Solid State Radio Engineering

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Preface

This book is about the analysis and design of the radio-frequency electronic circuits that are the building blocks of radio transmitters and receivers. It reflects the developments of the past decade, which have initiated an unprecedented growth in the use of analog radio systems for personal and business voice communications. Continuing advances in solid state technology have resulted in transmitters that are smaller, cheaper, and more reliable than ever before. Parallel developments have occurred in the home entertainment radio and television fields. As a result, radio engineers versed in the solid state art are in demand.

Because of the rapid changes in radio technology, teachers of courses in radio circuits have often had to rely on material that is scattered through many different textbooks, technical journals, and application notes. This volume meets the need for a comprehensive book on radio electronics.

Solid State Radio Engineering is unique because of its broad coverage of both receiver and transmitter circuits and its illustration of theoretical concepts with numerical examples from real circuits. Design that uses practical circuit elements instead of idealized mathematical models is emphasized. The letter symbols used for semiconductor device currents and voltages conform for the most part with IEEE Standard notation.

The last five chapters present for the first time in textbook form considerable information on RF power amplifiers. Currently, power amplifier design is often accomplished by using cut-and-try techniques and rules of thumb. Often, theoretical explanations of power amplifier operation are too complicated or require too much time for a designer to use. This book brings these principles to the student or practicing design engineer in a way that not only makes them understandable but also makes them useful for design. The discussions in Chapters 12 to 16 include not only accepted state-of-the-art technology, based on bipolar junction transistors, but also VMOS RF power FETs, high-efficiency techniques, envelope elimination and restoration, and other newly emerging technologies that are expected to play significant roles in radio engineering during the next decade.

This book is intended to be both a reference for the working engineer and a textbook for senior-level students in electrical engineering and electrical technology. A knowledge of complex algebra, Fourier series, and Fourier transforms will enable its reader to handle the mathematics in the book. As an aid to self-study, practical design examples are included throughout. These are reinforced by homework problems that are keyed to the corresponding sections of the text.

The material presented is appropriate for either a two-semester or three-quarter course sequence. For shorter course offerings, some chapters may be omitted. For example, if receiving systems are of primary interest, Chapters 1 to 11 can be used. For transmitters, Chapters 1 to 8 and 12 to 16 (with the possible omission of Sections 14-3 to 14-6) are recommended. If the students have an adequate background in noise and modulation theory, Chapters 2 and 8 can be omitted. Prior knowledge of resonant impedance matching might permit skipping all of Chapter 3, with the exception of Section 3-6, which is used frequently in the following chapters.

A brief introductory chapter considers the concept of modulation and the functions performed in a typical transmitter and receiver. It is followed by a discussion of electrical noise because of its importance in the design of RF amplifiers and mixers in receivers. Chapters 3 to 7 include the component parts of receiver systems, and Chapter 8 provides the modulation theory necessary for an understanding of the operation of AM, SSB, FM, and TV receivers.

A thorough treatment of the design of narrowband, tapped resonant circuits for impedance matching, as well as the use of tapped mutual inductance circuits for both wideband and narrowband matching, is given in Chapter 3. The design of small-signal, tuned amplifiers for maximum gain with a specified degree of stability is considered next. This is followed by an analysis of sinusoidal oscillations in *LC* and crystal oscillator circuits; and a unique, laboratory-tested procedure is given for the design of a common-base Colpitts oscillator for specified output.

A phase-locked loop will soon be included in nearly every radio receiver, transmitter, and piece of test equipment. Hence, the simpler aspects of loop operation are outlined in Chapter 6, along with the characteristics of the basic loop components and some applications to communication equipment. This is followed by analysis of diode, BJT, and FET mixer circuits.

Chapters 9 to 11 are devoted to receivers. Because design techniques are changing constantly with the introduction of new integrated-circuit packages, the fundamental signal processing in each type of receiver is stressed without a detailed description of all possible circuits. Analysis of various types of AM and FM detectors is found in the corresponding chapters, along with information on ceramic, crystal, and surface-acoustic-wave IF filters. The basic principles of color picture transmission are given in Chapter 11, along with a block-diagram explanation of the receiver circuitry. Although not directly related to the subject matter of the book, this is the one piece of radio equipment that the student owns and uses every day. Furthermore, it incorporates most of the principles studied in preceding chapters.

Chapters 12 to 16 are organized by practice rather than theory. Thus Class A and B amplification along with the broadband transformer and filter networks normally used in SSB transmitters are discussed first. Similarly, Class C and Class C mixed-mode power amplifiers and the discrete-element or transmission-line matching networks normally used with them, are presented together. Chapter 14 treats several types of high-efficiency power amplifiers (Classes D, E, F, and S). Chapter 15 includes CW, FM, and AM transmitters, since they have similar configurations. The last chapter examines single-sideband and multimode transmitters, envelope elimination and restoration, and other related techniques.

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Contents

1 Radio Communication Systems

1-1 Introduction

This book is devoted to the analysis and design of the electronic circuitry used in radio communication systems. It presumes that the reader is familiar with audio-frequency amplifiers; hence the primary emphasis will be on radio transmitter and receiver circuits. The transmitting and receiving antennas and the propagation path between them are important parts of an overall system, but a discussion of these elements is left to other texts.

Communication systems transmit information in the form of electrical signals that represent speech, music, television pictures, scientific and business data, and so forth. The waveforms of these signals are complex and continually changing, but the frequency spectrum of the signals is usually limited to a specified bandwidth either by the nature of the signal source or by filters in the transmitting equipment. Since many of these signals occupy a frequency band that extends downward to a few hertz, they cannot be transmitted in their original form over a common transmission path because it would not be possible to separate them at the receiving end. A separate transmission line or separate radio path for each signal would not be feasible from either an economic or a practical standpoint. Hence the overall communication system must provide a means for simultaneous transmission of a number of signals either by shifting them into different parts of the frequency spectrum or by sending samples of the signals on a time-shared basis.

The wavelength (λ) in meters of a radio wave is given by c/f, in which c is the velocity of light (3×10^8 meters per second), and f is in hertz. (For RF calculations it is convenient to remember that f in megahertz $\times$ λ in meters = 300.) A radio antenna should have a physical size of one-half wavelength or more for reasonable efficiency. Hence, as the transmission frequency is increased, the physical size and cost of the antenna are reduced and its efficiency increases.

1-2 Elements of a radio system

The process whereby the original message is converted into a new form suitable for radio transmission is called modulation. The modulation process causes some property—such as the amplitude, frequency, or phase—of a high-frequency carrier[1] wave to be deviated from its unmodulated value by an amount proportional to the instantaneous value of the modulating (message) signal. Thus the content of the original message is shifted to a portion of the frequency spectrum in the vicinity of the carrier frequency. In the receiver this process is reversed in a detector that recovers the original signal.

Figure 1-1 shows a simplified block diagram of a radio transmitter and receiver in order to illustrate the signal processing that takes place. The function of each block is explained below.

1. The source of the message signal may be a microphone, phono pickup, television camera, or other device that transforms the desired information into an electrical signal.

2. The signal is amplified and often passed through a low-pass filter to limit the bandwidth.

3. The RF oscillator establishes the carrier frequency or some submultiple of it. Since good frequency stability is required to keep the transmitter on its assigned frequency, the oscillator is often controlled by a quartz crystal.

4. One or more amplifier stages increase the power level of the signal from the oscillator to that needed for input to the modulator. Class C operation is used wherever possible to obtain high efficiency. Tuning of the output circuits to a harmonic of the input frequency results in "frequency multiplication" so that the final carrier frequency can be a multiple of the oscillator frequency.

5. The modulator combines the signal and carrier frequency components to produce one of the varieties of modulated waves discussed in Section 1-3. In the simplified system shown in Fig. 1-1 the output signal spectrum lies in the vicinity of the desired RF carrier frequency. In many transmitters a second oscillator and mixer (similar to blocks 10 and 11) are inserted between

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[1]The "carrier" may be a sinusoidal wave or a train of pulses.

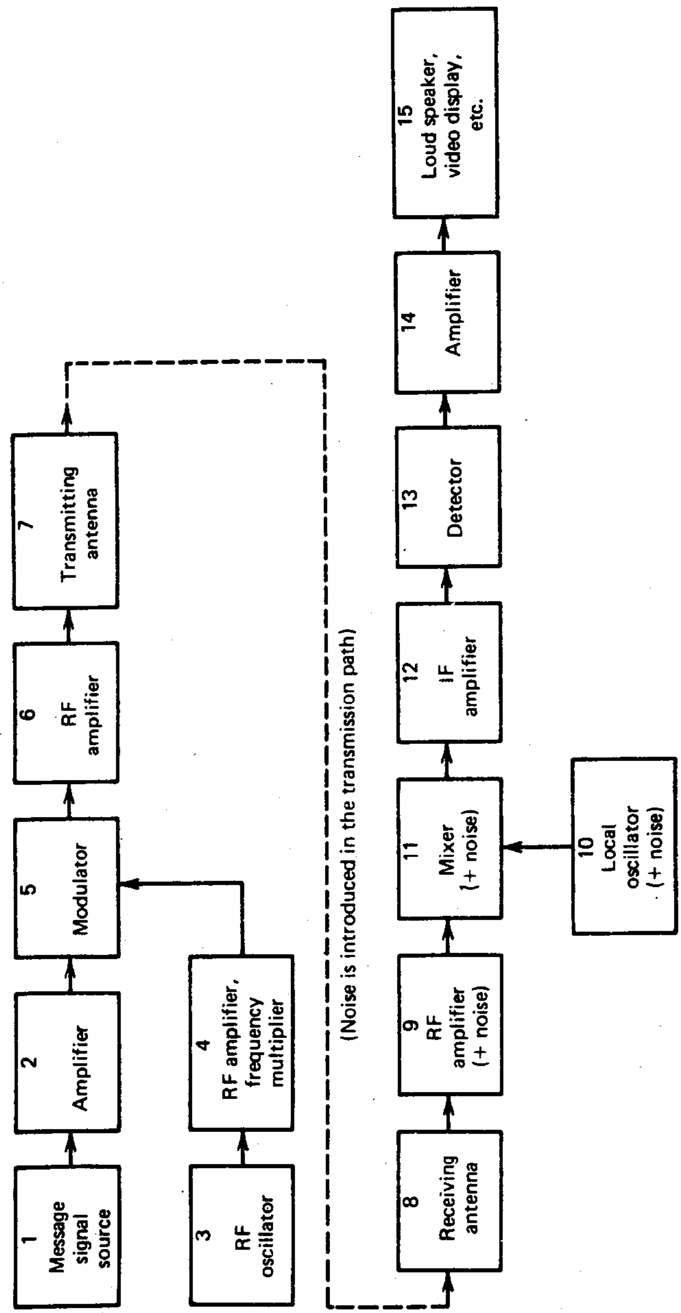

Fig. 1-1 Radio transmitter and receiver block diagram.

blocks 5 and 6 in order to shift the modulated wave to a higher-frequency range.

6. Additional amplification may be required after modulation to bring the power level of the signal to the desired value for input to the antenna.

7. The transmitting antenna converts the RF energy into an electromagnetic wave of the desired polarization. If a single (fixed) receiver is to be reached, the antenna is designed to direct as much of the radiated energy as possible toward the receiving antenna.

8. The receiving antenna may be omnidirectional for general service or highly directional for point-to point communication. The wave propagated from the transmitter induces a small voltage in the receiving antenna. The range of amplitudes of the induced antenna voltage may be from tens of millivolts to less than 1 microvolt, depending upon a wide variety of conditions.

9. The RF amplifier stage increases the signal power to a level suitable for input to the mixer and it helps to isolate the local oscillator from the antenna. This stage does not have a high degree of frequency selectivity but does serve to reject signals at frequencies far removed from the desired channel. The increase in signal power level prior to mixing is desirable because of the noise that is inevitably introduced in the mixer stage.

10. The local oscillator in the receiver is tuned to produce a frequency f_{LO} that differs from the incoming signal frequency f_{RF} by the intermediate frequency f_{IF}; that is, f_{LO} can be equal to $f_{RF} + f_{IF}$ or $f_{RF} - f_{IF}$.

11. The mixer is a nonlinear device that shifts the received signal at f_{RF} to the intermediate frequency f_{IF}. Modulation on the received carrier is also transformed to the intermediate frequency.

12. The IF amplifier increases the signal to a level suitable for detection and provides most of the frequency selectivity necessary to "pass" the desired signal and filter out the undesired signals that are found in the mixer output. Because the tuned circuits in blocks 11 and 12 always operate at a fixed frequency (f_{IF}), they can be designed to provide good selectivity. Ceramic or crystal filters are often used.

13. The detector recovers the original message signal from the modulated IF input.

14. The audio or video amplifier increases the power level of the detector output to a value suitable for driving a loudspeaker, a television tube, or other output device.

15. The output device converts the signal information back to its original form (sound waves, picture, etc.).

In addition to the desired signal that is processed by the receiver, electrical noise is added in the transmission path, and is generated within the RF amplifier, local oscillator, mixer, and so forth. The block diagrams shown in Fig. 1-1 are for illustrative purposes only. In practice, so many variations in transmitter and receiver systems are encountered that no single block diagram could even be considered typical. The general layout of receivers or transmitters for particular applications will be discussed in detail in later chapters.

1-3 Modulation

To extend the concept of modulation introduced in the previous section, the basic definitions of commonly used types of modulation will be given here. Let the voltage of an unmodulated carrier wave be given by

$$v(t) = V_c \sin(\omega_c t + \phi) = V_c \sin \theta(t) \tag{1-1}$$

in which ω_c is the carrier (radian) frequency, V_c the amplitude, and ϕ an arbitrary phase angle.

Amplitude Modulation

In an amplitude-modulated (AM) wave, the deviation of the amplitude V_c from its unmodulated value is proportional to the instantaneous value of the modulating wave. In other words, if the modulating signal is $F(t)$, the carrier amplitude must vary in time according to the expression

$$V_c(t) = V_c[1 + m_a F(t)] \tag{1-2}$$

in which m_a is the *modulation factor*. The value of $m_a F(t)$ cannot exceed unity without introducing distortion. Figure 1-2*a* illustrates a modulating signal $F(t)$, and the corresponding amplitude-modulated wave is shown in Fig. 1-2*b*. Note that the *envelope* of the AM wave [given by (1-2)] has the same shape as the modulating signal.

Angle Modulation

In angle modulation, the angle $\theta(t)$ in (1-1), rather than the amplitude, is varied from its unmodulated value by the modulating signal. Phase and frequency modulation are particular forms of angle modulation. In *phase modulation* (PM), the angle $\theta(t)$ in (1-1) is made to vary proportionately to the modulating signal $F(t)$. In *frequency modulation* (FM) the instantaneous frequency,

$$\omega(t) = \frac{d\theta(t)}{dt}$$