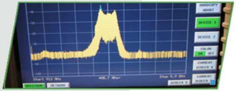


Radio Engineering

Lecture 1: Introduction

Florian Kaltenberger

Overview

1. Introduction
   - History of wireless communications
   - Types of services
   - Requirements for services
2. Technical challenges
   - Multipath propagation
   - Spectrum limitations
   - Limited Energy
   - User Mobility
3. Noise and Interference
   - Noise modeling
   - Link budget
   - Interference limited systems

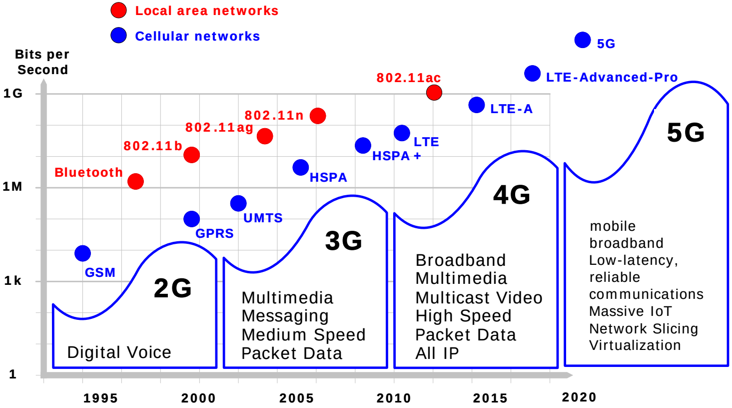
History of Wireless Communications

- 1873: James Clark Maxwell develops theory of electromagnetic waves (Maxwell's Equations)
- 1886: Heinrich Hertz: fundamental experiments confirming Maxwell's theory
- 1890-1905: First experiments for wireless information transmission (Tesla, Bose, Marconi).
- 1920: First radio broadcasting services in England
- 1948: Claude Shannon: fundamental information theory for modern communication systems [**?**]

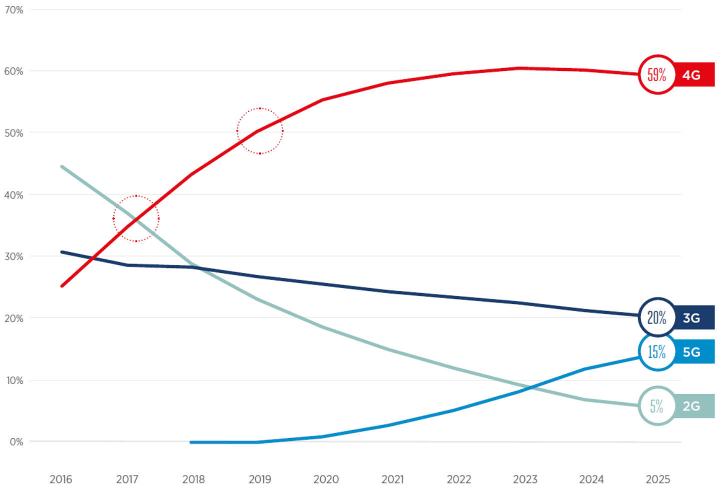
History of Wireless Communications (2)

- 1950-1980: Development of cellular telephony, first analog systems
- GSM (Global System for Mobile Communications)
  - Second generation fully digital standard
  - First deployment 1990 in Europe
  - Today more than 5 billion users in 212 countries (mostly used standard)
- Other second generation systems
  - IS-95 (cdmaOne): used mainly in US and Korea
  - PDC (Pacific Digital Cellular)

Evolution of Wireless Standards

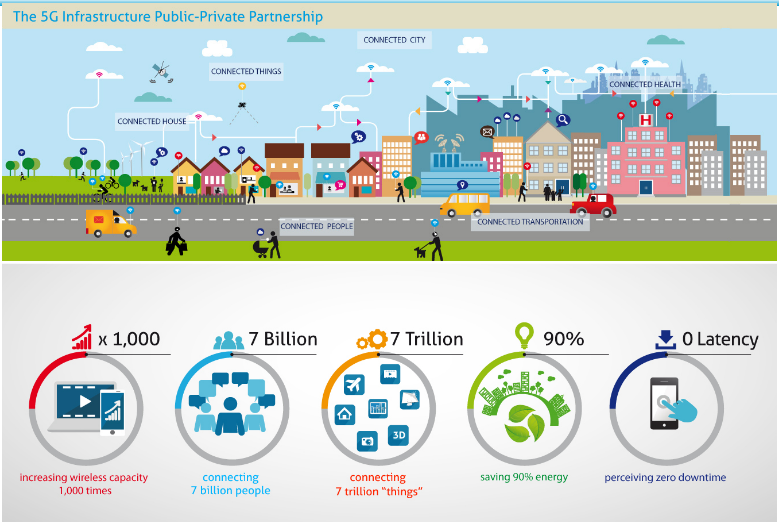


5G Market Share



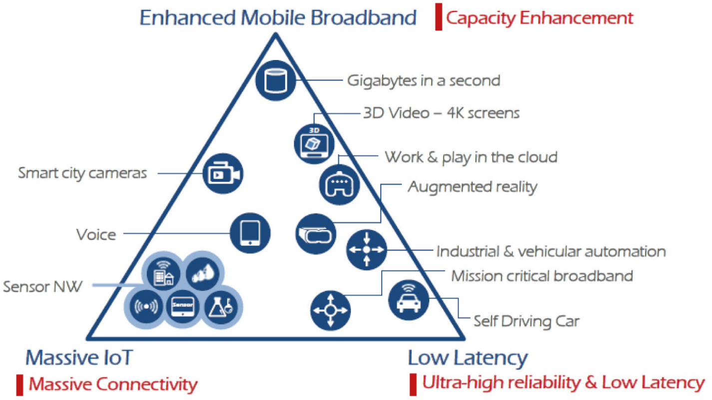
Source: www.5g-ppp.eu

5G requirements



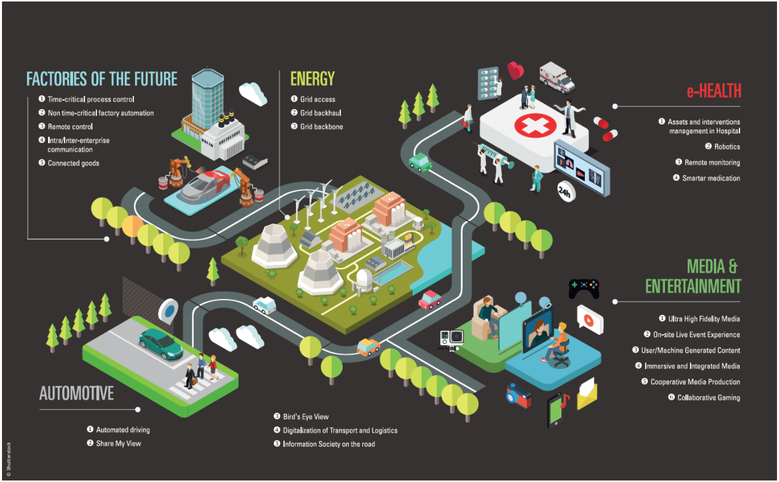
Source: www.5g-ppp.eu

5G use cases



(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

5G vertical industries



Global market

Internet of Things

9.1bn — 2018

Total connections

25.2bn — 2025

Smartphones

% of connections*

60% 2018

79% 2025

4G

% of connections*

43% 2018

59% 2025

5G

1.4bn 2025

15% of connections*

*Excluding cellular IoT

Unique mobile subscribers

2018

5.1bn

67% PENETRATION RATE (% of population) 71%

CAGR 2018–25

1.9%

5.8bn

2025

Mobile internet users

2018

3.6bn

47% PENETRATION RATE (% of population) 61%

CAGR 2018–25

4.8%

5.0bn

2025

Mobile industry contribution to GDP

4.6% of GDP

$3.9tn 2018

4.8%

$4.8tn 2023

SIM connections

Excluding cellular IoT

7.9bn

2018

9.2bn

2025

CAGR 2018–25

2.2%

103% PENETRATION RATE (% of population) 112%

Operator revenues and investment

2018

$1.03tn

$1.14tn

2025

Operator capex of $321 billion for the period 2019–2020

Public funding

Mobile ecosystem contribution to public funding (before regulatory and spectrum fees)

$510bn

2018

Employment

2018

14m Jobs

directly supported by the mobile ecosystem

+17m indirect jobs

Wireless network topologies

Main topic of this course:

- Local area networks (LAN)
  - includes body, personal, metropoltian, wide area networks
- Cellular neworks
  - Macro, micro, picocells, femtocells

Also important

- Fixed wireless link
- Broadcast (TV, Radio)
- Ad-hoc and sensor networks
- Mesh networks
- Satellite Networks

Requirements for wireless services

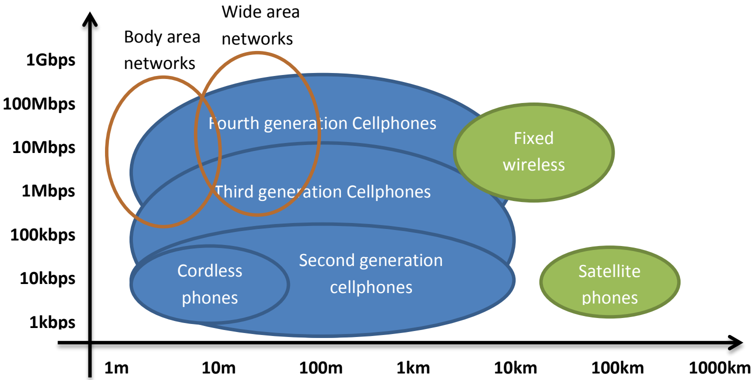
- Data rate
- Range
- Mobility
- Number of users
- Spectrum Usage
- Power consumption

Trade-offs between requirements

Data Rate

- Sensor networks: <1kbit/s; central nodes need up to 10 Mbit/s
- Speech communications: 5-64 kbit/s, depending in speech coder (vocoder)
- Elementary data services (email, simple web pages): 10-100 kbit/s
- More sophisticated web pages: a few Mbit/s
- Video streaming: 1 Mbit/s - 1Gbit/s (4K uncompressed)
- Virtual reality: a few Gbit/s

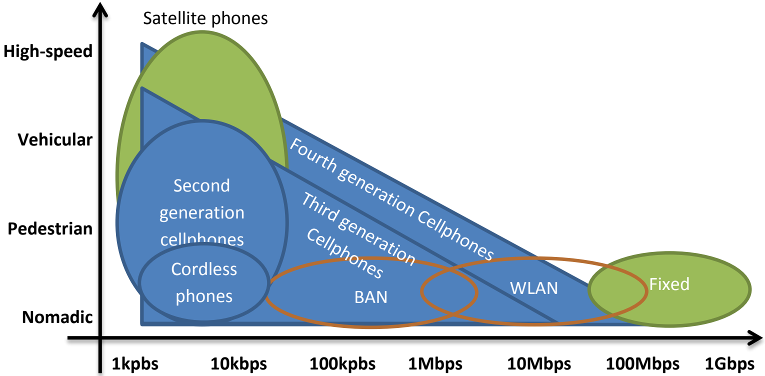
Data Rate vs Range



Mobility

- Fixed devices: stay in one location; temporal variations due to moving objects in surroundings
- Nomadic devices: MS placed at certain location, stays there for a while (WLANs)
- Low mobility: pedestrian speeds (cordless phones)
- High speed: cellphones in cars
- Extremely high speed: high-speed trains, planes, ...

Data Rate vs Speed



Spectrum Usage

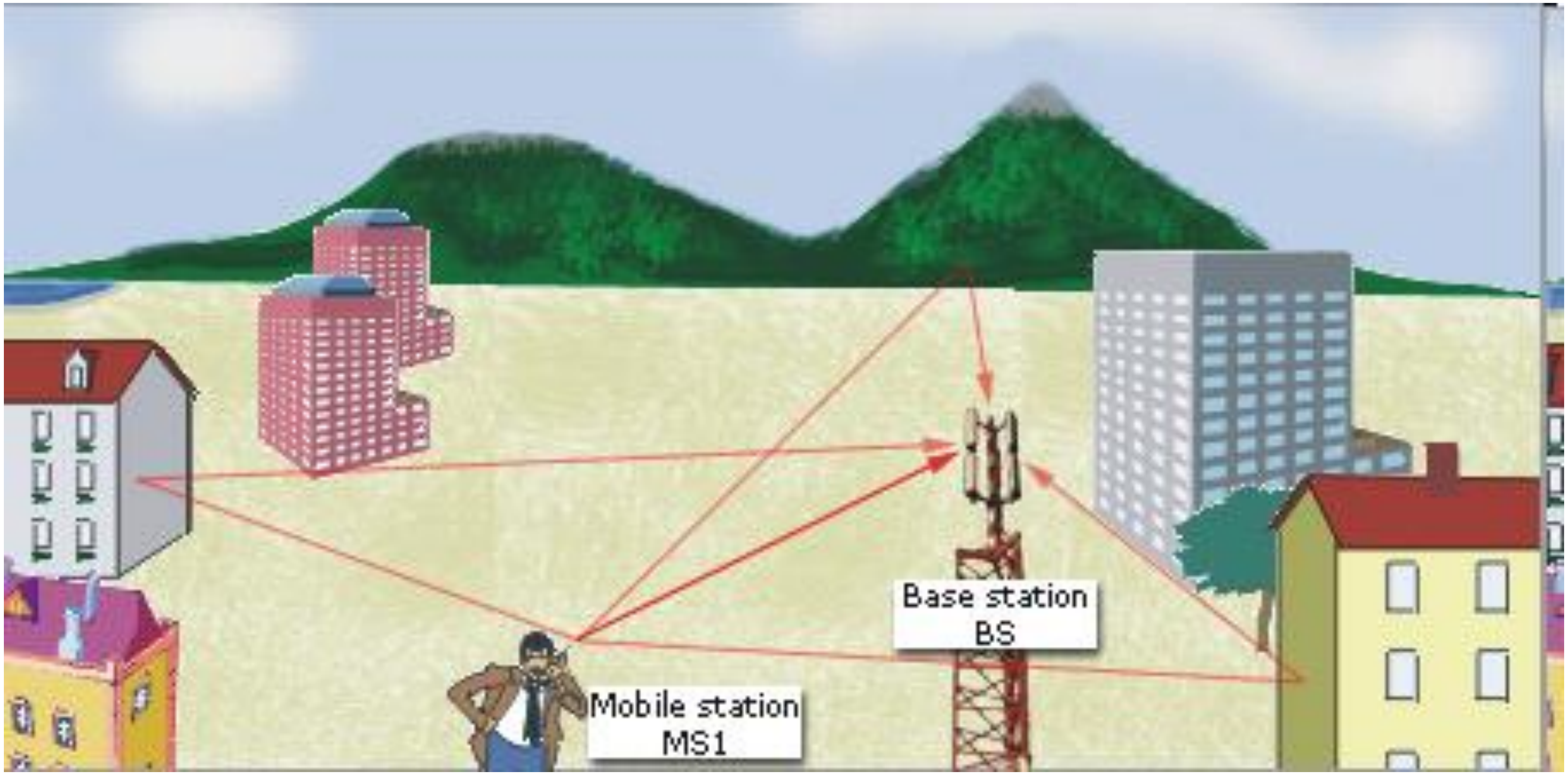
- Regulated spectrum: dedicated to specific service and/or operator
  - Cellular phones, TV, Military, etc
  - Manged by national regulators (with some worldwide harmonization)
  - Typically very costly for operators
- Unregulated (Free) spectrum
  - Industrial, scientific and medical (ISM) bands: 915MHz, 2.4GHz, 5.8GHz
  - WiFi, Bluetooth, DECT, ZigBee, etc.
- Multi-tier spectrum access
  - Allows secondary users to access to licensed spectrum under condition that it is not disturbing the incumbent user
  - Based on geolocation databases and propagation models or spectrum sensing
  - Example: TV white space (unused broadcast spectrum freed by switching from analogue to digital TV)
- Licensed Shared Access, Authorized Shared Access
  - Operators share spectrum based on some negotiation mechanism.
  - Examples: 3.5GHz in US, 2.4 GHz in France

Technical challenges of wireless communications

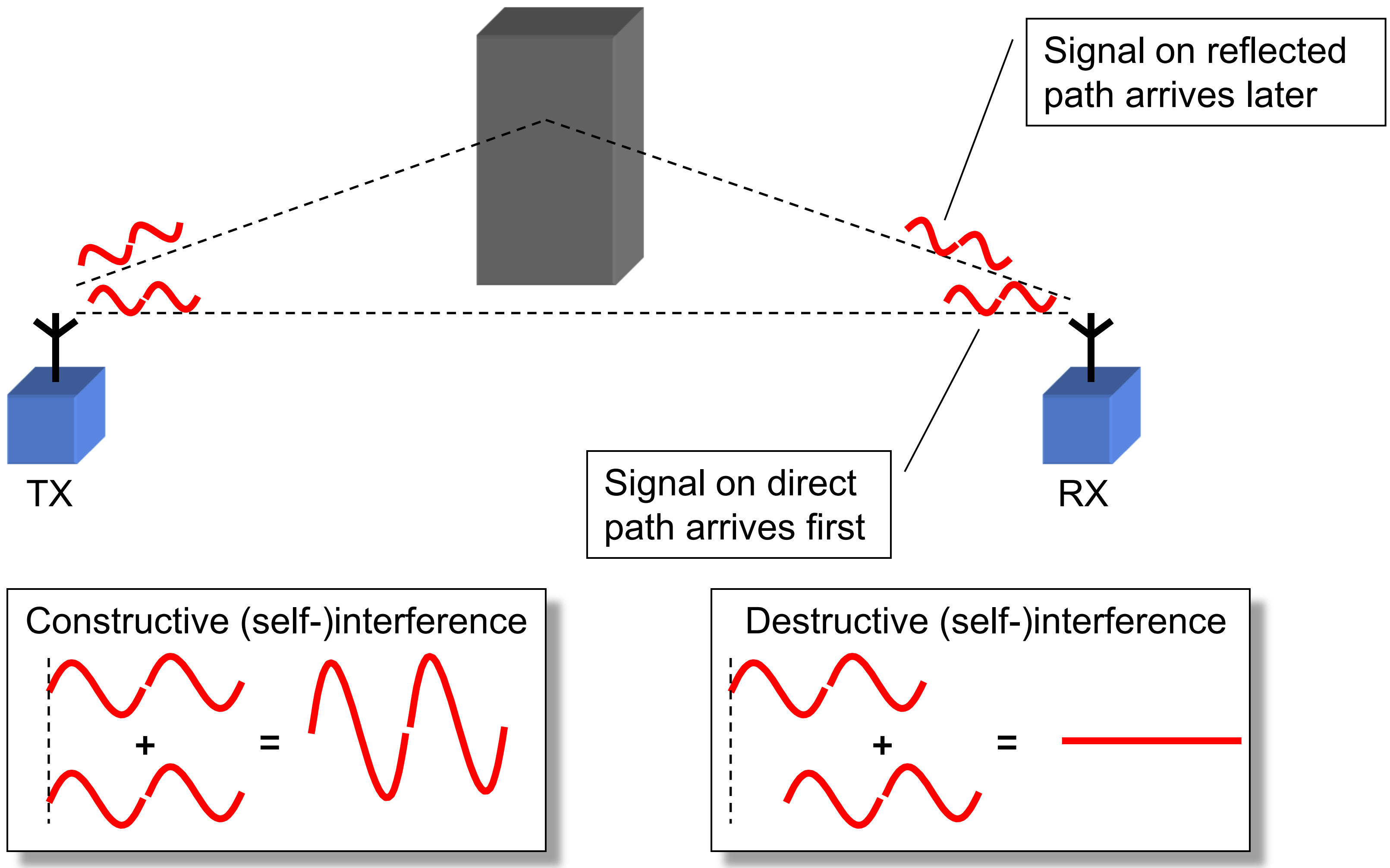
The major challenges

- Multipath propagation
- Spectrum limitations
- Limited energy
- User mobility

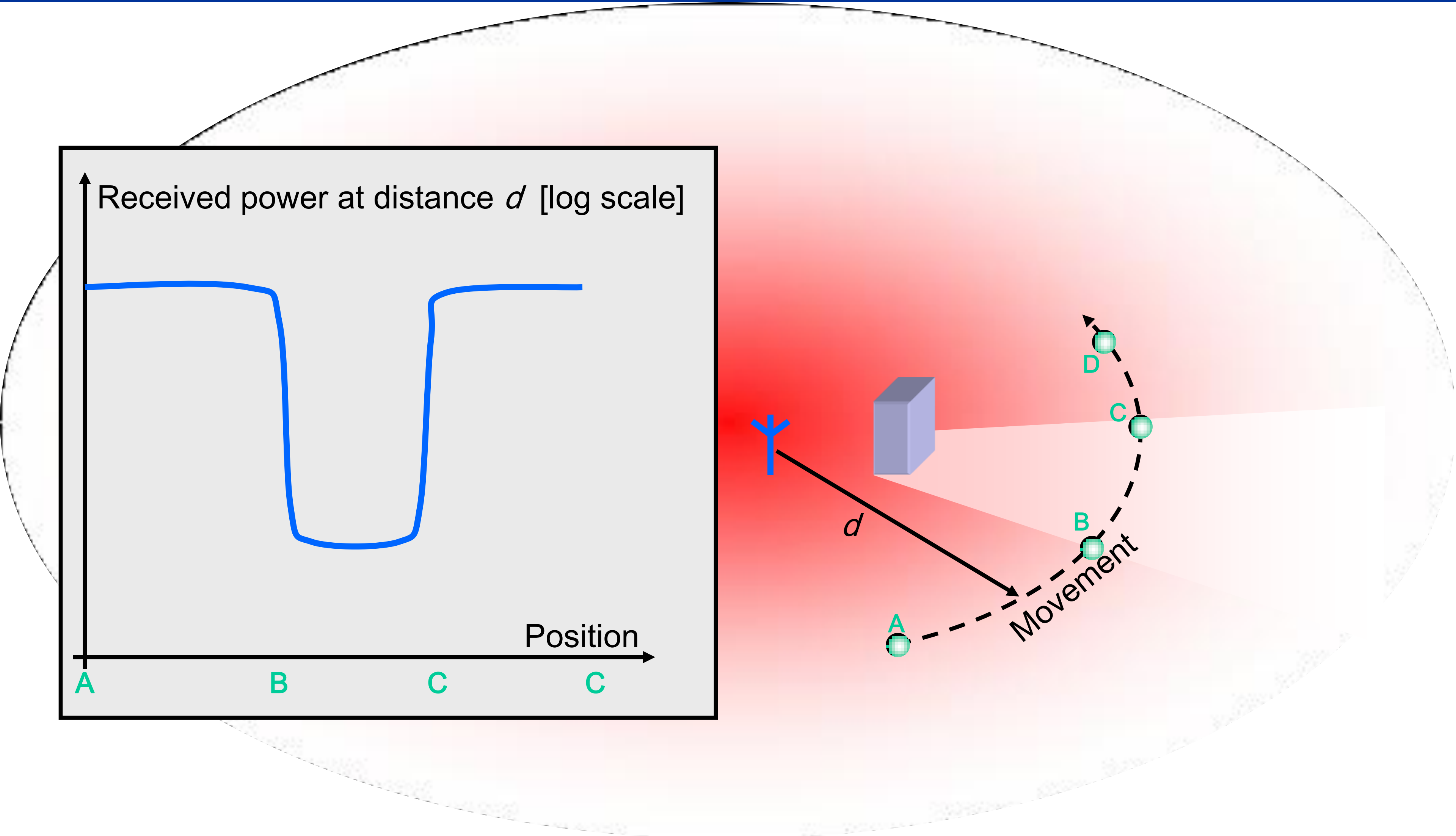
Multipath propagation



Small-scale fading



Large-scale fading

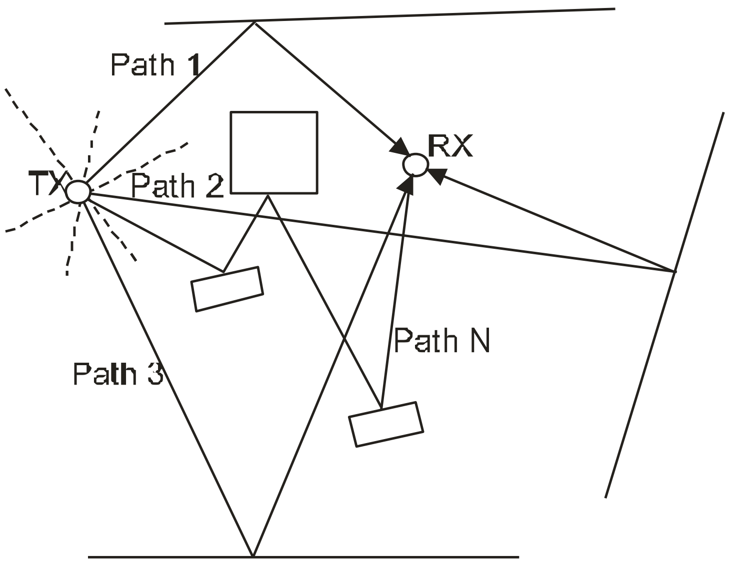


Consequences of fading

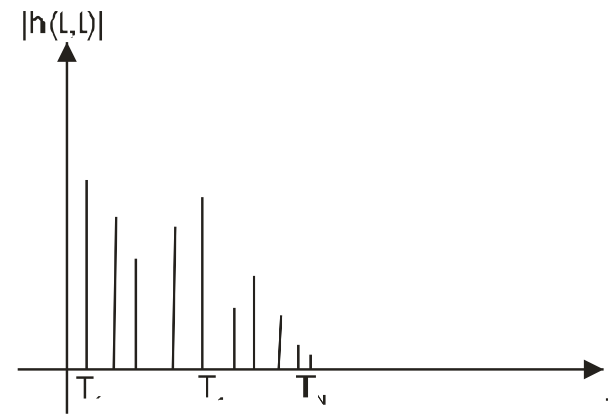
- Error probability is dominated by probability of being in a fading dip
- Error probability decreases only linearly with increasing SNR
- Fighting the effects of fading becomes essential for wireless transceiver design
- Deterministic modeling of channel at each point very difficult
- Statistical modeling of propagation and system behavior

Intersymbol interference (1)

- Channel impulse response is delay-dispersive

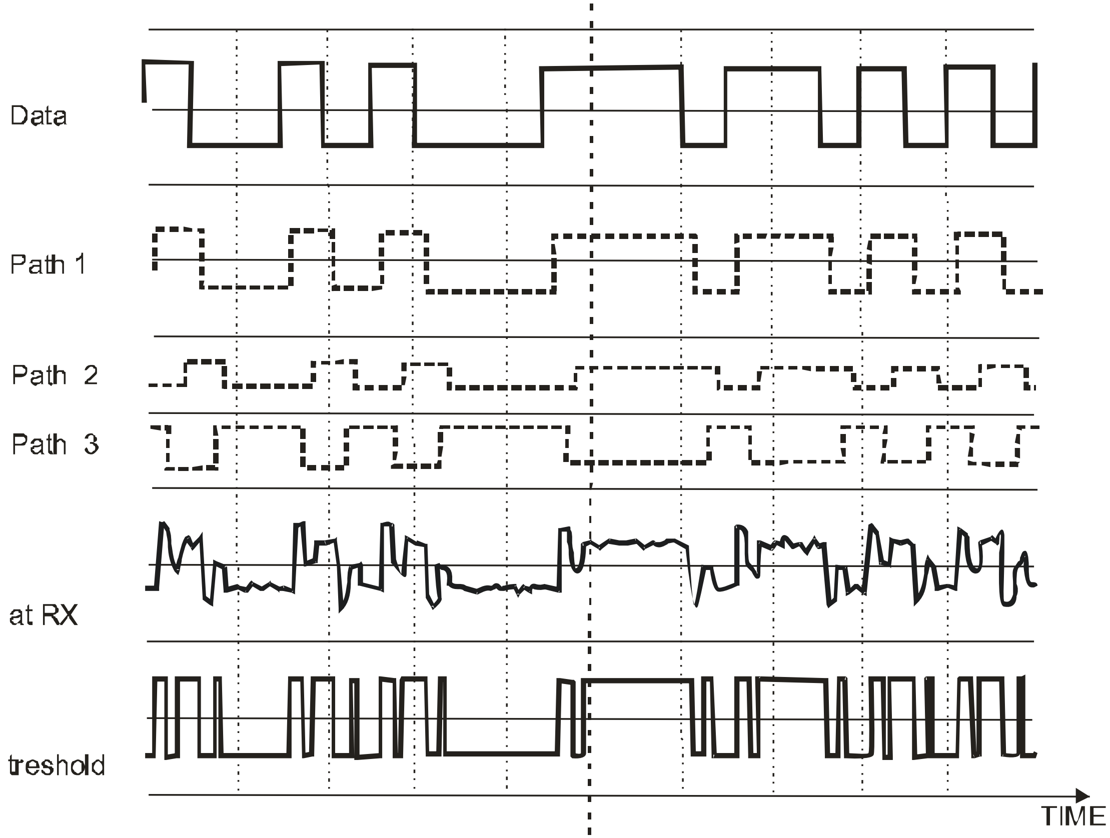


Multipath components with different runtimes



Channel impulse response

Intersymbol interference (2)

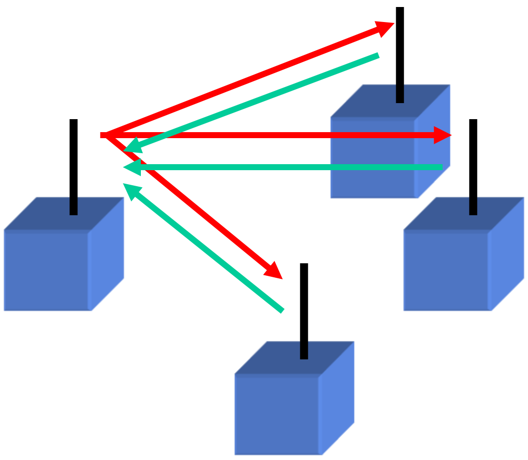


Spectrum Limitations

- Spectrum used for terrestrial wireless communications today 100MHz - 6GHz
  - limited mainly by antenna size, which scales with wavelength
  - propagation characteristics: lower frequencies propagate further and penetrate building more easily
- 28GHz will be used for 5G systems
  - more spectrum available
  - challenging due to poor propagation properties and small antenna size;
  - beamforming and massive MIMO needed to increase antenna efficiency
- Available spectrum is limited
  - the same frequency (range) has to be reused at many different locations (frequency reuse, cell planning),
  - shared between users (multiple access), and
  - shared between uplink and downlink (duplexing)

Duplexing and multiple access

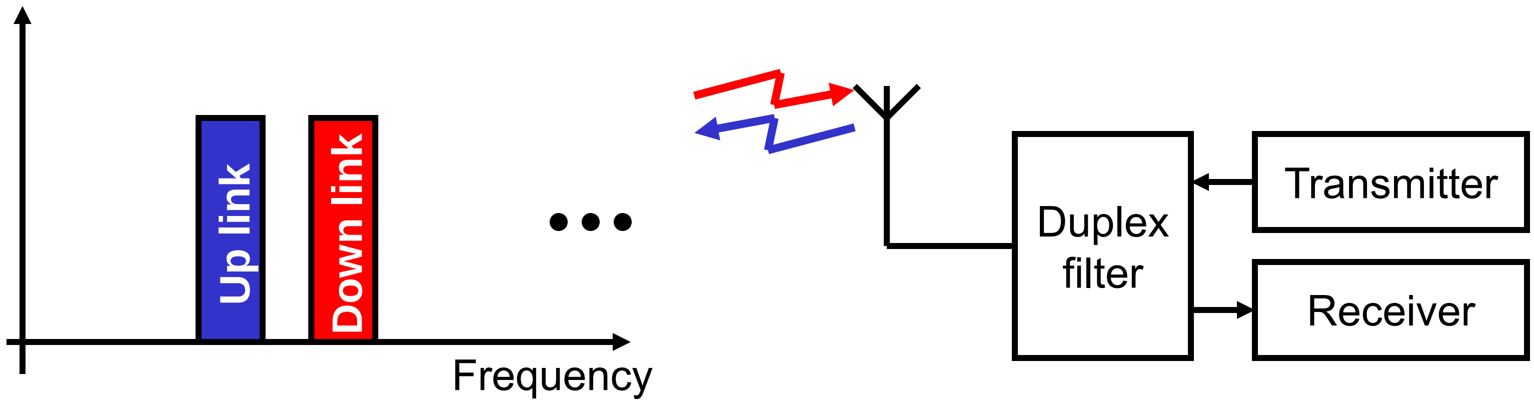
- Within each frequency band, multiple users need to communicate with one BS (multiple access)



Mobile telephony, wireless LAN, ...

- Cellphones have to be able to transmit and receive voice communications (duplexing)

DUPLEX
Frequency-division Duplex (FDD)

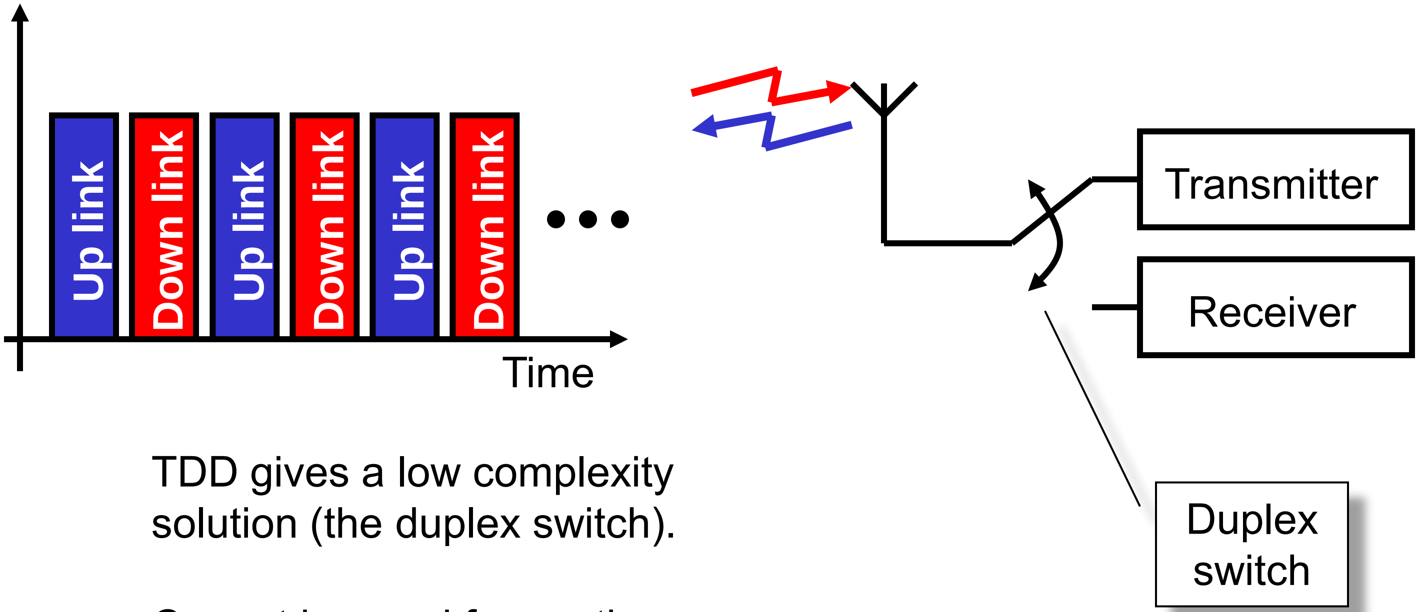


FDD gives a more complex solution (the duplex filter).

Can be used for continuous transmission.

Examples: Nodic Mobile Telephony (NMT), Global System for Mobile communications (GSM), Wideband CDMA (WCDMA)

DUPLEX
Time-division duplex (TDD)

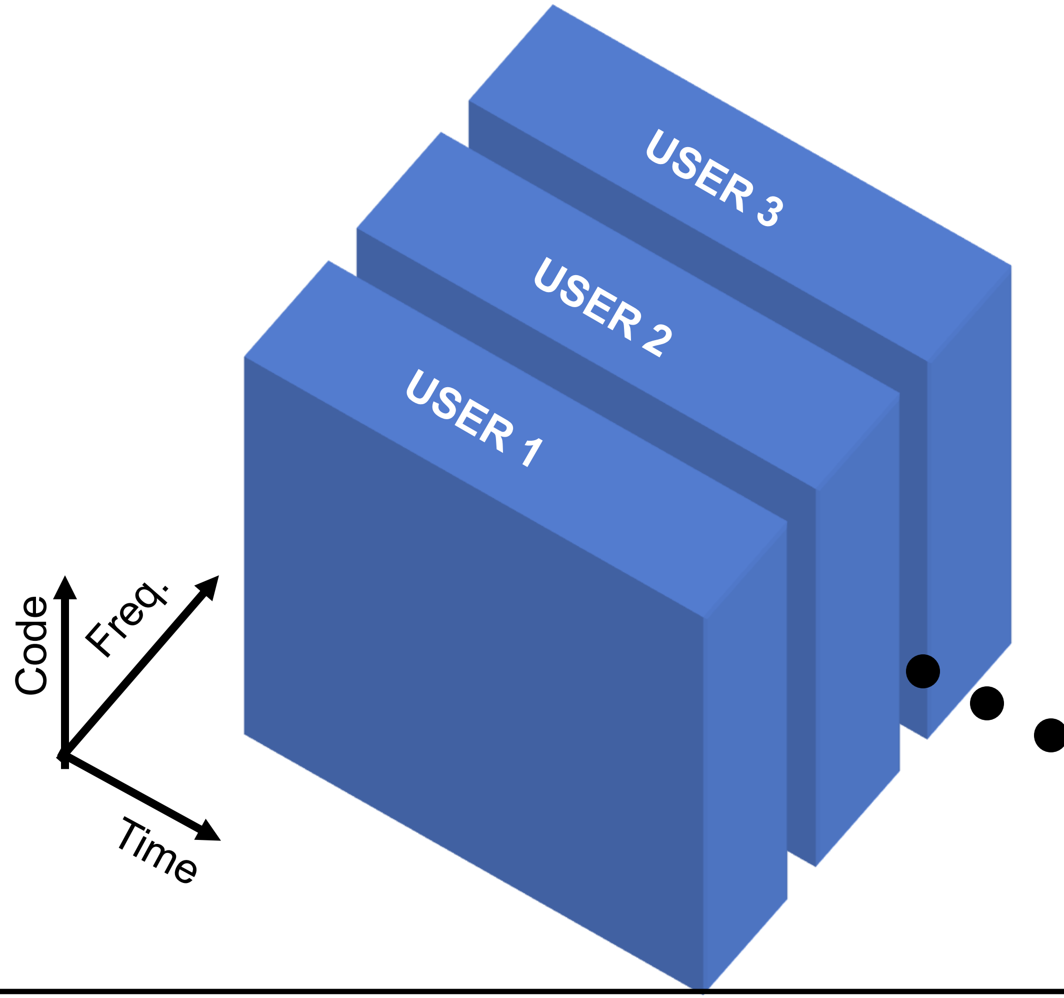


TDD gives a low complexity solution (the duplex switch).

Cannot be used for continuous transmission.

Examples: Global System for Mobile communications (GSM), Wideband CDMA (WCDMA)

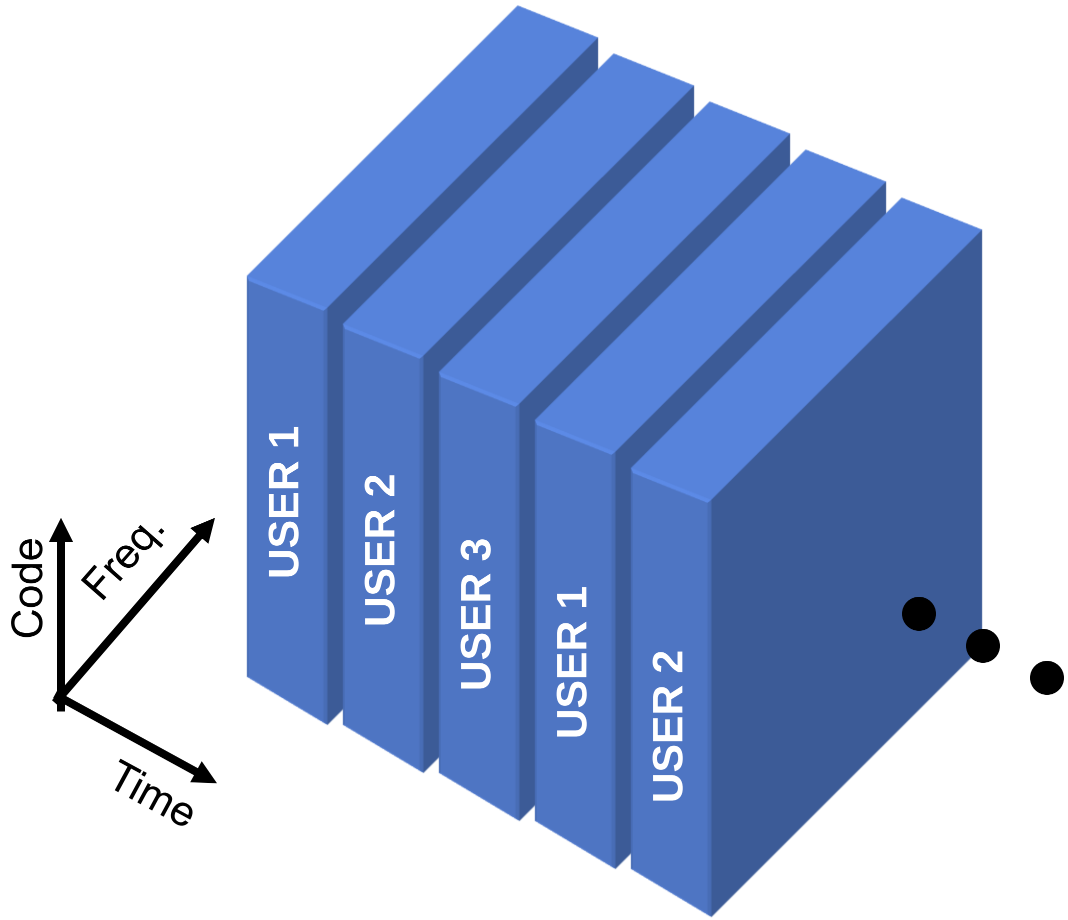
MULTIPLE ACCESS
Freq.-division multiple access (FDMA)



Users are separated in frequency bands.

Examples: Nordic Mobile Telephony (NMT), Advanced Mobile Phone System (AMPS)

MULTIPLE ACCESS
Time-division multiple access (TDMA)

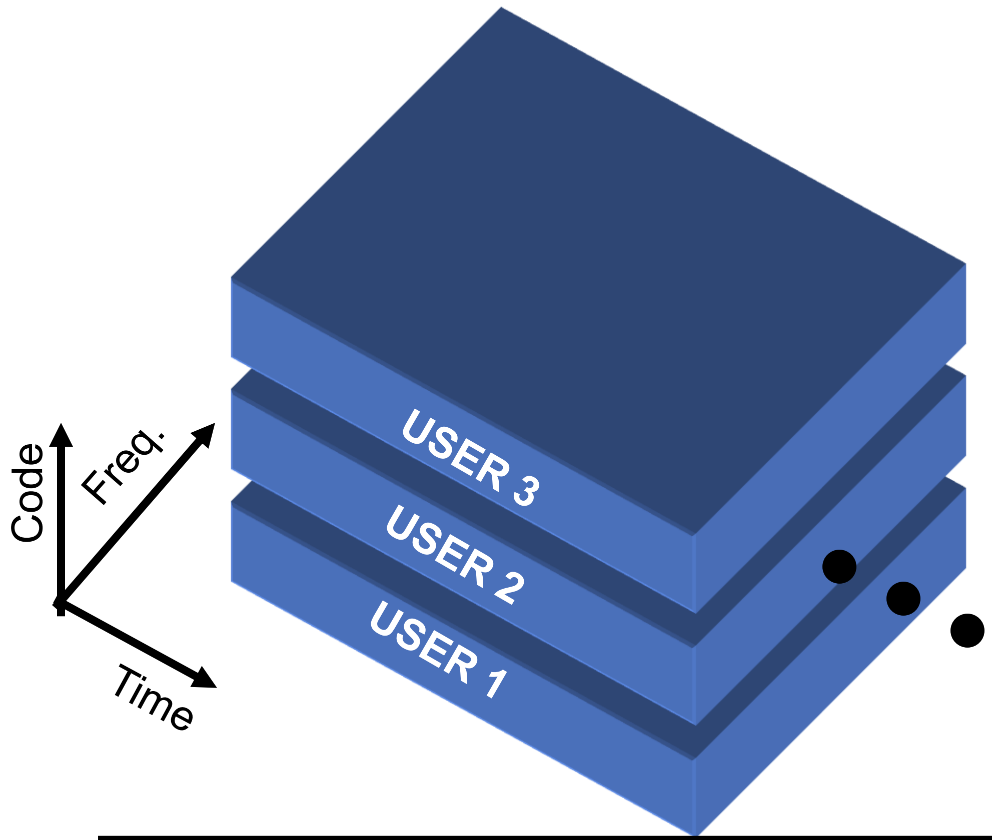


Users are separated in time slots.

Example: Global System for Mobile communications (GSM)

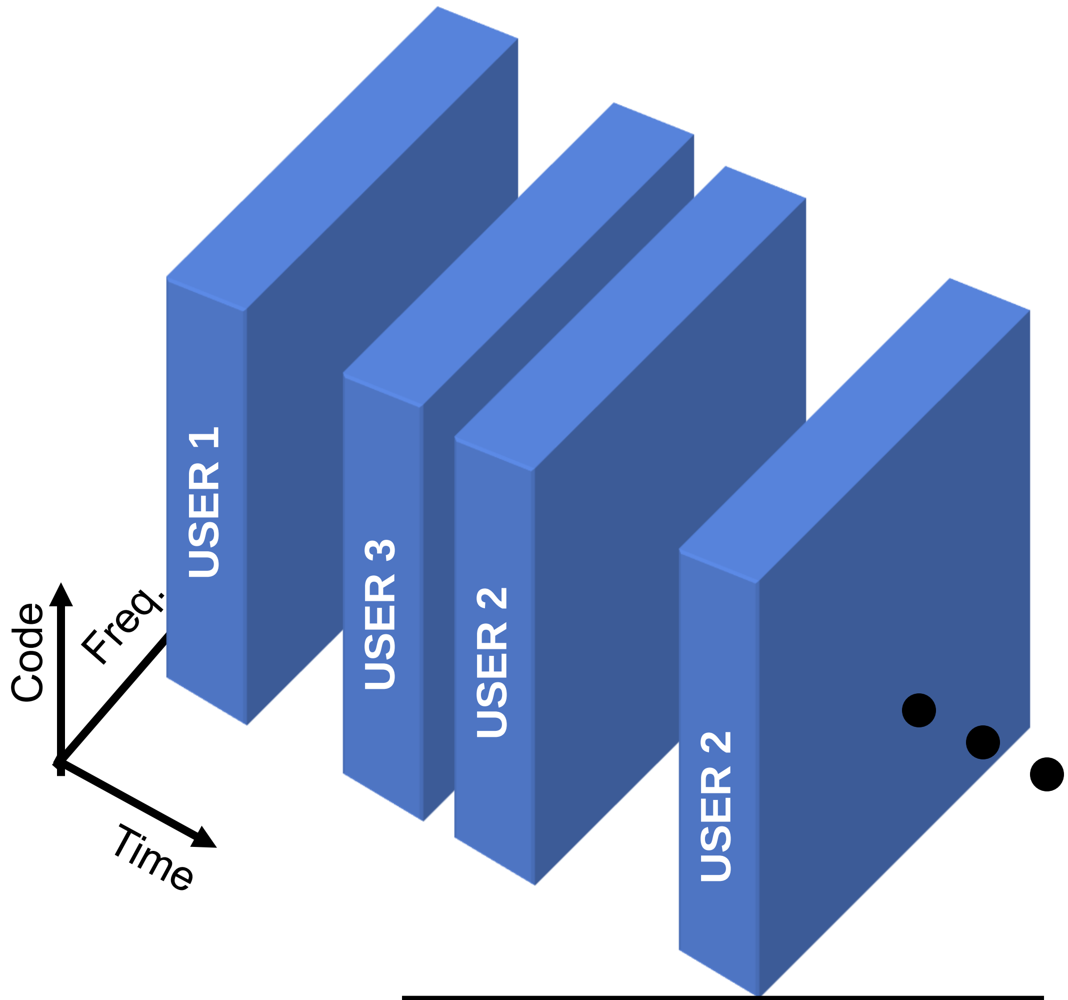
MULTIPLE ACCESS
Code-division multiple access (CDMA)

Users are separated by spreading codes.



Examples: CdmaOne, Wideband CDMA (WCDMA), Cdma2000

MULTIPLE ACCESS
Carrier-sense multiple access (CSMA)



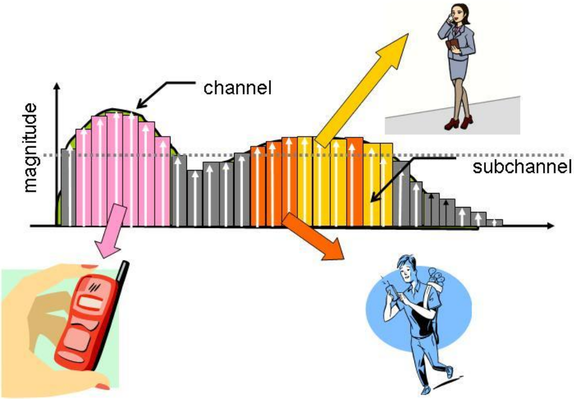
Users are separated in time but not in an organized way. The terminal listens to the channel, and transmits a packet if it's free.

Collissions can occur and data is lost.

Example: IEEE 802.11 (WLAN)

MULTIPLE ACCESS
Orthogonal Frequency Division Multiplexing

- Similar to FDMA, but more efficient
- Blocks of subcarriers are assigned to different users
- Used in LTE downlink and WiMax



Limited Energy

- Mobile devices are powered by batteries and thus need to be energy efficient.
- Wireless chipset is not the main energy consumer in modern smartphones, but still important
- Today's standards already include various power-saving modes for phones
- Also infrastructure needs to be designed in power efficient way to reduce cost (minimize bits/Hertz/Joule).
- Sensor networks even more concerned: battery supposed to last for years

User mobility

- User can change position
- Mobility within one cell (i.e., maintaining a link to a certain BS): mostly effect on propagation channel (fading)
- Mobility from cell to cell: Handover, roaming, etc

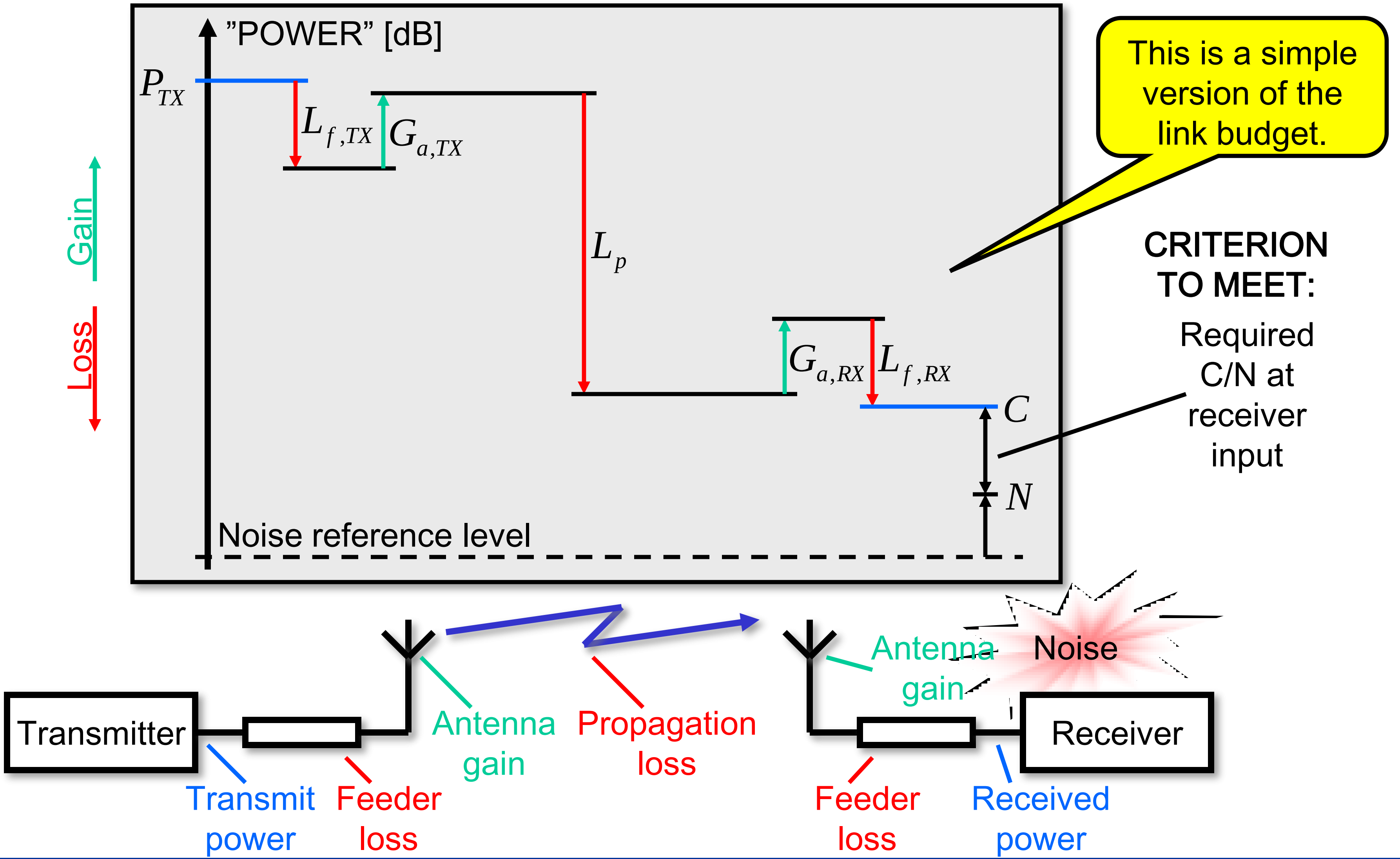
Chapter 3

Noise- and interference limited systems

Basics of link budgets

- Link budgets show how different components and propagation processes influence the available SNR
- Link budgets can be used to compute, e.g., required transmit power, possible range of a system, or required receiver sensitivity
- Link budgets can be most easily set up using logarithmic power units (dB)

SINGLE LINK
The link budget – a central concept



dB in general

When we convert a measure X into decibel scale, we always divide by a reference value X_{ref}:

$$\frac{X\,|_{non-dB}}{X_{ref}\,|_{non-dB}}$$

Independent of the dimension of X (and X_{ref}), this value is always dimension-less.

The corresponding dB value is calculated as:

$$X\,|_{dB} = 10\log\left(\frac{X\,|_{non-dB}}{X_{ref}\,|_{non-dB}}\right)$$

Power

We usually measure power in Watt (W) and milliWatt [mW]

The corresponding dB notations are dB and dBm

	Non-dB	dB
Watt:	$P\|_W$	$P\|_{dB} = 10\log\left(\frac{P\|_W}{1\|_W}\right) = 10\log\left(P\|_W\right)$
milliWatt:	$P\|_{mW}$	$P\|_{dBm} = 10\log\left(\frac{P\|_{mW}}{1\|_{mW}}\right) = 10\log\left(P\|_{mW}\right)$
RELATION:	$P\|_{dBm} = 10\log\left(\frac{P\|_W}{0.001\|_W}\right) = 10\log\left(P\|_W\right) + 30\|_{dB} = P\|_{dB} + 30\|_{dB}$	

Example: Power

Sensitivity level of GSM RX: 6.3×10^{-14} W = -132 dB or -102 dBm

Bluetooth TX: 10 mW = -20 dB or 10 dBm

GSM mobile TX: 1 W = 0 dB or 30 dBm

GSM base station TX: 40 W = 16 dB or 46 dBm

ERP – Effective Radiated Power

Vacuum cleaner: 1600 W = 32 dB or 62 dBm

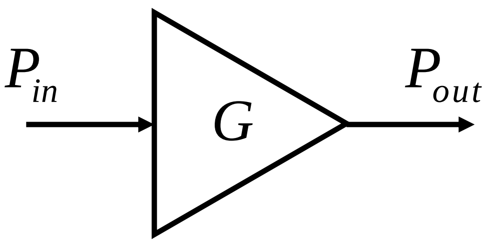
Car engine: 100 kW = 50 dB or 80 dBm

TV transmitter (Hörby, SVT2): 1000 kW ERP = 60 dB or 90 dBm ERP

Nuclear powerplant (Barsebäck): 1200 MW = 91 dB or 121 dBm

Amplification and attenuation

(Power) Amplification:



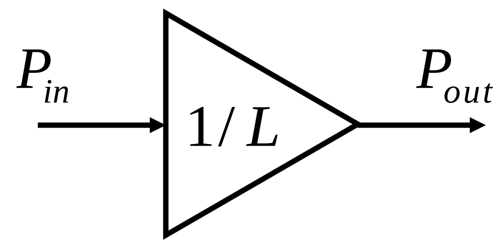
$$P_{out} = G P_{in} \Rightarrow G = \frac{P_{out}}{P_{in}}$$

The amplification is already dimension-less and can be converted directly to dB:

$$G|_{dB} = 10 \log_{10} G$$

Note: It doesn't matter if the power is in mW or W. Same result!

(Power) Attenuation:

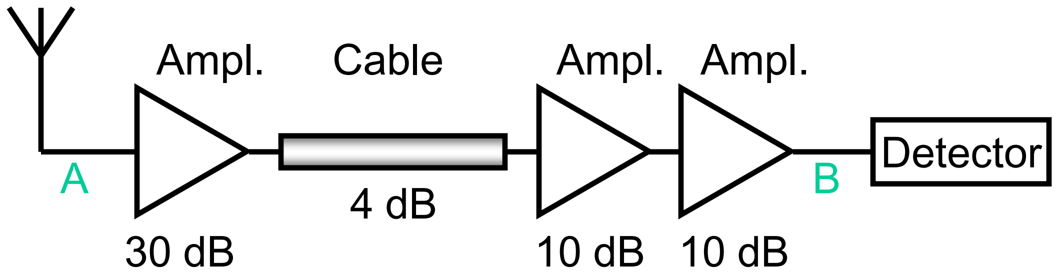


$$P_{out} = \frac{P_{in}}{L} \Rightarrow L = \frac{P_{in}}{P_{out}}$$

The attenuation is already dimension-less and can be converted directly to dB:

$$L|_{dB} = 10 \log_{10} L$$

Example: Amplification and attenuation

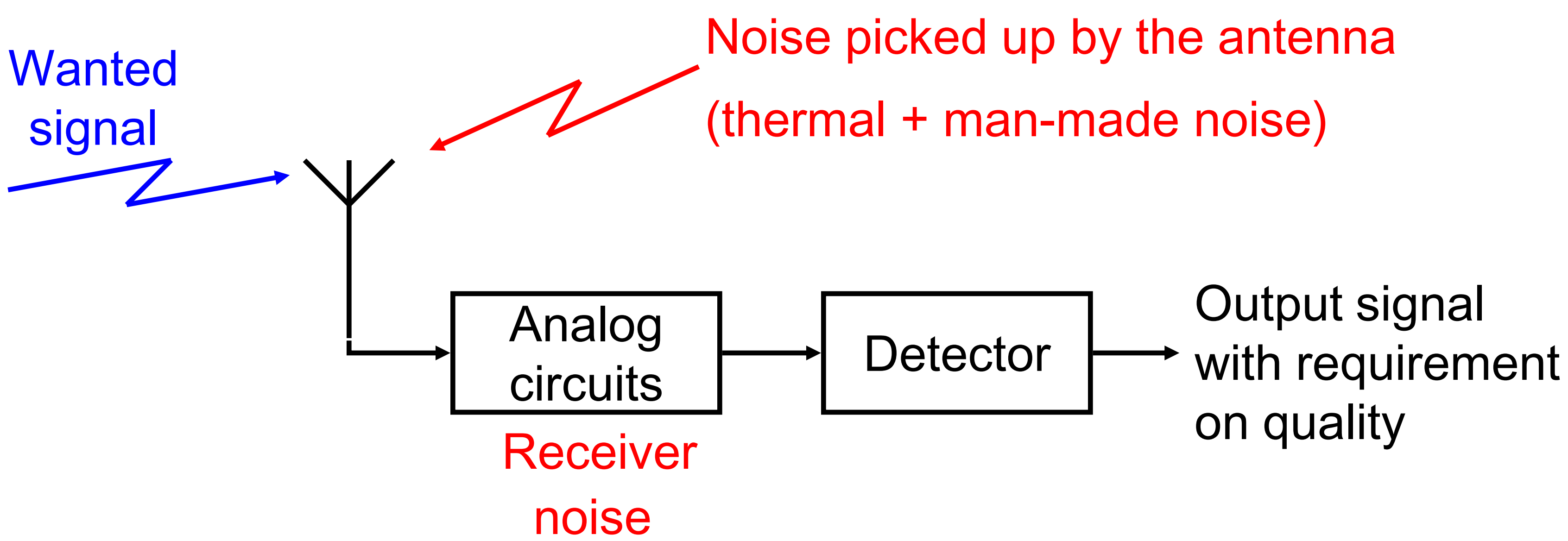


The total amplification of the (simplified) receiver chain (between A and B) is

$$G_{A,B}\,|_{dB} = 30 - 4 + 10 + 10 = 46$$

Noise sources

The noise situation in a receiver depends on several noise sources

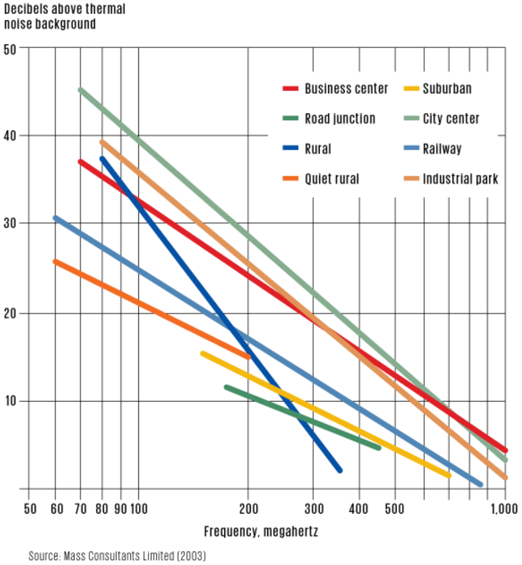


Thermal Noise

$$N_0 = k_B T_e$$

- N_0 thermal noise in Watt/Hz,
- $k_B = 1.38 \times 10^{-23}$ Joule/Kelvin Boltzman constant (Joule = Watt$\times$second),
- T_e environment temperature in Kelvin
- Average temperature on surface of the earth $T_e \approx 300$K $\Rightarrow N_0 \approx -174$dBm/Hz
- For a receiver with a total bandwidth of B Hz, the total received noise is $P_n = N_0 B$
- Example: $B = 200$kHz $\Rightarrow P_n = -174 + 10\log_{10}(B) \approx -121$ dBm

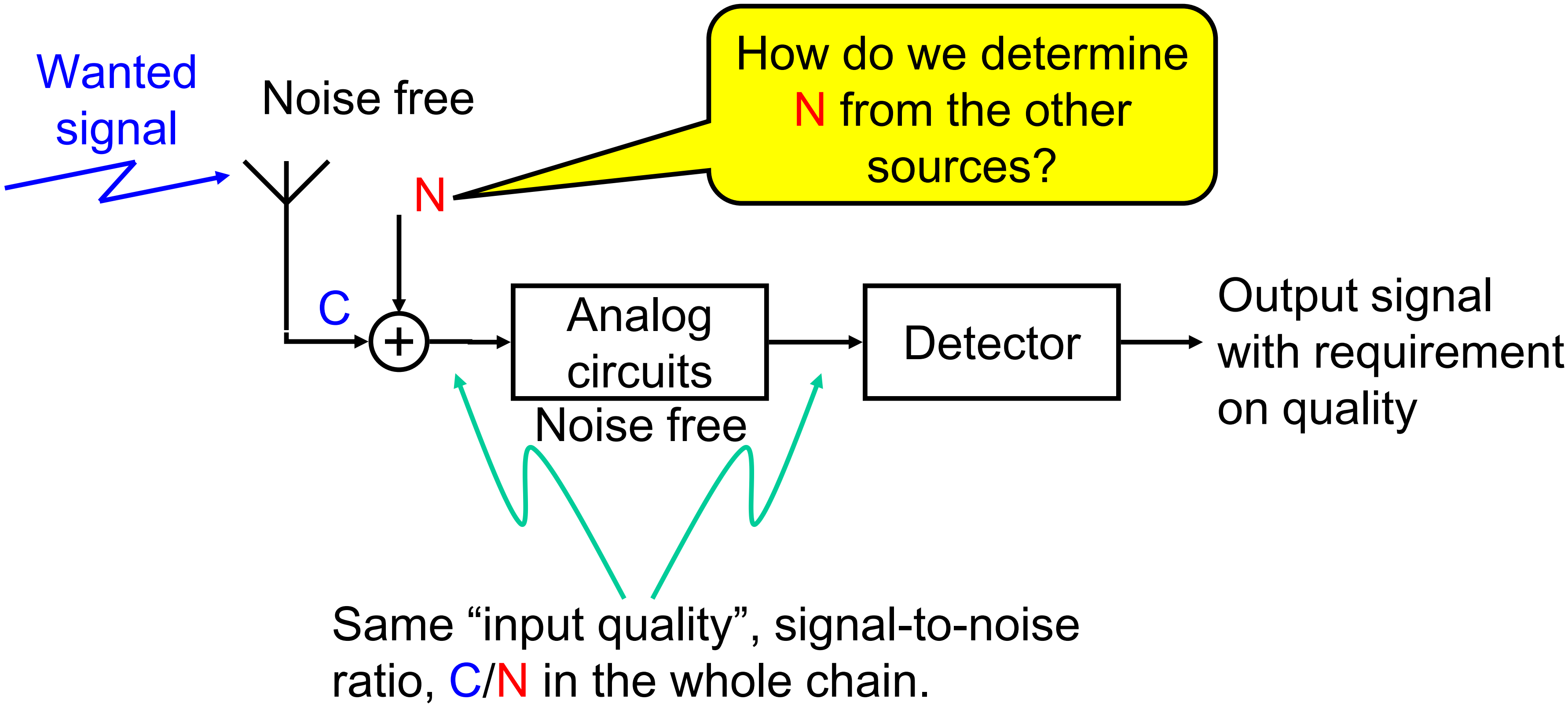
Man-made noise



Source: M.A. McHenry, D. Roberson, R.J. Matheson, "Electronic Noise Is Drowning Out the Internet of Things," IEEE Spectrum, September 2015.

Receiver noise: Equivalent noise source

To simplify the situation, we replace all noise sources with a single equivalent noise source.



Receiver noise: Noise sources (1)

The power spectral density of a noise source is usually given in one of the following three ways:

1) Directly [W/Hz]: N_s

2) Noise **temperature** [Kelvin]: T_s

3) Noise **factor** [1]: F_s

This one is sometimes given in dB and called **noise figure**.

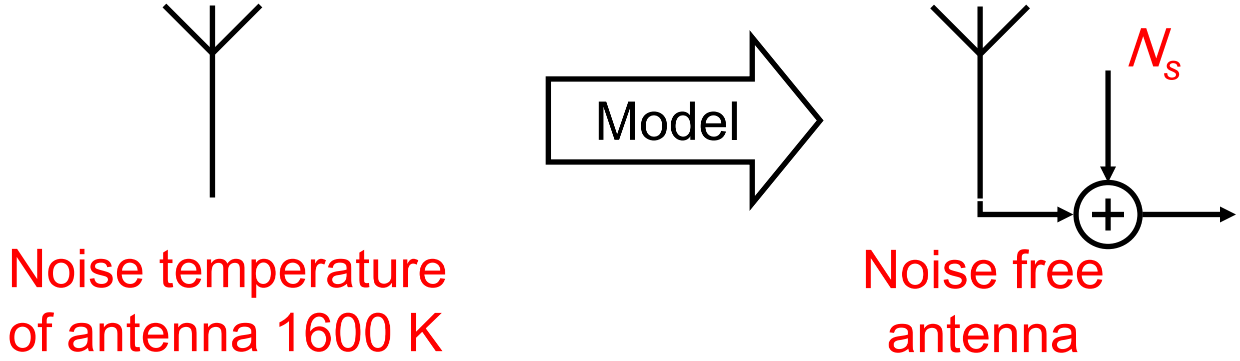
The relation between them is

$$N_s = kT_s = kF_sT_0$$

where k is **Boltzmann's constant** (1.38x10^{-23}J/K) and T_0 is the, so called, **room temperature** of 290 K (17^{o} C).

Receiver noise: Noise sources (2)

Antenna example



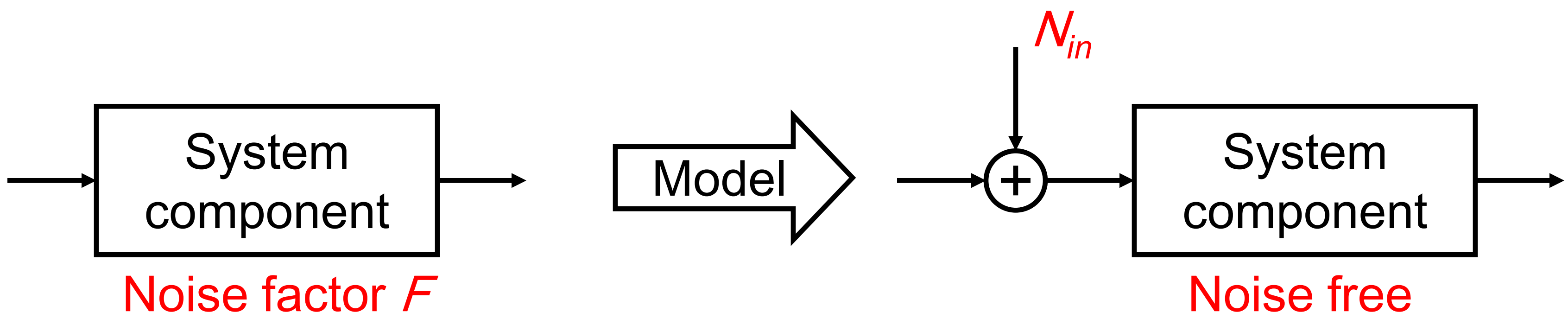
Power spectral density of antenna noise is

$$N_s = 1.38 \times 10^{-23} \times 1600 = 2.21 \times 10^{-20} \text{ W/Hz} = -196.6 \text{ dB[W/Hz]}$$

and its noise factor/noise figure is

$$F = 1600/290 = 5.52 = 7.42\text{dB}$$

Receiver noise: System noise



Due to a definition of noise factor (in this case) as the ratio of noise powers on the output versus on the input, when a resistor in room temperature (T_0=290 K) generates the input noise, the PSD of the equivalent noise source (placed **at the input**) becomes

$$N_{in} = k\underbrace{\left(F-1\right)T_0}_{\text{Equivalent noise temperature (at the input)}} \text{ W/Hz}$$

Don't use dB value!

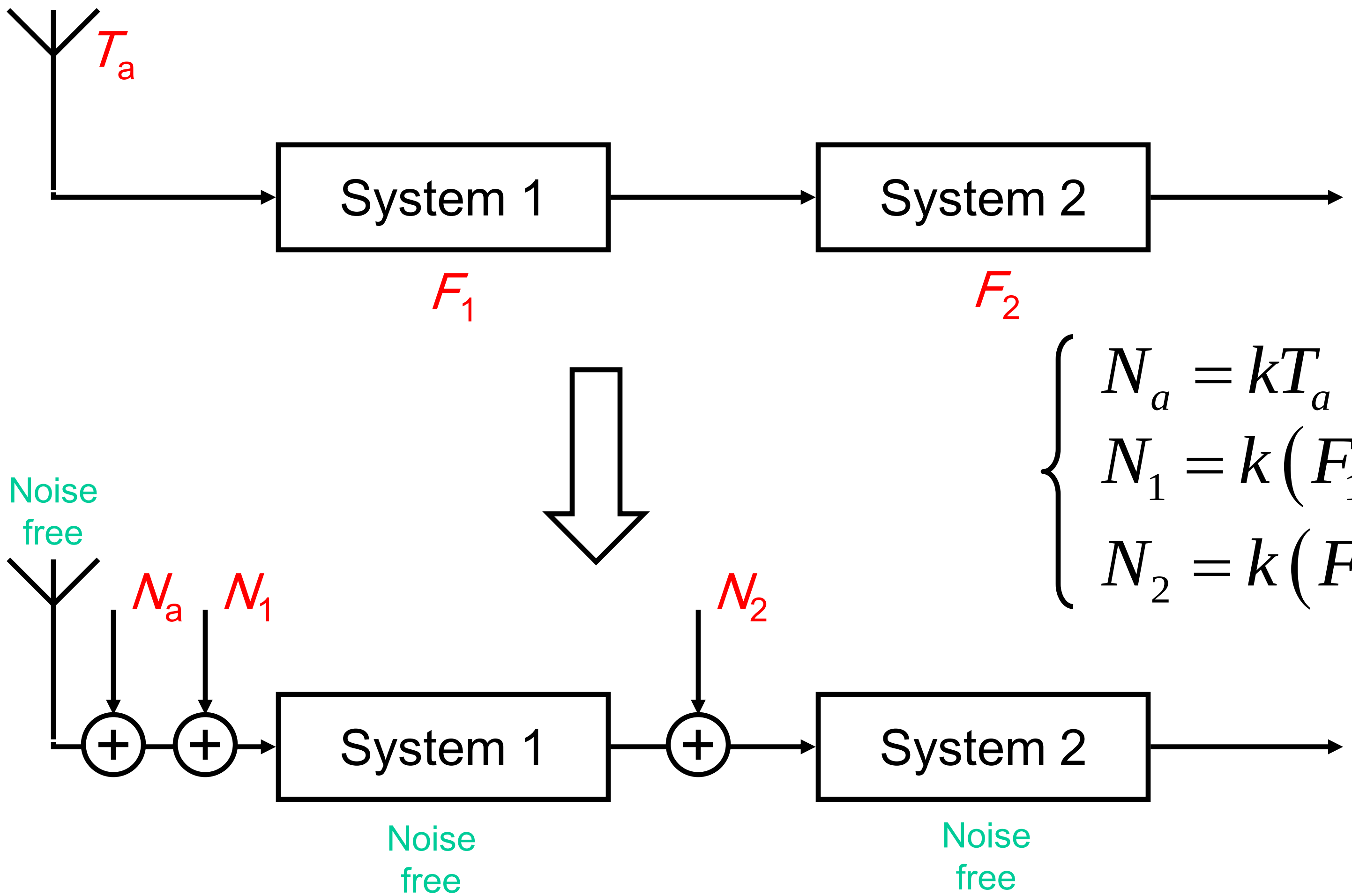
Receiver Noise: Example

A GSM receiver has a bandwidth of 200kHz and requires that its input SNR is at least 10dB when the input signal is -104dBm.

1. What is the thermal noise level at the receiver?
2. What is the maximum permitted value of the receiver noise figure?
3. What it the equivalent input noise temperature of such a receiver?

Receiver noise: Sev. noise sources (1)

A simple example

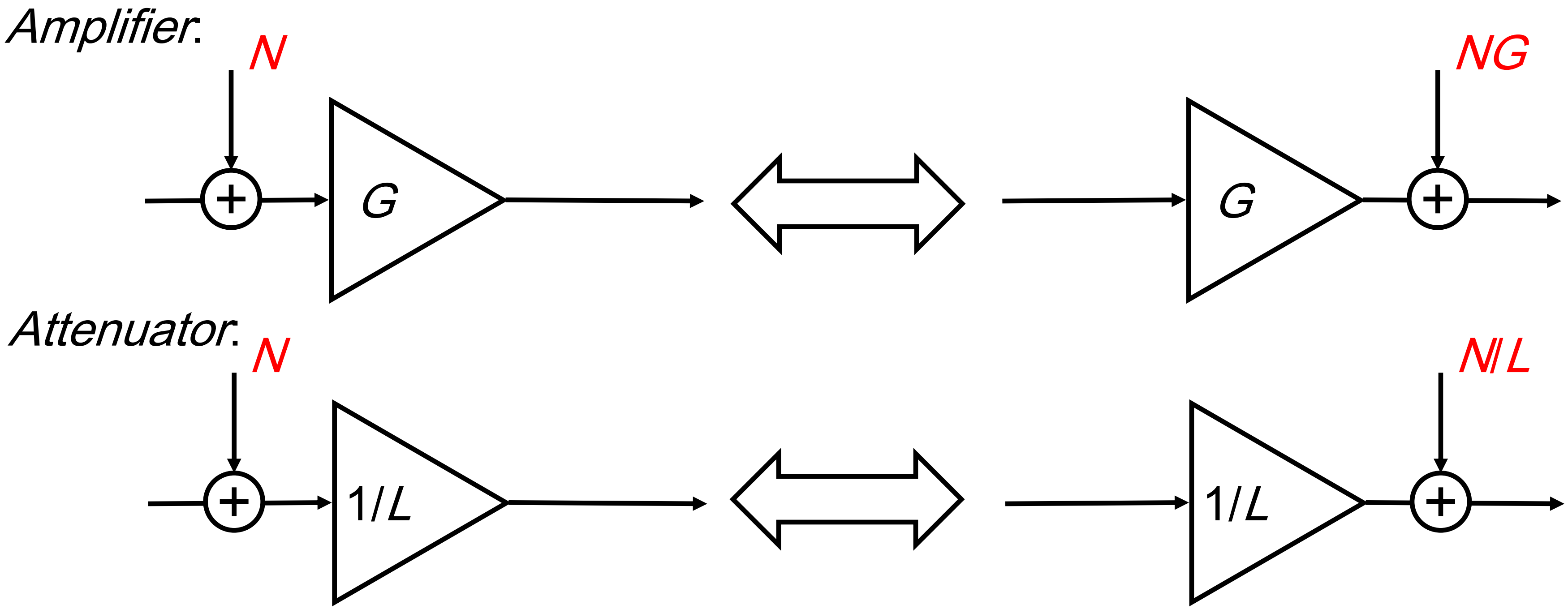


$$\begin{cases} N_a = kT_a \\ N_1 = k\left(F_1 - 1\right)T_0 \\ N_2 = k\left(F_2 - 1\right)T_0 \end{cases}$$

Receiver noise: Sev. noise sources (2)

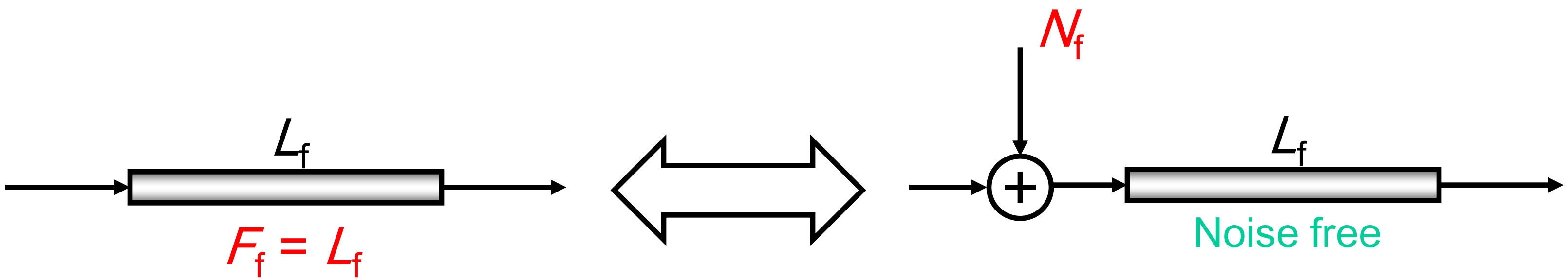
After extraction of the noise sources from each component, we need to move them to one point.

When doing this, we must compensate for amplification and attenuation!



Pierce's rule

A passive attenuator, in this case a feeder, has a noise figure equal to its attenuation.



$$N_f = k\left(F_f - 1\right)T_0 = k\left(L_f - 1\right)T_0$$

Remember to convert *from* dB!

Cascading several elements

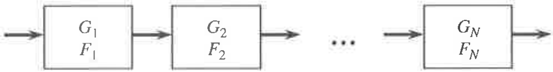


Figure 5.3: A cascade of two-port elements

- Total Gain:

$$G = G_1 \cdot G_2 \cdots G_N$$

- Total Noise Figure:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 \cdots G_{N-1}}$$

- Total effective noise temperature:

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots + \frac{T_{eN}}{G_1 \cdots G_{N-1}}$$

Example: Cascading several elements

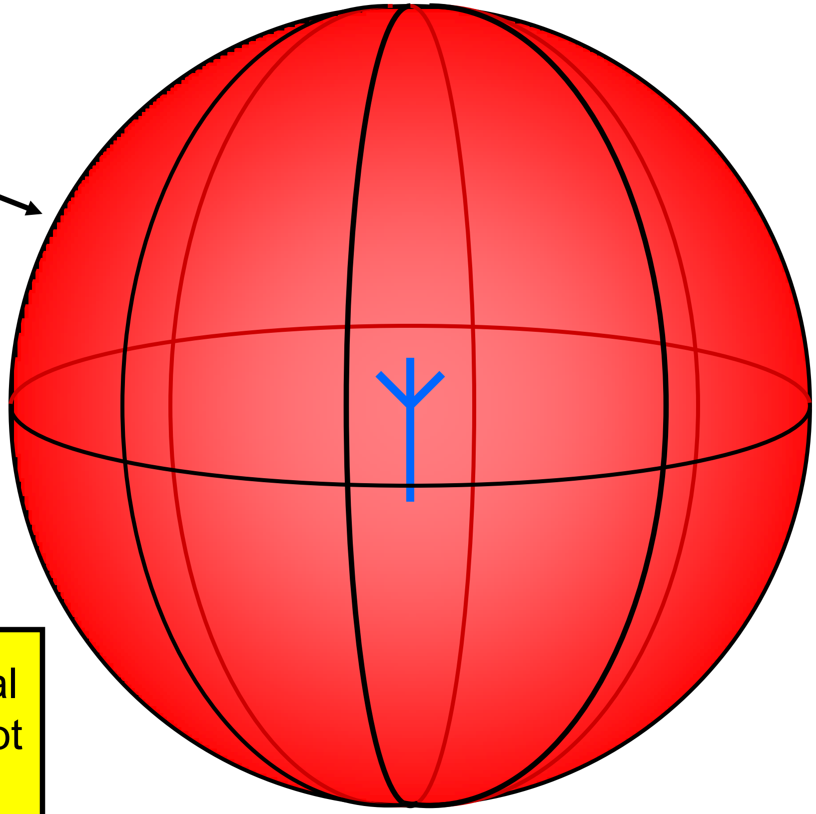
A receiver is made up of three main elements: a preamplifier, a mixer, and an IF amplifier with noise figures of 3, 6, and 10 dB.

- If the overall gain of the receiver is 30 dB, and the IF amplifier gain is 10 dB, what is the minimum gain of the preamplifier to achieve an overall noise figure of no more that 5 dB?
- If its gain is set to this minimum, what would the system noise figure become if the noise figure of the amplifier is increased to 20 dB?

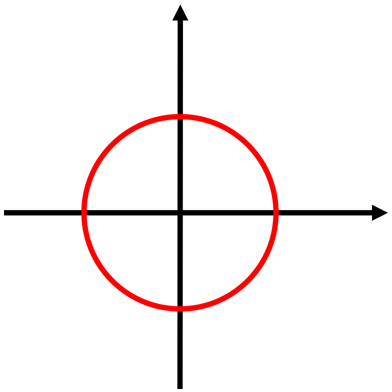
The isotropic antenna

The **isotropic antenna** radiates equally in all directions

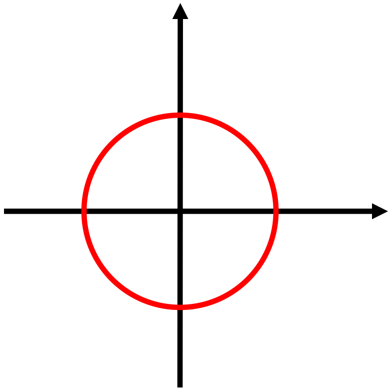
Radiation pattern is spherical



Elevation pattern



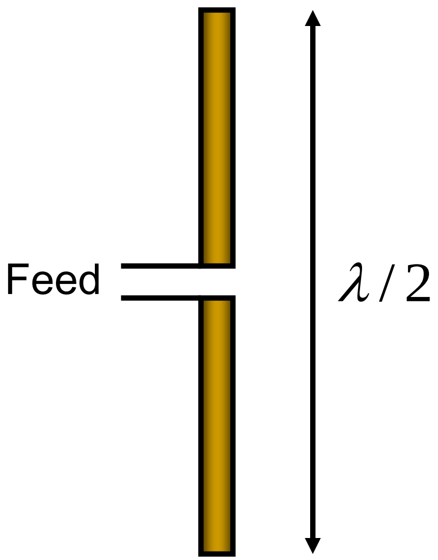
Azimuth pattern



This is a theoretical antenna that cannot be built.

The dipole antenna

$\lambda/2$-dipole

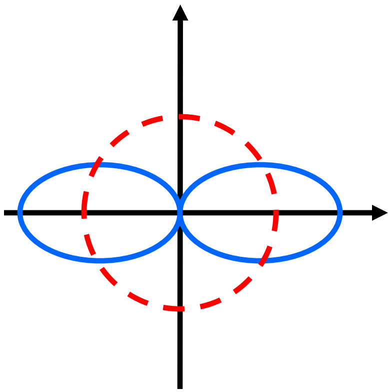


This antenna does not radiate straight up or down. Therefore, more energy is available in other directions.

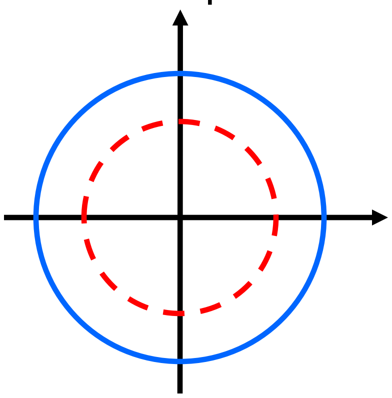
THIS IS THE PRINCIPLE BEHIND WHAT IS CALLED *ANTENNA GAIN*.

A dipole can be of any length, but the antenna patterns shown are only for the $\lambda/2$-dipole.

Elevation pattern



Azimuth pattern

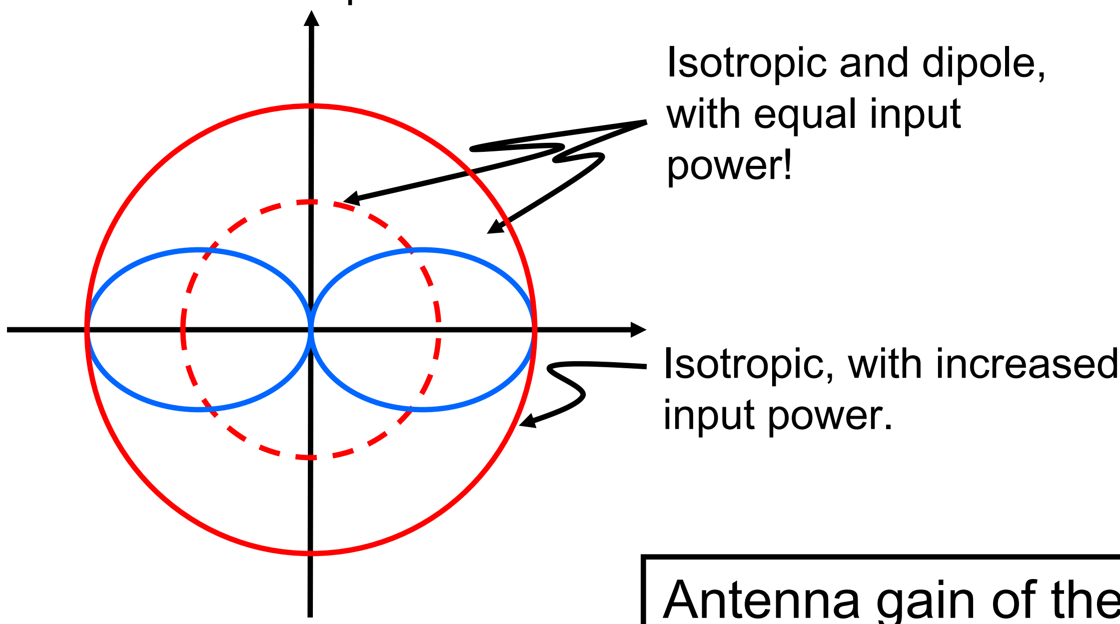


– – Antenna pattern of isotropic antenna.

Antenna gain (principle)

Antenna gain is a relative measure.

We will use the isotropic antenna as the reference.



The amount of increase in input power to the isotropic antenna, to obtain the same maximum radiation is called the **antenna gain**!

Antenna gain of the $\lambda/2$ dipole is **2.15 dB**.

A note on antenna gain

Sometimes the notation **dBi** is used for antenna gain (instead of dB).

The "**i**" indicates that it is the gain relative to the isotropic antenna (which we will use in this course).

Another measure of antenna gain frequently encountered is **dBd**, which is relative to the λ/2 dipole.

$$G|_{dBi} = G|_{dBd} + 2.15$$

Be careful! Sometimes it is not clear if the antenna gain is given in dBi or dBd.

EIRP: Effective Isotropic Radiated Power

EIRP = Transmit power (fed to the antenna) + antenna gain

$$EIRP\,|_{dB} = P_{TX|dB} + G_{TX|dB}$$

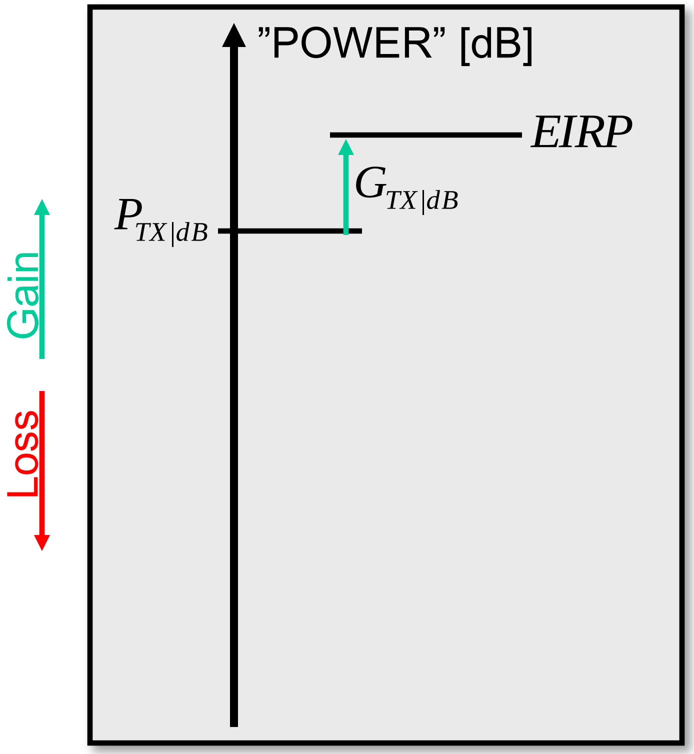
Answers the questions:

How much transmit power would we need to feed an isotropic antenna to obtain the same maximum on the radiated power?

How ”strong” is our radiation in the maximal direction of the antenna?

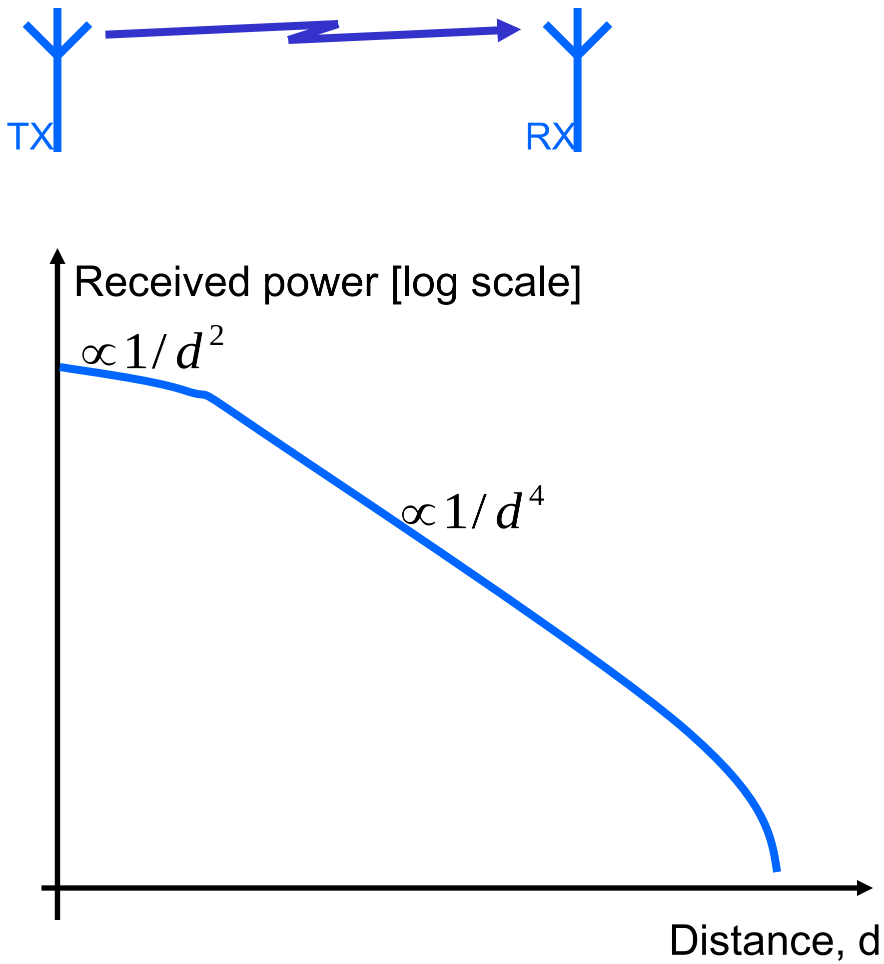
This is the more important one, since a limit on EIRP is a limit on the radiation in the maximal direction.

EIRP and the link budget



$$EIRP\,|_{dB} = P_{TX|dB} + G_{TX|dB}$$

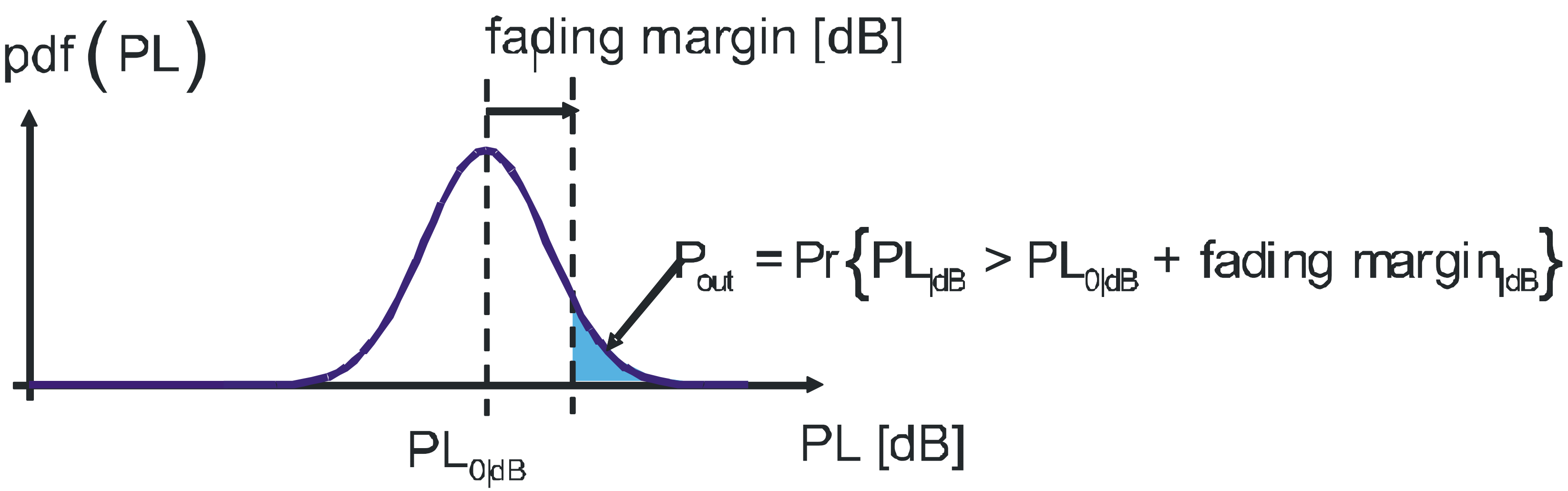
Path loss


TX
RX
Received power [log scale]
$\propto 1/d^2$
$\propto 1/d^4$
Distance, d

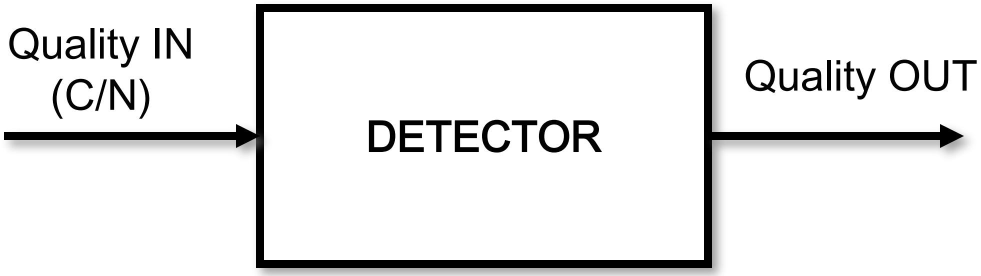
Fading margin

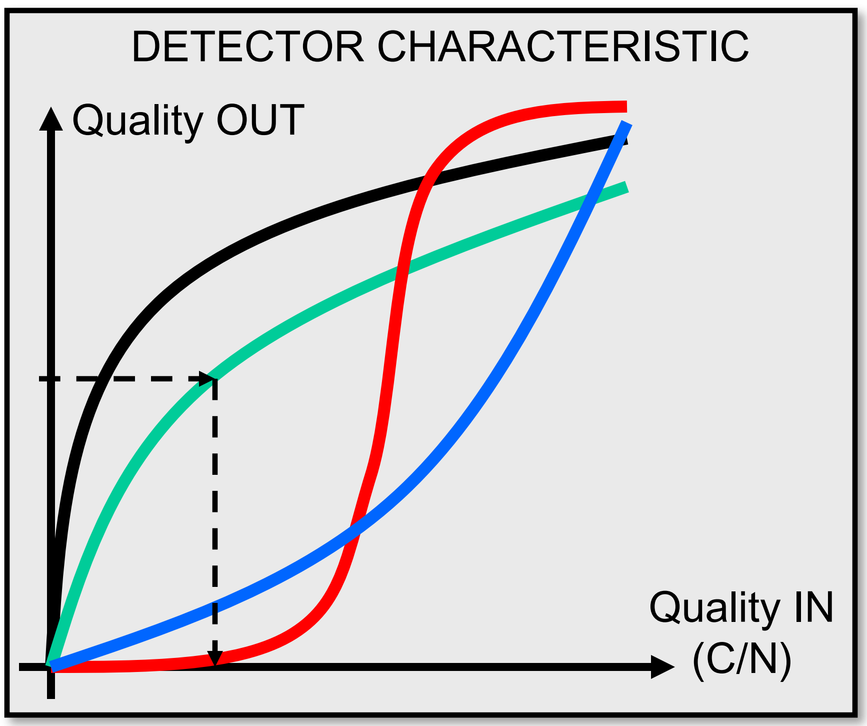
Received signal strength is not deterministic, more like a random process

-> include Fading margin to account for this uncertainty



Required C/N – another central concept



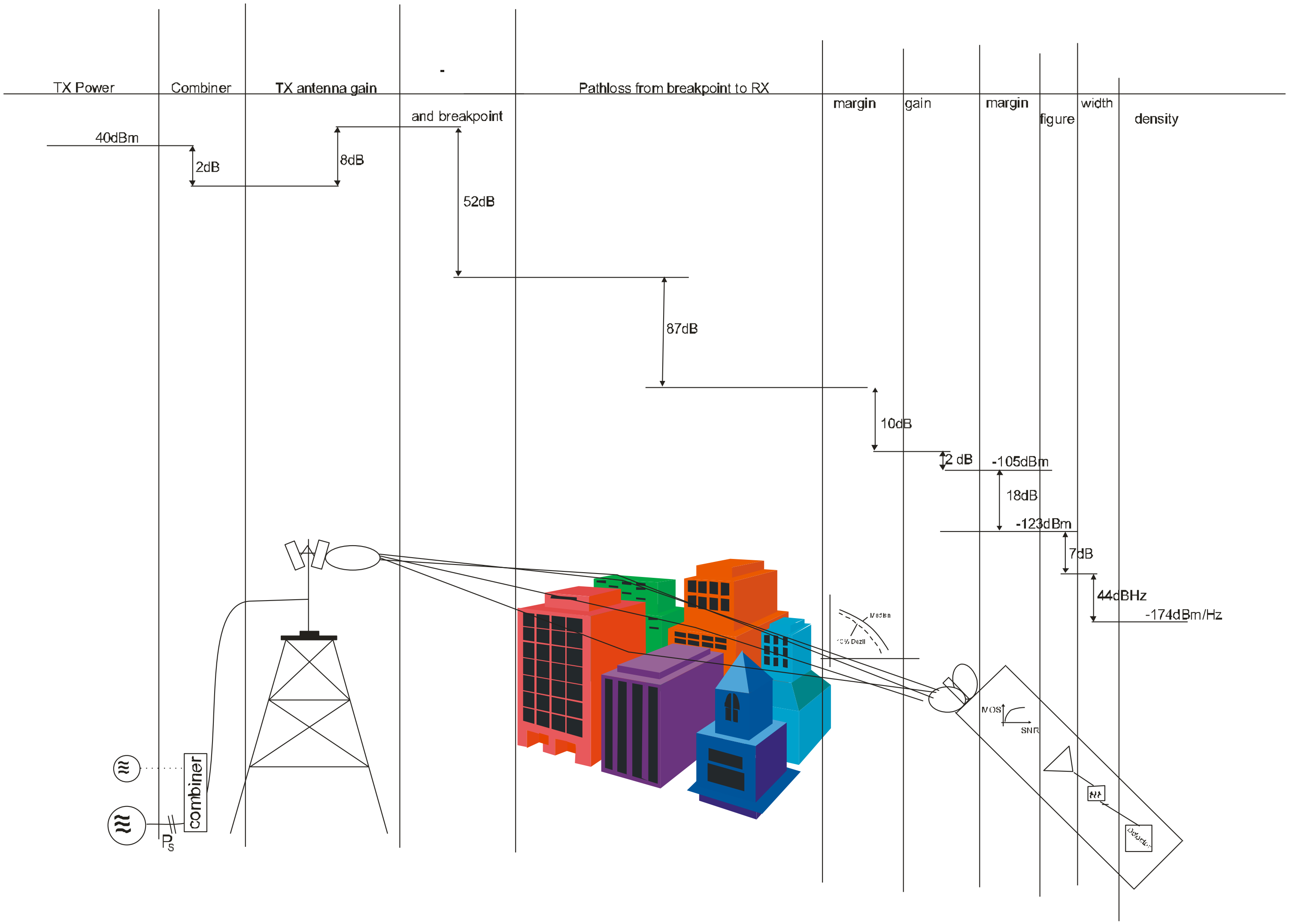


The detector characteristic is different for different system design choices.

REQUIRED QUALITY OUT:

Audio SNR
Perceptive audio quality
Bit-error rate
Packet-error rate
etc.

Example for link budget



Path loss model

- Path loss

$$P_{\mathrm{RX}}(d) = \frac{P_{\mathrm{TX}}}{PL(d)} \quad \text{or} \quad P_{\mathrm{RX}}(d)|_{\mathrm{dB}} = P_{\mathrm{TX}}|_{\mathrm{dB}} - PL(d)|_{\mathrm{dB}}$$

- Simple model

$$PL(d) = \left(\frac{4\pi d}{\lambda}\right)^2 \quad 0 \le d \le d_{\mathrm{break}}$$

$$PL(d) = PL(d_{\mathrm{break}})\left(\frac{d}{d_{\mathrm{break}}}\right)^n \quad d > d_{\mathrm{break}}$$

Link Budget: Example

Consider a GSM system with the following characteristics:

- Carrier frequency $f_c = 900\text{MHz}$,
- Bandwidth $B = 200\text{kHz}$,
- Operating temperature $T = 300$ K,
- Antenna gains $G_{\text{TX}} = 8$ dB and $G_{\text{RX}} = -2$ dB,
- Cable losses at TX $L_{\text{TX}} = 2$ dB,
- Receiver noise figure $F = 7$ dB.

The propagation characteristics are

- The path loss exponent is $n = 3.8$,
- the breakpoint distance is 10 m,
- the fading margin is 10 dB.

The required operating SNR is 8 dB, the desired range of coverage 2 km. **What is the minimum TX power?**

References

Claude Elwood Shannon,
"A mathematical theory of communication,"
The Bell System Technical Journal, vol. 27, pp. 379–432, July 1948.