RF/MICROWAVE CIRCUIT DESIGN FOR WIRELESS APPLICATIONS
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To Professor Vittorio Rizzoli

who has been instrumental in the development of the powerful harmonic-balance analysis tool, specifically Microwave Harmonica, which is part of Ansoft’s Serenade Design Environment. Most of the success enjoyed by Compact Software, now part of Ansoft, continues to be based on his far-reaching contributions.
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One of the wonderful things about living in these times is the chance to witness, and occasionally be part of, major technological trends with often profound impacts on society and people’s lives. At the risk of stating the obvious, one of the greatest technological trends has been the growth of wireless personal communication—the development and success of a variety of cellular and personal communication system technologies, such as GSM, CDMA, and Wireless Data and Messaging, and the spreading of the systems enabled by these technologies worldwide. The impact on people’s lives has been significant, not only in their ability to stay in touch with their business associates and with their families, but often in the ability to save lives and prevent crime. On some occasions, people who have never before used a plain old telephone have made their first long distance communication using the most advanced satellite or digital cellular technology. This growth of wireless communication has encompassed new frequencies, driven efforts to standardize communication protocols and frequencies to enable people to communicate better as part of a global network, and has encompassed new wireless applications. The wireless web is with us, and advances in wireless global positioning technology are likely to provide more examples of lifesaving experiences due to the ability to send help precisely and rapidly to where help is urgently needed.

RF and microwave circuit design has been the key enabler for this growth and success in wireless communication. To a very large extent, the ability to mass produce high quality, dependable wireless products has been achieved through the advances of some incredible RF design engineers, sometimes working alone, oftentimes working and sharing ideas as part of a virtual community of RF engineers. During these past few years, these advances have generated a gradual demystification of RF and microwave circuitry, moving RF techniques ever so reluctantly from “black art” to science. Dr. Ulrich Rohde has long impressed many of us as one of the principal leaders in these advances.

In this book, *RF/Microwave Circuit Design for Wireless Applications*, Dr. Rohde helps clarify RF theory and its reduction to practical applications in developing RF circuits. The book provides insights into the semiconductor technologies, and how appropriate technology decisions can be made. Then, the book discusses—first in overview, then in detail—each of the RF circuit blocks involved in wireless applications: the amplifiers, mixers, oscillators, and frequency synthesizers that work together to amplify and extract the signal from an often hostile environment of noise and reflected signals. Dr. Rohde’s unique expertise in VCO and PLL design is particularly valuable in these unusually difficult designs.
It is a personal pleasure to write this foreword—Dr. Rohde has provided guest lectures to
engineers at Motorola, and provided suggestions on paths to take and paths to avoid to several
design engineers. The value his insights have provided are impossible to measure, but are so
substantial that we owe him a “thanks” that can never be expressed strongly enough. I believe
that his impact on the larger RF community is even more substantial. This book helps share
his expertise in a widely available form.

ERIC MAASS
Director of Operations, Wireless Transceiver Products
Motorola, SPS
When I started two years ago to write a book on wireless technology—specifically, circuit design—I had hoped that the explosion of the technology had stabilized. To my surprise, however, the technology is far from settled, and I found myself in a constant chase to catch up with the latest developments. Such a chase requires a fast engine like the Concorde.

In the case of this somewhat older technology, its speed still has not been surpassed by any other commercial approach. This tells us there is a lot of design technology that needs to be understood or modified to handle today’s needs. Because of the very demanding calculation effort required in circuit design, this book makes heavy use of the most modern CAD tools. Hewlett-Packard was kind enough to provide us with a copy of their Advanced Design System (ADS), which also comes with matching synthesis and a wideband CDMA library. Unfortunately, some of the mechanics of getting us started on the software collided with the already delayed publication schedule of this book, and we were only in a position to reference their advanced capability and not really demonstrate it. The use of this software,
including the one from Eagleware, which was also provided to us, needed to be deferred to
the next edition of this book. To give a consistent presentation, we decided to stay with the
Ansoft tools. One of the most time-consuming efforts was the actual modeling job, since we
wanted to make sure all circuits would work properly. There are too many publications
showing incomplete or nonworking designs.

On the positive side, trade journals give valuable insight into state-of-the-art designs, and
it is recommended that all engineers subscribe to them. Some of the major publications
include:

- Applied Microwave & Wireless
- Electronic Design
- Electronic Engineering Europe
- Microwave Journal
- Microwaves & RF
- Microwave Product Digest (MPD)
- RF Design
- Wireless Systems Design

There are also several conferences that have excellent proceedings, which can be obtained
either in book form or on CD:

- GaAs IC Symposium (annual; sponsored by IEEE-EDS, IEEE-MTT)
- IEEE International Solid-State Circuits Conference (annual)
- IEEE MTT-S International Microwave Symposium (annual)

There may be other useful conferences along these lines that are announced in the trade journals
mentioned above. There are also workshops associated with conferences, such as the recent
"Designing RF Receivers for Wireless Systems," associated with the IEEE MTT-S.

Other useful tools include courses, such as Introduction to RF/MW Design, a four-day
short course offered by Besser Associates.

Wireless design can be split into a digital part, which has to do with the various modulation
and demodulation capabilities (advantages and disadvantages), and an analog part, the
description of which comprises most of this book.

The analog part is complicated by the fact that we have three competing technologies. Given
the fact that cost, space, and power consumption are issues for handheld and
battery-operated applications, CMOS has been a strong contender in the area of cordless
telephones because of its relaxed signal-to-noise-ratio specifications compared with cellular
telephones. CMOS is much noisier than bipolar and GaAs technologies. One of the problems
then is the input/output stage at UHF/SHF frequencies. Here we find a fierce battle between
silicon-germanium (SiGe) transistors and GaAs technology. Most prescalers are bipolar, and
most power amplifiers are based on GaAs FETs or LDMOS transistors for base stations. The
most competitive technologies are the SiGe transistors and, of course, GaAs, the latter being
the most expensive of the three mentioned. In the silicon-germanium area, IBM and Maxim
seem to be the leaders, with many others trying to catch up.

Another important issue is differentiation between handheld or battery-operated applica-
tions and base stations. Most designers, who are tasked to look into battery-operated devices,
ultimately resort to using available integrated circuits, which seem to change every six to
nine months, with new offerings. Given the multiple choices, we have not yet seen a
systematic approach to selecting the proper IC families and their members. We have therefore decided to give some guidelines for the designer applications of ICs, focusing mainly on high-performance applications. In the case of high-performance applications, low power consumption is not that big an issue; dynamic range in its various forms tends to be more important. Most of these circuits are designed in discrete portions or use discrete parts. Anyone who has a reasonable antenna and has a line of sight to New York City, with the antenna connected to a spectrum analyzer, will immediately understand this. Between telephones, both cordless and cellular, high-powered pagers, and other services, the spectrum analyzer will be overwhelmed by these signals. IC applications for handsets and other applications already value their parts as "good." Their third-order intercept points are better than −10 dBm, while the real professional having to design a fixed station is looking for at least +10 dBm, if not more. This applies not only to amplifiers but also to mixer and oscillator performance. We therefore decided to give examples of this dynamic range. The brief surveys of current ICs included in Chapter 1 were assembled for the purpose of showing typical specifications and practical needs. It is useful that large companies make both cellular telephones and integrated circuits or their discrete implementation for base stations. We strongly believe that the circuits selected by us will be useful for all applications.

Chapter 1 is an introduction to digital modulation, which forms the foundation of wireless radiocommunication and its performance evaluation. We decided to leave the discussion of actual implementation to more qualified individuals. Since the standards for these modulations are still in a state of flux, we felt it would not be possible to attack all angles. Chapter 1 contains some very nice material from various sources including tutorial material from my German company, Rohde & Schwarz in Munich—specifically, from the digital modulation portion of their 1998 Introductory Training for Sales Engineers CD. Note: On a few rare occasions, we have used either a picture or an equation more than once so the reader need not refer to a previous chapter for full understanding of a discussion.

Chapter 2 is a comprehensive introduction to the various semiconductor technologies to enable the designer to make an educated decision. Relevant material such as PIN diodes have also been covered. In many applications, the transistors are being used close to their electrical limits, such as a combination of low voltage and low current. The $f_t$ dependence, noise figure, and large-signal performance have to be evaluated. Another important application for diodes is their use as switches, as well as variable capacitances frequently referred to as tuning diodes. In order for the reader to better understand the meaning of the various semiconductor parameters, we have included a variety of datasheets and some small applications showing which technology is best for a particular application. In linear applications, noise figure is extremely important; in nonlinear applications, the distortion products need to be known. Therefore, this chapter includes not only the linear performance of semiconductors, but also their nonlinear behavior, including even some details on parameter extraction. Given the number of choices the designer has today and the frequent lack of complete data from manufacturers, these are important issues.

Chapter 3, the longest chapter, has the most detailed analysis and guidelines for discrete and integrated amplifiers, providing deep insight into semiconductor performance and circuitry necessary to get the best results from the devices. We deal with the properties of the amplifiers, gain stability, and matching, and we evaluate one-, two-, and three-stage amplifiers with internal dc coupling and feedback, as are frequently found in integrated circuits. In doing so, we also provide examples of ICs currently on the market, knowing that every six months more sophisticated devices will appear. Another important topic in this chapter is the choice of bias point and matching for digital signal handling, and we provide
insight into such complex issues as the adjacent channel power ratio, which is related to a form of distortion caused by the amplifier in its particular operating mode. To connect these amplifiers, impedance matching is a big issue, and we evaluate some couplers and broadband matching circuits useful at these high frequencies, as well as providing a tracking filter as preselector, using tuning diodes. Discussion of differential amplifiers, frequency doublers, AGC, biasing and push-pull/parallel amplifiers comes next, followed by an in-depth section on power amplifiers, including several practical examples and an investigation of amplifier stability analysis. A selection of power-amplifier datasheets and manufacturer-recommended applications rounds out this chapter.

Chapter 4 is a detailed analysis of the available mixer circuits that are applicable to the wireless frequency range. The design and the necessary mathematics to calculate the difference between insertion loss and noise figure are both presented. The reader is given insight into the differences between passive and active mixers, additive and multiplicative mixers, and other useful hints. We have also added some very clever circuits from companies such as Motorola and Siemens, as they are available as ICs.

Chapter 5, on oscillators, is a logical next step, as many amplifiers turn out to oscillate. After a brief introduction explaining why voltage-controlled oscillators (VCOs) are needed, we cover the necessary conditions for oscillation and its resulting phase noise for various configurations, including microwave oscillators and the very important ceramic-resonator-based oscillator. This chapter walks the reader through the various noise-contributing factors and the performance differences between discrete and integrated oscillators and their performance. Here too, a large number of novel circuits are covered.

Chapter 6 deals with the frequency synthesizer, which depends heavily on the oscillators shown in Chapter 5 and different system configurations to obtain the best performance. All components of a synthesizer, such as loop filters and phase/frequency discriminators, are evaluated along with their actual performance. Included are further applications for commercial synthesizer chips. Of course, the principles of the direct digital frequency synthesizer, as well as the fractional-N-division synthesizer, are covered. The fractional-N-division synthesizer is probably one of the most exciting implementations of synthesizers, and we have added patent information for those interested in coming up with their own designs.

The book then ends with two appendixes. Appendix A is an exciting approach to high-frequency modeling and integrated parameter extraction for HBTs. An enhanced noise model has been developed that gives significant improvement in the accuracy of determining the performance of these devices.

Appendix B is another CAD-based application for determining circuit performance—specifically, how to implement load-pulling simulation.

Appendix C is an electronic reproduction of a manual for a GSM handset application board that can be downloaded via web browser or ftp program from Wiley’s public ftp area at ftp://ftp.wiley.com/public/sci-tech-med/microwave. It is probably the most exciting portion for the reader who would like to know how everything is put together for a mobile wireless application. Again, since every few months more clever ICs are available, some of the power consumption parameters and applications may vary relative to the system discussed, but all new designs will certainly be based on its general principles.

We would like to thank the many engineers from Ansoft, Alpha Industries, Motorola, National Semiconductor, Philips, Rohde & Schwarz, and Siemens Semiconductor (now Infineon Technologies) for supplying current information and giving permission to reproduce some excellent material.
In the area of permissions, National Semiconductor has specifically asked us to include the following passage, which applies to all their permissions:

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I am also grateful to John Wiley & Sons, specifically George Telecki, for tolerating the several slips in schedule, which were the result of the complexity of this effort.

ULRICH L. ROHDE

Upper Saddle River, New Jersey
March, 2000
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RF/MICROWAVE CIRCUIT DESIGN FOR WIRELESS APPLICATIONS
INTRODUCTION TO WIRELESS CIRCUIT DESIGN

1-1 OVERVIEW

Wireless circuits are not that different from commonly known two-way radio, television, and broadcast arrangements. Some of them require high linearity in modulation (TV picture); some work via relay stations (two-way radio). The real differences lie in the fact that the cell sizes are much smaller, and that in most cases we attempt multiple channel use (reuse) using time-division multiplex, spread spectrum, or some other efficient means of reducing the bandwidth required for communication. One can argue that the wireless circuits include simple devices, such as garage-door openers and wireless keys for automobiles (we have seen many cases where strong interfering signals prevented the car owners from reclaiming their cars until the interfering signal disappeared). Another longtime favorite is cordless telephones: initially, 50-MHz models with essentially no privacy protection; later, more sophisticated models that operate at 900 MHz; and now, dual-band designs that use 900 MHz and 2.4 GHz.

The largest wireless growth area is probably the cellular telephones. The two major applications are the handsets, commonly referred to as cell phones or occasionally as “handies,” and the base stations. The base stations have many more problems with large-signal-handling linearity at high power, although handset users may run into similar problems. An example of this is the waiting area of an airport, where many travelers are trying to conduct last-minute business: In one instance, we concluded that about 30% of all the people present were on the air! It would have been fun to evaluate this receiver-hostile environment with a spectrum analyzer.

From such use comes anxiety factors, the lesser of which is “When will my battery die?”—a spare battery tends to help—and the greater of which the ongoing question, “Will this cell-phone transmitter harm my body?” [22]. A brief comment for the self-proclaimed experts in this area: A 50–100-kW TV transmitter, specifically its video or picture portion, connected to a high-gain antenna, emits levels of energy in line-of-sight paths that by far exceed the pulsed energy from a cell phone. Specifically, the duration of energy is signifi-
2 INTRODUCTION TO WIRELESS CIRCUIT DESIGN

cantly smaller, and the absolute energy is more than a thousandfold higher, than the radio frequency (RF) supposedly harming us from the cellular phone. Handheld two-way radios have been used for the last 30 years or so by police and other security interests, operating in the frequency range from 50 to 900 MHz with antennas close to the users' heads, and there are no known cases of cancer or any other illnesses caused by these handheld radios. Recent studies in England, debatably or not, showed that the reaction-time level of people using cell phones actually increased—but then there are always the skeptics and politically motivated who ignore the facts, try to influence the media, and have their 15 minutes of fame (as Andy Warhol used to say).

As to the "harmful" radiation, Figure 1-1 shows the simulated radiation of a Motorola flip phone. While there are no absolute values attached to the pattern colors, it is interesting to see that the antenna extension inside the plastic casing also radiates, but most of the energy definitely is emitted by the top of the antenna. It seems to be a good idea to hold the telephone in such a way that the antenna points away from the head, "just in case." The user will find a "warm" sensation that will have more to do with the efficiency of the RF power amplifier heating up the case than the effect of radiation.

With this introduction in place, we will first take a look at a typical ultra-high-frequency/super-high-frequency (UHF/SHF) transceiver and explain the path from the microphone to the antenna and back. After this, we will inspect the radio channel and its effect on various methods of digital modulation. Analysis of wireless receivers and transmitters will be next, followed by a look at available building blocks and how they affect the overall system. To validate proper system operation, a fairly large number of measurements and tests must be performed, and conveying their purpose and importance will necessitate the definition of a number of system characteristics and concepts, such as dynamic range. Finally, after this is done, we will look at the issue of wireless system testing. Again, we intend to

Figure 1-1  Simulated antenna radiation of a Motorola flip phone.
give guidance applicable to battery-operated, handheld operation as well as high-powered base stations.

1-2 SYSTEM FUNCTIONS

A cellular telephone is a hybrid between a double-sideband and frequency-modulated [FM; or phase-modulated (PM)] transceiver. The actual transmission is not continuous but is pulsed, and because of the pulse spectrum there is a signal bandwidth concern due to keying transients, not unlike intermodulation products of a single-sideband (SSB) transceiver cluttering up adjacent channels. The cellular telephone is also a linear transceiver in the sense that its signal-handling circuitry must be sufficiently amplitude- and phase-linear to preserve the modulation characteristics of the AM/PM hybrid emissions it transmits and receives. Containing such an emission's spectral regrowth, which affects operation on adjacent channels, is not unlike the linearity requirements we encounter in SSB transceivers—requirements so stringent that amplifiers must be run nearly in Class A to meet them. The time-division multiple access (TDMA) operating mode, which allows many stations to use the same frequency through the use of short, precisely timed transmissions, requires a system that transmits with a small duty cycle, putting much less thermal stress on a power amplifier than continuous operation. Power management, including a sleep mode, is another important issue in handset design.

Figure 1-2 shows the block diagram of a handheld transceiver. This is applicable for cellular telephones and other systems that allow full duplex. For those not too familiar with transceivers, here is a “walk” through the block diagram. The RF signal intercepted by the antenna is fed through a duplexer filter into a front end consisting of a preamplifier, an additional filter, and a mixer. The duplexer is optimized more for separating transmit and receive frequencies than extreme selectivity, but because of the typical low field strengths of incoming signals, it provides enough selectivity to guard the receiver path against overload and intermodulation products. The preamplifier is either a single transistor or a cascode arrangement with a filter following it. These high-band filters, mostly supplied by Murata, are typically surface acoustic wave (SAW) filters with very small dimensions. We would already like to point out in this part of the block diagram that these filters typically have high-impedance inputs and outputs (somewhere between 200 $\Omega$ and 1 k$\Omega$), therefore eliminating the nice test-setup possibilities typically provided in a 50-$\Omega$ system. Generally, integrated circuit (IC)-type mixers also operate at high impedances, which makes matching easier. The filter following the mixer is responsible for reducing the image, and then we go to the intermediate frequency (IF) and demodulation. The particular chip or chips mentioned here, supplied by Philips, are set out for a double-conversion receiver, and the demodulation is accomplished with a quadrature detector for FM analog modulation. The rest of the circuitry on the horizontal path does digital signal processing (DSP) and overall control functions. The four blocks at the far right refer to the central processor, which handles such things as display, power management, and information storage (such as frequently used telephone numbers). A nice overview about DSP in “readable” form is given by Kostic [1].

The transmit portion consists of an independent synthesizer that is modulated. There are dual synthesizer chips available to accommodate this. Both receive and transmit frequencies are controlled by a miniature temperature-compensated crystal oscillator (TCXO). One of its outputs is also used as the system master clock for all the digital activities. The output of the voltage-controlled oscillator (VCO) is then amplified and fed to the antenna through the
Figure 1-2  Block diagram of a handheld cellular telephone transceiver.
Figure 1-3  Single-chip direct-conversion transceiver by Alcatel. Channel selection is accomplished at baseband by low-pass switched-capacitor filters in a companion mixed-signal complementary metal-oxide semiconductor (CMOS) IC. A trimmed resistance-capacitance/capacitance-resistance (RC/CR) network generates the necessary quadrature signals for the chip's mixers.

same duplex filter as the receive portion. There are also schemes available for advanced modulation methods, specifically, code-, frequency-, and time-division multiple access (CDMA, FDMA, and TDMA, respectively). In these cases, the transmitter is not active all the time, and the duplexer can be replaced with a diode switch using a quarter-wavelength transmission line together with a PIN diode for the required switching.

Many modern devices use "zero IF" or direct conversion, which simplifies the IF or modulation portion of the unit significantly. Figure 1-3 shows an Alcatel single-chip direct-conversion transceiver. The signal is fed to an image-reject mixer with the local oscillator (LO) in quadrature, and the selectivity is obtained by manipulating the "audio bandwidth." Today we have a large number of implementations using different schemes that are beyond the scope of this book; therefore, we have decided to limit ourselves to a basic introduction because most of the relevant demodulation and coding are done in DSP, for which we will give appropriate references. A nice overview of different architectures is found in Razavi [2].

1-3  THE RADIO CHANNEL AND MODULATION REQUIREMENTS

1-3-1  Introduction

The transmission of information from a fixed station to a mobile is considerably influenced by the characteristics of the radio channel. The RF signal not only arrives at the receiving antenna on the direct path but is normally reflected by natural and artificial obstacles in its way. Consequently the signal arrives at the receiver several times in the form of echoes, which are superimposed on the direct signal (Figure 1-4). This superposition may be an advantage as the energy received in this case is greater than in single-path reception. This feature is made use of in the digital audio broadcasting (DAB) single-frequency network. However,
this characteristic may be a disadvantage when the different waves cancel each other under unfavorable phase conditions. In conventional car radio reception this effect is known as fading. It is particularly annoying when the vehicle stops in an area where the field strength is reduced because of fading (e.g., at traffic lights). Additional difficulties arise when digital signals are transmitted. If strong echo signals (compared to the directly received signal) arrive at the receiver with a delay on the order of a symbol period or more, time-adjacent symbols interfere with each other. In addition, the receive frequency may be falsified at high vehicle speeds because of the Doppler effect so that the receiver may have problems in estimating the instantaneous phase in the case of angle-modulated carriers. Both effects lead to a high symbol error rate even if the field strength is sufficiently high. Radio broadcasting systems using conventional frequency modulation are hardly affected by these interfering effects. If an analog system is replaced by a digital one that is expected to offer advantages over the previous system, it has to be ensured that these advantages—for example, better audiofrequency signal/noise (AF S/N) and the possibility of supplementary services for the subscriber—are not at the expense of reception in hilly terrain or at high vehicle speeds because of extreme fading.

For this reason a modulation method combined with suitable error protection has to be found for mobile reception in a typical radio channel, which is immune to fading, echo, and Doppler effects.

With a view to this, more detailed information on the radio channel is required. The channel can be described by means of a model. In the worst case, which may be the case for reception in built-up areas, it can be assumed that the mobile receives the signal on several indirect paths but not on a direct one. The signals are reflected, for example, by large buildings; the resulting signal delays are relatively long. In the vicinity of the receiver these paths are split up into a great number of subpaths; the delays of these signals are relatively short. These signals may again be reflected by buildings but also by other vehicles or natural obstacles like trees. Assuming the subpaths are statistically independent of each other, the superimposed signals at the antenna input cause considerable time- and position-dependent field-strength variations with an amplitude obeying the Rayleigh distribution (Figures 1-5 and 1-6).

If a direct path is received in addition, the distribution changes to the Rice distribution, and finally, when the direct path becomes dominant, the distribution follows the Gaussian distribution with the field strength of the direct path being used as the center value.
In a Rayleigh channel the bit error rate (BER) increases dramatically compared to the BER in an additive white Gaussian noise (AWGN) channel (Figure 1-7).

### 1-3-2 Channel Impulse Response

This scenario can be demonstrated by means of the channel impulse response. Let’s assume that a very short pulse of extremely high amplitude [in the ideal case, a Dirac pulse $\delta(t)$] is sent by the transmitting antenna at a time $t_0 = 0$. This pulse arrives at the receiving antenna direct and in the form of reflections with different delays $\tau_i$ and different amplitudes because of path losses. The impulse response of the radio channel is the sum of all received pulses (Figure 1-8). Since the mobile receiver and also some of the reflecting objects are moving, the channel impulse response is a function of time and of delays $\tau_i$; that is, it corresponds to

\[ x = vt \]

\[ t = \frac{x}{v} \]