RF/Microwave Circuit Design for Wireless Applications. Ulrich L. Rohde, David P. Newkirk

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Ulrich L. Rohde
Synergy Microwave Corporation

David P. Newkirk
Ansoft Corporation

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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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FOREWORD

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

PREFACE

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 applications 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.

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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

RF/MICROWAVE CIRCUIT DESIGN FOR WIRELESS APPLICATIONS

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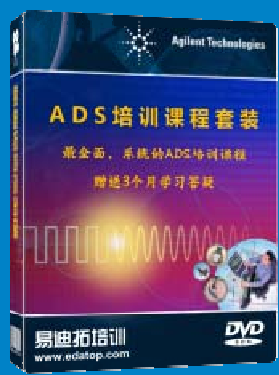

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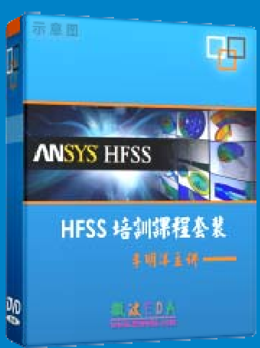

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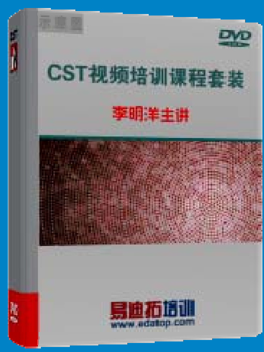

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