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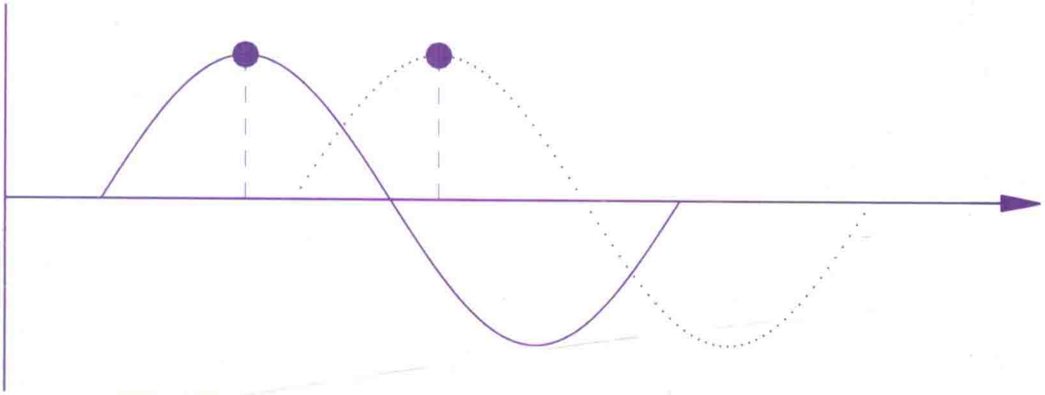

RADIO FREQUENCY CIRCUIT DESIGN

W. ALAN DAVIS

SECOND EDITION

WILEY

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Radio Frequency Circuit Design

Second Edition

W. ALAN DAVIS
University of Texas Arlington

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Radio Frequency Circuit Design

WILEY SERIES IN MICROWAVE AND OPTICAL ENGINEERING

KAI CHANG, Editor
Texas A&M University

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In memory of Margaret
and to our children
Brent, Nathan, and Janelle

Preface to the Second Edition

Since the first edition of this book was published almost 10 years ago, radio frequency design techniques and applications have continued to rapidly expand. Readers of this second edition will find many changes from the first edition such as expansion of power amplifiers, oscillator phase noise, and impedance matching and deletion of other material. Some chapters and sections have been rearranged to provide a more logical flow. In particular, the chapter on noise now precedes the chapter on class A amplifiers. However, when this book is used in our course on radio frequency circuits, students are asked to do a design project using the software, Advanced Design System, from Agilent. It has been found helpful for students to start their project after understanding basic amplifier design and then treat the noise problem in their design subsequently. Throughout the book, design examples are given based on the text. Source code for the programs illustrated in the text are available at the website given in Chapter 1. These programs should be helpful to the working engineer in need of a quick solution and to the student wishing to understand some of the details in a computation.

I wish to acknowledge the many contributions made by Krishna K. Agarwal in the first edition of this book and the contributions to the class E power amplifier section by William Cantrell in this edition. I also wish to acknowledge the valuable suggestions given by the reviewers.

W. ALAN DAVIS

Arlington, Texas
May 2010

Preface to the First Edition

The cellular telephone has become a symbol for the rapid change in the communications business. Within this plastic container reside the talents of engineers working in the areas of efficient power supplies, digital circuit design, analog circuit design, semiconductor device design, antennas, linear systems, digital signal processing, packaging, and materials science. All these talents are carefully coordinated at a cost that allows a wide cross section of the world's population to have available instant communication. The particular aspect of all these that is of primary focus in this text is in the area of analog circuit design with primary emphasis on radio frequency electronics. Topics normally considered in electronics courses or in microwave and antenna courses are not covered here. For example, there is no mention of distributed branch line couplers, since at 1 GHz their size would be prohibitive. On the other hand, topics such as transmission line transformers are covered because they fit so well into this frequency range.

This book is meant for those readers who have at least advanced standing in electrical engineering. The material in this text has been taught as a senior and graduate-level course in radio frequency circuit design at the University of Texas at Arlington. This class has continued to be popular for at least the last 20 years under the guidance of at least four different instructors, two of whom are the present authors. Because of the activity in the communications area, there has been ever greater interest in this subject. It is the intent of the authors, therefore, to update the current text offerings while at the same time avoiding simply reworking a microwave text.

The authors gratefully acknowledge the contribution of Michael Black, Raytheon Systems Company, to the phase lock loop discussion in Chapter 12.

W. ALAN DAVIS
KRISHNA K. AGARWAL

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CHAPTER ONE

Information Transfer Technology

1.1 INTRODUCTION

The design of radio frequency (RF) circuits borrows from methods used in low frequency audio circuits as well as from methods used in design of microwave circuits. However, there are also important departures from audio and microwave frequency methods, so that design of radio frequency circuits requires some specialized techniques not found in these other frequency ranges. The radio frequency range for present purposes will be taken to be approximately somewhere between 300 MHz and 3 GHz. It is this frequency range where much of the present day activity in wireless communication occurs. In this range of frequencies, the engineer must be concerned with radiation, stray coupling, and frequency response of circuit elements that, from the point of view of lumped, low frequency analysis, might be expected to be independent of frequency. At the same time, the use of common microwave circuit elements such as quarter wave transformers is impractical because of the long line lengths required. The use of monolithic circuits have enabled many high frequency designs to be implemented with lumped elements, yet the frequency response of these "lumped" elements still must be carefully considered. The small size of lumped elements in integrated circuits has provided practical designs of filters, transformers, couplers, etc. in lumped element form. Therefore discussion of designs for low noise amplifiers, power amplifiers, oscillators, mixers, and phase lock loops will be addressed with both lumped and distributed elements. Several of the numerical examples given in the text use computer programs. Source code for these programs are available

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on the web*. However, before getting into the details in the design of radio frequency circuits, it is important to understand that the purpose for these circuits is to transmit information.

1.2 INFORMATION AND CAPACITY

What exactly is information? *Random House Dictionary* 1966 states that "information" is "knowledge communicated or received concerning a particular fact or circumstance. ..." A narrower technical definition more closely aligns with the focus given here is that "information" is an "indication of the number of possible choices of messages, expressible as the value of some monotonic function of the number of choices, usually log to the base 2." *Information* then is a term for data that can be coded for digital processing.

Some examples of data that illustrate the meaning of information is helpful. If a signal were sent through a communication channel that never changed, then it would be conveying no information. There must be change to convey a message. If the signal consisted of 1 0 1 0 1 0 1 0 ... , there would be changes in the signal but still no information is conveyed because the next bit would be perfectly predictable. So while change is important, it is not the sole criterion for information. There is one last example. If a signal in an amplitude modulation system consists of purely random voltage fluctuations, then again no information is being transmitted. It is simply noise, and the receiver is no more knowledgeable after having heard it.

A communication system consists of a transmitter, a receiver, and a channel. The channel is capable of carrying only a certain limited amount of information. A water pipe can be seen as a rough analogy to a communication channel. The limitation in a communication channel is given the technical term *capacity*. It refers to the amount of information that is transmitted over a time interval of T seconds. The time interval can be broken up into short time intervals, each of duration τ. Clearly, the more distinct time intervals τ there are in the total time span T, the more information that can be transmitted. The minimum size of τ is determined by how well one pulse in one time frame can be distinguished from a pulse in a neighboring time frame. The limitation on how short a time frame can be is related to the channel bandwidth. In the water pipe analogy, the channel bandwidth corresponds to the pipe diameter.

In addition, the signal voltage will have a maximum amplitude that is limited by the available power in the system. This voltage range can be divided into many levels, each level representing a bit of information that is distinguished from another bit. The voltage range cannot be split indefinitely because of the noise that is always present in the system. Clearly, the more voltage intervals in a given time frame τ, the more information capacity there is in the system. Just as the flow of water through a pipe is limited by the amount of

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*http://www-ee.uta.edu/online/adavis/rfsoftware pressure on the water, by the friction on the walls of the pipe, and by the diameter of the pipe, so the capacity of a transmission system is limited by the maximum voltage level, by the noise in the system that tends to muddle the distinction between one voltage level and another, and by the bandwidth of the channel, which is related to the rise time of a pulse in the system.

In one of the time intervals, τ, there are n voltage levels. The smaller that τ is and the larger n is, the more information that can be transmitted through the channel. In each time interval, there are n possible voltage levels. In the next time interval there are also n possible voltage levels. It is assumed that the voltage level in each time frame is independent of what is going on in other time frames. The amount of information transmitted in a total of T seconds corresponds to the products of the possibilities in each interval:

$$n \cdot n \cdot n \cdot n \cdots n = n^{T/\tau} \tag{1.1}$$

The total information, H, transmitted intuitively is directly proportional to the total time span T, and is defined as the log of the above product. By convention, the base 2 logarithm is used.

$$H = T/\tau \log_2 n \tag{1.2}$$

The system capacity is simply the maximum *rate* of transmission (in bits/s) through a system:

$$C = H/T = 1/\tau \log_2 n \tag{1.3}$$

System capacity is inversely proportional to the minimum time interval over which a unit of information can be transmitted, τ. Furthermore, as the number of voltage levels increases, so does the capacity for more information.

Information can be transmitted through a channel in a variety of different forms, all giving the same amount of information. For example, suppose that a signal can take on any one of eight different voltage levels, 0,1, … , 7, in a given time interval τ. But the eight-level signal could also equally be sent with just two levels, 0,1. However, for every interval that has eight possible levels, three intervals will be needed for the two-level signal. A convenient conversion between the two systems is shown in Table 1.1.

Clearly, a 16-level signal could be transmitted by a sequence of 4 binary signals, and a 32-level signal with a sequence of 5 binary signals, and so on. For n levels, $\log_2 n$ bits are needed. The information content of a signal is defined then to be the number of binary choices, or bits, that are needed for transmission. A system that is designed to transmit speech must be designed to have the capacity to transmit the information contained in the speech. While speech is not the total of what humans communicate, in a communication system, it is that with which engineers have to work. A decision must be made as to what level of fidelity the speech is to be transmitted. This translates to the bandwidth

TABLE 1.1 Eight-Level and Two-Level Systems

$n = 8$	$n = 2$
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

requirement of an analog system, or the number of voltage levels available in a given total voltage range. Ultimately the restriction is always present even if sophisticated coding techniques are used. The capacity of the system must be greater than or equal to the rate of information that is to be transmitted. Beyond this, system cost, power levels, and available transmission media must be considered.

1.3 DEPENDENT STATES

The definitions of the preceding section imply that the voltage level in each time interval, τ, is independent of the voltage level in other time intervals. However, one very simple example where this is not the case is the transmission of the English language. It is known in the English language that the letter *e* is much more likely to appear than the letter *z*. It is almost certain that the letter *q* will be followed by the letter *u*. So in transmitting a typical message in English, less information is being actually sent than there would be if each letter in the alphabet were equally likely to occur. A way to express this situation is in terms of probability. The total number of signal combinations that could occur in a message T seconds long if the value in each interval is independent of the others is $n^{T/\tau}$. On average, every possible message T seconds long would have a probability of occurrence of $1/n^{T/\tau}$.

The probability takes the form

$$P = \frac{\text{number of occurrences of a particular event}}{\text{total number of events}} \tag{1.4}$$

Information can be measured in terms of probability. The probability is $P = 1/n$ if there are n possible events specified as one of n voltage levels, and each of these events is equally likely. For any one event, the information transmitted is written $H_1 = -P\log_2 P$. For m intervals, each τ seconds long, there will be m