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The first step to RF Engineer's link budget

From the early days of humans making sounds to communicate, later using words, and sentences, and fast forward to 100 years back with Marconi's telegraphy to today's mobile phones. Wireless communication has always been challenging because the medium of propagation, *the* ***air*** is a non-deterministic, time-varying, boundaryless *free space* over which the signal propagates from transmitter to receiver.

While *free space* is called so, the space between transmitter and receiver is not free and comprises air, water molecules, trees, buildings, and so on.
Additionally, the biggest challenge which makes the medium also called a *wireless channel* unreliable is mobility. The users are moving and this makes the channel highly random and unpredictable. Statistical methods can be used to create mathematical models of such wireless channels.

The signal traveling on the wireless channel is called ***electromagnetic (EM) waves***, unlike audio waves which are what humans communicate with.
Electromagnetic waves have the freedom to move around anywhere once they leave the transmitter but the method through which they reach the receiver can be broadly categorized in 2 ways:

- Line of Sight (LOS)
- Non-Line of Sight (NLOS)

In LOS, both the transmitter and receiver antennas can see each other despite the distance separating them. Common examples are global positioning system (GPS) and satellite TV like Airtel direct-to-home (DTH) systems.

In NLOS, the transmitter and receiver antennas do not have a direct view of each other. Popular example is mobile phone communication.

The focus of this article is on free-space propagation which pertains to LOS communication.
Below is the equation which is based on the Friis transmission formula to calculate received power when the transmitter and receiver are not co-located.

FIGURE-1: Friss Free-space Equation

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi d)^2 \cdot L}$$

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The metric to consider is ***received power (P_r)*** which is on the left-hand side of the equation.

The parameters on the numerator are *supporting* factors for the communication to happen and the parameters on the denominator are the factors *opposing* communication.

The received power at the receiver is aided by transmit power (**P_t**) the transmit antenna gain (**G_t**), receive antenna gain (**G_r**), and wavelength (**λ**) of operation.
The received power is limited by distance (**d**) between the transmitter and receiver. The received power is also reduced due to system hardware losses (**L**).

In the numerator, it is easy to comprehend that transmit power is the supporting factor along with transmitter and receiver antenna gains. For these 3 parameters, the higher the value, the higher the received power.

But wavelength on the numerator is a surprise entry. How is wavelength contributing to increased receiver power? The amount of power received at the receiver is directly proportional to the *effective* physical area of the receiving antenna. Note the word – effective. Not all energy falling on the antenna is utilized and only a certain area of the antenna is useful in maximizing the received power.
The physical antenna dimension is related to the wavelength of operation. Thus higher wavelength implies more effective physical area and hence better power reception. In practical systems, unfortunately, the designer does rarely have the freedom to choose the operating frequency and in turn the operating wavelength.

Denominator has constant 4π, distance and system losses. With distance, the power drops so **d** is in the denominator. **L** represent the system losses that are not related to free space and are only related to the transmitter and receiver hardware.
4π may seem like a surprise entry. This can be explained when the entire transmit-receive operation is imagined to happen in a 3-D space and not in a 2-D space as it is drawn on paper. Thus, the transmitter at the centre of the sphere in a 3-D space sends out a signal to the receiver at distance "d" which is the radius of this sphere. Area of the sphere explains **$4\pi d^2$** in the denominator.

To summarize free-space propagation is a fundamental nature of any wireless signal traveling over the air. As a designer, certain factors are in full or partial control like transmit power, system losses, and antenna gains. Then there are factors like distance and wavelength which are not under control but should be well thought out to build an efficient communication system.