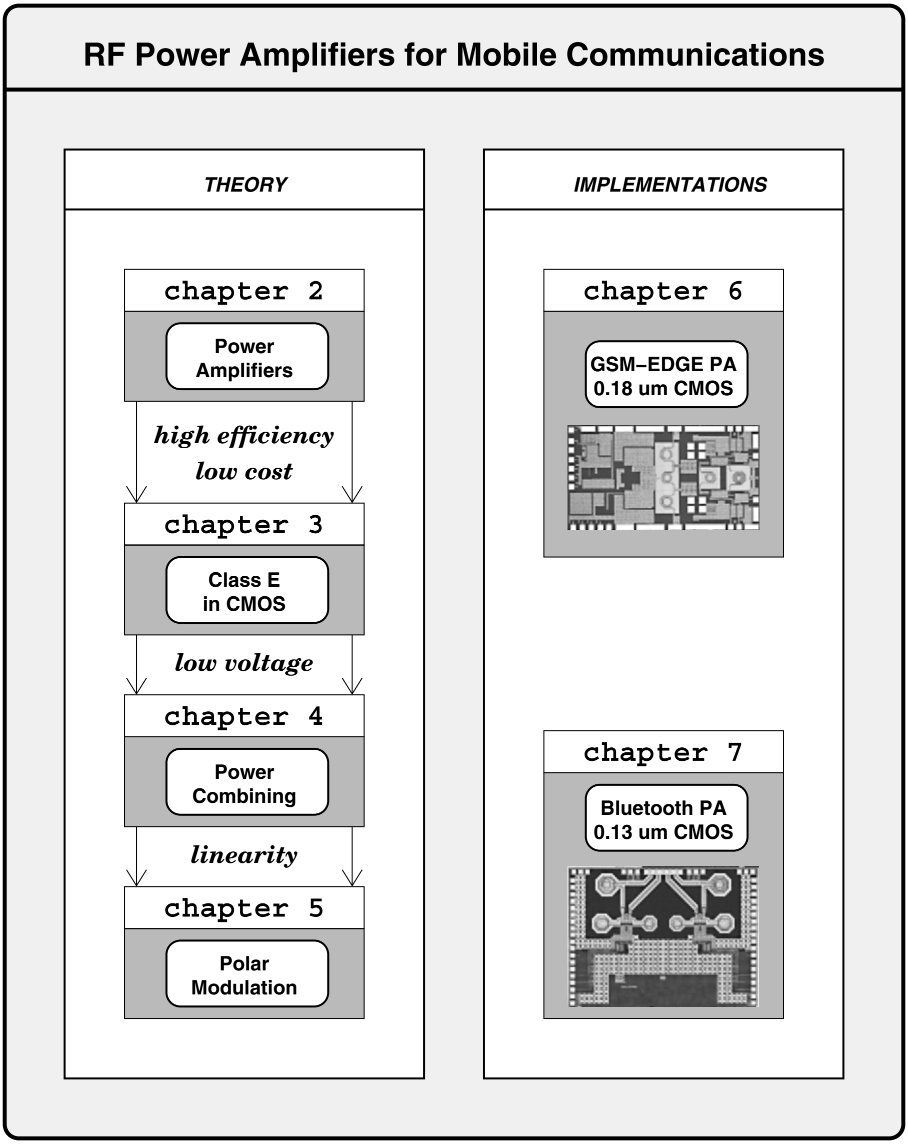


Figure 1.2. Outline of the Work.

Chapter 2

MOBILE COMMUNICATION SYSTEMS AND POWER AMPLIFICATION

2.1 Introduction

Amplifying an electrical signal is the sole purpose of a power amplifier. Though trivial at first sight, several conditions will impede the design and the implementation. For a power amplifier that is designed for a mobile or wireless communication system, *output power*, *efficiency*, *gain* and *linearity* are the most important properties, and they can easily be quantified. On the other hand *cost* and *reliability* are not as easy to quantify but their importance should not be underestimated.

To gain better insight in the different tradeoffs, this chapter will first discuss some system level aspects of mobile communication systems and the properties of the signals that need to be amplified. Next, some key parameters of an RF power amplifier are defined, as they will frequently be used throughout this text. In section 2.4, a classification of power amplifiers is given based on the classical theory of conduction angle, overdrive level and harmonic termination at the output. The classification is focussed on the difficulties regarding CMOS implementation and integration. Finally, in section 2.5 the tradeoff between efficiency and linearity is clarified and some efficiency improvement and linearization techniques are discussed.

2.2 Mobile Communication Systems

The very first step in designing a power amplifier for wireless or mobile communication is a good knowledge of the communication system itself and the signals that needs to be amplified. Therefore, this first section will review some important concepts of digital modulation and some signal properties that are important for power amplifier are defined.

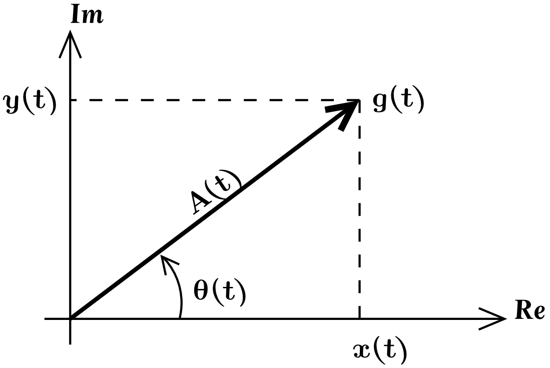


Figure 2.1. Representation of the complex envelope in the complex plane.

2.2.1 Modulated Bandpass Signals

A modulated bandpass signal can be represented as [Couc97]

$$v(t) = \mathrm{Re}\left\{g(t)e^{j\omega_c t}\right\} \tag{2.1}$$

with $f_c = \omega_c/2\pi$ the carrier frequency and $g(t)$ the *complex envelope* of $v(t)$. The complex function $g(t)$ thus modulates the phasor $e^{j\omega_c t}$. Since $g(t)$ is a complex function, its instantaneous value can be represented in the complex plane, see figure 2.1.

A single point in the complex plane can also be represented by Cartesian and polar coordinates.

$$g(t) = x(t) + jy(t) = A(t)e^{j\theta(t)} \tag{2.2}$$

Using the Cartesian and polar representation of $g(t)$, the modulated signal $v(t)$ can now be expressed as

$$v(t) = x(t)\cos(\omega_c t) - y(t)\sin(\omega_c t) \tag{2.3}$$

$$v(t) = A(t)\cos(\omega_c t + \theta(t)) \tag{2.4}$$

Looking at above equation, $A(t)$ carries the amplitude modulation and $\theta(t)$ contains the phase information. In short, $A(t)$ is called the *envelope signal* or *amplitude signal* and $\theta(t)$ is called the *phase signal.* For similar reasons, $x(t)$ is the *in-phase* or $I(t)$ signal and $y(t)$ is the *quadrature* or $Q(t)$ signal. All these signals are baseband signals with a relatively low bandwidth, at least compared to ω_c. The conversion between the two equivalent representations is as follows

$$A(t) = \sqrt{x(t)^2 + y(t)^2} \tag{2.5}$$

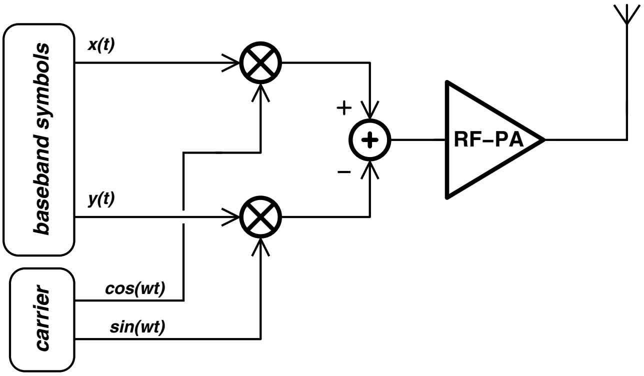


Figure 2.2. Transmitter architecture based on a Cartesian representation of a modulated signal.

$$\begin{aligned}\theta(t) &= \arctan\left(\frac{y(t)}{x(t)}\right) && (2.6)\\ x(t) &= A(t)\cos(\theta(t)) && (2.7)\\ y(t) &= A(t)\sin(\theta(t)) && (2.8)\end{aligned}$$

In most wireless transmitter architectures, the Cartesian representation of the signal is directly converted in a circuit diagram, as shown in figure 2.2.

In figure 2.3, the example of a two-tone signal is given. From this signal, the envelope and phase signal can be calculated as

$$\begin{aligned}v(t) &= \sin(\omega_{LF}t)\cos(\omega_c t) && (2.9)\\ &= |\sin(\omega_{LF}t)| \cdot \mathit{sign}\left[\sin(\omega_{LF}t)\right] \cdot \cos(\omega_c t) && (2.10)\\ &= |\sin(\omega_{LF}t)| \cos\left(\omega_c t + \pi/2 - \pi/2 \cdot s(\omega_{LF}t)\right) && (2.11)\\ &= A(t)\cos\left(\omega_c t + \theta(t)\right) && (2.12)\end{aligned}$$

It can easily be seen that

$$\begin{aligned}A(t) &= |\sin(\omega_{LF}t)| && (2.13)\\ \theta(t) &= \pi/2 - \pi/2 \cdot s(\omega_{LF}t) && (2.14)\\ x(t) &= \sin(\omega_{LF}t) && (2.15)\\ y(t) &= 0 && (2.16)\end{aligned}$$

with $s(\omega_{LF}t) = \mathit{sign}\left[\sin(\omega_{LF}t)\right]$ being a ± 1 switching function having the same sign as $\sin(\omega_{LF}t)$. To conclude, the envelope signal is a rectified sine wave and the phase signal is a square wave between 0 and π, as indicated by figure 2.3. Therefore, a two-tone signal exhibits both amplitude and phase modulation.

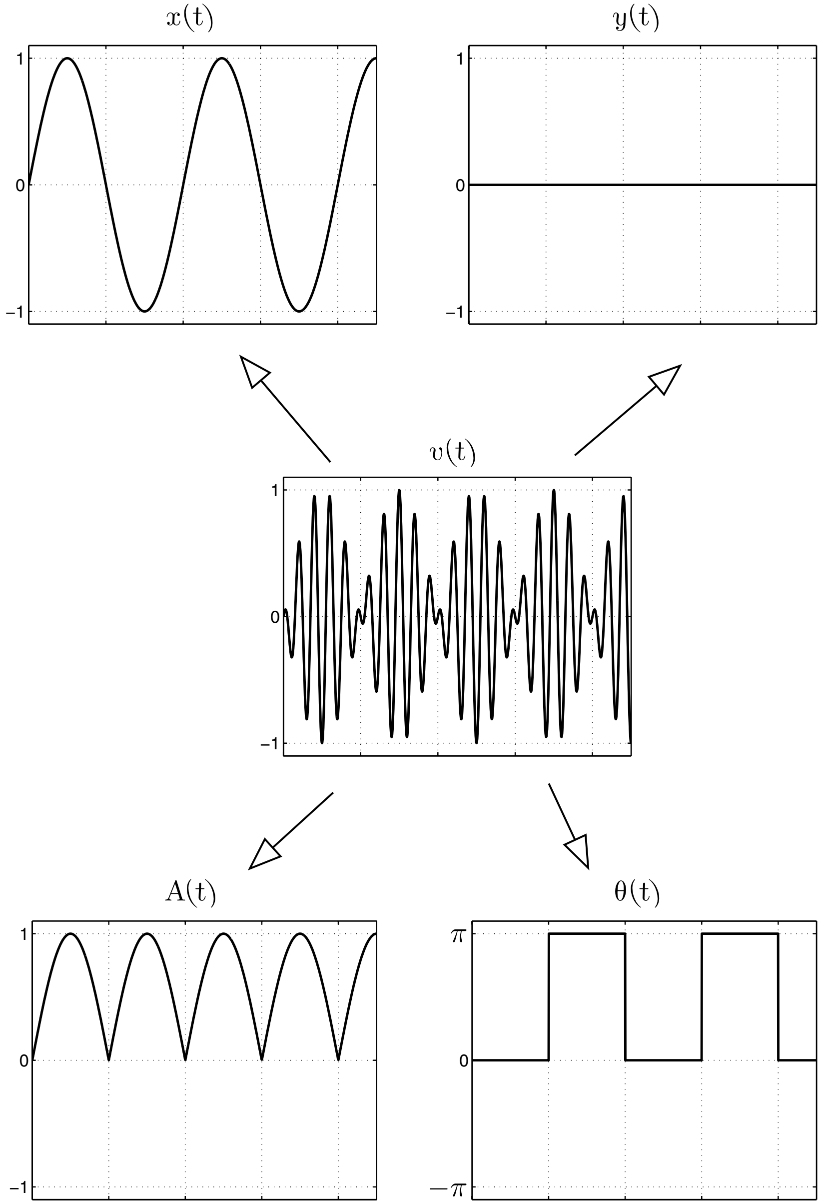


Figure 2.3. Two-tone signal and the corresponding envelope and phase signals.

To summarize, table 2.1 gives an overview of the different signals and their symbols as used throughout this text.

Table 2.1. nomenclature of modulated signals

symbol	name
$v(t)$	modulated RF signal
$g(t)$	complex envelope signal, complex baseband signal
$A(t)$	envelope signal, amplitude signal
$\theta(t), P(t)$	phase signal
$e^{j\theta(t)}$, $e^{jP(t)}$	complex phase signal
$v_P(t) = \cos(\omega t + P(t))$	RF phase signal
$x(t), I(t)$	in-phase signal
$y(t)$, $Q(t)$	quadrature signal

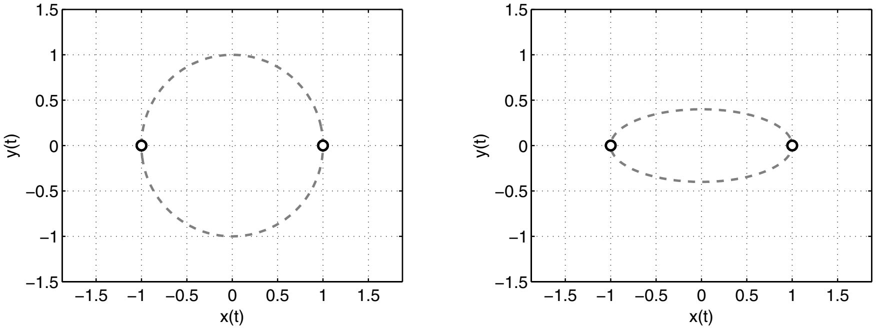
2.2.2 Digital Modulation

In digital modulation systems, a digital signal, i.e. a time discrete signal with a finite set of amplitudes, is mapped on a finite number of points in the complex plane, and these points are called *constellation points*. The corresponding graph showing all possible constellation points is named a *constellation diagram*.

One should realize that a constellation diagram is only half the story. How the complex envelope moves from one constellation point to another will determine the bandwidth of the transmitted RF signal. The complex envelope will not move instantaneously to another constellation point, as this would require an infinite bandwidth. Rather, the transition from one point to another constellation point is smoothed by applying a baseband filter on both the in-phase signal $x(t)$ and the quadrature signal $y(t)$.

The trajectory from one constellation point to another will also determine the envelope variations of the output RF signal. It will be shown later that these variations have a large impact on the design of the power amplifier. As a first example, consider the case of a Binary Phase Shift Keying (BPSK) constellation diagram, consisting of 2 constellation points. If the trajectory between the two points follows a circle, the amplitude of the complex envelope signal, i.e. the magnitude of the complex vector $g(t)$ and thus the amplitude signal $A(t)$, will not change and the RF output signal that needs to be transmitted has a *constant envelope*. In other words, $A(t)$ does not change in time. This is depicted in figure 2.4(a).

However, the path between the two constellation points of the previous example can be shortened by using an ellipse or a straight line between the two points. If a straight line is chosen, the trajectory would then go through the origin of the complex plane. The length of the complex vector will continuously change and this can be seen as a variation of the amplitude of the RF output



(a) constant envelope

(b) non-constant envelope

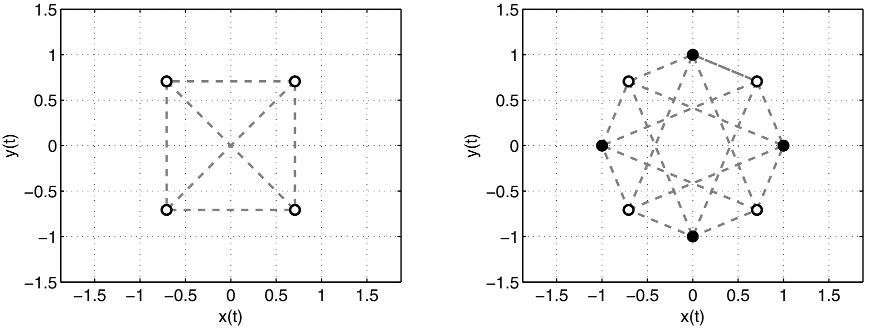
Figure 2.4. BPSK modulation.

signal. The RF signal at the output will have a changing envelope, which is denoted as a *non-constant envelope signal.* In short, $A(t)$ will change in time. This is demonstrated in figure 2.4(b).

The same holds for Quadrature Phase Shift Keying (QPSK) modulation, depicted in figure 2.5(a). A common technique to reduce the variation of the envelope signal is to use two constellation schemes that are rotated to each other. The trajectory is continuously switching between the two constellation diagrams. As an example, consider the $\pi/4$-QPSK of figure 2.5(b). The two QPSK constellation diagrams are rotated 45 degrees to each other. As such, the origin is avoided and the amplitude variations of the complex envelope signal are less severe compared to the QPSK example. Therefore, the amplitude variations of the RF signal that needs to be transmitted will also be less. In other words, the modulation depth of the amplitude modulation is reduced.

It can be concluded that envelope variations of the RF output signal are not only caused by the fact that constellation points are not lying on a circle. The transitions between the constellation points are as important to determine the envelope variations of the RF output signal. Even if the constellation points are lying on a circle, the output RF signal can still have envelope variations.

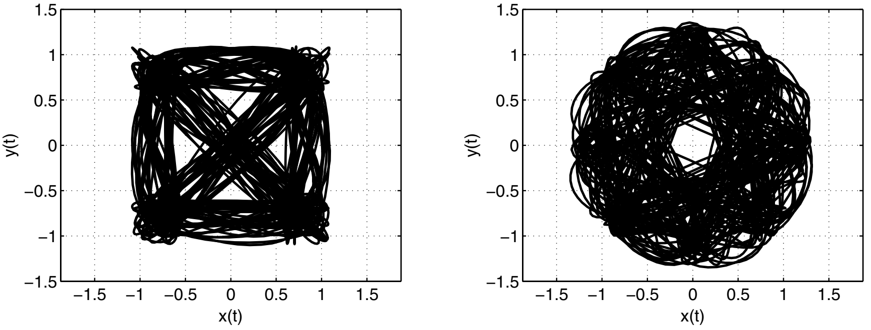
Furthermore, the transitions between the constellation points are filtered by a baseband filter, to limit the bandwidth of the transmitted signal, and this filtering operation will also effect the variation of the envelope signal. As an example, the QPSK and $\pi/4$-QPSK modulation schemes of figure 2.5 is filtered by a commonly used root-raised cosine filter with a roll-off of 0.35. Figure 2.6 shows the resulting filtered constellation diagram. Depending on the sequence of the transmitted symbols, the overshoot and undershoot of the



(a) QPSK

(b) $\pi/4$-QPSK

Figure 2.5. Unfiltered complex envelope signal for (a) QPSK and (b) $\pi/4$-QPSK modulation. The trajectory avoids the origin in $\pi/4$-QPSK modulation.



(a) QPSK

(b) $\pi/4$-QPSK

Figure 2.6. Filtered complex envelope signal for (a) QPSK and (b) $\pi/4$-QPSK modulation. A root-raised cosine baseband filter (r=0.35) has been applied.

baseband filter will add or subtract and thus the dynamic range of the complex signal is increased. Also, the *eye* or opening of the $\pi/4$-QPSK modulation around the origin, becomes smaller due to the baseband filtering.

2.2.3 Probability Density Function of the Envelope Signal

The location of the constellation points and the transitions or trajectories between these points, will both determine how the transmitted RF signal will look like. Nevertheless, even for the most complex (multi-carrier) modulation scheme, one can still think of it as a carrier that is modulated both in amplitude and phase.

The design of the power amplifier will be constrained by (1) the bandwidth of the phase signal, (2) the bandwidth of the amplitude signal and (3) the variation of the envelope or amplitude signal. If no amplitude modulation is present, one denotes this as a constant envelope signal or system and amplitude linearity is of no concern. As such, the design of the power amplifier is facilitated.

A more complete description of the amplitude modulation of the carrier is given by the *probability density function of the envelope signal* (*PDF*). It gives the relative amount of time the envelope spends at a certain value. Besides the probability density function, one can also define the *cumulative density function* (*CDF*) . It describes the probability that $A(t)$ is lower than a certain value.

Signals that only use phase or frequency modulation, do not have a varying envelope signal. Therefore, as the envelope is at a constant value, the corresponding probability density function will be a Dirac impulse. It should be stressed that, for RF communication, it is more common to look at the envelope *PDF* . In baseband amplifiers and line drivers, it is more common to look at the *PDF* of the actual output signal.

The envelope *PDF* is important for the optimization of the amplifier. After all, the *PDF* tells the designer what signal the amplifier will have to transmit, most of the time. As such, one could optimize the power amplifier in the region where the *PDF* is high.

As an example, the QPSK and $\pi/4$-QPSK modulation schemes can be used again. The envelope waveform can be obtained from figure 2.6 and the corresponding envelope probability density function is shown in figure 2.7. For QPSK, the envelope has a peak value of 1.58, an average value of 0.96 and an rms value of 1. The crest factor is 3.97 dB. Notice that the envelope for which the probability density is maximum, does not correspond to either the average or rms value of the envelope. For $\pi/4$-QPSK, the envelope has a peak value of 1.5, an average value of 0.97 and an rms value of 1. The crest factor is 3.28 dB. As said before, the $\pi/4$-QPSK modulation scheme avoids the origin, and this can clearly be seen in the corresponding PDF.

2.3 Some Aspects of Power Amplification

2.3.1 Output Power

Consider the basic circuit of figure 2.8, which shows a power amplifier connected to an antenna. The output power is defined as the active power, delivered by the power amplifier and flowing into the antenna. Inside the antenna, the power is *dissipated* under the form of a radiated electromagnetic wave. In most cases, the antenna impedance Z_{ant} is designed to be purely resistive at