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Introduction to
RF Link Budgeting

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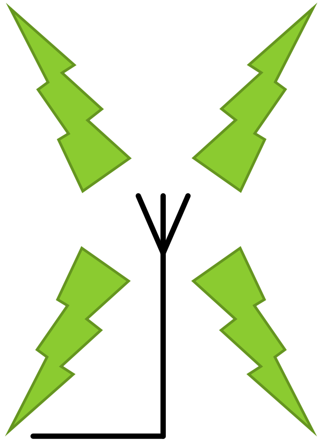
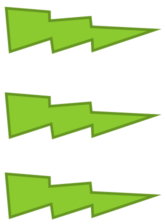
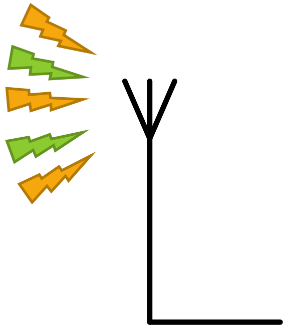
The Radio Channel

Find the signal-to-noise ratio (SNR) at the receiver







Signal

- Transmitter power
- Antenna gain

- Path loss
- Fading
- Other channel effects

- Receiver gain

Noise

- Thermal noise
- Receiver noise figure

Combining Gains and Losses

- When dealing with power in Watts, multiply and divide

Signal x Gain / Loss   SNR = Signal / Noise

- When dealing with power in dB, add and subtract

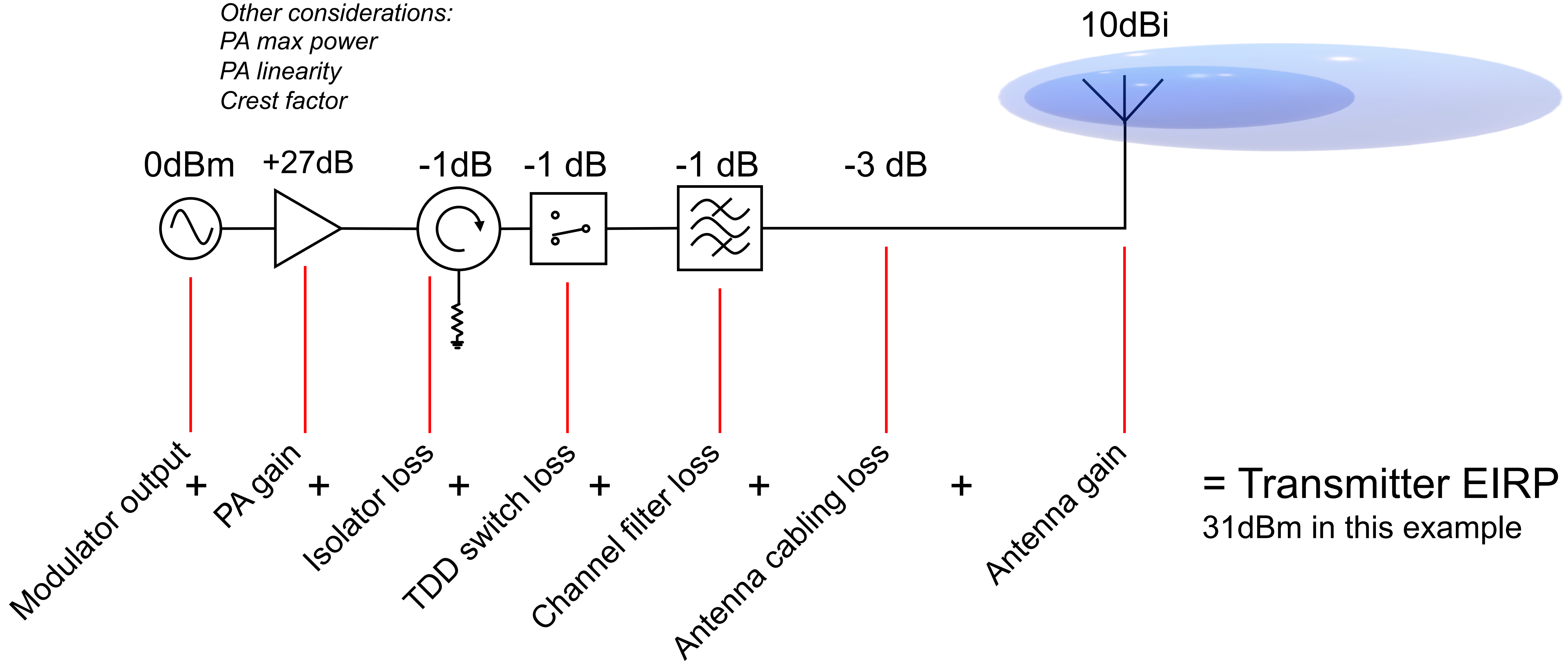
$$dBm = 10\log_{10}(mW)$$

$Signal_{dB} + Gain_{dB} – Loss_{dB}$ $SNR_{dB} = Signal_{dB} - Noise_{dB}$

The Transmitter

Transmitter Power

Other considerations:
PA max power
PA linearity
Crest factor



= Transmitter EIRP
31dBm in this example

The Channel

Free-space Path Loss

An **isotropic** antenna radiates a perfect sphere

Transmitted energy is spread over the surface of the sphere

Surface area of a sphere: $\boldsymbol{A = 4\pi d^2}$ (d is Tx-Rx distance)

Energy density **decreases** with the **square of distance**

Free-space Path Loss

The size of an isotropic antenna is related to wavelength

As the wavelength gets shorter, the antenna gets smaller

Captures less energy

The “size” of the receiving antenna is its **aperture**

Aperture of an isotropic antenna: $\boldsymbol{A_e = \frac{\lambda^2}{4\pi}}$

Energy captured **increases** with the **square of wavelength**

Free-space Path Loss

Due to the “expanding sphere” of energy with **distance**:

Free space path loss $\propto \boldsymbol{4\pi d^2}$

Due to the increasing receiver aperture with **wavelength**:

Free space path loss $\propto \boldsymbol{\frac{4\pi}{\lambda^2}}$

Free space path loss $= (4\pi d^2)\left(\frac{4\pi}{\lambda^2}\right) = \boldsymbol{\left(\frac{4\pi d}{\lambda}\right)^2}$

Free-space Path Loss

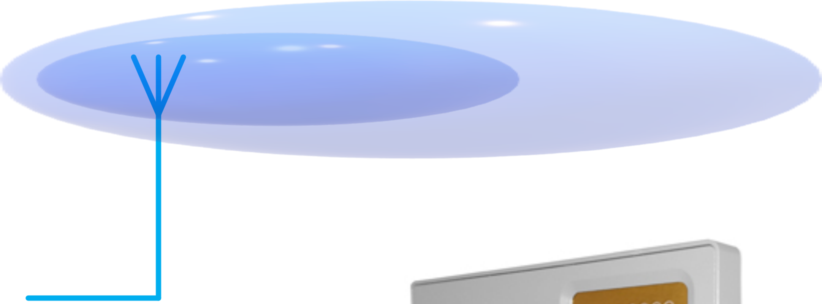
Free space path loss $= \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$

Expressed in decibels, $10\log_{10}(\text{FSPL})$:

$= 20\log_{10}(4\pi/c) + 20\log_{10}(d) + 20\log_{10}(f)$

$= \mathbf{20\log_{10}(d) + 20\log_{10}(f) - 147.55}$

Antenna Gain



Free space path loss = $20log_{10}(d) + 20log_{10}(f) - 147.55$

Does not include antenna gain – directivity

Shaped beam, rather than spherical

Changes the **radiation pattern** in Tx

Changes the **effective aperture** in Rx

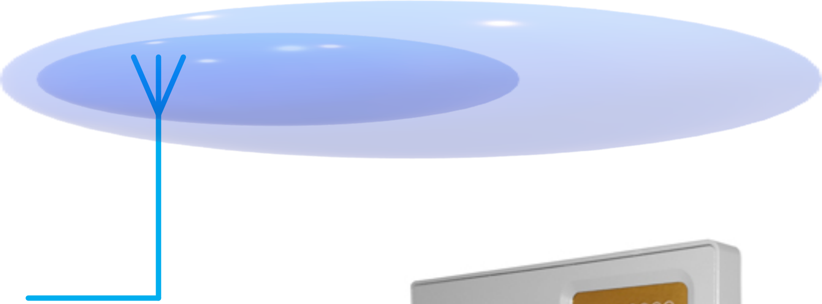
Antenna Gain

Units are **dBi** – dB **relative to the isotropic case**

e.g. 3-sector cell tower, 120° propagation

$$\mathbf{10\log_{10}(3) = 4.8dBi}$$

(additional gain in elevation gives up to ~15dBi)



Power at transmitter port + antenna gain = **EIRP**

- equivalent isotropic radiated power

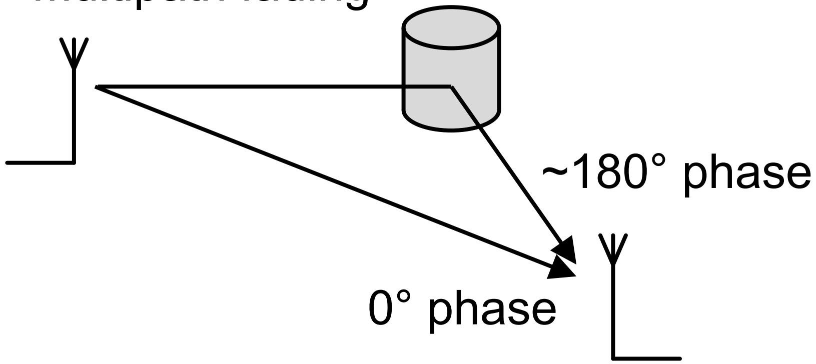
Gain (log) terms that simply add

Other Sources of Loss

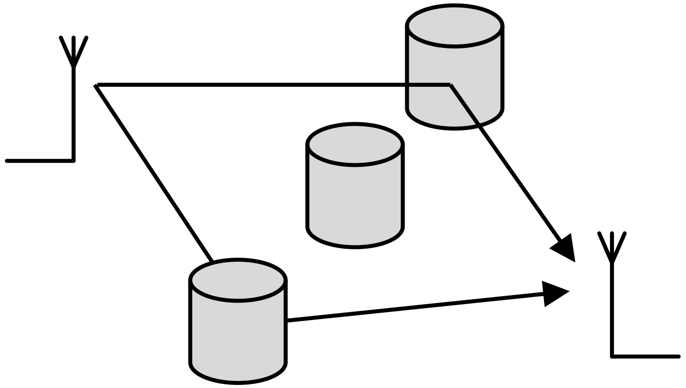
- Fading due to multipath (fast fading)
- Shadowing (slow fading) due to no LOS
- Empirical channel models attempt to take these into account.

  Examples include:
  - Okumura–Hata model
  - COST Hata model
  - COST231-Walfish-Ikegami model
- Interferers
- Highly deployment-dependent
- Margin added to allow for these based on modelling or field measurements

Multipath fading

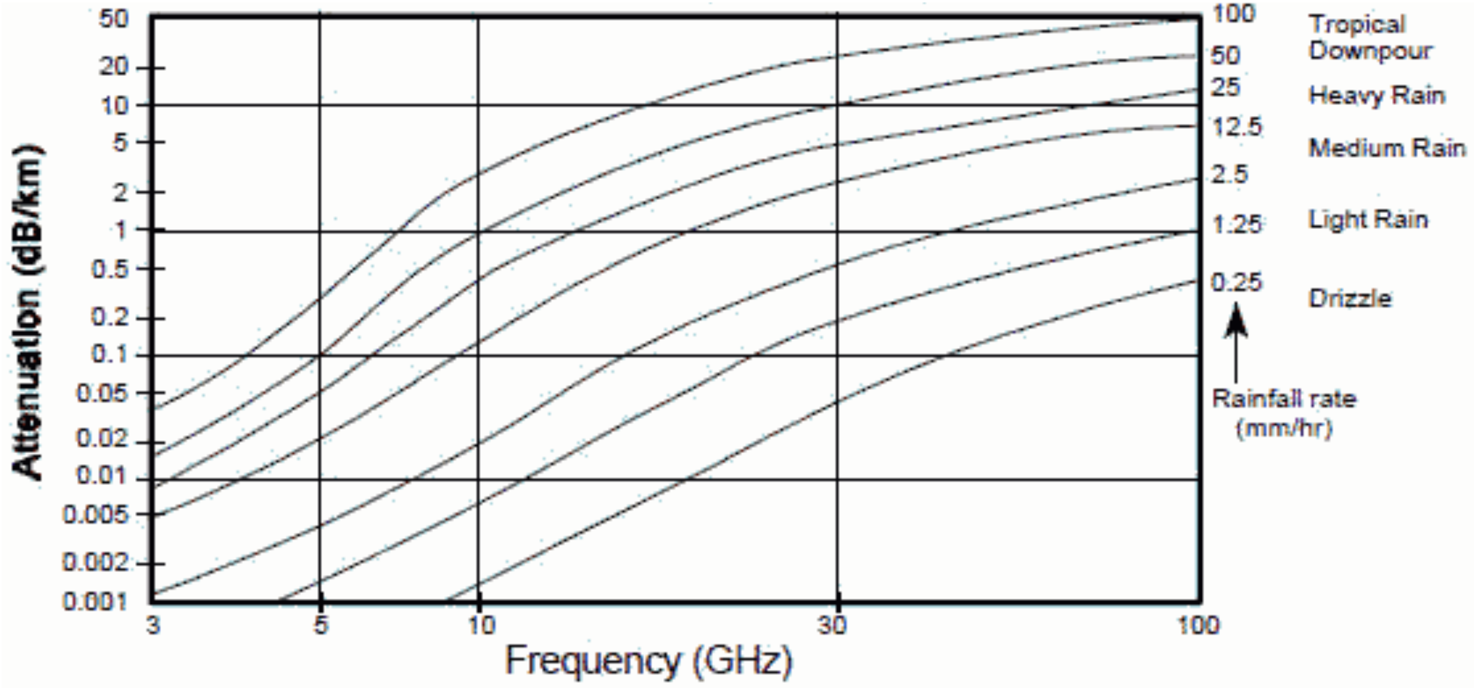


Shadowing



Other Sources of Loss

- Atmospheric absorption – negligible vs. FSPL in most cases



The Receiver

Calculating Noise at the Receiver

$$N = kTB$$

Bandwidth (Hz)

Noise power (Watts)

Receiver temperature (Kelvin)

Boltzmann's constant (1.38e-23)

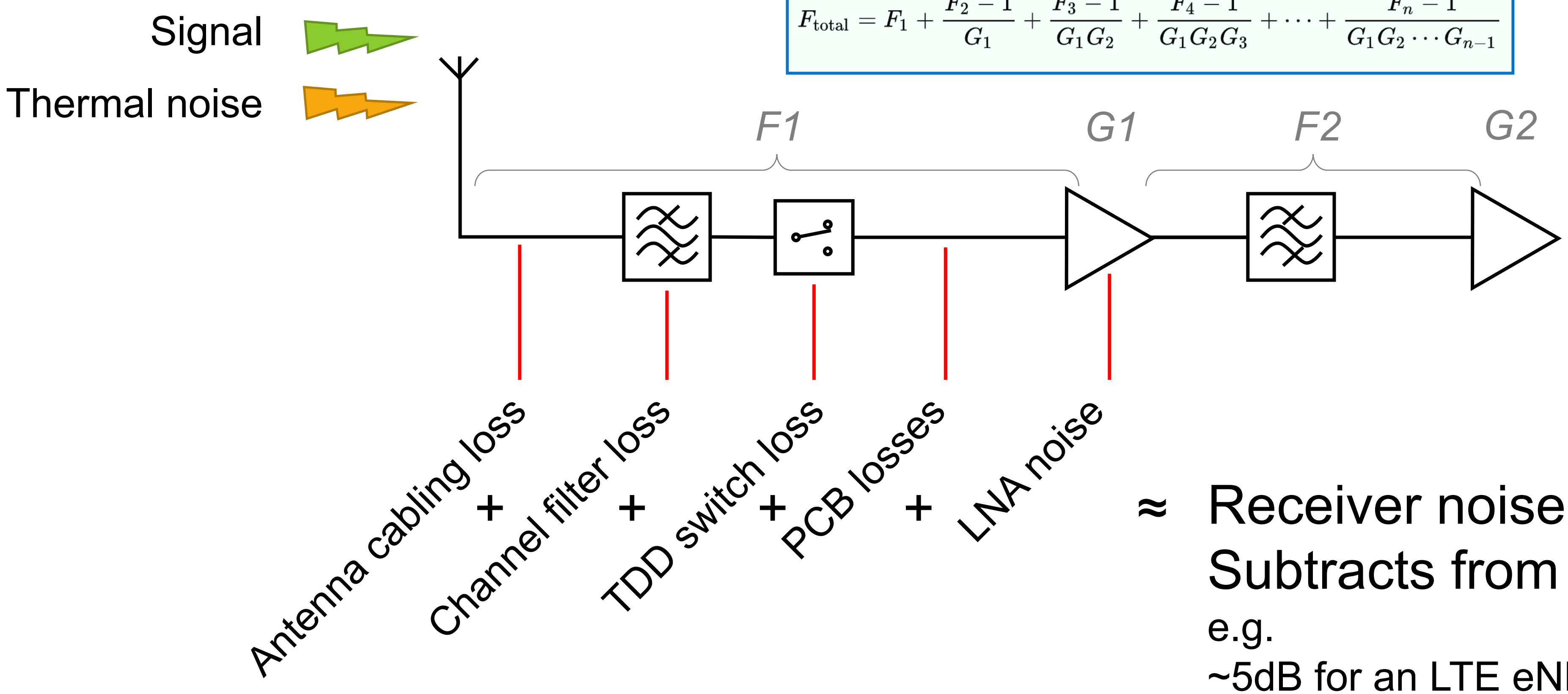
-174dBm/Hz at room temperature

+ $10\log_{10}(18.015e6)$ = -101dBm for a 20MHz LTE carrier

Calculating Noise at the Receiver

Friis formula for noise

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$$



≈ Receiver noise figure
Subtracts from SNR

e.g.
~5dB for an LTE eNB
~9dB for an LTE UE

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SNR and Throughput

Overall SNR Calculation – LTE Example

- Sum all gains and losses to get absolute power at receiver
- Subtract noise power to get SNR

$$20\log_{10}(1000) + 20\log_{10}(3.5\times10^{9}) - 147.55$$

Signal at receiver	Gain	Units
Transmitter power	24	dBm
Tx antenna gain	5	dBi
Free space path loss	-103	dB
Rx antenna gain	0	dBi
Signal at receiver	**-74**	**dBm**

$$10\log_{10}(1.38\times10^{-23}\times294\times18.015\times10^{6})$$

Noise at receiver	Gain	Units
Receiver thermal noise	-101	dBm
Rx noise figure	9	dB
Noise at receiver	**-92**	**dBm**

Signal – Noise = SNR = **18dB**

Overall SNR Calculation – 5G FR2 Example

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- Sum all gains and losses to get absolute power at receiver
- Subtract noise power to get SNR

$$20\log_{10}(1000) + 20\log_{10}(28\times10^{9}) - 147.55$$

Signal at receiver	Gain	Units
Transmitter power	24	dBm
Tx antenna gain	5	dBi
Free space path loss	-121	dB
Rx antenna gain	0	dBi
Signal at receiver	**-92**	**dBm**

$$10\log_{10}(1.38\times10^{-23}\times294\times200\times10^{6})$$

Noise at receiver	Gain	Units
Receiver thermal noise	-91	dBm
Rx noise figure	9	dB
Noise at receiver	**-82**	**dBm**

Signal – Noise = SNR = **-10dB**

Overall SNR Calculation – 5G FR2 Example

- Sum all gains and losses to get absolute power at receiver
- Subtract noise power to get SNR

$$20\log_{10}(1000) + 20\log_{10}(28\times10^{9}) - 147.55$$

Signal at receiver	Gain	Units
Transmitter power	24	dBm
Tx antenna gain	18	dBi
Free space path loss	-121	dB
Rx antenna gain	18	dBi
Signal at receiver	**-61**	**dBm**

$$10\log_{10}(1.38\times10^{-23}\times294\times200\times10^{6})$$

Noise at receiver	Gain	Units
Receiver thermal noise	-91	dBm
Rx noise figure	9	dB
Noise at receiver	**-82**	**dBm**

Signal – Noise = SNR = **21dB**

Calculating Throughput – Shannon Limit

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

Channel capacity (bps)

Bandwidth (Hz)

Signal-to-noise ratio (linear!)

- Capacity increases linearly with bandwidth

  (but so does noise)
- Capacity increases logarithmically with transmitter power
- Includes channel coding, equalisation etc.
- Diversity (e.g. MIMO) effectively creates extra channels

Calculating Throughput – Mobile Standards

Standard	Max spectral Efficiency (bit/sec/Hz) (SISO)
2G (GSM)	0.52
3G (CDMA2000 EV-DO)	2.50
4G (LTE)	4.08
5G (256-QAM)	5.84
WiFi (802.11ac)	5.42

Each standard has its own requirements for SNR

Calculating Throughput – LTE Example

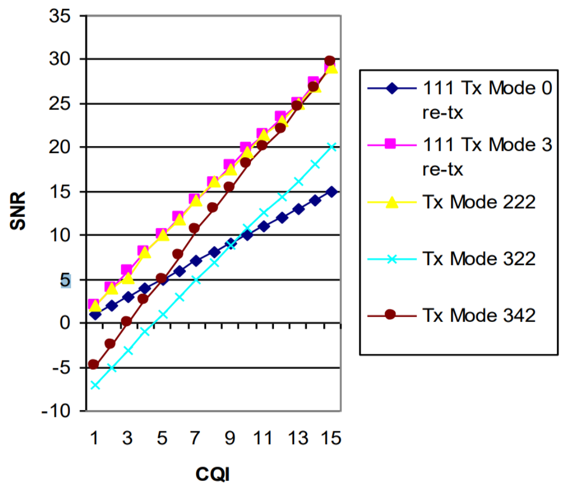
- Consider 18dB SNR from earlier example
- Estimate Channel Quality Indicator CQI = 12
- Spectral efficiency = 3.9b/s/Hz
- Bandwidth = 18.015MHz
- **Throughput ≈ 70.3Mbps**

- Shannon limit:

$$18\times10^{6}\cdot\log_2\left(1+10^{18/10}\right)=\mathbf{108Mbps}$$

3GPP 36.213 rel10 Table 7.2.3-1

CQI index	Modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547



Downlink SNR to CQI Mapping for Different Multiple Antenna Techniques in LTE, Kawser et al 2012

Summary

- Transmitter power plus antenna gain gives **Tx EIRP**
- Calculate **path losses** based on distance, frequency etc.
- Add up all the gains and losses in the system to get **Rx power**
- Calculate **Rx noise**
- Subtract noise to get **SNR**
- Calculate **throughput** based on SNR