Link budget: reference models

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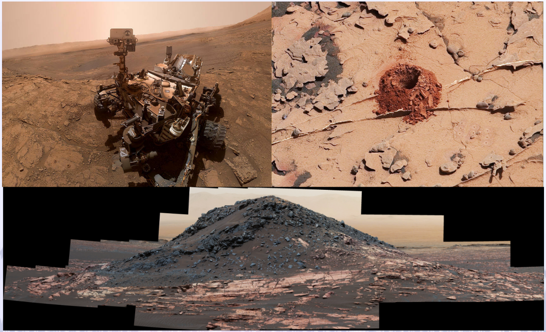
Outline

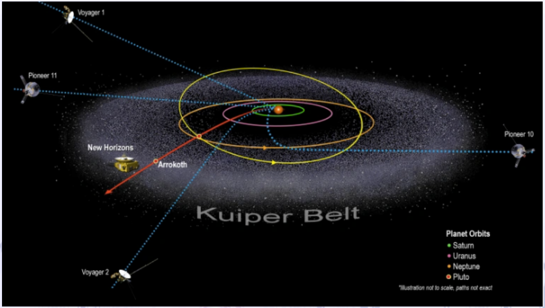
Deep space exploration



Mars

- 173.25 million km
- light takes around 3 minutes to cover that distance

Deep space exploration



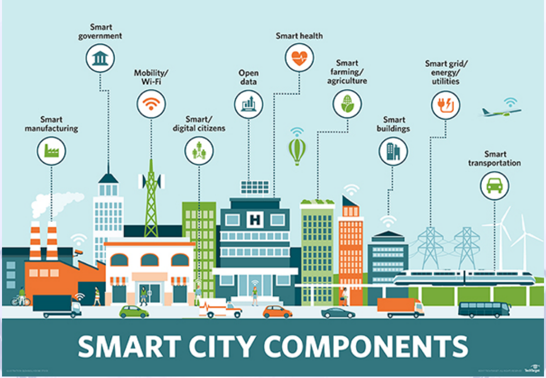
Voyager 1

- 23.844 billion km
- light takes around 22h to cover that distance

Satellite Comm and sensing

SatCom

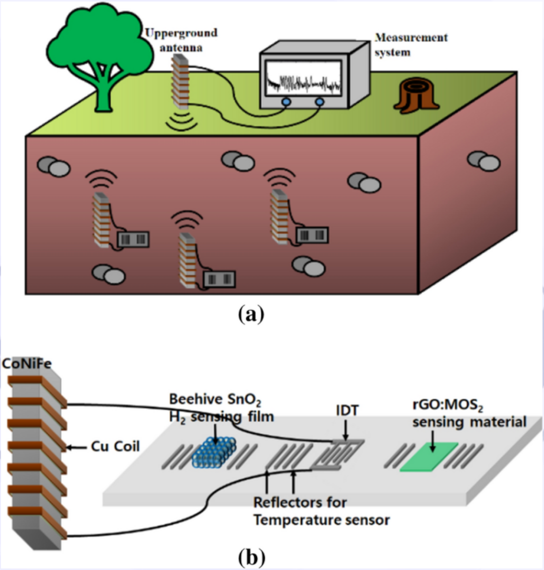
- 36000 km
- light takes around 0.13s to cover that distance



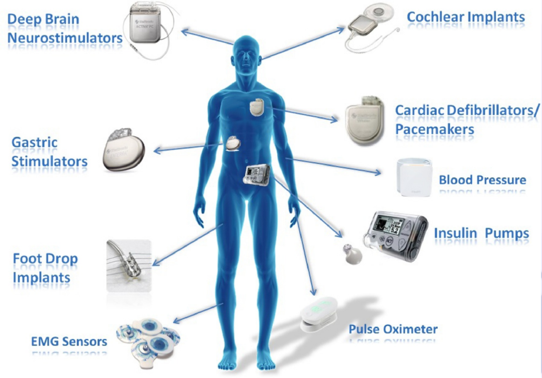
Smart cities

- up to few km

Wireless underground networks



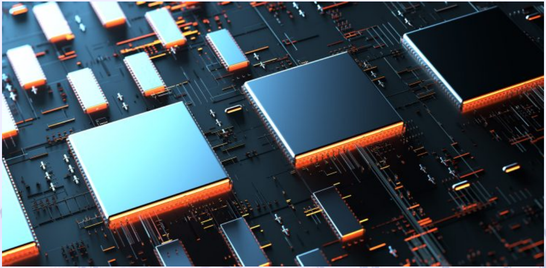
Wireless body networks



Digital health care

- up to few cm

Wireless Network-on-Chip



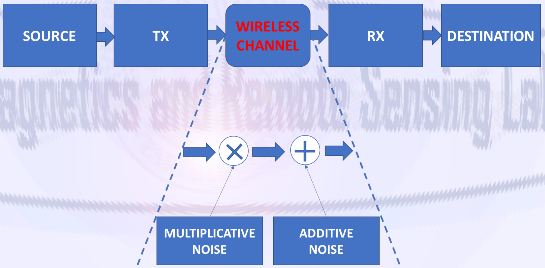
Multi-core processors

- up to mm

Wireless channel

Two types of noise

Modeling the wireless channel consists of giving an understanding of the mechanisms that affect the propagation from the TX to the RX. This is done by modeling two sources of noise that affect wave propagation.



Outline

Link budget

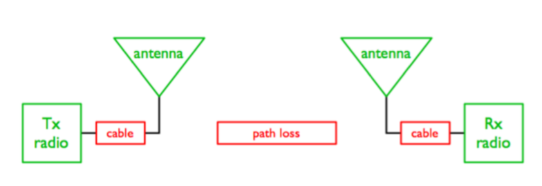
- It is a way to quantify the link performance.
- It relies on the calculation of all gains and losses from TX to RX through the medium.

A simple link budget equation looks like this:

- RX P (dB) = TX P (dB) + Gains (dB) - Losses (dB)

Note that decibels are logarithmic measurements, so adding decibels is equivalent to multiplying the actual numeric ratios.

Link budget



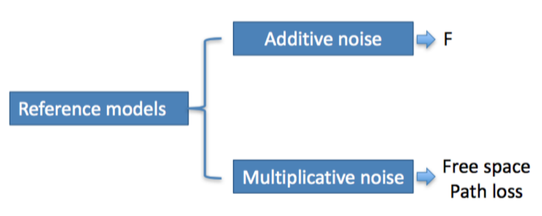
If the estimated received power is sufficiently large (typically relative to the receiver sensitivity), which may be dependent on the communications protocol in use, the link will be useful for sending data.

Fade (or link) margin

The amount by which the received power exceeds receiver sensitivity is called the link margin. The link margin must be positive, and should be maximized (should be at least 10dB or more for reliable links)

Reference models

The calculation of signal and noise powers for a complete communication link, i.e.; drawing the link budget, is a key step to design a communication system.



- Path loss includes all the losses associated with interaction between em wave and obstacles.
- The reference model is the free space path loss, i.e.; all the other losses are to be meant as excess wrt free space path loss.

Receiver sensitivity

The sensitivity of an electronic device

It is the minimum magnitude of input signal required to produce an output signal calling for a given signal-to-noise ratio (SNR).

- The receiver sensitivity indicates how faint an input signal can be to be successfully received by the receiver, the lower power level, the better.
- When the power is expressed in dBm the larger the absolute value of the negative number, the better the receiver sensitivity.

Lower power for a given SNR means better sensitivity since the receiver's noise contribution is smaller.

Additive noise

Two port network

- The total noise associated with the communication system can be evaluated considering the system as the cascade of two-port elements characterized by a single input and output.
- The receiver is the main source of additive noise.

Each element is characterized by:

- G: the gain, i.e.; the output signal to the input signal ratio.
- F: the noise factor, i.e.; the ratio between the power of the output noise (referred to the input -> divided by G) and the input noise.

Two port network

- The input noise power can be defined as the power deriving from a resistor working a T Kelvin:

$$P_N = K_B T B, \tag{1}$$

with $K_B = 1.39 \times 10^{-23} W Hz^{-1} K^{-1}$ being the Boltzmann's constant and B is the effective noise bandwidth.

- Hence, the noise factor is given by:

$$F = \frac{N_o}{N_i} = \frac{N_o}{K_B T B}, \tag{2}$$

where N_o stands for the output actual noise divided by G.

Two port network

The noise figure is simply the dB value of F:

$$F_{dB} = 10 \log F \tag{3}$$

Cascade of two-port elements

The whole communication system can be considered as a cascade of two-port elements, each characterized by its G and F values.

- The total gain and the overall F are given by:

$$G = G_1 \times G_2 \dots G_N \tag{4}$$

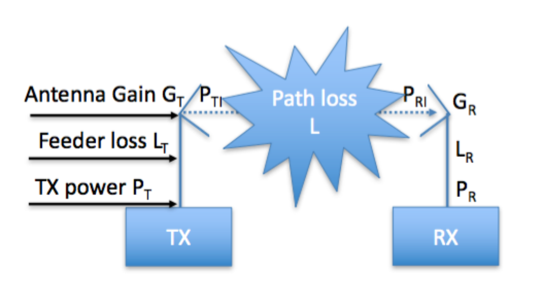
$$F = F_1 + \frac{F_2 - 1}{G1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_N - 1}{G_1 G_2 \times \dots \times G_{N-1}} \tag{5}$$

The first element is the most critical one. It is mandatory to select a low noise element, i.e.; characterized by low F and high G.

Path loss

The path loss between TX and RX antennas is the transmitted to received power ratio.

- It includes all the possible losses that affect the wave when propagating from TX to RX.
- It depends also on losses and gains in the radio system.



Friis formula

Let the TX and RX antennas located in free space and separated by a distance r large enough to make the two antennas in each other's far-field regions.

- Assuming that the directions of maximum gain of the two antennas are aligned and their polarization matched, the power received at the terminals of the RX antenna is given by:

$$P_R = \frac{P_T G_T A_R}{4\pi r^2} \tag{6}$$

A_R is the effective aperture of the receiving antenna that can be related to its gain $G = \frac{4\pi}{\lambda^2} A [m^2]$.

Friis formula

- Hence, replacing A_R in eq.(6) with G_R:

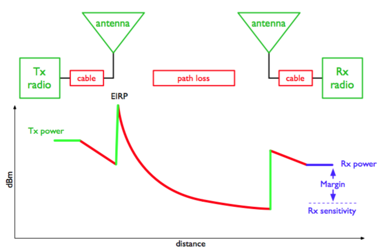
Friis transmission formula

$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi r} \right)^2 . \quad (7)$$

- It predicts a reduction of the received power with the square of the distance (square law behavior).
- Polarization and/or impedance mismatching result in additional reduction of the received power.

Path loss vs system and environment

It is more convenient to have a Path loss that depends on environment only



This allows splitting the path loss into two component:

1. Predicted using a distance-dependent path loss model.
2. Fade margin to lead the system resilient against unpredictable effects.

Effective isotropic radiated power (EIRP)

- The power measured at the receiver terminals, once gains and losses are defined as powers ratios with powers measured in watts, is given by:

$$P_R = \frac{P_T G_T G_R}{L_T L L_R} \quad (8)$$

Antenna gains, which are defined wrt an isotropic radiator, are considered along with the direction of the other antenna.

EIRP includes antenna gain and feeder loss

$$P_{TI} = \frac{P_T G_T}{L_T} \quad (9)$$

$$P_{RI} = \frac{P_R L_R}{G_R} \quad (10)$$

Path loss

L

The path loss is typically expressed in terms of EIRPs using eqs.(9- 10). This makes L

- independent of system parameters;
- dependent on the propagation medium and wave-obstacles interactions.

$$L = \frac{P_{TI}}{P_{RI}} = \frac{P_T G_T G_R}{P_R L_T L_R} \tag{11}$$

- Propagation models allow predicting L to determine the range of the radio system.
- The maximum acceptable path loss corresponds to the range which results in a power level that equals the receiver sensitivity.

dB unit

It is 1-tenth of a Bell and is a logarithmic power ratio

$$\text{Power ratio in dB} = 10 log \frac{P}{P_{ref}} \tag{12}$$

- It is mandatory to specify the reference power to make dB unit consistent.
- It can be also used to express field intensity:

$$\text{Field intensity ratio in dB} = 10 log \left(\frac{E}{E_{ref}}\right)^2 = 20 log \frac{E}{E_{ref}}. \tag{13}$$

dB unit

Unit	Reference power	Application
dBW	1 W	Absolute power
dBm	1 mW	Absolute power P [dBW] = P [dBm] − 30
dBμV	1 μV e.m.f.	Absolute voltage, typically at the input terminals of a receiver (dBμV = dBm + 107 for a 50 Ω load).
dB	Any	Gain or loss of a network, e.g. amplifiers, feeders or attenuators
dBμV m^{-1}	1 μVm^{-1}	Electric field strength
dBi	Power radiated by an isotropic reference antenna	Gain of an antenna
dBd	Power radiated by a half-wave dipole	Gain of an antenna 0 dBd = 2.15 dBi

Outline

Free space loss

- Adapting the Friis formula (7) to the path loss formula (11) on can obtain the free space path loss:

$$L_F = \frac{P_T G_T G_R}{P_R} = \left(\frac{4\pi r}{\lambda}\right)^2 = \left(\frac{4\pi r f}{c}\right)^2 \quad . \tag{14}$$

- It exhibits a square law behavior with respect to the distance and the frequency.
- It is commonly expressed in dB:

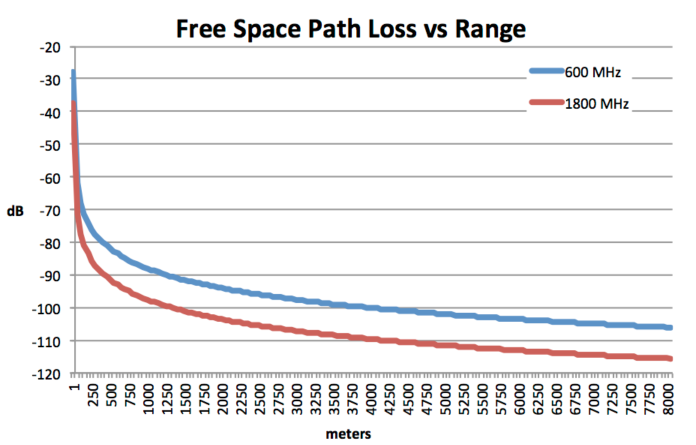
L_F as a basic reference model

$$L_F = 32.4 + 20 \log r[km] + 20 \log f[MHz] \tag{15}$$

L_F is commonly considered a reference propagation loss. Hence, the total loss is considered in excess of this reference value:

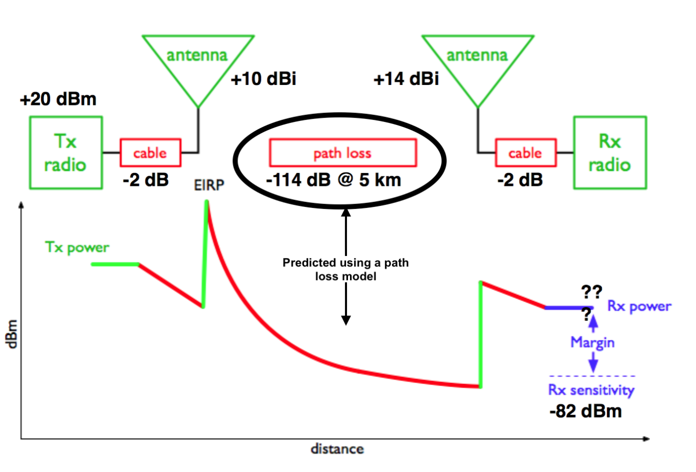
$$L = L_F + L_{ex} \tag{16}$$

Free space loss



- L_F increases with a rate of 20dB per decade in either f or r.
- The loss between two antennas is larger than L_F.

Example link budget calculation: AP2Client



Example link budget calculation: AP2Client

20 dBm (TX Power AP)
+ 10 dBi (Antenna Gain AP)
- 2 dB (Cable Losses AP)
+ 14 dBi (Antenna Gain Client)
- 2 dB (Cable Losses Client)

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40 dB Total Gain
-114 dB (free space loss @5 km)

-73 dBm (expected received signal level)
--82 dBm (sensitivity of Client)

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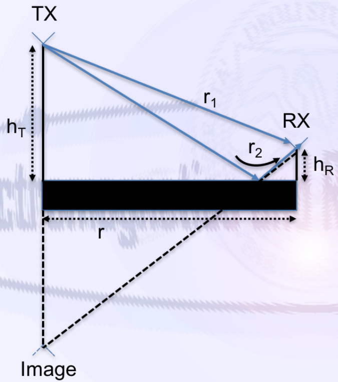
8 dB (link margin)

Outline

Plane Earth loss geometry

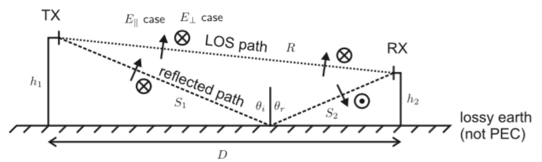
TX and RX antennas are located on a perfectly conducting flat ground (plane Earth) at different heights.



- There is a direct path (r_1) and a reflected ray (r_2).
- The two rays sum coherently at the receiver.
- Their phase difference is related to the different path length.

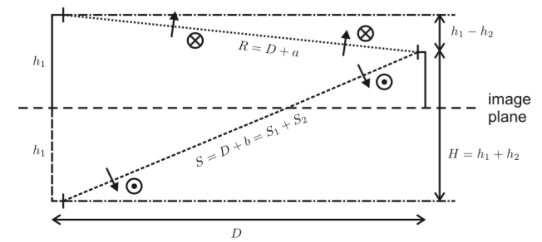
The geometry

It is the most significant source of reflection introduced by the environment when dealing with terrestrial links.



- There is a direct (LOS) path and a reflected one.
- The E-field is depicted in the TE and TM case.
- The reflected wave exhibits a 180° phase shift wrt the LOS wave. This results from grazing angle ($\vartheta_i \rightarrow 90°$) reflection at a lossy interface. Grazing condition relies on the fact that $h_1, h_2 \ll D$.
- There is also a path difference between LOS and reflected paths.

Evaluating the received power



- We invoke a "modified" image theory that allows accounting for the 180° phase shift due to the sign of the reflection coefficient.
- We need to evaluate the path difference between the LOS and the reflected paths.
- We consider that the direct and the reflected paths consist of a common length (equal to the horizontal separation D) plus an extra length equal to a and b, respectively.

Evaluating the received power

- The E-field at the receiver is given by the superposition of the LOS and the reflected waves. Note that, due to grazing conditions, the reflection coefficient is equal to -1:

$$E_d + E_r = \frac{e^{-j\beta R}}{R} - \frac{e^{-j\beta S}}{S} = \frac{e^{-j\beta R}}{R}\left(1 - \frac{e^{-j\beta(S-R)}}{S/R}\right). \tag{17}$$

- The term outside the parentheses is just a standard LOS propagation term.
- The term in parentheses can be seen as a correction term that describes the reflection. To specify this term, $S - R$ and S/R are to be evaluated.

$$S - R = D + b - D - a = b - a \quad ; \quad S/R \approx 1 \tag{18}$$

Evaluating the received power

- To evaluate the excess paths a and b, the large and small triangles in the previous figure must be analyzed.

$$H^2 + D^2 = S^2 = (D+b)^2 = D^2 + b^2 + 2Db \quad (19)$$
$$H^2 \approx 2Db$$

- The approximation is justified by the fact that $D \gg b$. Hence:

$$b = \frac{(h_1 + h_2)^2}{2D} \quad (20)$$

- Similarly (considering the small triangle) one can find:

$$a = \frac{(h_1 - h_2)^2}{2D} \quad (21)$$

- Hence:

$$S - R = b - a = \frac{2h_1 h_2}{D} \quad (22)$$

Evaluating the received power

- The correction term in eq.(17) can be rewritten as:

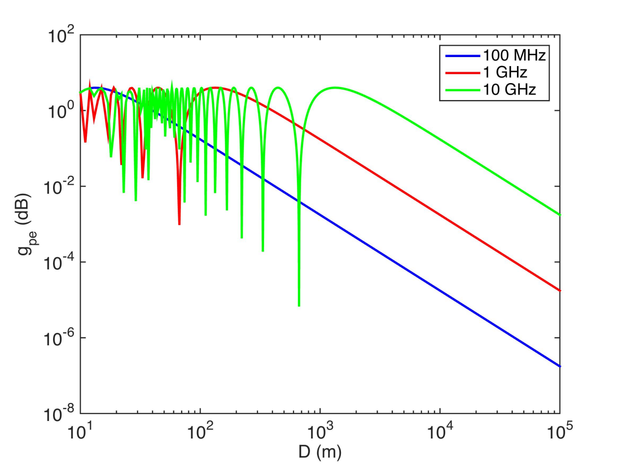
$$1 - \frac{e^{-j\beta(S-R)}}{S/R} = 1 - e^{-j\frac{4\pi}{\lambda}\frac{h_1 h_2}{D}} \tag{23}$$
$$= e^{-j\frac{2\pi}{\lambda}\frac{h_1 h_2}{D}} \left(e^{j\frac{2\pi}{\lambda}\frac{h_1 h_2}{D}} - e^{-j\frac{2\pi}{\lambda}\frac{h_1 h_2}{D}} \right)$$
$$= j2e^{-j\frac{2\pi}{\lambda}\frac{h_1 h_2}{D}} \sin\left(\frac{2\pi h_1 h_2}{\lambda D}\right)$$

Plane Earth reflection term

- The square magnitude of this correction term is given by:

$$g_{pe}(\lambda, h_1, h_2, D) = 4\sin^2\left(\frac{2\pi h_1 h_2}{\lambda D}\right) \tag{24}$$

g_{pe}



For small distances there are peaks and sinks due to the combination of the direct and reflected waves.

Path loss

- The power is proportional to the squared amplitude, hence:

$$P_R = 4E_d^2 \sin^2 k\frac{\Delta}{2} \tag{25}$$

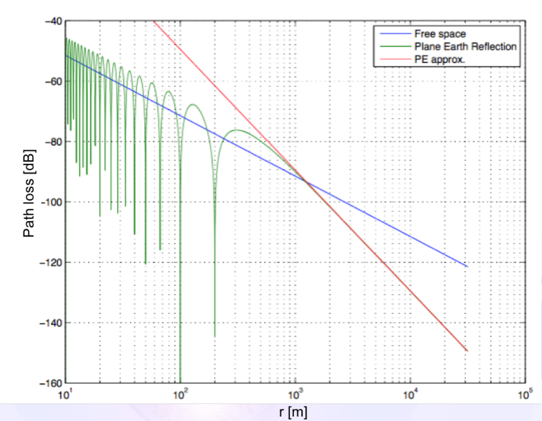
- Since, $\sin^2 x = \frac{1}{2} - \frac{1}{2}\cos 2x$, and considering that the direct power (E_d^2) is the free-space one:

$$P_d = P_T \left(\frac{\lambda}{4\pi r}\right)^2,$$

eq.(25) becomes:

$$L_{PE} = \frac{P_R}{P_T} = 2\left(\frac{\lambda}{4\pi r}\right)^2 (1 - \cos k\Delta) \tag{26}$$

Path loss



As the distance increases L_{PE} decreases monotonically.

Path loss

- For large distances L_{PE} exhibits a monotonically decreasing behavior.
- This can be mathematically derived considering that, for small angles, $\cos\theta \approx 1 - \frac{\theta^2}{2}$. Hence:

$$L_{PE} \approx \frac{h_T^2 h_R^2}{r^4} \tag{27}$$

L_{PE} in dB unit

$$L_{PE} = 40 \log r - 20 \log h_R - 20 \log h_T \quad . \tag{28}$$

- This is the usual form of the plane Earth loss.
- It increases more rapidly than L_F but it is still frequency-independent.