RF Systems: Fundamental Concepts

An Online Continuing Education Course for Engineers

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RF SYSTEMS: FUNDAMENTAL CONCEPTS

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What is a "system"?

A system is "a regularly interacting or interdependent group of items forming a unified whole". (Webster's New Collegiate Dictionary, G.&C. Merriam Co.) The definition applies to many fields and it is important to emphasize that an RF (radio frequency) system, like others, has a purpose or purposes which are realized by an assembly of functional devices. Each has its individual function and characteristics, and understanding those will promote an understanding of a system and how it works.

Terminology

In this area of technology, as in all others, a lexicon has developed during its evolution from rudimentary functions to today's complex devices. To the uninitiated (and sometimes to the experts), some terms seem ambiguous or misleading. The RF field may be worse than most in that regard. Uncertainties are usually resolved by the immediate context. This course will define or explain terminology where needed. Be aware that a few words and expressions are not universally defined in the ways they are commonly used in this field, and that all knowledgeable engineers do not necessarily have precisely the same definitions. Those given here are based on the author's experience and observations over the past 40 years. Any differences are rarely critical in understanding the concepts presented.

Some terms which should be understood are:

Electromagnetic wave: The energy flow in space or other medium which propagates radio frequencies. Consists of two orthogonal components, an electric field and a magnetic field.

Hertz (Hz): Basic unit of frequency; until the 1960's, called "cps" (cycles per second). Standard multiplier prefixes are used, most commonly, G (Giga), M (Mega), K (Kilo).

Wavelength (λ): The length of one cycle of a specific frequency F, most often stated in meters (m) with standard multiplier prefixes m (milli), u (micro), and n (nano). Unless identified otherwise, wavelength is free-space value.

$$\lambda = \text{velocity of light (c)} / F = 300/F(\text{MHz}) \text{ meters} \quad (1)$$

It can be stated in any other linear measurement, e.g., feet, inches.

$$\lambda = 984/F\,(\text{MHz}) \text{ feet}$$

RF (Radio Frequency): 1) Generically, any frequency capable of being transmitted by electromagnetic wave. 2) Sometimes, distinguishes the region above audio (sound) frequencies, typically above 20 KHz (but RF can actually extend to very low frequencies). 3) To those working in this field, relates to the lower range of frequencies up to a nonspecific crossover to "microwave" frequencies, generally at 1 GHz.

> **Note**: The generic definition of RF is used throughout unless stated otherwise.

Microwave: Relates to frequencies nominally 1 to 20 GHz (0.3 m to 15 mm wavelength), above RF and below the millimeter- wave frequency range.

> **Note**: In this range and above, free-space wavelength, rather than frequency, is often used as the signal definition. Amateur radio (ham) operators typically define the RF region also in wavelengths.

Millimeter-, micrometer-wave: Relates to frequencies in contiguous ranges above 20 GHz.

> **Note**: The range of radio signals extends in concept to very high frequencies, in the hundreds of GHz.

Watt (W): Basic unit of power as commonly understood, with standard multiplier prefixes. M (Mega), K (Kilo), m (milli), u (micro) are most common.

dB (decibel): Ratio of two power or power-equivalent quantities, expressed in logarithmic form, commonly used to define gain or loss (negative value) of RF devices. For device output and input power levels P2 and P1, respectively.

Gain = 10 * log(P2/P1) dB

dBx: Decibel value of a power or power-equivalent quantity relative to a reference value identified by the 'x' character. Common uses:

dBW: 'W' denotes one Watt reference. For 1 KW,
10 * log(1000/1) = 30 dBW

dBm: 'm' denotes one milliwatt (mW) reference. For 1 KW,
10 * log(1000/0.001) = 60 dBm

Fundamental System

An elementary system is illustrated in Figure 1, about as simple as it can be. In 1901, Guglielmo Marconi used devices even simpler than one might suppose to transmit a signal from England to Newfoundland, some 2000 miles. This was not the first radio transmission, but it proved that signals could be transmitted across very long distances. That ushered in the age of radio telegraphy, followed eventually by modern RF technology.

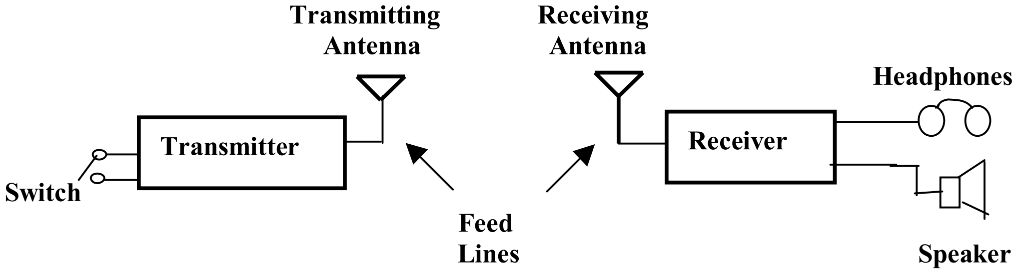

Figure 1: Simplified System Diagram

The major functional elements of a system are:

> Transmitter - Generates the RF signal at the desired frequency with sufficient power for the application; contains a means of applying intelligence to the signal.
> Transmitting antenna - Radiates the electrical signal into space as an electromagnetic (EM) wave.
> Feed line - the signal link between an electronic component and an antenna.
> Receiving antenna - Intercepts a portion of the EM wave and converts it back to an electrical signal.
> Receiver - Amplifies the signal to a useful level, recovers the intelligence, and provides output functions according to the system purpose.

Marconi's "transmitter" was a high-voltage source which caused an electrical arc between two electrodes when the switch was closed. Such an arc creates a broad spectrum of frequency components, which were radiated as electromagnetic waves by a set of vertical wires suspended vertically above the ground. ("Spark-gap" transmitters are illegal now, since they cause widespread radio interference.) A similar receiving wire antenna intercepted a tiny portion of the wave, converting it back to an electrical signal. A device called a "coherer", acting as a "detector", changed the alternating-current signal to direct-current, just large enough to cause an indication. As the transmitting switch was repeatedly actuated in England, corresponding indications were received in Newfoundland. With certain patterns of on-off switching, i.e., code, to create intelligent communication, radio telegraphy was achieved.

Transmitter

Modern transmitters are not so simple. A small device may have a single transistor which oscillates in conjunction with a small printed-circuit loop used to set the frequency. The loop radiates the signal to a nearby receiver. In large systems, the transmitter is a complex assembly of many components which generate frequencies, apply modulation, and amplify the primary signal to a high level of output power, often many KW. Other devices oscillate as well as generate high power, like the magnetron in a microwave oven supplying 600 W of RF power for cooking. Megawatts of power are produced in sophisticated systems.

Modulation, Frequency Spectrum, and Bandwidth

If the transmitted signal had been left on continuously, Marconi's demonstration would have been astounding but not worth much. No information would have been conveyed. By switching the signal on and off, any amount of information could be conveyed in coded form given enough time. That is the most basic form of modulation, the process of imposing intelligence onto an RF wave. Ham operators refer to such transmission as CW, meaning "continuous wave" but implying that it is switched on and off (keyed"), according to a defined criteria such as Morse code. The RF signal which is modulated and carries the modulation in transmission is called the "carrier" or "carrier frequency", Fc.

Many types of modulation have evolved, the most basic types being the following:

> AM (amplitude modulation): Varies the amplitude of the carrier, typically in a linear fashion corresponding to the modulating waveform, to carry sound frequencies for voice transmission, for example.
>
> Pulse modulation: Switches the carrier on and off (or between high and low power levels), carrying coded signals for information transfer or short pulses for range-delay reflection measurements in radar systems.
>
> Frequency (FM) or Phase (PM) modulation: Shifts the frequency or phase of the carrier signal, either linearly or in steps. These use different implementation techniques but are directly related mathematically.

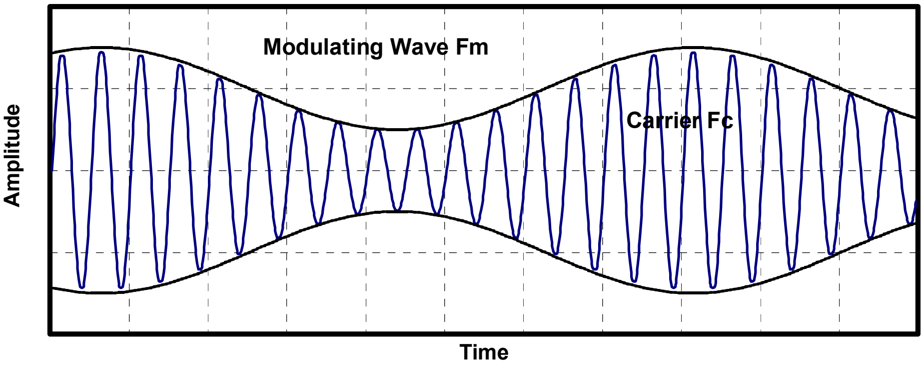

Figure 2: Amplitude-Modulated (AM) Signal Waveform

Figure 2 illustrates the waveform of a carrier signal Fc amplitude-modulated by a lower-frequency sine wave Fm. Numerous variations and combinations of modulations are used.

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A signal has a corresponding set of frequency components, its <u>RF spectrum</u> characteristic - the Fourier transform of its time-based waveform. On a spectrum analyzer, the modulating sine wave Fm and a carrier Fc each would appear, before modulation, as a single frequency line, the modulating signal typically much lower in frequency than the carrier. With AM, the carrier acquires two sidebands, above and below its frequency and spaced from the carrier frequency by the frequency of the modulating signal, i.e., Fc + Fm and Fc - Fm. Such a spectrum is illustrated in Figure 3.
The carrier may be suppressed, i.e., reduced in amplitude well bel ideband
amplitude. In another variation, both the carrier an ill be
suppressed, leaving only the upp gle-sideband
modulation (SS c. A sideband
a

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Anten

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antennas coined by a frustrated trouble-shooter trying to
locate a s radiation.

An antenna may be described by shape, size, construction, directional characteristics, similarity to other objects, frequency range, bandwidth, name of its inventor(s), and other, sometimes very imaginative, terms. They range in size from very small antennas in handheld devices (GPS receivers, remote door locks) to large TV satellite 7-foot dishes (the older ones), to a 1000-foot diameter dish used for radio astronomy, built into a mountain-top depression in Puerto Rico and pointing into space.