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HANDBOOK OF ELECTRONIC COMMUNICATION

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PREFACE

The field of electronic communications is most dynamic. This handbook provides practical and up-to-date coverage of the field for the following interest groups:

I. The engineers and technicians presently working in the field of electronic communications.
II. Specialists in the field of digital electronics who have a need to understand the basics of communications.
III. Amateur radio enthusiasts with a desire to increase their knowledge of communications theory.
IV. Students in virtually any of the many educational systems available for the study of electronics.

The questions and problems for each chapter at the end of the book are keyed to the pertinent chapter section. For example, problem 1-19-5 indicates chapter 1, the 19th problem, and section 1-5 contains the information for the problem solution. An asterisk before the question indicates a question taken from the

FCC "Study Guide and Reference Material for Commercial Radio Operator Examinations." The number following an FCC question indicates the element and question number. For example, the number 3.232 indicates that it is question 232 from element 3 of the FCC study guide. An S before the number (e.g. S3.232), indicates that the question is from the FCC supplement to the study guide. The FCC license is highly recommended to all in the field of electronics. Although certain jobs require specific types of FCC licenses, the prestige value of an FCC license is useful in getting a job, a promotion or a salary increase.

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CONTENTS

1

NOISE AND BANDWIDTH

The function of a communication system is to transfer information from one point to another by means of a communication link. The first type of "information" that was electrically transferred was the human voice, in the form of code (the Morse code), which was then converted back to words at the receiving site. Human beings had a natural desire to communicate rapidly between distant points on the earth, and that initially was the major concern of these developments. As that goal became a reality, and with the evolution of new technology following the invention of the triode vacuum tube, new and less basic applications were also realized, such as entertainment, radar, television, and telemetry. The field of communications is still a highly dynamic one, with new semiconductors and advancing technology constantly making new equipment possible or allowing improvement in old systems. Communications was the basic origin of the electronics field, and no other major branch of electronics developed until the transistor made modern digital computers a reality. We now have two major subcategories in the field of electronics: communications and digital systems. As will be seen in Chapter 8, communications plays a major role in digital systems, and vice versa.

1-1 MODULATION

Basic to the field of communications is the concept of modulation. *Modulation* is the process of impressing information onto a high-frequency carrier for transmission. In essence, then, the transmission takes place at the high frequency (the carrier), which has been modified to "carry" the lower-frequency information. The low-frequency information is often termed the *intelligence signal,* or simply the *intelligence.* It follows, then, that once this information is received, the intelligence must be removed from the high-frequency carrier, a process known as *demodulation.* At this point, you may be thinking, why bother to go through this modulation/demodulation process? Why not just transmit the information directly? The problem is that the frequency of the human voice ranges from about 20 to 4000 Hz. If everyone transmitted those frequencies directly as radio waves, interference between them would cause them all to be ineffective. Another limitation of equal importance is that it is virtually impossible to transmit such low frequencies anyway, since the required antennas for efficient propagation would have to be miles in length.

The answer to these problems is modulation, which allows propagation of the low-frequency intelligence with a high-frequency carrier. The high-frequency carriers are chosen such that only one transmitter in an area operates at the same frequency to minimize interference, and that frequency is high enough such that efficient antenna sizes are manageable. There are three basic methods of impressing low-frequency information onto a higher-frequency carrier. Equation (1-1) is the mathematical representation of a sine wave which we shall assume to be the high-frequency carrier:

$$v = V_p \sin(\omega t + \phi) \tag{1-1}$$

where v = instantaneous value

V_p = peak value

ω = angular velocity = $2\pi f$

ϕ = phase angle

Any one of the last three terms could be varied in accordance with the low-frequency information signal so as to produce a modulated signal that contains the intelligence. If the amplitude term, V_p, is the parameter varied, it is termed *amplitude modulation* (AM). If the frequency is varied, it is termed *frequency modulation* (FM); varying the phase angle, ϕ, results in *phase modulation* (PM). In subsequent chapters, we shall study these systems in detail.

1-2 COMMUNICATION SYSTEMS

Communication systems are often categorized by the frequency of the carrier. Table 1-1 provides the names for the various ranges of frequencies in the radio spectrum. The extra-high-frequency range begins at the starting point of infrared

TABLE 1-1

Radio-Frequency Spectrum

Frequency	*Designation*	*Abbreviation*
30–300 Hz	Extremely low frequency	ELF
300–3000 Hz	Voice frequency	VF
3–30 kHz	Very low frequency	VLF
30–300 kHz	Low frequency	LF
300 kHz–3 MHz	Medium frequency	MF
3–30 MHz	High frequency	HF
30–300 MHz	Very high frequency	VHF
300 MHz–3 GHz	Ultra high frequency	UHF
3–30 GHz	Super high frequency	SHF
30–300 GHz	Extra high frequency	EHF

frequencies, but the infrareds extend considerably beyond 300 GHz (300×10^9 Hz). After the infrareds in the electromagnetic spectrum (of which the radio waves are a very small portion) come light waves, ultraviolet, X-rays, gamma rays, and cosmic rays.

A communication system can be very simple but can also assume very complex proportions. Figure 1-1 represents a simple system in block diagram form. Notice that the modulated stage accepts two inputs, the carrier and the information (intelligence) signal. It produces the modulated signal, which is subsequently amplified before transmission. Transmission of the modulated signal can take place by any one of three means: antennas, waveguides, or transmission lines. The receiving unit of the system then picks up the transmitted signal but must reamplify it to compensate for attenuation that occurred during its transmission. Once suitably amplified, it is fed to the demodulator (often referred to as the *detector*), where the information signal is extracted from the high-frequency carrier. The demodulated signal (intelligence) is then fed to the power amplifier. The signal is brought to a suitably high level by the power amplifier to drive a speaker or any other output transducer (load).

There are *two basic limitations* on the performance of a communication system: (1) electrical noise, and (2) the bandwidth of frequencies allocated for the transmitted signal. The rest of this chapter is devoted to these topics.

1-3 NOISE

Electrical noise may be defined as any undesired voltages or currents that ultimately end up appearing in the load of the communications receiver (usually a speaker). To the listener, this electrical noise often manifests itself as *static*. It may only be annoying, such as an occasional burst of static, or it may be continuous and of such amplitude that the desired information is obliterated.

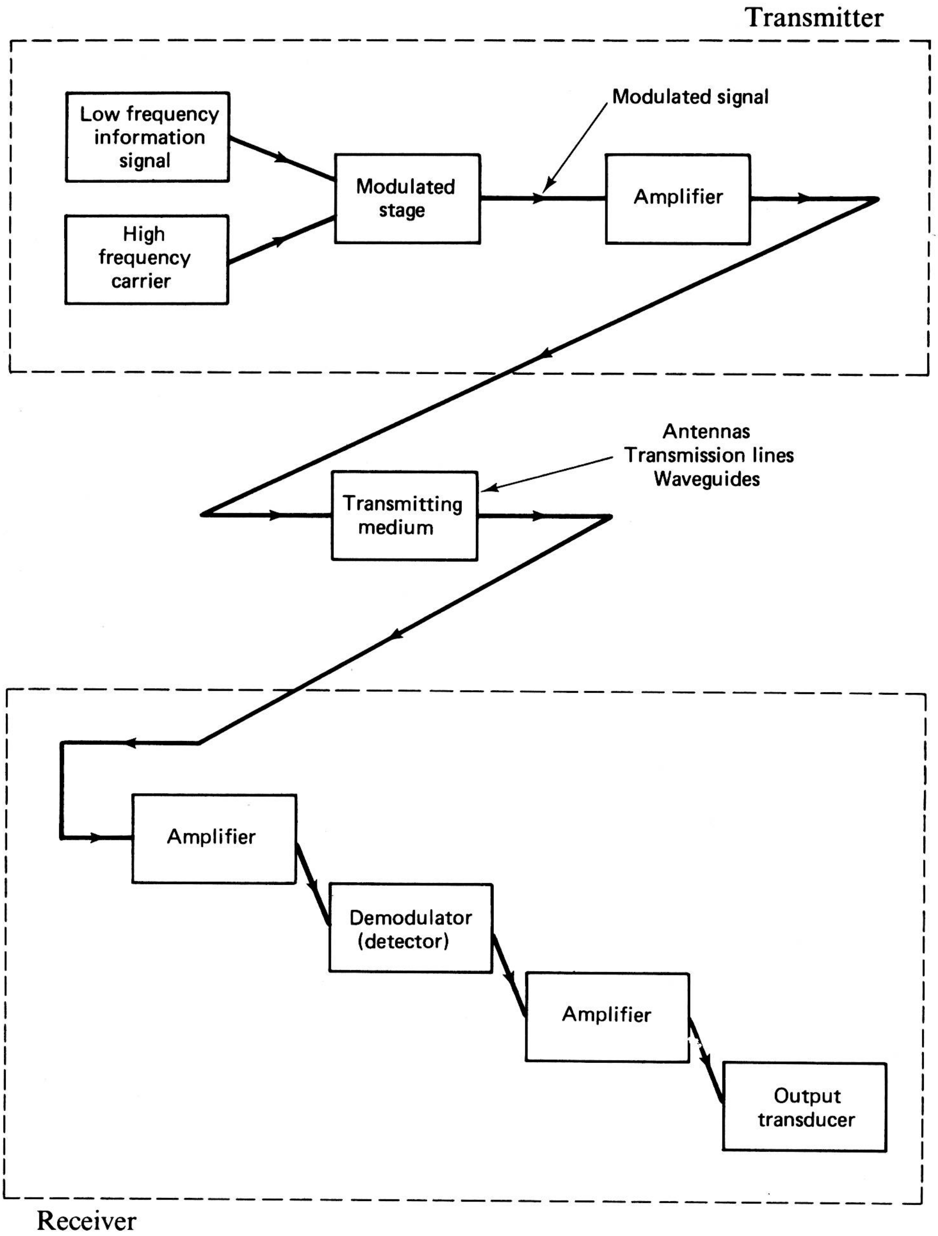

Fig. 1-1. Communication system block diagram.

Noise signals at their point of origin are generally very small—for instance, in the microvolt or millivolt level. You may be wondering, therefore, why they create so much trouble. Well, a communications receiver is a very sensitive instrument that is usually only given a very small signal at its input, which must be greatly amplified before it can drive a speaker. Consider the receiver block diagram shown in Fig. 1-1 to be representative for a standard FM radio (receiver). The first amplifier block, which forms the "front end" of the radio, is required to amplify a signal received from the radio's antenna, which is often less than 10 μV. It does not take a very large dose of undesired voltage (noise) to ruin reception. This is true even though the transmitted signal from the transmitter may be many thousands of watts, since when it reaches the receiver it is always severely attenuated. Therefore, if the desired signal received is of the same order of magnitude as the undesired noise signal, it is likely that the result will be unintelligible. This situation is made even worse by the fact that the receiver itself introduces noise in addition to the noise already present in the received signal.

The noise present in a received radio signal has been introduced in the transmitting medium and is termed *external noise.* The noise introduced by the radio receiver itself is termed *internal noise.* The important implications of noise considerations in the study of communication systems cannot be overemphasized.

External Noise

Man-made noise. The most troublesome form of external noise is usually of the man-made variety. It is often produced by spark-producing mechanisms such as engine ignition systems, fluorescent lights, and commutators in electric motors. This noise is actually *radiated* or transmitted from its generating source through the atmosphere in the same fashion that a transmitting antenna sends desirable electrical signals to a receiving antenna. If the man-made noise exists in the vicinity of the transmitted radio signal and contains some of the same frequencies, these two signals will "add" together. This is obviously an undesirable phenomenon. Man-made noise occurs randomly at frequencies up to approximately 500 MHz.

Another common source of man-made noise is contained on the power lines that supply the energy for most electronic systems. In this context, the ac ripple in a dc power supply output can be classified as noise (an unwanted electrical signal) and must be minimized in receivers that are accepting extremely small intelligence signals. The ac power lines contain surges of voltages caused by the switching on and off of heavy inductive loads such as motors. It is certainly ill-advised to operate sensitive electrical equipment in close proximity to such a load as an elevator! Since man-made noise is weakest in sparsely populated areas, this explains the locations of extremely sensitive communications equipment, such as satellite tracking stations, in desert-type locations.

Atmospheric noise. *Atmospheric noise* is caused by naturally occurring disturbances in the earth's atmosphere, lightning discharges being the most prominent contributors. Its frequency content is spread over the entire radio spectrum, but its intensity is inversely related to frequency. It is, therefore, most troublesome at the lower frequencies. It manifests itself in the static noise that you hear on standard AM radio receivers. It has the greatest intensity when a storm is in your vicinity but occurs in much greater quantity (but with less intensity) as a result of storms throughout the world. This is often apparent when listening to a distant station at night on an AM receiver. It is not a significant factor for frequencies exceeding about 20 MHz.

Space noise. The other form of external noise arrives from outer space and is therefore termed *space noise*. Space noise is pretty evenly divided in origin between the sun and all the other stars. That originating from our star (the sun) is termed *solar noise*. Solar noise is cyclical and reaches very annoying peaks every 11 years. These 11-year peaks are also cyclical, with the 1957 peak being the highest in recorded history. It was, therefore, selected by scientists around the world as the date for the International Geophysical Year, since this large increase in the sun's activity offered better opportunity to study its origin and characteristics.

All the other stars also generate this space noise, and their contribution is termed *cosmic noise*. Since they are much farther away than the sun, their individual effects are small, but they make up for this by their countless numbers and their additive effects. Space noise occurs at frequencies from about 8 MHz to over 1 GHz (10^9 Hz). While space noise contains energy at less than 8 MHz, these components are absorbed by the earth's ionosphere before they can reach the atmosphere. The ionosphere is a region above the atmosphere where free ions and electrons exist in sufficient quantity to have an appreciable effect on wave travel. It includes the area from about 60 miles up to several hundred miles above the earth.

Internal Noise

As previously stated, internal noise is that which is introduced by the receiver itself. Thus, the noise already present at the receiving antenna (external noise) has another component added to it before it reaches the receiver's output. The receiver's effective noise contribution is normally limited to its very first stage of amplification. It is there that the desired signal is at its lowest level, and noise injected at that point will be at its largest value in proportion to the intelligence signal. A glance at Fig. 1-2 should help clarify this point. Even though all following stages also introduce noise, those effects are usually negligible with respect to the very first stage because of the much higher signal level of the stages following the first one. Note that the noise injected between amplifiers 1 and 2 has not appreciably increased the noise on the desired signal, even though it is of the same magnitude as the noise injected into amplifier 1. For this reason, the very first receiver stage must be very carefully designed to have low noise characteristics, with the following stages being decreasingly important as the desired signal gets larger and larger.

Thermal noise. There are two basic types of noise generated by electronic circuits. The first is due to thermal interaction between the free electrons and

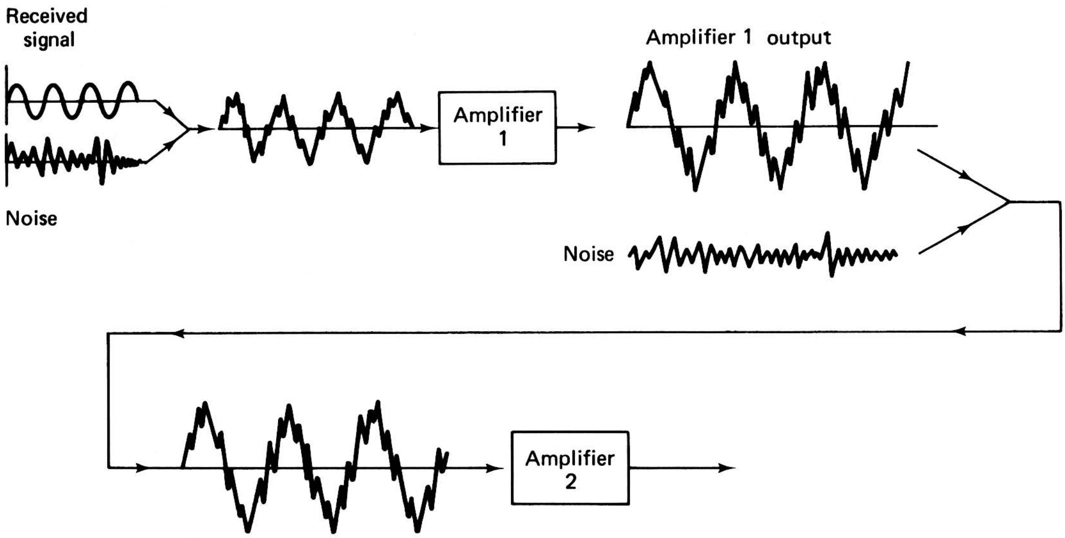

Fig. 1-2. Noise effect on a receiver's first and second amplifier stages.

vibrating ions in a conductor. Resistors are the major contributors, but noise exists within all other electrical devices. Thus, a resistor, all by itself, is constantly producing a voltage. This form of noise was first thoroughly studied by J. B. Johnson in 1928 and is often termed *Johnson noise*. Since it is dependent on temperature, it is also referred to as *thermal noise*. Its frequency content is spread equally throughout the usable spectrum, which leads to a third designator, *white noise* (from optics, where white light contains all frequencies or colors). The terms Johnson, thermal, and white noise may be used interchangeably. Johnson was able to show that the power of this generated noise is given by

$$P_{noise} = KT\,\Delta f \qquad (1\text{-}2)$$

where K = Boltzmann's constant (1.38×10^{-23}) joule/°K

T = resistor temperature (°K)

Δf = bandwidth of frequencies that the subsequent amplifier is able to amplify

Since this noise power is directly proportional to the band of frequencies involved, it is advisable to limit the bandwidth of a receiver to the smallest usable value.

Since $P = E^2/R$, it is possible to rewrite Eq. (1-2) to determine the noise voltage generated by a resistor:

$$e_{noise} = \sqrt{4kT\,\Delta f R} \qquad (1\text{-}3)$$

where e_{noise} = rms noise voltage generated

R = resistance (ohms)

The thermal noise associated with all nonresistor devices is a direct result of their