RF Basics - Part 1

This is the first article in the multi-part series on RF Basics. We start the series by reviewing some basic RF concepts: Decibels (dB), Antenna Gain, Free-space RF Propagation, RF Attenuation, Noise, Signal-to-Noise Ratio (SNR), Receive Sensitivity and Link Budget Analysis. Throughout this series, the terms 2.4 GHz and 5 GHz refer to the 2.4 - 2.4835 GHz and 5.15 - 5.85 GHz bands respectively.

Demystifying the dB

The term dB is an abbreviation of decibel, which is equal to 1/10th of a **Bel** (named after Alexander Graham Bell). The unit Bel, used to represent very small quantities, is a *logarithmic* measure of the *ratio* between two quantities. The dB is used to represent a variety of parameters in engineering fields varying from acoustics to electronics.

Specifically, power in dB is represented by the following equation, where P_0 is the power reference:

$$P_{dB} = 10 \ \log_{10} \frac{P}{P_0}$$

The unit dB can also be used to represent an *absolute* power value, by defining a reference and adding the corresponding suffix to dB. For example, dBm stands for dB with reference to 1 milliwatt (mW). In the above equation, dB can be replaced by dBm when P_0 is set to 1 mW. Therefore, 1 mW of power is equal to 0 dBm (=$10 \ \log_{10} 1$). Similarly, the gain of an antenna is specified in dBi or dBd (more on this in next section). The following table shows some mW values and their equivalent dBm values.

Table 1: Milliwatts to dBm Conversion

mW	**0.00001**	**0.0001**	**0.001**	**0.01**	**0.1**	**1**	**2**	**10**	**100**	**200**	**400**	**1000**
dBm	-50	-40	-30	-20	-10	0	3	10	20	23	26	30

Since [$10 \ \log_{10} 2$] is ~3.01, adding 3 dB to an absolute power value in dBm is equivalent to doubling the power in milliwatts and subtracting 3 dB is equivalent to halving the power and so on. The transmit power of wireless devices are specified in either mW (or Watts for high power transmitters) or dBm.

Antenna Gain

The gain of an antenna is specified in dBi, which is the power gain of the antenna compared to an *isotropic* antenna. An isotropic antenna is an ideal (theoretical) antenna that spreads energy in all directions (in a sphere) with equal power, which is impossible to design in practice. Some antennas may have their gains expressed in dBd (though less

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common), which is the power gain of the antenna compared to a *dipole* antenna. The dBd value can be converted to dBi, using the formula 0 dBd = 2.15dBi.

Antennas are typically connected to a radio through a cable and one or more connectors, depending on whether the antennas are integral or external. Some antenna configurations may also use internal switches to connect multiple antennas (e.g., a 2.4 GHz and a 5 GHz antenna or an integral and an external antenna or two diversity antennas) to the same radio. All cables, connectors and switches incur RF loss, where the cable loss is typically specified in dB per 100 feet.

Free-space RF Propagation

The RF signals emitted by an antenna go through significant attenuation, even in free space (i.e., no obstructions between the transmitter and the receiver), before they reach the intended recipient. The free-space propagation loss in dB is given by the formula:

$$L_p = 32.4 + 20 \log_{10} f + 10n \log_{10} d$$

The frequency of transmission f is specified in MHz and the distance d is specified in kilometers. Tthe higher the transmission frequency, the higher the propagation loss is for the same distance.

The parameter n is known as the path loss exponent (indicating how fast the signal attenuates with distance), whose value is 2 for free-space communication. In non-line-of-sight communication, many other factors such as attenuation due to absorption, reflections and multipath come into this equation. If the types of material and the exact amount of the attenuation are known, these losses may be added to the propagation loss formula to calculate the actual loss. In a mixed environment, such as an indoor office environment, a different path loss exponent value may be used instead to approximate the path loss. For example, a value of 2.5 to 4 may be typical of most indoor environments, though the path loss exponent can be as high as 8 in some RF unfriendly environments.

For example, the free-space loss for 2.4 GHz at 100 meters from the transmitter is about 80 dB. If the radiated power is 30 dB (=1000 mW or 1 W), the received signal at 100 meters will be -50 dB, which is equal to 0.00001 mW. Therefore, in 100 meters, the RF signal loses 99.99999% of the power! This explains why dB units are used to represent RF power values, saving us the trouble of remembering the number of zeros in 0.00001 mW.

RF Attenuation

In practice, a radio signal may encounter many objects in its transmission path and undergoes additional attenuation depending on the absorption characteristics of the objects. There are many types of objects, including fixed, mobile and transient objects that absorb RF energy and cause RF attenuation. Similar to the free-space propagation loss, higher frequencies attenuate much faster than lower frequencies. Therefore, 5 GHz RF signals typically have higher attenuation than 2.4 GHz, though there are a few exceptions.

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The following table shows the loss (or attenuation in dB) introduced by various objects. Most of the attenuation numbers are given as a range, as the actual value depends on the exact frequency on transmission and the thickness as well as specific type of material used. Moreover, the numbers measured at different locations do not always agree, as the measurement conditions may be different. In particular, the attenuation numbers for concrete walls are the most controversial. This is due to the fact that there are different types of concrete materials in use in different parts of the world and the thickness and coating differ depending on whether it is used in floors or interior or exterior walls. Brick walls usually have attenuation at the lower end of the range shown in the table.

Table 2: Common objects and corresponding attenuation in dB

	2.4 GHz	5 GHz
Interior drywall	3-4	3-5
Cubicle Wall	2-5	4-9
Wooden Door (Hollow - Solid)	3-4	6-7
Brick/Concrete Wall	6 -18	10 - 30
Glass Window (Not tinted)	2-3	6-8
Double Pane Coated Glass	13	20
Bullet Proof Glass	10	20
Steel/Fire Exit Door	13-19	25-32

While trees are good for the environment, they have significant impact on RF propagation. The attenuation caused by trees varies significantly depending on the shape and thickness of the foliage. The rule of thumb is about 1.2 dB of attenuation per meter for 5 GHz and about 0.5 dB per meter for 2.4 GHz. Another major source of attenuation is water, though it is not at all a good idea to have RF links pass through water, unless of course it is absolutely required. In one of the experiments with three one-gallon water bottles placed in a triangle, the 2.4 GHz signals attenuated about 4 dB whereas the 5 GHz signals attenuated over 14 dB. However, rain, snow and fog attenuations are very small for frequencies under 10 GHz. The rain attenuation at 5 GHz is barely noticeable (< 1 dB per kilometer).

Human bodies, made of about 70% water, also attenuate RF signals. The attenuation caused by a human body in 2.4 GHz is about 3dB and in 5 GHz is about 5 dB. This especially makes it quite challenging to design dense wireless networks for crowded facilities.

Noise

The noise at the radio receiver consists of the Thermal Noise and the Noise Figure of the Receiver. The Thermal Noise at room temperature is a known quantity, -174 dBm/Hz. Since 802.11 operates on 20 MHz channels, the Thermal Noise Floor at room temperature is -174 dBm + 73 dB [$10 \ \log_{10}(20\,MHz)$] = -101 dBm. The typical Noise Figure of an 802.11 receiver varies from 4 dB to 10 dB. The Noise Figure of the receiver

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depends on the type and quality of the components used in the design (e.g., amplifiers). Based on these numbers, the typical minimum Noise Floor of an 802.11 device is in the range of -97 dBm to -91 dBm. The IEEE 802.11a standard specifies that the Noise Figure due to components, design and implementation be kept at or below 15 dB, thereby requiring a minimum Noise Floor of – 86 dBm.

Introduction of additional thermal noise or components with higher noise figures would alter the noise floor of the receiver. In addition, Noise Floor may also be affected by certain types of interference sources, though not all interference types result in increased noise floor. We will cover the interference topics in a later article. Since noise floor of a receiver may be affected by a variety of factors and may change with the operating environment, an 802.11 wireless device typically recalibrates the Noise Floor at periodic intervals (e.g., every 30 or 60 seconds). This is especially useful for client devices, where the noise floor may vary depending on the noise introduced by components used in the computer or client device. Since a client may be mobile, the external sources of noise from the environment may also change over time. It is also a good practice to periodically recalibrate the fixed wireless devices (e.g. Access Points), as the Noise Floor may change over time due to external or thermal factors.

Signal-to-Noise Ratio (SNR)

The signal to noise ratio is the ratio of the signal strength (dBm) at the receiver to the noise (dBm) floor. Since dBm is in logarithmic scale, SNR is obtained by subtracting the noise from the signal strength. The minimum required SNR for a receiver varies depending on the bit rate or modulation. The design of the receiver also plays a role in the minimum required SNR for a specific bit rate. A positive SNR is required (i.e., signal strength should be a higher than the noise) for reliable detection of a radio signal.

The typical minimum SNR requirements for 802.11 are shown in the table below. The theoretical minimum SNR values for specific modulations shown in the table are usually lower, however in practice the SNR values are closer to the values given in the table. A minimum of about 4 dB SNR (± 2 dB depending on the design) is required for any reliable 802.11 communication (at 1 Mbps or 6 Mbps).

Table 3: Typical minimum required SNR for proper detection of 802.11 rates

Rate	1	2	5.5	11	6	9	12	18	24	36	48	54
SNR	4	6	8	10	4	5	7	9	12	16	20	21

Receive Sensitivity

The receive sensitivity of a receiver is the minimum power required at the receiver for reliable detection. In other words, the Rx sensitivity indicates the weakest signal the receiver can reliably decode. Similar to the SNR, the Rx sensitivity very much depends on the modulation and the bit rate. The design of the radio also plays a role in the Rx sensitivity, as some radios may have better (lower) Rx sensitivity than others for the same bit rate. The typical Rx sensitivity values for 802.11 vary from -91 (±3) dBm at 1 Mbps to -67 (±4) dBm at 54 Mbps. The lower the Rx sensitivity, the better the radio is. It

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should be noted that the Rx sensitivity alone is not a good indication of the weakest signal that can be reliably decoded. If the SNR is not sufficient due to higher noise floor, the system may be limited by the noise floor rather than the Rx sensitivity.

Link Budget Analysis

Since each bit rate requires a specific receive sensitivity for a given radio, any wireless network (simply referred to as link for the purpose of this discussion) design must estimate the available link budget in dB to make sure that that the link budget is at least 0 dB for the highest bit rate desired. It is also a good practice to leave some reasonable margin (e.g., 10 dB) in the link budget to accommodate any variations in signal strength caused by interferers or reflectors and to increase the reliability of the link. The link budget analysis can be used to estimate the range or capacity or to select an antenna.

The first step in the calculation of the link budget is to calculate the received power at the receiver.

The Received Power is given as:

Received Power = Radiated Power/EIRP – Path Loss + Receiver Gain

The radiated power (EIRP or Effective Isotropic Radiated Power is the correct technical term) in dBm is given as:

EIRP (dBm) = Radio Transmit Power (dBm) – Cable/Connector/Switch Loss (dB) at Transmitter + Transmit Antenna Gain (dBi)

The Path Loss can be calculated using the appropriate path loss exponent, as discussed earlier, and may include attenuations caused by other objects in the path, if known. The Receiver Gain is given as:

Receiver Gain = Receive Antenna Gain (dBi) - Cable/Connector/Switch Loss (dB) at Receiver

One important point to note here is that the antenna gain is *reciprocal*, i.e., the antenna gain can be added to the wireless device at either end to increase the overall link budget. For example, a wireless system with a 10 dBi antenna on the transmitter and a 2 dBi antenna on the receiver will have the same range as a system with a 4 dBi antenna the transmitter and an 8 dBi antenna on the receiver, everything else being equal. Therefore, adding a high gain antenna allows a device not only to transmit signals farther, but also to receive weaker signals.

Once the received power (or signal strength) is known, the link budget can be calculated by subtracting the receive sensitivity of the receiver from the received power, i.e.,

Link Budget = Received Power – Receive Sensitivity

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The Noise Floor at the receiver can be subtracted from the received power to calculate the SNR. If the noise is lower than the Rx sensitivity, the link will be limited by the Rx sensitivity. Otherwise, the link will be limited by the Noise Floor.

For example, with 30 dB EIRP (e.g., 23 dBm Transmit Power, 10 dBi antenna gain and 3 dB cable/connector loss) in 2.4 GHz, the signal attenuates to -50 dBm at 100 meters in free space. For a receiver with Receive Gain of 0 dB (e.g., 2 dBi Receiver antenna and 2 dB cable/connector loss), the received power is -50 dBm. If the receive sensitivity is -91 dBm for 1 Mbps, then the link margin is 41 dB. However, if the Noise Floor is -85 dBm, then the SNR is 35 dB. In either case, the signal is more than enough to decode 1 Mbps. However, as the distance increases the Noise Floor will be the limiting factor in this specific example.

The choice of an antenna and transmit power are dictated by the specific requirements of the wireless system. For example, in order to create symmetric links (i.e., each end of the wireless link can talk to the other end with same bit rate at the same reliability), the transmit power at both ends should be kept the same, assuming the RX sensitivity and Noise Floor are identical at both ends. The range of the system for such symmetric networks should be increased by selecting the appropriate antennas on both ends, rather than increasing the transmit power at one end (which increases the range in only one direction). It is also important to calculate the link budget in both directions separately to make sure that the bidirectional system requirements are met, given the system parameters in each direction.

In the next article in this series, we will discuss details of the antenna types, antenna parameters, antenna propagation characteristics and antenna diversity.

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