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Link budget lab #6

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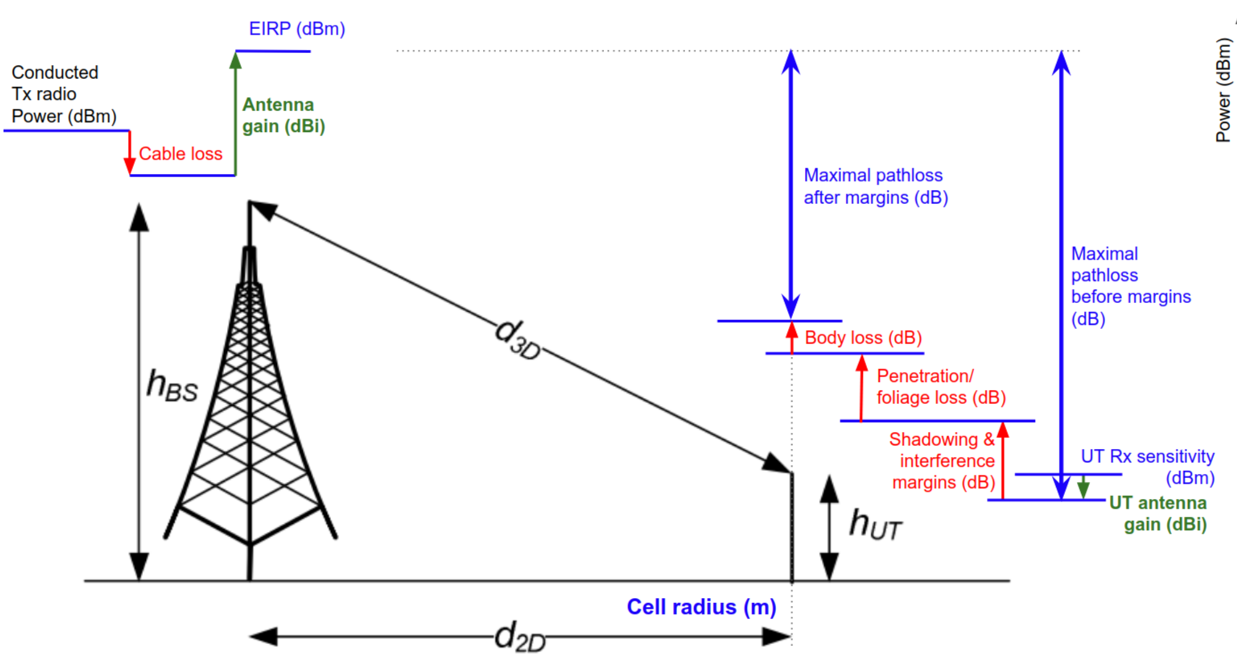
5G link budget

Link budget is an important tool in a cellular network design. It is used to determine the cell radius or, in other words, coverage area. By knowing the cell radius, we know how closely spaced cellular sites need to be. For instance, if we have a 10km×10km area, and if we determine that sites need to be located every 1km (individual cell radius is 500m), we need approximately 100 sites to cover the entire area. If, on the other hand, sites need to be located every 250m, we need approximately $40 \times 40 = 1600$ sites, which implies a much higher cost of the network deployment.

We start the 5G link budget exrcise by first defining the link budget as a measure of Maximum Allowable Pathloss (MAPL, or simply MPL) between the transmitter and the receiver both in the downlink and uplink direction. From the MAPL, and by making use of one of the pathloss models introduced in the lectues, we can determine the cell radius. A 5G link budget diagram is illustrated below.

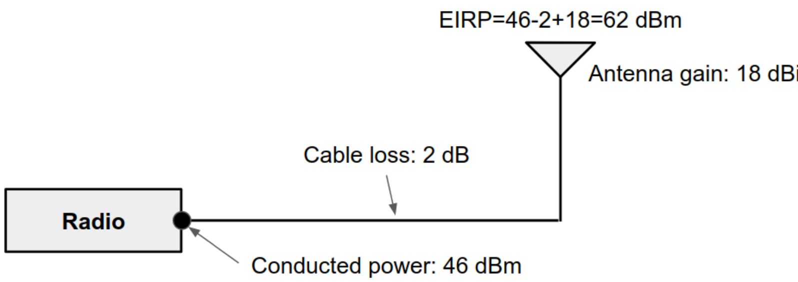


Entries with a black font such are conducted Tx radio power, basestation antenna height h_{BS} and user terminal heights h_{UT} are provided as input parameters, although in practice they may also be part of the link budget evaluation (i.e., higher basestation antenna height will result in higher MAPL). Power levels incicated with a blue font, like the EIRP value and the UT receiver sensitivity, are calculated and so is the cell radius corresponding to the calculated MAPL value. Losses (red font) and gains (green fonts) are part of the calculation. The MAPL value, before various margins are applied, is simply the difference between the EIRP level and the receiver sensitivity:

$$MAPL = EIRP + G_{UT} - P_{\text{UT sensitivity}}$$

and if we include the clutter (shadowing margin), interference margin and body loss, the MAPL value is reduced, resulting in shorter cell radius, as illustrated above.

Let us first look at the downlink 4G LTE link budget example, for a carrier operating at $f_c = 2150$ MHz. The output power at the radio port, called conducted power, is 46 dBm (40 W). The cable that connects the radio to the antenna is a few tens of meters long, and reduces the signal power by 2 dB, whereas the transmit antenna gain is 18 dBi (see the illustration below).



An illustration of a physical antenna mounted on top of a building with jumper cables connecting it to the radio is shown below.

The EIRP value, in dBm scale, is:

$$\mathit{EIRP} = 46 - 2 + 18 = 62 \text{ dBm}.$$

In this example, the target data rate at the cell edge is set to 1 Mbps, which is quite low by today's standards (typically, 10 Mbps or more are targeted). Assuming a 10 MHz channel bandwidth (the occupied bandwidth is $W = 9$ MHz), and $\alpha = 0.65$ is the Shannon capacity scaling factor, the required SNR for the desired service is:

$$\mathit{SNR} = 2^{\frac{1}{\alpha \times W}} - 1 = 0.12579$$

which corresponds to $\mathit{SNR}\,|_{dB} = -9$ dB.

To calculate the sensitivity of the user terminal (UT), we need the noise figure, which in this example is $\mathit{NF} = 7$ dB, so that the sensitivity level is:

$$\begin{aligned} P_{\text{UT sensitivity}} &= -174 + 10\log_{10}(W) + \mathit{NF} + \mathit{SNR}\,|_{dB} \\ &= -174 + 10\log_{10}\left(9 \times 10^6\right) + 7 - 9 \\ &= -106.46 \text{ dBm.} \end{aligned}$$

The MAPL before the margins is:

$$\begin{aligned} \mathit{MAPL} &= \mathit{EIRP} + G_{\mathit{UT}} - P_{\text{UT sensitivity}} \\ &= 62 + 0 - (-106.46) \\ &= 168.46 \text{ dB.} \end{aligned}$$

Win an interference margin of $\mathit{IM} = 5$ dB, the maximal allowable pathloss before clutter and penetration losses is:

$$\mathit{MAPL} = 168.46 - 5 = 163.46 \text{ dB.}$$

To determine the cell radius for non-line of sight conditions (NLOS), that is when the UT is indoors and the basestation is outdoors, we need to add the following margins:

1. **Shadowing margin** - based on the shadowing standard deviation $\sigma = 6$ dB for urban environment (see TS 38.901) and a typical target of 85% cell edge reliability, the shadowing margin is calculated as:

$$M = \sqrt{2}\sigma \operatorname{erfcinv}\left(2P_{\mathit{OUTAGE}}\right) = 6.22 \text{ dB}$$

2. **Penetration loss** - for a given carrier carrier frequency of $f_c = 2150$ MHz, which corresponds to mid-bands in terms of frequency ranges for LTE, wall penetration is typically between 17 and 20 dB. We will assume a penetration loss of 18 dB.

3. **Body loss** - typical value is 3 dB when a user terminal is held in hand.

After combining all the margins, the reduced MAPL is:

$$\mathit{MAPL} = 163.46 - 6.22 - 18 - 3 = 136.24 \text{ dB.}$$

By inverting the Urban Macro formula for NLOS condition from the TS 38.901, we can calculate the cell radius for the given carrier frequency and pathloss:

$$\begin{aligned} PL_{\mathit{NLOS}}(d_{3D}) &= 13.54 + 39.08\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 0.6\,(h_{\mathit{UT}} - 1.5) \\ 136.27 &= 13.54 + 20\log_{10}(2.15) + 39.08\log_{10}(d_{3D}) \\ 39.08\log_{10}(d_{3D}) &= 116.08123080168791 \\ d_{3D} &= 10^{\frac{116.08}{39.08}} = 934\text{m} \\ d_{2D} &= \mathit{CellRadius} = \sqrt{d_{3D}^2 - (h_{BS} - h_{UT})^2} = 933.7\text{m.} \end{aligned}$$

Note: The TS 38.901 specifies the pathloss for $h_{BS} = 25$m only. For different basestation antenna heights, refer to TR 36.873. Also, see the Python notebook for the pathloss implementation that is based on two different specifications.

Using the same methodology outlined above, but taking into account the impact of the control plane overhead, we can calculate the 5G link budget. The only difference compared to above is in the mapping from SNR to spectral efficiency, which when the overhad is taken into account, is:

$$SE = \frac{R_{data}}{BW_N} \frac{1}{1 - OH_{CP}}$$

Task, 5G link budget: For the 5G link budget calculations, we will assume the following:

- Carrier frequency: $f_c = 2150$ MHz
- Channel bandwidth: $BW = 40$ MHz. For the noise bandwidth, assume 216 resource blocks, which translates to $BW_N = 216 \times 0.18 = 38.88$ MHz.
- Conducted transmit power: $P_T = 200$ watts (53 dBm)
- Cable loss: $L_{cable} = 0.5$ dB
- Tx antenna gain (basestation side): $G_T = 18$ dBi
- Rx antenna gain (at the UT): $G_R = -1$ dBi
- UT noise figure: $NF = 7$ dB
- Alpha-Shannon scaling factor: $\alpha = 0.6$ (note: normally, mapping between the SE and the required SNR is done using vendor specified tables, but for the purpose of evaluation, the TR 38.803 formula can be used)
- Control plane overhead: $OH_{CP} = 0.3$, that is, 30%
- Pathloss model: Urban Macro, non-line of sight (NLOS), following 3GPP TS 38.901. This model assumes $h_{BS} = 25$m and $h_{UT} = 1.5$m.
- Interference margin: $IM = 4$ dB
- Body loss: $L_{body} = 3$ dB
- Building penetration loss: $BPL = 20$ dB
- Cell edge reliability: 85% ($P_{OUTAGE} = 0.15$)
- Target cell edge data rate: $R_{data} = 20$ Mbps

Solution: Each of the steps is outlined below.

1. The EIRP value at the transmitter, in dBm scale, is:

   $$EIRP = \qquad \text{dBm.}$$

2. Receiver sensitivity at the UT is calculated through the following steps:

   The receiver noise floor is;

   $$P_N = -174 + 10\log_{10}(BW_N) + NF = \qquad \text{dBm}$$

   The spectral efficiency required to achieve a target data rate is:

   $$SE = \frac{R_{data}}{BW_N} \frac{1}{1 - OH_{CP}} = \qquad \text{bps/Hz}$$

and the required SNR is:

$$\mathit{SNR} = 2^{\frac{SE}{\alpha}} - 1 =$$
$$\mathit{SNR}|_{dB} = 10\log_{10}(SNR) = \quad \text{dB.}$$

Finally, the receiver sensitivity is:

$$\begin{aligned} P_{sensitivity} &= P_N + \mathit{SNR}|_{dB} \\ &= \\ &= \quad \text{dBm.} \end{aligned}$$

The minimal UT signal level, taking into account the antenna gain of the receiver and the interference margin is:

$$P_{UT,min} = P_{sensitivity} - G_R + IM = \quad \text{dBm.}$$

3. Maximal pathloss, before the margins are applied, is:

$$\mathit{MAPL} = EIRP - P_{UT,min} = \quad \text{dB.}$$

4. All the margins combined are:

$$\mathit{Margins}_{total} = \mathit{BPL} + L_{body} + M = \quad \text{dB},$$

where $M =$ dB is previously calculated shadowing margin.

5. Maximal pathloss, after the margins are applied, is:

$$\mathit{MAPL} = \quad - \mathit{Margins}_{total} = \quad \text{dB.}$$

6. The cell radius is determined by inverting the pathloss model from the TS 38.901, the same way as in 4G example. Calculated distance (see the Python code) is:

$$\mathit{CellRadius} = \quad \text{m.}$$