



Basic Concepts

RF Basics

The technology involving the generation, the manipulation, the transmission and the reception of radio waves, and the use of these to transmit information (both in analog and digital way), is called RF technology or, nowadays, *wireless* technology. The literal meaning of RF is *Radio Frequency*, but this term is often use in the figurative sense of “anything related to electromagnetic signals”.

An electromagnetic or RF signal is a controlled variation of electrical energy over time. The simplest example of such a variation is when the intensity of the electric field grows to some maximum, then goes back to zero, becoming negative and reaching some minimum value, before returning back to zero and then starting the process again, following the shape of the trigonometric function called *sine*. The *sine wave* is the basic example of a signal that can be generated, transmitted and received with RF equipment. It may be characterized by its *frequency* and its *amplitude*:

- the frequency is the number of times a signal goes through a complete “up and down” cycle in one second of time, and is measured in *Hertz* (being 1 Hz the frequency of a signal that makes a complete cycle every second);
- the amplitude of a signal is the difference between its maximum and its minimum value during one cycle. It is measured with the same unit used for the intensity of the electric field, the *Volt* (V), and is related with the strength, or power, of the signal.

The units used to measure frequency and amplitude may become inadequate when the numeric values of such quantities become very small or very big, so that a different notation is needed, called the scientific notation, that use the powers of ten to multiply the values. It gives also standard names to the many prefixes associated with these multiplying factors.



Some are listed here:

milli (m)	1/1000	10 to the power of -3	ex.: 1 mV
micro (μ)	1/1000000	10 to the power of -6	ex.: 1 μ V
kilo (k)	1000	10 to the power of 3	ex.: 1 kHz
Mega (M)	1 million	10 to the power of 6	ex.: 1 MHz
Giga (G)	1 billion	10 to the power of 9	ex.: 1 GHz

Frequency, bands and bandwidth

The concept of frequency is the key to understanding RF, because almost everything in the RF world is frequency-dependent. Signals can be distinguished on the basis of their different frequencies, and RF devices are almost always characterized by the range of frequencies they can generate, measure or handle.

The range of frequencies used is also the most common way to distinguish one wireless application from another. This is achieved using the concept of *frequency band*, that is a standard way to name a specific range of frequencies. A list of RF bands of common use is given here:

HF	High Frequency	3 MHz - 30 MHz
VHF	Very High Frequency	30 MHz - 300 MHz
UHF	Ultra High Frequency	300 MHz - 3 GHz
SHF	Super High Frequency	3 GHz - 30 GHz
EHF	Extra High Frequency	30 GHz - 300 GHz

While for the microwave range a more detailed band list is this one:

L band	1GHz - 2 GHz
S band	2GHz - 4GHz
C band	4GHz - 8GHz
X band	8GHz - 12GHz
Ku band	12GHz - 18GHz
K band	18GHz - 27GHz
Ka band	27GHz - 40GHz



The bands we are mostly interested in for this handbook are the ISM (Industrial, Scientific and Medical) radio bands, that were originally reserved internationally for non-commercial use of RF electromagnetic fields for industrial, scientific and medical purposes. The ISM bands are defined by the ITU-T in S5.138 and S5.150 of the Radio Regulations and are used for license-free error-tolerant digital communications applications such as wireless LANs and Bluetooth:

“900MHz” ISM band	902MHz - 928MHz (Americas only)
“2.4GHz” ISM band	2400MHz - 2483.5MHz
“5GHz” ISM band	5725MHz - 5875MHz

Many other RF bands and possible classifications and definitions exist, that we will not consider here.

Together with the concept of frequency, there is another useful one: the *bandwidth*. While in the telecommunications world the term bandwidth has a general meaning of how much information can be carried in a given period of time (usually a second) over a wired or wireless communications link, in the RF world the bandwidth is the width of the range of frequencies that an electronic signal occupies on a given transmission medium. Any RF signal has a bandwidth, expressed in terms of the difference between the highest-frequency signal component and the lowest-frequency signal component. A typical voice transmission like a phone call has a bandwidth of approximately 3 kHz; a stereo musical signal like a FM radio broadcast has a bandwidth of 200 KHz; an analog television (TV) broadcast video signal has a bandwidth of 6 MHz.



Wavelength

The wavelength is the distance a radio wave will travel during one cycle. The formula which relates the wavelength to the frequency is the following:

$$\lambda = \frac{c}{f}$$

where λ is the wavelength, expressed in meters , c is the speed of light, which is exactly 299793,07 meters/second, and f is the frequency. Following is a table with the wavelength for different ISM frequencies:

Frequency	Wavelength
900 MHz	0.33 m
2.4 GHz	0.125 m
5.0 GHz	0.06 m

The speed of propagation at a certain frequency in a coaxial cable is slower than in air, so the wavelength is shorter. The velocity of propagation of electromagnetic waves in coaxial cables is usually given as a percentage of the free space velocity, and it is different for different types of coaxial cables, and is called Velocity Factor (VF).

Amplitude and power

The amplitude of an RF signal, measured in Volts, is not of common use in the RF world, while the related concept of *power* of a signal is much more used and useful.

The power of a constant low-frequency signal is measured in *Watts*, symbolized by W , and is the product of the amplitude (or voltage, measured in Volts) and the current (measured in Amperes). One watt is also the power resulting from an energy dissipation, conversion, or storage process equivalent to one Joule per second. At high frequencies, in which energy is stored and released (as well as dissipated or converted), the relation between power, amplitude and current is more complex.



In a DC circuit, a source of E volts, delivering I Amperes, produces P Watts according to the formula:

$$P = EI$$

When a current of I Amperes (A) passes through a *resistance* of R Ohms (Ω), then the power in Watts dissipated or converted by that component is given by:

$$P = I^2R$$

When a potential difference of E Volts appears across a component having a resistance of R Ohms, then the power in Watts dissipated or converted by that component is given by:

$$P = E^2/R$$

In a DC circuit, power is a scalar (one-dimensional) quantity. In the general RF case, the determination of power requires two dimensions, because RF power is a vector quantity. Assuming there is no reactance (opposition to RF but not to DC) in an RF circuit, the power can be calculated according to the above formulas for DC, using root-mean-square values for the alternating current and voltage. If reactance exists, some power is alternately stored and released by the system. This is called apparent power or reactive power. The resistance dissipates power as heat or converts it to some other tangible form; this is called true power. The vector combination of reactance and resistance is known as impedance.

Decibels and dB math

The *decibel* (abbreviated as *dB*) is a logarithmic expression of the ratio between the power, voltage, or current of two signals. A decibel is one-tenth of a Bel, a seldom-used unit named for Alexander Graham Bell.



Suppose a signal has a power of P_1 watts, and a second signal has a power of P_2 watts. Then the power ratio in decibels, symbolized P_{dB} , is:

$$P_{dB} = 10 \log_{10} (P_2 / P_1)$$

Decibels can also be calculated in terms of the effective voltage if the load impedance remains constant. Suppose a signal has an RMS (root-mean-square) voltage of V_1 across a load, and a second signal has an RMS voltage of V_2 across another load having the same impedance. Then the voltage amplitude difference in decibels, symbolized V_{dB} , is:

$$V_{dB} = 20 \log_{10} (V_2 / V_1)$$

When a decibel figure is positive, then the second signal is stronger than the first signal and the power ratio is called *gain*. When a decibel figure is negative, then the second signal is weaker than the first signal and the power ratio is called *loss*. In amplifiers, the gain, also called the amplification factor, is often expressed in decibels.

For example, if a signal at the output of an amplifier is 100 times bigger than the signal at its input, the amplifier has a gain of 100 or, using the definition of decibel, of 20 dB. Some useful values to remember are:

- +3 dB means two times bigger
- +10 dB means ten times bigger
- 3 dB means one half
- 10 dB means one tenth

To express power using decibels we need a specific power to be assumed as a reference. In the RF world the common standard is to refer powers to 1 mW (0.001 Watts). Such power ratio, expressed in decibels, is called dBm. Following the definition of dB, we have:

$$P_{dBm} = 10 \log_{10} (P_{\text{Watts}} / 1 \text{ mW})$$



A table of correspondence between Watts and dBm is given here:

1 μ W	=	-30 dBm
10 μ W	=	-20 dBm
100 μ W	=	-10 dBm
1 mW	=	0 dBm
10 mW	=	10 dBm
100 mW	=	20 dBm
1 W	=	30 dBm
10 W	=	40 dBm
100 W	=	50 dBm

The advantage of using decibels instead of Watts to express the power of a signal along an *RF chain* (a chain composed by RF devices like transmitters, receivers, cables, amplifiers, attenuators, measurement instruments, loads, etc.) is that instead of dividing or multiplying powers to take care of amplifications and attenuations, we just add or subtract the gains and the losses expressed in decibels. An example follows:



Using amplification and attenuation factors and expressing the powers in Watts, we obtain the value of the power at the receiver's input in this way:

$$P_{\text{Receiver}} = P_{\text{Transmitter}} \times \frac{1}{\text{Attenuation}_{\text{Cable1}}} \times \text{Amplification} \times \frac{1}{\text{Attenuation}_{\text{Cable2}}}$$

If we use dB to express the gains and the losses and dBm to express the powers, the calculation becomes a simple addition:

$$P_{\text{Receiver}} = P_{\text{Transmitter}} + \text{Loss}_{\text{Cable1}} + \text{Gain}_{\text{Amplifier}} + \text{Loss}_{\text{Cable2}}$$

The procedure of adding gains and losses to obtain the resulting power for an RF chain is very common and is called *Power Budget Calculation*.