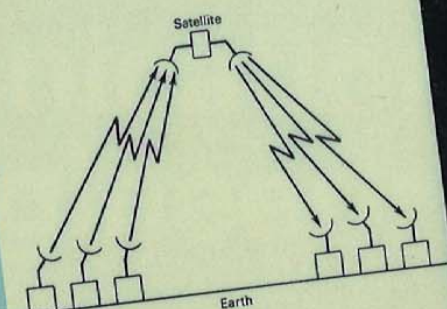
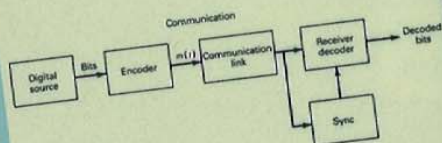
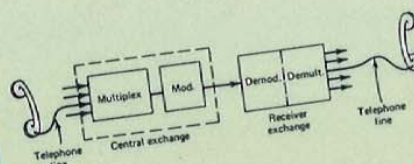
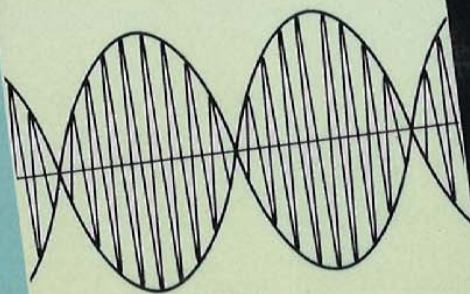


INTRODUCTION TO COMMUNICATIONS ENGINEERING

Second Edition



Robert M. Gagliardi

Introduction to Communications Engineering

Second Edition

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COMMUNICATION SYSTEM MODELS

The principal objective of a communication system is to transmit *information signals* (waveforms) from one point to another. The information signals may be the result of a voice message, a television picture, or a meter reading or may take on a variety of other formats depending on the specific application. The points between which the information is to be sent may be located in close proximity or may be continents, or even planets, apart. *Communications engineering* involves the analysis, design, and fabrication of an operating system that satisfactorily performs the communication objective. In this book we are concerned with the development and application of the basic analytical tools and system alternatives necessary to carry out the communications engineering tasks.

The required transfer of information is most often accomplished by *modulating* (superimposing) the desired information signal onto a *carrier* (sine wave) and converting the carrier to an electromagnetic field. This field is then *transmitted* (propagated) to the desired destination, where it is *received* (intercepted) and the information signal *demodulated* (recovered). The design objective is to construct a suitable system that accomplishes these operations with minimal *distortion* (perturbations) of the information signal itself. To produce such a design, it is necessary to understand the basic functional aspects of each component of the system model, along with their various characteristics and properties that influence the eventual performance.

1.1 ELEMENTS OF COMMUNICATION SYSTEMS

A communication system can be divided into three primary parts, as shown in Figure 1.1. The *transmitter* represents the part of the system where the information signal is generated, modulated, and transmitted. Each of these

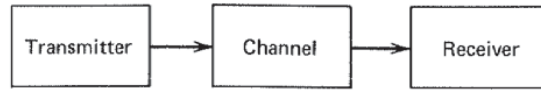


Figure 1.1. The basic communication system.

operations is not necessarily physically located at the same place, so that the transmitter block does not always represent a single, self-contained unit. The *receiver* portion performs the necessary operation for intercepting the transmitted carrier and recovering the information signal at the desired destination. It also need not represent a single, self-contained unit. The *channel* represents the propagating media or the electromagnetic path interconnecting the transmitter and the receiver. It is from this transmission channel that various anomalies and interference effects enter the system operation. Thus, although the design and fabrication of the transmitter and receiver portions are, for the most part, entirely in the hands of the communication engineer, it is often the properties of the channel that ultimately influence and dictate such design procedures. As we shall see, knowledge of these channel properties is mandatory for successful engineering. The combination of transmitter, channel, and receiver is referred to as a communication *link*. Any part of a communication system is called a *subsystem*, and the overall design is accomplished by properly interfacing the individual subsystems.

The transmitter block can be further subdivided into the subsystems shown in Figure 1.2a. The information *source*, whatever its form, generates the electronic signal to be sent to the receiver. Information sources are classified as either *analog* or *digital* sources. An analog source produces a time continuous electronic waveform as its output. A digital source produces sequences of data symbols for its output. Although Figure 1.2a shows only a single source output, we may in fact have several different outputs from a single source, and perhaps even more than one distinct source. In such cases the communication system must be capable of handling simultaneously the complete set of source signals.

Source signals are generally converted into a baseband waveform to prepare it for the carrier transmission. The principal objective of this baseband conversion is to insert suitable control and proper formulation of the source output prior to carrier modulation. In some simple systems baseband conversion is not used, and the analog source output is used directly for carrier modulation. In other systems the conversion operation may take on a variety of forms. For example, it may involve only filtering of the source waveform, or it may involve a separate modulation of the source signal onto a secondary carrier (called a *subcarrier*) before modulating onto the main carrier. For digital sources, baseband conversion is used to convert the source symbols into baseband waveforms for transmission, and the conversion operation is called *encoding*. In a multiple source environment

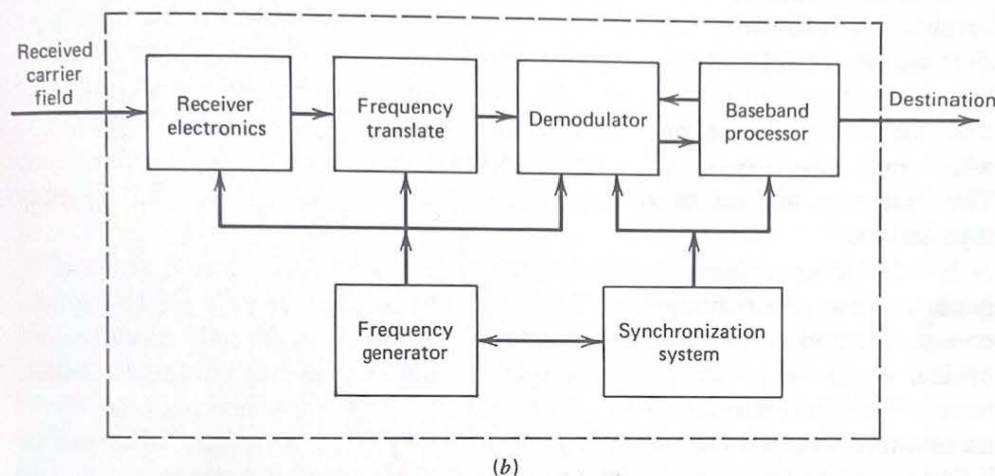
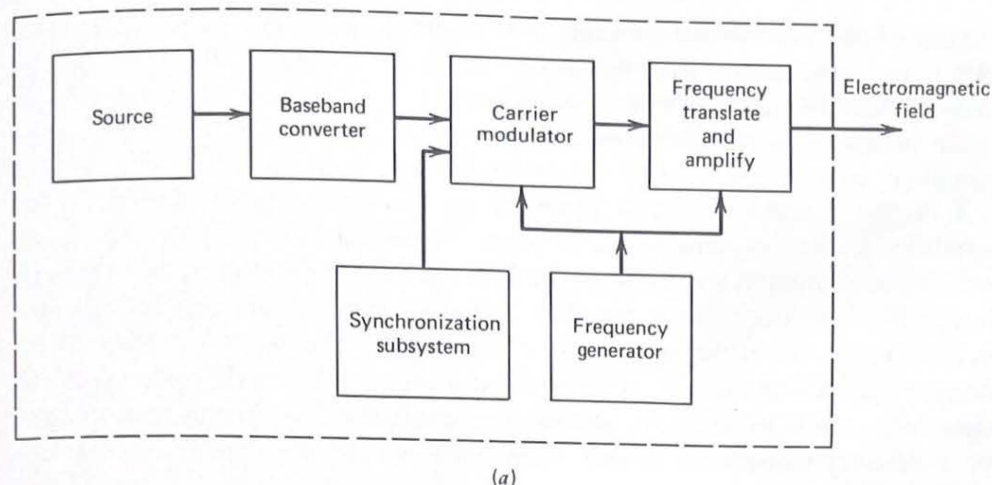


Figure 1.2. Transmitter and receiver block diagrams: (a) transmitter, (b) receiver.

the converter involves additionally a combining of all the various source outputs into a single baseband waveform, the latter conversion called *multiplexing*. The selection of the proper baseband conversion operation so as to achieve satisfactory communication becomes an important aspect of transmitter design. In later discussions the various types and alternatives for the conversion operation are examined in detail.

The baseband waveform is modulated onto the carrier to form the carrier waveform. The basic objective of performing a modulation is to generate a transmission waveform that is best suited for the electromagnetic propagation and communication reception. These advantages are made more obvious in subsequent chapters. Here again the modulation may take on various forms, each with its own advantages and disadvantages relative to the channel and receiver. Modulation formats are important in determining the

extent of the channel interference and combating the associated distortion. Also, the modulation method must interface properly with the baseband conversion operation and the basic parameters of the receiving system.

In addition to the subsystems devoted to the processing of the source signal, it may be necessary to provide auxiliary transmitter waveforms that aid in the transmission and recovery of the desired information. These auxiliary waveforms can be classified as transmitter *synchronization* signals whose basic objective is to keep the link operationally aligned and properly interfaced with the transmitter. These synchronization signals can take on a variety of forms and may be superimposed on the source, baseband, or carrier waveforms. In the sophisticated system characterizing modern design, the ability to maintain adequate synchronization and alignment must be a primary consideration and often becomes the ultimate limit to attainable performance.

At the transmitter the modulated carrier is often frequency translated and amplified to a desired power level. Frequency translation involves a direct shift of the modulated carrier from one frequency band to another. (These bands are discussed in Section 1.2). This frequency shifting is accomplished with the aid of signals produced from devices called *frequency generators*, which may also provide the carrier waveforms needed for the modulation. The majority of modern systems use some form of transmitter frequency translation.

In electronic communication systems, the amplified carrier is used to generate the electromagnetic field for channel propagation. In optical communication systems, the baseband signal is used to directly modulate an optical source to produce an electromagnetic field corresponding to a light beam. The predominate use of light beams is with optical fibers, in which transmitter and receiver are interconnected by a glass "pipe." The use of lightwave fiber systems as a communication link is rapidly becoming one of our most important communication channels.

All propagating electromagnetic fields and optical beams are characterized by their *polarization* (the orientation of their electric field in space) and their transmitted power distribution (beamshape) in the various directions of propagation. Electromagnetic transmission channels can be roughly divided into *guided* and *unguided* channels. In an unguided channel the transmitter propagates the field formed from the carrier freely in a medium with no attempt to control its propagation other than by its field propagation pattern. The prime example of an unguided channel is the so-called space channel, in which the medium involved may be free space, the atmosphere, or the ocean (under water). In a guided channel a waveguide is used to confine the field propagation from transmitter to receiver. The prime example of guided system is the cable, hard-wire, or optical fiber channel. Specific properties of these various channels are discussed (in Chapter 3).

The system receiver can be divided into the subsystems shown in Figure 1.2b. The front end electronics receives and processes the electromagnetic

field and attempts to eliminate as much channel interference as possible. The received electromagnetic field is then demodulated to recover the baseband waveform. In an optical receiver a photodetector is used in the front end to regenerate the baseband. Channel effects are generally exhibited at this point and cause the recovered baseband to no longer represent the transmitter baseband identically. The recovered baseband is then deconverted to produce the recovered information signal (or signals, in the multiple source case) for the final destination. In general, this deconversion simply attempts to invert the operation performed at the transmitter. It may, for example, involve baseband filtering, subcarrier demodulation, *decoding* (reconverting the baseband back into digital symbols), or possibly *demultiplexing* (splitting the baseband into its various source waveforms). Over the past several decades there have been increased efforts to improve receiver design to achieve better system performance in terms of both theoretical analysis and hardware fabrication. Much of this effort is concentrated on more sophisticated receiver baseband processing, and the selection of the appropriate processing alternative becomes a vital part of successful system engineering.

If synchronization signals were provided at the transmitter, they must also be recovered and properly used in the receiver processing. In this case a synchronization subsystem must be included within the receiver to separate out the synchronization waveform and reinsert it into the correct receiver subsystem (Figure 1.2b). This synchronization information may be used in the carrier, in the baseband, or in the eventual application of the recovered source signal at the destination. Chapter 10 is devoted to some common synchronization subsystems and their associated design.

The system model shown in Figure 1.2 implies that a single carrier is involved, which indeed represents the most common situation. In discussing more advanced modern communication systems, however, we extend this basic model to include the case where more than one simultaneous carrier is involved in the transmitting operation. Such a system is called a *multiple carrier* system, and its analysis requires modification and extension of many of the results to be derived for the single carrier case.

1.2 COMMUNICATION SYSTEMS

The communication system models depicted in Figures 1.1 and 1.2 are simply generalized forms of some of the basic communication systems with which we are personally familiar. Three of the most common examples in our everyday life are the telephone, television, and teletype systems (sketched in Figure 1.3). In the telephone system the speaker's voice is converted to an electrical signal directly in the hand-held phone set, which therefore acts as an analog source for the link. The voice signal is then sent by wire to a central telephone exchange. Here it is carrier modulated and relayed via a

CARRIER TRANSMISSION

After the modulated carrier is produced, it must be prepared for transmission to the receiver. Since the modulated carrier is usually formatted at a carrier frequency much lower than the desired transmission frequency, a typical RF transmitter generally involves stages of frequency conversion and power amplification, as shown in Figure 3.1. Frequency conversion (translating the modulated carrier at one frequency to a band at another frequency) requires additional carrier waveforms, produced from subsystems referred to as *frequency generators*. In this chapter these transmitter blocks are reviewed, with the primary objective of modeling their operation and understanding their inherent limitations. Later in the chapter, the effect of the propagation channel on the transmitted field is examined.

3.1 OSCILLATORS, CARRIER WAVEFORMS, AND FREQUENCY GENERATORS

A key requirement in any communication system is the generation of a pure unmodulated carrier at a fixed frequency. These sine wave tones are needed for modulation, as we saw in Chapter 2, and may also be needed for the frequency conversions shown in Figure 3.1.

Carrier tones are generated from oscillator circuits, the latter composed of active devices coupled to tuning mechanisms via some type of feedback [1], as shown in Figure 3.2. Resonances of the tuning circuits allows a sustained feedback oscillation to occur, producing an output tone at the resonant frequency. The oscillator tuning circuits commonly used are the resistance, inductance, capacitance (*RLC*) electronic or microwave circuit, the crystal quartz resonator, and the atomic resonators. *RLC* circuits are the simplest and easiest to construct and therefore are the more frequently used oscillator. However component imperfections and aging often makes it difficult to set and maintain a precise tone frequency over long time intervals. Crystal oscillators use the crystal structure itself as a resonant

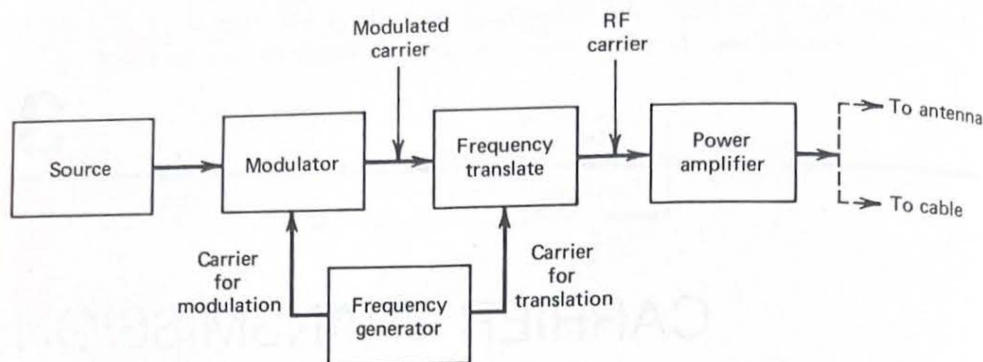


Figure 3.1. Transmitter block diagram.

circuit (or a component of a resonant circuit) to produce sharply tuned resonances and relatively stable output tones. A cut quartz crystal with properly attached electrodes acts like a high Q series—parallel electronic resonant circuit [2–5]. The frequency of the oscillation can be set by either the series resonance or the parallel resonances of the crystal. These resonant frequencies depend on the way the crystal is cut and formed and the crystal thickness. The parallel resonant frequency is usually used for oscillator frequencies below about 20 MHz, since high frequency oscillation with parallel resonance require extremely thin crystal cuts. Hence the series resonance of the crystal is usually used for the higher frequencies. Quartz crystal has a sharply tuned resonance, producing highly stable oscillators. Crystal oscillators at 5 and 10 MHz are common communication elements in modern RF systems.

The common atomic resonator is the cesium beam, which uses a stream of cesium atoms to interact with a magnetic field so as to produce an almost perfect oscillator at the specific frequency 9.152 GHz. Rubidium resonators, using light beams interacting with rubidium vapor, produce a fixed oscillation at 6.8 GHz. Atomic oscillators are often inserted as frequency mea-

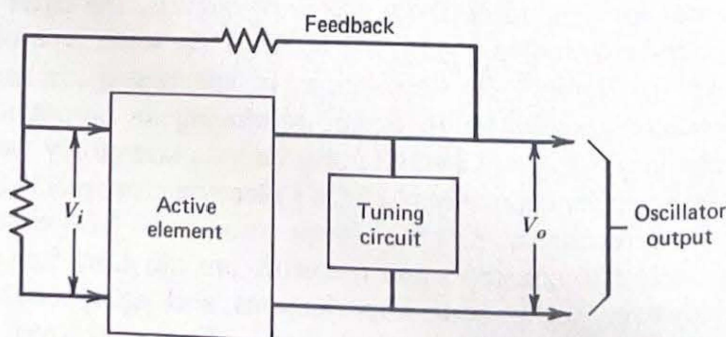


Figure 3.2. Basic oscillator system.

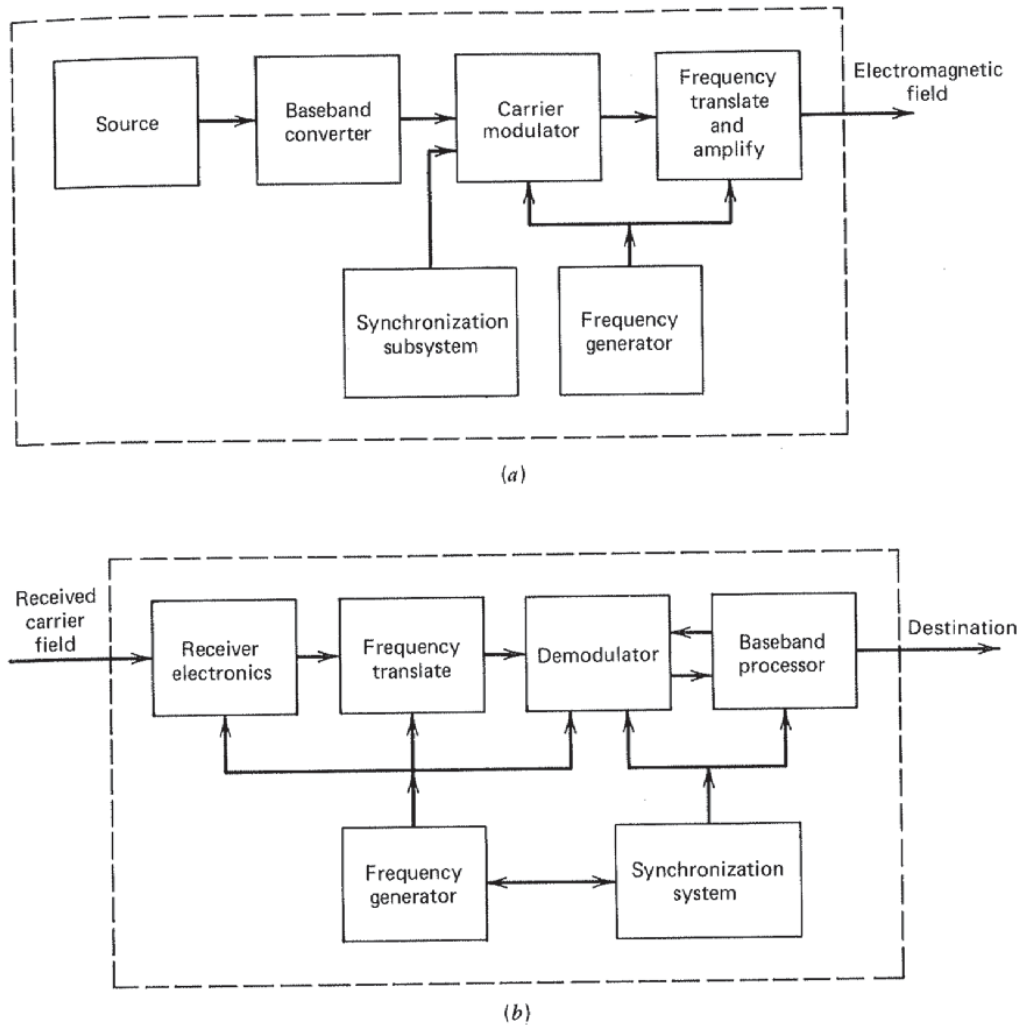


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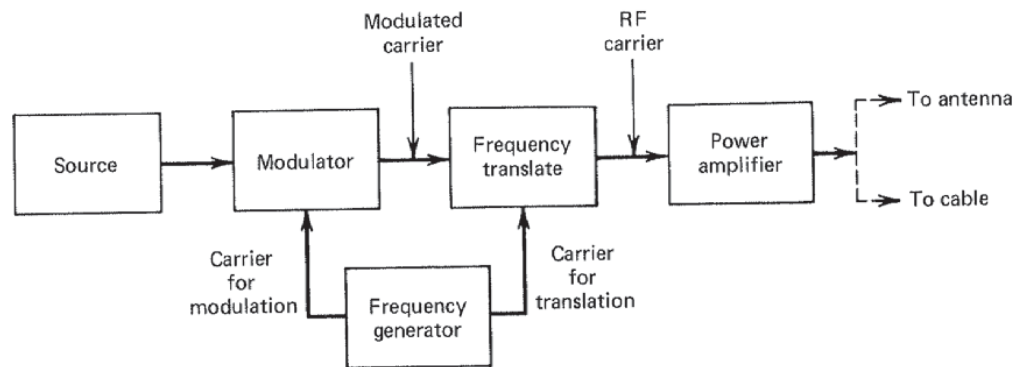


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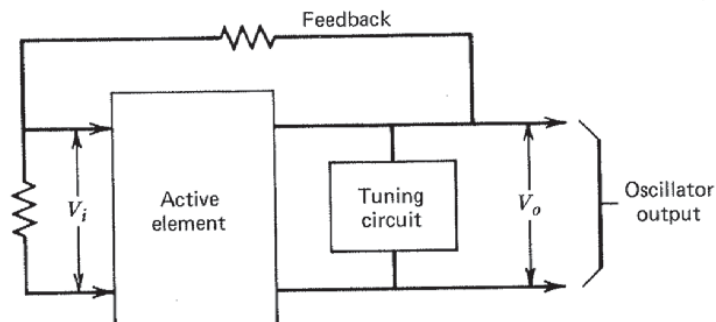


Figure 3.2. Basic oscillator system.

surement standards and are used primarily as reference tones for systems requiring extreme frequency accuracy, such as time measurement and ranging systems.

Often there is need to vary the oscillator output frequency according to an external control signal. This is achieved by using the control voltage to vary or adjust the tuning circuit parameter, resulting in an output frequency directly proportional to the control. Such devices are referred to as *voltage controlled oscillators* (VCOs). *RLC* oscillators are most often used as a VCO, since electronic elements such as resistors and capacitors are easily adjusted, and voltage control over a relatively wide frequency range is usually feasible. Voltage controlled crystal oscillators (VCXOs) can also be used, but frequency range is often limited, because of the sharp tuning of the crystal structures. Hence a VCXO is only used if the “pulling range” of the oscillator is relatively small.

An ideal oscillator produces a pure sinusoidal carrier with fixed amplitude, frequency, and phase, as we assumed in Chapters 1 and 2. Practical oscillators, however, produce carrier waveforms with parameters that may vary in time, due to temperature changes, component aging, and inherent tuning circuit noise. Amplitude variations are somewhat tolerable since they can be easily controlled with electronic clipper circuits and limiting amplifiers. More important to a communication system are the variations in frequency and phase that may appear on an oscillator output. Although preliminary system design may be based on the supposition of ideal carriers, the possibility of imperfect oscillators and the degradation they may produce must eventually be considered.

Frequency offsets in oscillators are usually specified as a fraction of the oscillator design frequency. This fraction is generally normalized by a 10^{-6} factor and stated in units of parts per million (ppm). An offset of Δf Hz in an oscillator designed for f_0 Hz output frequency will therefore be stated as having an offset of $(\Delta f/f_0)10^6$ ppm. Thus, for example, a 5 MHz oscillator, specified as having a stability of ± 2 ppm, will be expected to produce an output frequency that is within $\pm 2 \times 10^{-6} \times 5 \times 10^6 = \pm 10$ Hz of the desired 5 MHz output.

Oscillator frequency offsets are contributed primarily by frequency uncertainty (inability to exactly set the desired frequency), frequency drift (long term variations due to component changes, stated in ppm/sec), and short term, random frequency variations. The latter appears as a phase jitter on the oscillator, which effectively converts the fixed carrier phase ψ of an ideal oscillator to a randomly varying phase noise process $\psi(t)$. This phase noise typically has a spectrum that is predominantly low frequency, extending out to about several kilohertz [6–9]. This means that the phase noise process generally varies slowly relative to phase modulation waveforms, justifying the assumption that $\psi(t)$ is approximately constant over the time variations of the modulation. Since internal oscillator phase noise will add directly to any phase or frequency modulation placed on that oscillator carrier, phase

noise will always be of primary concern in angle modulated systems. The specific phase noise spectrum becomes important in phase tracking analysis and is considered again in Chapter 10. In general, *RLC* oscillators will tend to have higher phase noise than crystal oscillators, while atomic resonators have almost negligible phase noise.

Frequency generators are constructed from oscillators by multiplying a reference oscillator carrier to the desired frequencies needed throughout the transmitter. Multiplication of an oscillator carrier frequency can be achieved by straightforward generation of its harmonics via an electronic nonlinearity. The most common is a simple squaring device followed by a bandpass filter, as shown in Figure 3.3*a*. If the oscillator produces the reference tone $A \cos(\omega_0 t + \psi)$, its square is

$$[A \cos(\omega_0 t + \psi)]^2 = \frac{A^2}{2} + \frac{A^2}{2} \cos(2\omega_0 t + 2\psi) \quad (3.1.1)$$

This corresponds to a constant (dc) signal plus the second harmonic tone at $2\omega_0$. The latter is extracted by the bandpass filter centered at $2\omega_0$, producing a direct frequency doubling at the output. Higher order nonlinearities can be used, but the higher harmonics tend to be progressively reduced in amplitude. Additional amplification is then necessary to restore the desired carrier amplitude. Note that the phase is also multiplied by the same frequency multiplication factor. This means that any phase noise on the

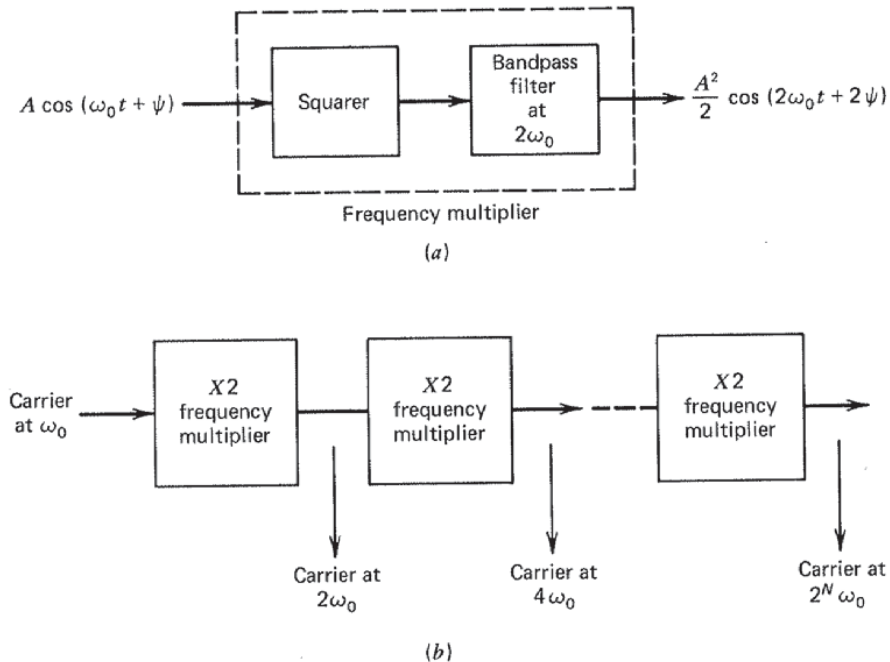


Figure 3.3. Frequency multipliers: (a) $\times 2$ multiplier, (b) multiplier chain.

input carrier will have its spectrum scaled up during frequency multiplication.

By cascading N sequential stages of a “times two” multiplier, the reference can be multiplied to $2^N \omega_0$ (Figure 3.3b). Multiplier chains of this type are commonly used in modern systems to generate multiple carrier frequencies from a single reference oscillator, as shown. Subsystems of this type, producing all the required carriers from a common source, are referred to as *master frequency generators* (MFGs).

Frequency multiplication can also be achieved by frequency synthesizers [10], as shown in Figure 3.4. These are feedback systems in which the reference oscillator is used to control the frequency of a separate VCO, via a frequency divider circuit. Divide-down counters are obtained by simple cycle counting subsystems that produce an output pulse every N input cycle zero crossings. A low pass filter then passes the first harmonic of the pulse sequence, having a frequency of $1/N$ th of the divider input frequency. If the VCO output frequency in Figure 3.4 is at f_0 Hz, then the divide-down frequency is at f_0/N Hz. A frequency comparison circuit produces an output error voltage proportional to the frequency difference between the reference carrier frequency f_r and the divider output carrier. This error voltage is then used to control the VCO frequency so as to null out the frequency difference. The loop therefore stabilizes such that $f_0/N - f_r = 0$, or at the VCO frequency

$$f_0 = Nf_r \quad (3.1.2)$$

Hence the synthesizer (VCO) output frequency is maintained at a frequency that is a direct multiplication of the input reference oscillator frequency by the divided factor N . Since divider circuits can be easily constructed with relatively high (2000–4000) factors, synthesizers can be achieved with similar multiplication factors. Furthermore, since the reference oscillator is generally selected as an extremely stable reference, the output frequency of the VCO will be maintained with a similar stability. Thus the feedback operation effectively shifts the frequency stability of the reference to the higher frequency VCO. Frequency synthesizers are becoming increasingly

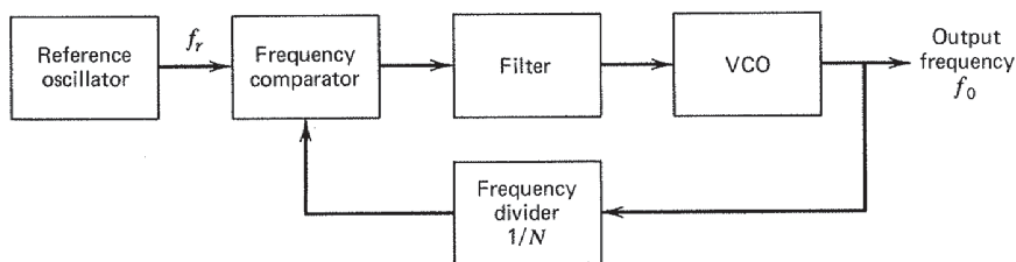


Figure 3.4. Frequency synthesizer.

important in modern high frequency systems, and entire frequency generators can be constructed by using a single reference to control a multiple set of VCO frequencies via parallel divide-down feedback loops.

There has also been rapid advancement in the development of digital frequency generators (DFG). These devices use digital software in conjunction with a stable reference oscillator to produce a subharmonic output carrier. A DFG operates by storing in memory a sequence of numerical values of one period of a sine wave. These numbers are then continually read out in sequence at a prescribed clock rate driven by the reference

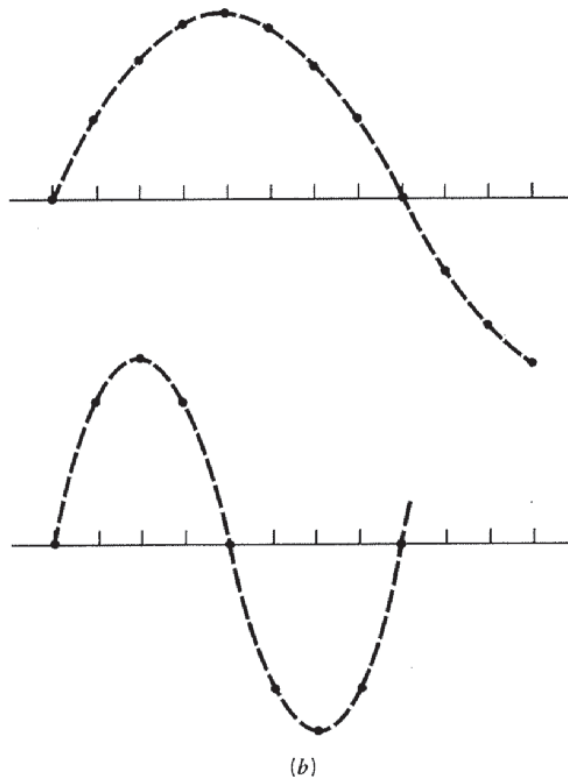
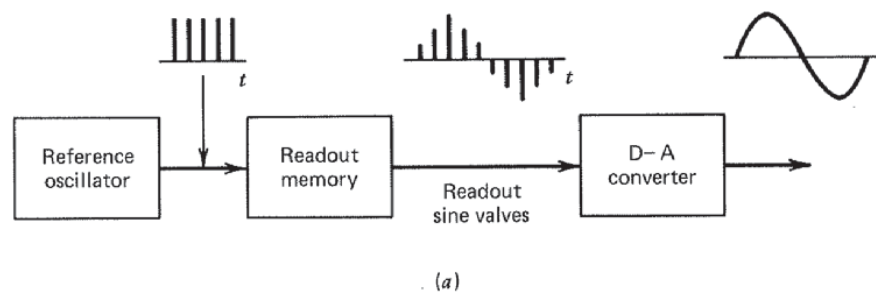


Figure 3.5. Digital frequency generator: (a) block diagram, (b) readout samples.

oscillator. This produces in series the discrete numerical values of a sine wave, which are then converted to an analog waveform by digital–analog (D-A) conversion, forming the output carrier, as shown in Figure 3.5a.

Since the sine wave values (including the zero crossings) are clocked by the reference oscillator, the output frequency contains the periodic stability of the reference, with the voltage accuracy of the stored samples. If there are M stored sine words in memory, the output frequency in Figure 3.5a will be $f_1 = f_0/M$, where f_0 is the reference frequency.

Suppose that we now alter the readout from memory by reading out every other value at the same clock rate (Figure 3.5b). We now produce a higher output frequency at $f_2 = 2f_1 = 2f_0/M$. By reading out every fourth sine wave value, the output frequency is again doubled. Continuing in this manner, the output frequency can increase to $f_0/4$ (at least four values, including zero crossings, are needed to define a sine wave). Hence a DFG is primarily used for generating low frequency, fine-resolution harmonics, with the lower limit depending only on the storage capability of the memory.

3.2 CARRIER MIXING AND UPCONVERSION

In Section 3.1 it was shown how an oscillator carrier can be frequency multiplied to form a frequency generator. Often, however, the modulated carrier itself must be frequency shifted to place it at the desired RF transmission frequency. This frequency shifting to a higher frequency band (called *upconversion*) is accomplished by a mixer circuit.

An ideal mixer (Figure 3.6a) corresponds to an electronic multiplier followed by a bandpass filter. The inputs to the multiplier are the modulated carrier and a pure carrier mixing tone provided by the frequency generator. Denote the general modulated carrier again by

$$c(t) = a(t) \cos(\omega_c t + \theta(t) + \psi) \quad (3.2.1)$$

and denote the mixing carrier by

$$l(t) = A_l \cos(\omega_l t + \psi_l) \quad (3.2.2)$$

By trigonometrically expanding the product, we see that the result of multiplying produces the sum and difference frequency terms

$$\begin{aligned} c(t)l(t) = G_m \left\{ \frac{A_l a(t)}{2} \cos[(\omega_c + \omega_l)t + \theta(t) + \psi + \psi_l] \right. \\ \left. + \frac{A_l a(t)}{2} \cos[(\omega_c - \omega_l)t + \theta(t) + \psi - \psi_l] \right\} \end{aligned} \quad (3.2.3)$$

where G_m is the multiplier gain constant. The bandpass filter eliminates the

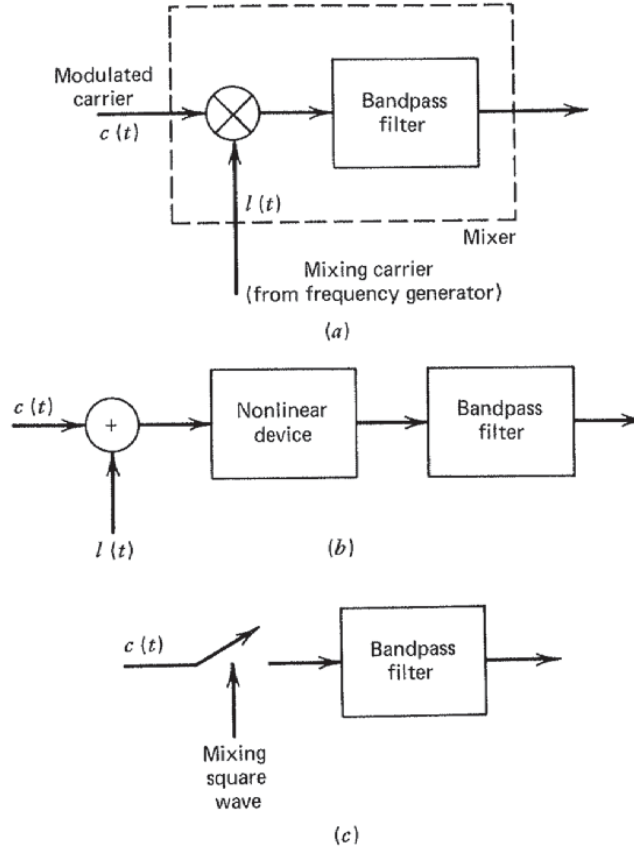


Figure 3.6. Mixer block diagrams: (a) multiplier, (b) sum-nonlinear model, (c) switching model.

difference frequency for upconversion, assuming $(\omega_c + \omega_l) \gg |(\omega_c - \omega_l)|$. The output of the mixer is then

$$c_o(t) = K_m a(t) \cos [(\omega_c + \omega_l)t + \theta(t) + \psi + \psi_l] \quad (3.2.4)$$

where $K_m = G_m A/2$. The mixer output is itself a modulated carrier, having the same amplitude and phase variation of the input carrier, but at the sum frequency $(\omega_c + \omega_l)$. The input modulated carrier therefore has been frequency translated from ω_c to $(\omega_c + \omega_l)$ while preserving its modulation. The amplitude modulation is scaled by the overall mixer gain K_m , while the angle modulation is unaffected if the mixing carrier phase ψ_l is constant. By properly selecting ω_l , the modulated carrier can be upconverted to any desired RF frequency. This is why the frequency generator subsystem, which produces the mixing carriers, plays an important role in RF transmitters. Note that the amplitude A_l of the mixing carrier in (3.2.2) is important only in setting the overall mixer gain K_m .

In practice the carrier multiplication in Figure 3.6a is accomplished by

either nonlinear or switching devices. In the nonlinear method a squaring device, as in Figure 3.3a, or a general amplifier nonlinear gain characteristic is typically used to generate the required cross product. The two carriers that are to be mixed are first summed, then the nonlinearity generates the required product term that is filtered off by the bandpass mixer filter, as shown in Figure 3.6b. A second mixing method is by switching circuitry, in which the input modulated carrier is "chopped," or gated, in time by a square wave at the carrier mixing frequency, as in Figure 3.6c. The switching or gating operation is generally accomplished with diodes, transistors, or transformers. The gating operation performs an effective multiplication of the input carrier by the gating square wave, of which the fundamental component generates the desired mixer product.

In some RF systems upconversion is accomplished via several stages of mixing. The modulated carrier is first upconverted to an intermediate frequency, then upconverted again to the desired RF frequency. This simplifies the design of the frequency generator by reducing the frequency multiplication factors it must provide.

3.3 CARRIER AMPLIFICATION

After the modulated RF carrier is generated and frequency converted, the transmitter power amplifier then must amplify the carrier signal to the desired power value for transmission, over either the antenna or cable propagation system, as was shown in Figure 3.1. We shall find that system performance invariably depends on the amount of carrier amplification that can be generated at the transmitter. Therefore, there always exists a requirement for extremely high power amplification at carrier frequencies. Furthermore, this amplification must extend over the complete bandwidth of the modulated carrier, so as not to cause carrier amplitude or phase distortion. In some transmitters there may be multiple carriers to be amplified by a single power amplifier. The power amplifier must have sufficient gain and bandwidth to properly amplify all carriers simultaneously.

Conventional electronic amplifiers are limited by parasitic capacitance and electron transit times, both tending to reduce gain at the higher carrier frequencies. For this reason, cavity amplifiers are necessary for producing higher power levels over wide, high frequency bandpass bandwidths. Such devices are physically large and usually have relatively poor amplifier *efficiency*. Efficiency is the ratio of the carrier power output to the prime power (batteries, generators, solar cells, etc.) that must be provided to operate the amplifier. The lower the efficiency, the less the carrier power for a given amount of prime power, or, conversely, the more prime power to achieve a desired carrier power. Also important is the fact that the unused prime power (one minus the efficiency times the prime power) represents power that must be dissipated as heat in some way at the transmitter. In