UiO : Department of Technology Systems
University of Oslo

TEK5110: L2 Radio propagation

Radio propagation

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TEK5110 - Before we start

- Questions to L1 - introduction?

- Paper selection, state of the art based on your interest
  - preparation, evaluation
  - when to present

- Group work (later)

- Questions for Exam: http://its-wiki.no/wiki/TEK5110/List_of_Questions (to be completed)
  - Compendium: http://its-wiki.no/wiki/Building_Mobile_and_Wireless_Networks_Compendium

TEK5110 - Lecture Plan

Lecture plan is detailed on:
its-wiki.no/wiki/TEK5110

Learning outcomes

http://its-wiki.no/wiki/Building_Mobile_and_Wireless_Networks_Compendium

- Radio communications
  - Understand the basics of communication
  - Relation between range, frequency and capacity
- Radio Systems
  - from vicinity to long range
- Digital communication
  - Nyquist, Shannon
  - Capacity

⌘ History and Future[edit]

- History of wireless communications
- Maxwell, Hertz, Marconi and other pioneers
- 1G, 2G ... 5G networks
- Frequencies and Standards
- Future Challenges

⌘ TOC - Basics of Communication[edit]

- Electromagnetic Signals
- Radio Communication Principles
- Digital communication: Nyquist, Signal/Noise Ratio
- Signal strength and Capacity: Shannon

Connectivity & Affordability

The Unconnected Market Landscape

Unique Mobile Internet Users

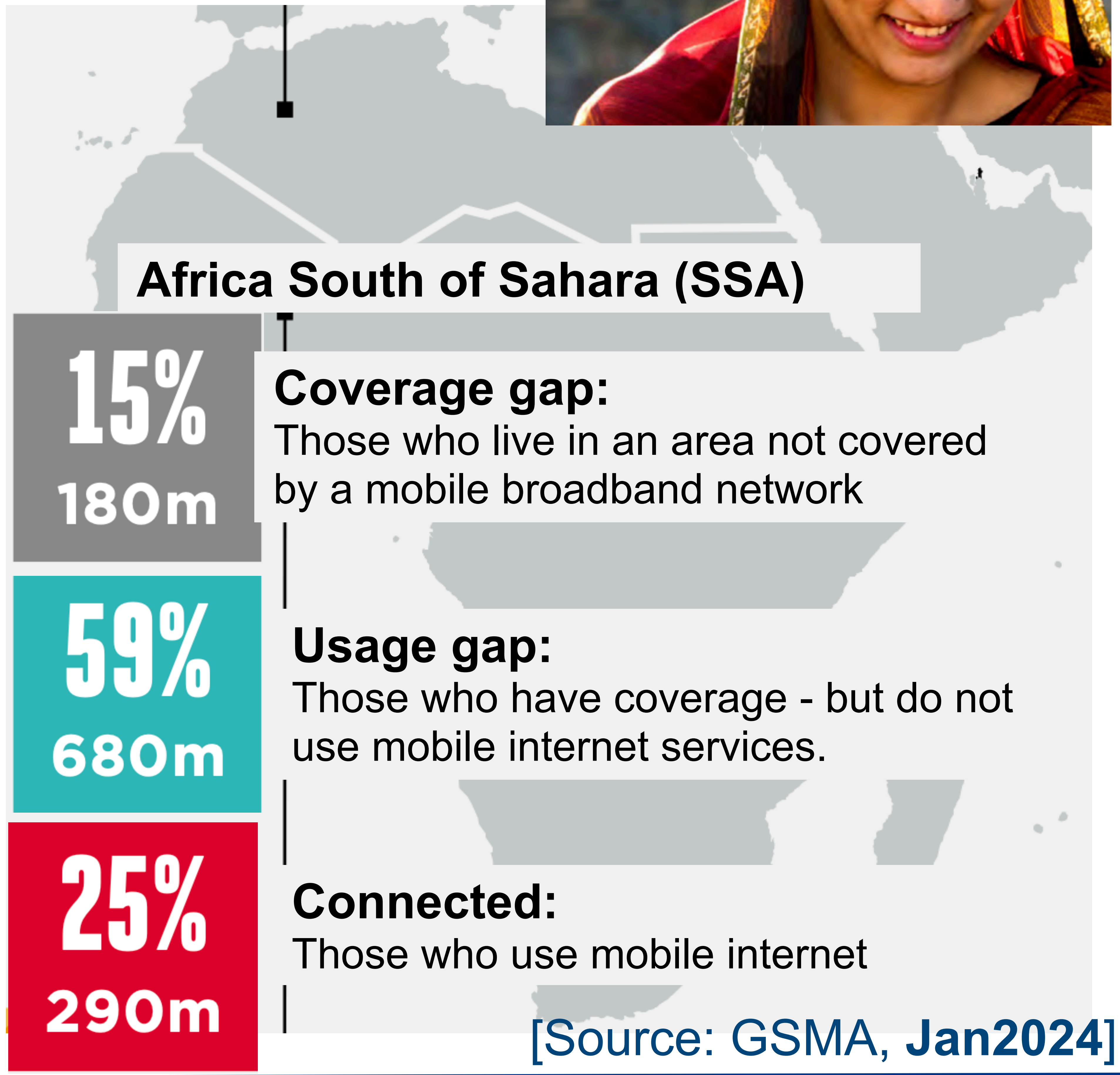
Population 15+ (bn)	Total	BMI	NMI	Unconnected	
Developed World	0.9	0.6	0.1	0.3	
Developing World	4.3	1.0	0.8	2.5	3.3
Total	5.2	1.6	0.9	2.8	

Penetration 15+ (%)	Total	BMI	NMI	Unconnected	
Developed World	100%	64%	8%	27%	
Developing World	100%	23%	18%	59%	77%
Total	100%	30%	[illegible]	53%	

Source: GSMA Intelligence; figures reflect position at end of 2014
BMI = Broadband Mobile Internet (3G/4G); NMI = Narrowband Mobile Internet (<3G)

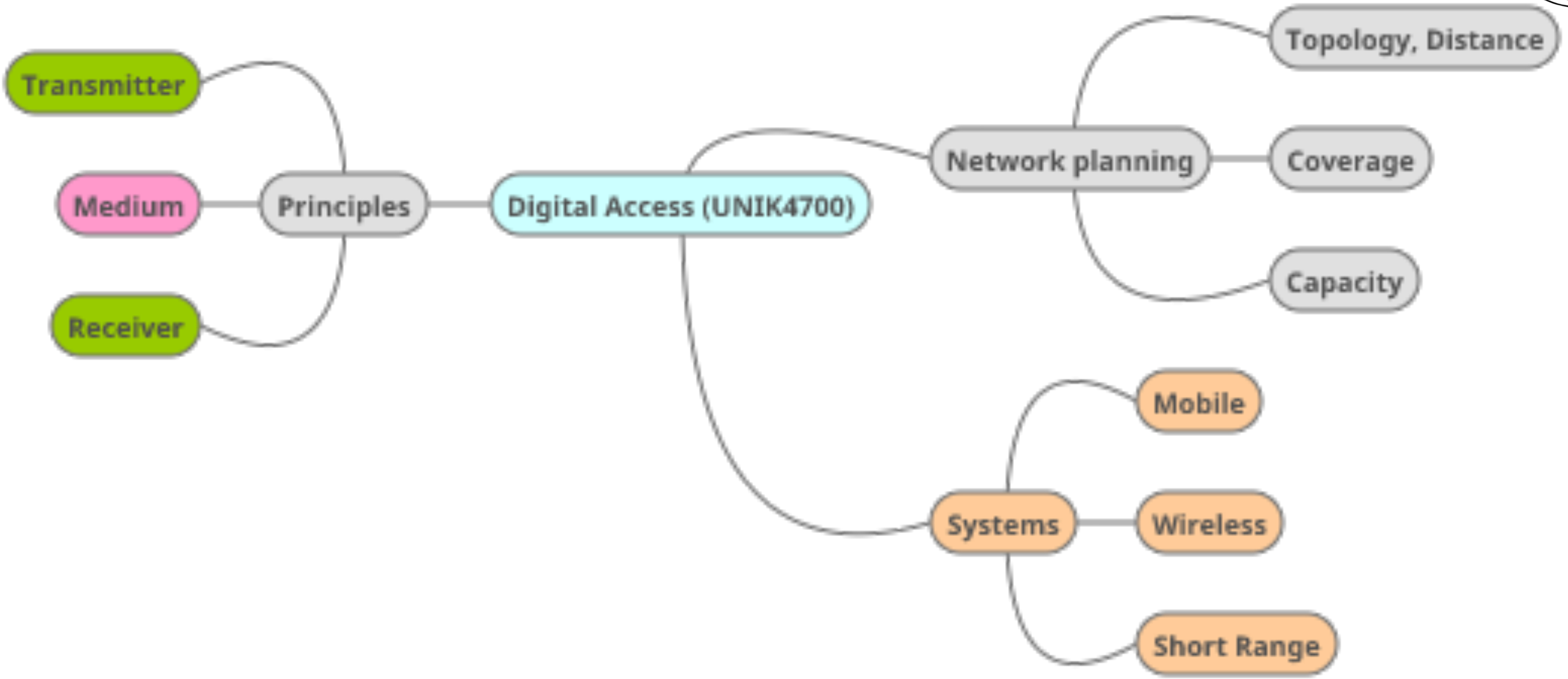
77% don't have decent access

[Source: GSMA, **Nov2015**]

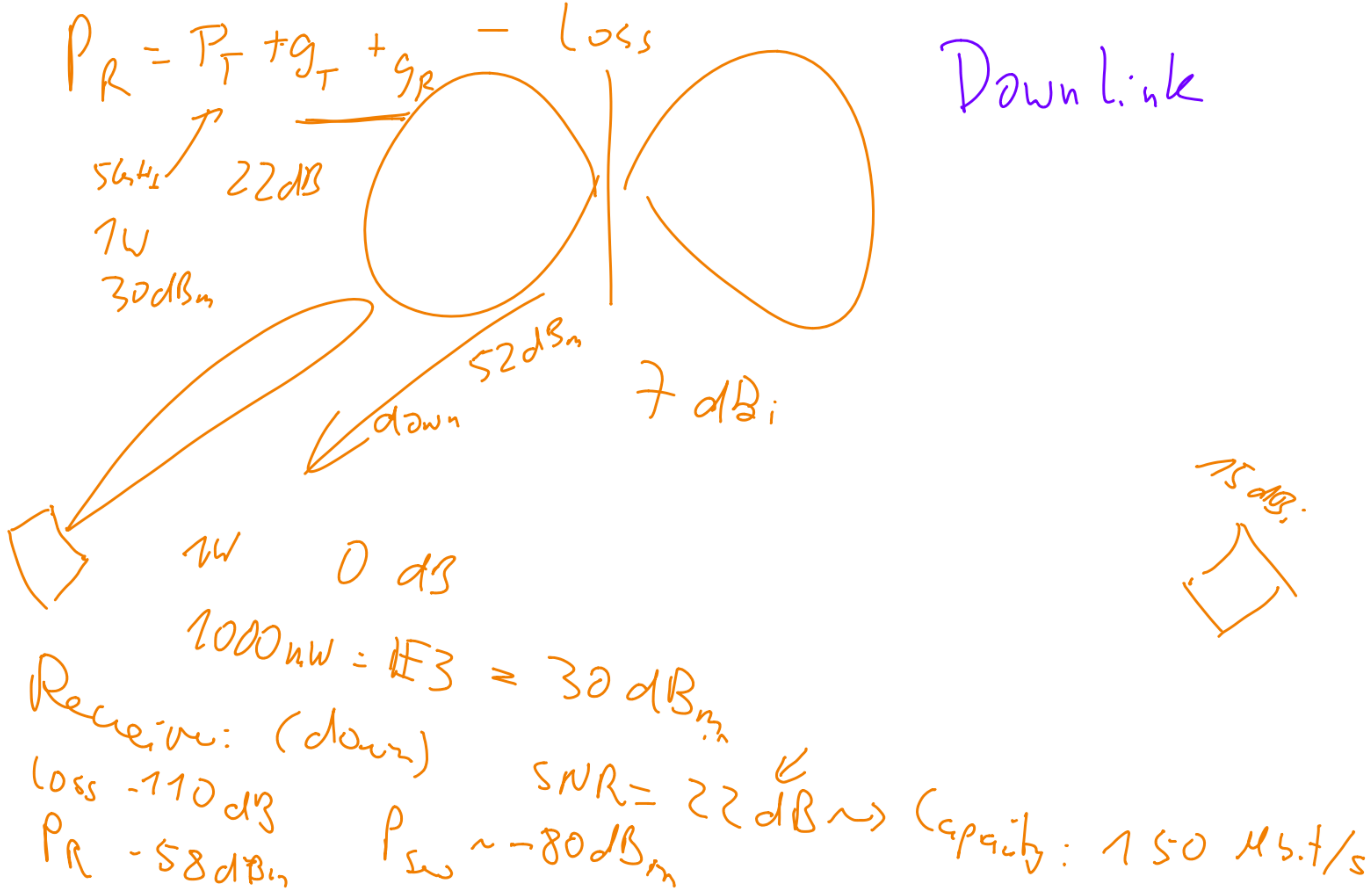


[Source: GSMA, **Jan2024**]

Overview over topics in the course



Can you do this calculation?

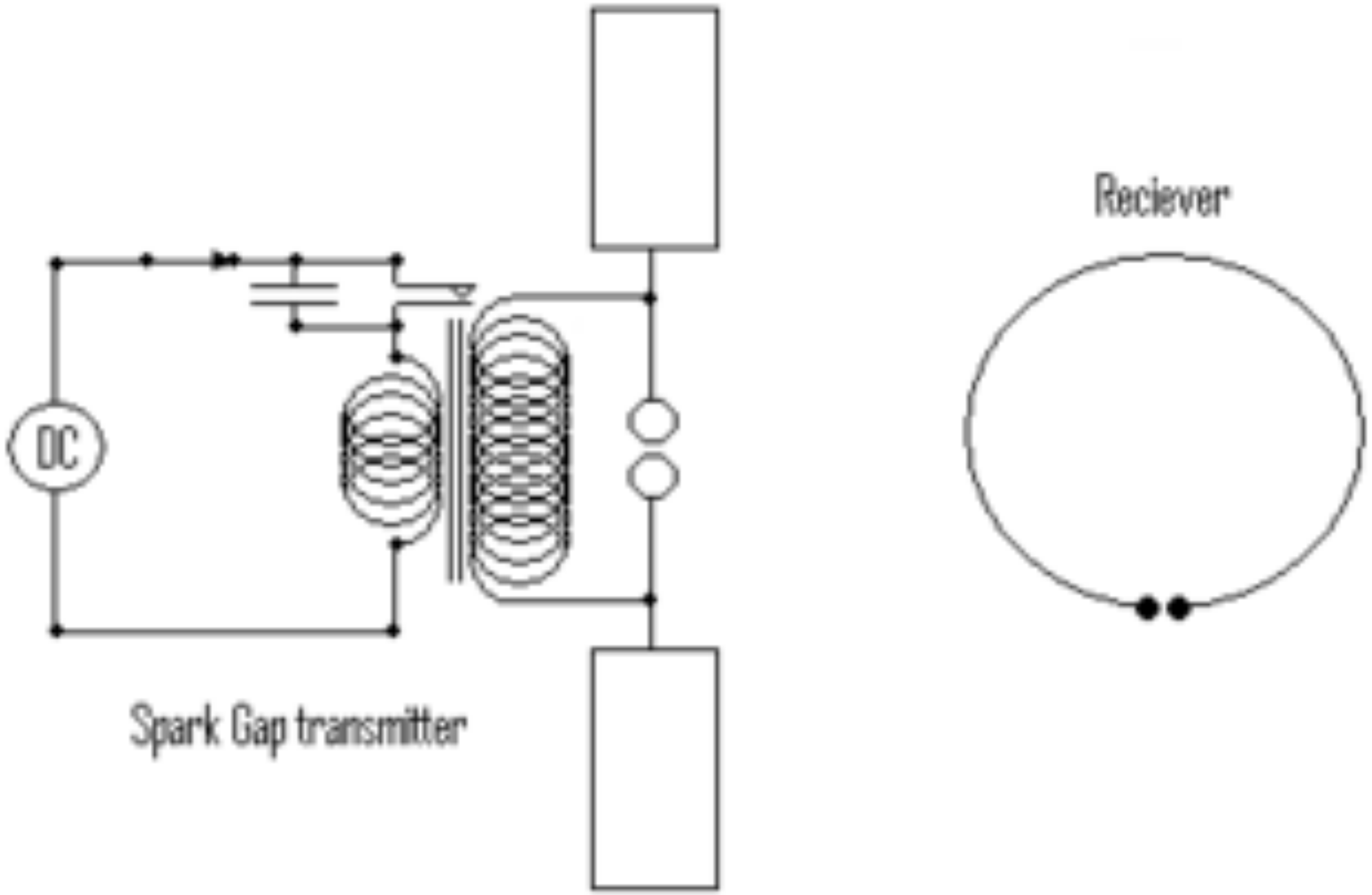


Voice vs electromagnetics

- How do we communicate?
- What are the factors influencing voice quality?
- Is there a capacity in voice communication?
- And what is different in electromagnetics?

The real researchers

- Michael Faraday (1791 - 1867), focussing on the static fields
- James Clerk Maxwell (1831 - 1879), establishing the Maxwell equations for the interaction of the electrical and the magnetic component of an electromagnetic wave
- Heinrich Rudolf Hertz (1857 - 1894) experimented the theory for the understanding of electromagnetic waves



[Source:Magne Pettersen, Wikipedia]

Heinrich Hertz - The electromagnetic wave

- Hertz did not realise the practical importance of his experiments. He stated that, "It's of no use whatsoever[...] this is just an experiment that proves Maestro Maxwell was right - we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there." [3]

- Asked about the ramifications of his discoveries, Hertz replied, "Nothing, I guess." [3]

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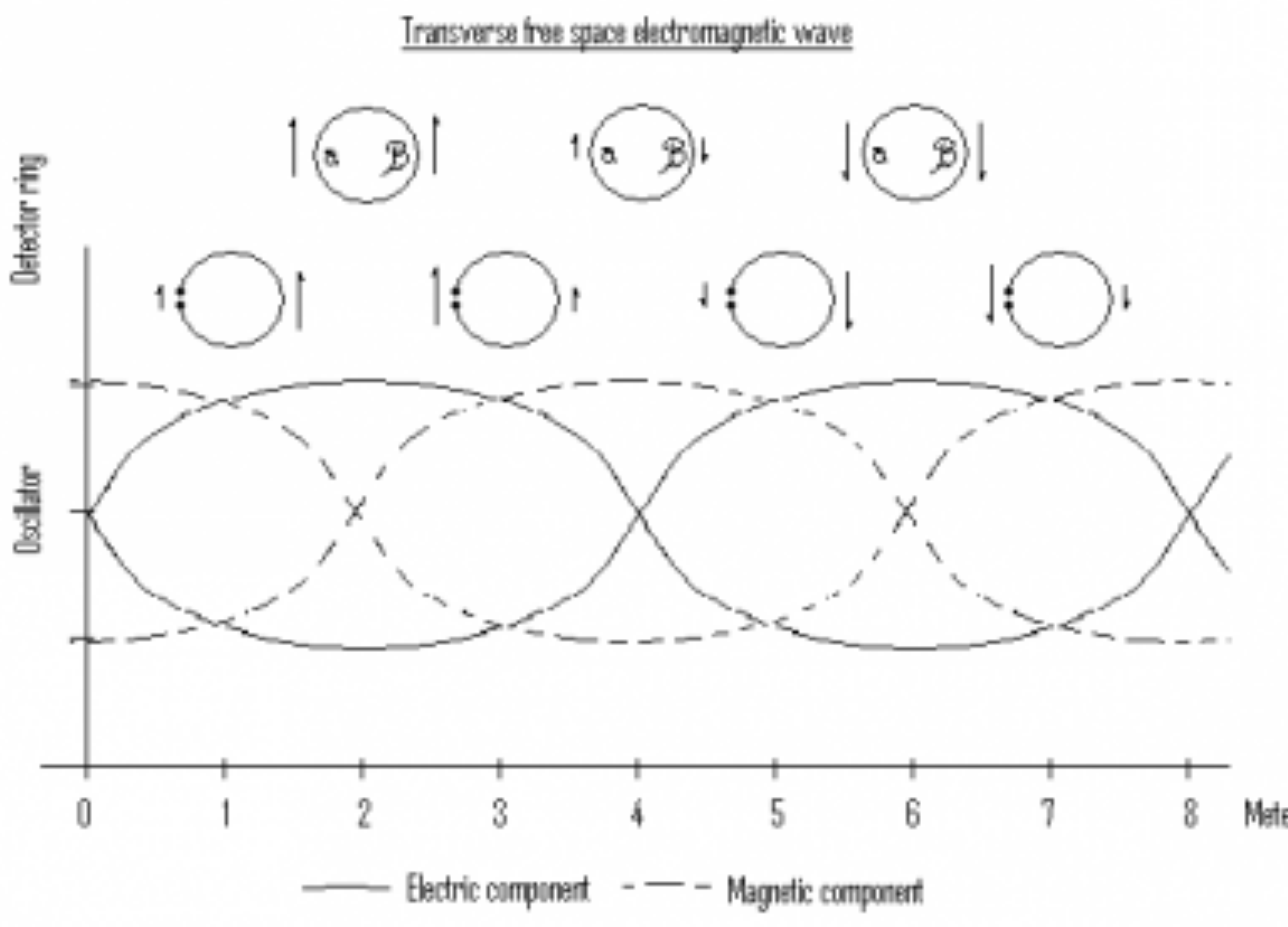


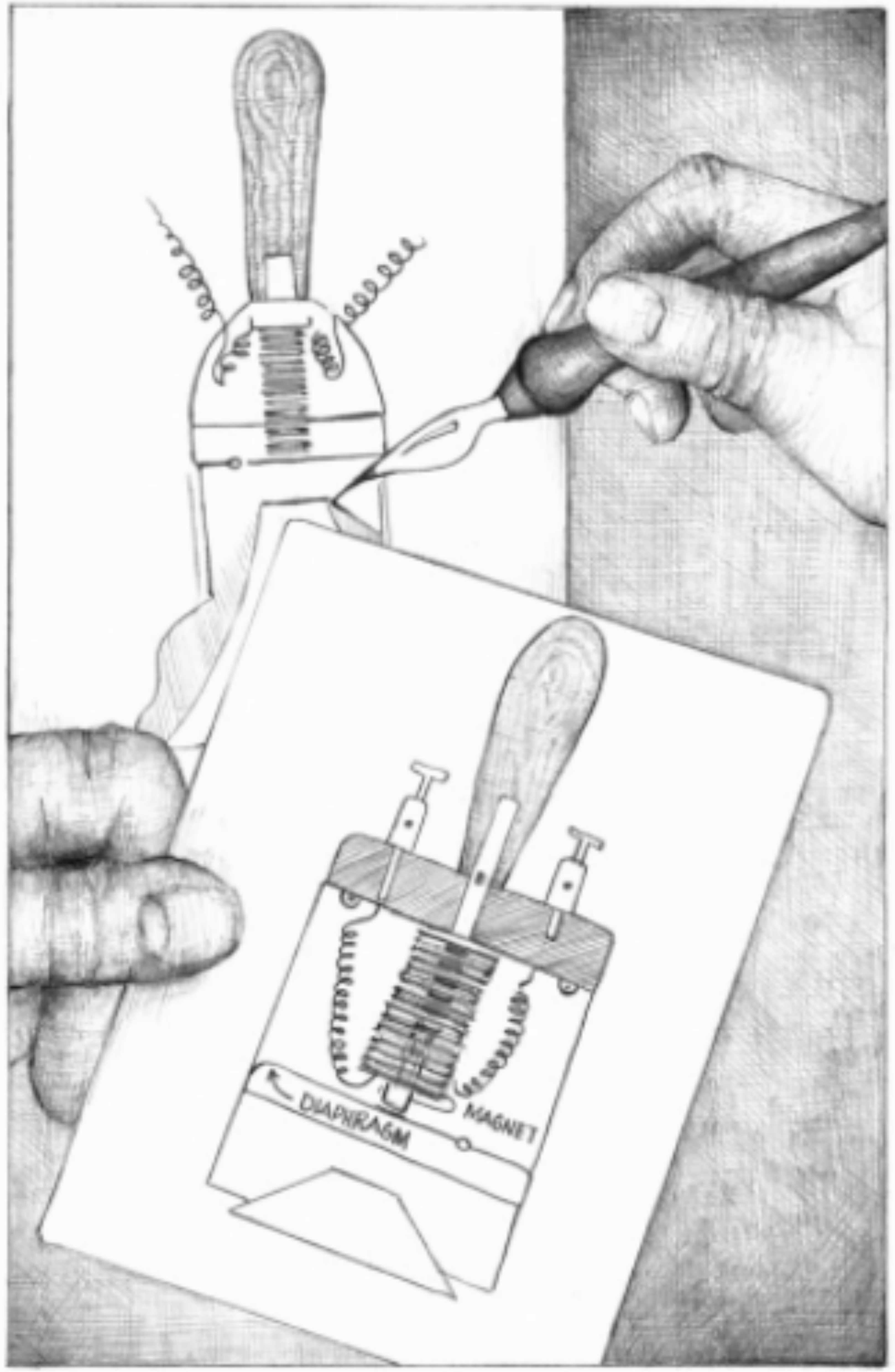
[Source:Magne Pettersen, Wikipedia]

Guglielmo Marconi - inventor

- Guglielmo Marconi (1874 - 1937) experimented with Hertz waves in 1894/1895
  - used 50000 UK pound on a transatlantic experiment in 1901
  - brought electromagnetics to life

Antonio Meucci - inventor

- ➡ Invented the phone in 1856
- ➡ transferred voice from one room to another one
- ➡ surveillance of an ill person
- ➡ registered patent in 1871
  - ▪ failed to name "electromagnetics"
  - ▪ Graham Bell patented in 1876



Antonio's Drawings of Telettrofono, Illustration by Shirlely Trievel

[Source: Wikipedia & Sandra Meucci, "Antonio and the electric scream: The man who invented the telephone", Branden Books, 2010]

Graham Bell - inventor

- Graham Bell (1874 -1922) invented the phone,...
- but who invented also the mobile phone back in 1924?
- Bell considered his most famous invention an intrusion on his real work as a scientist and refused to have a telephone in his study room

[Source: unknown]

Wave propagation and absorption mechanisms

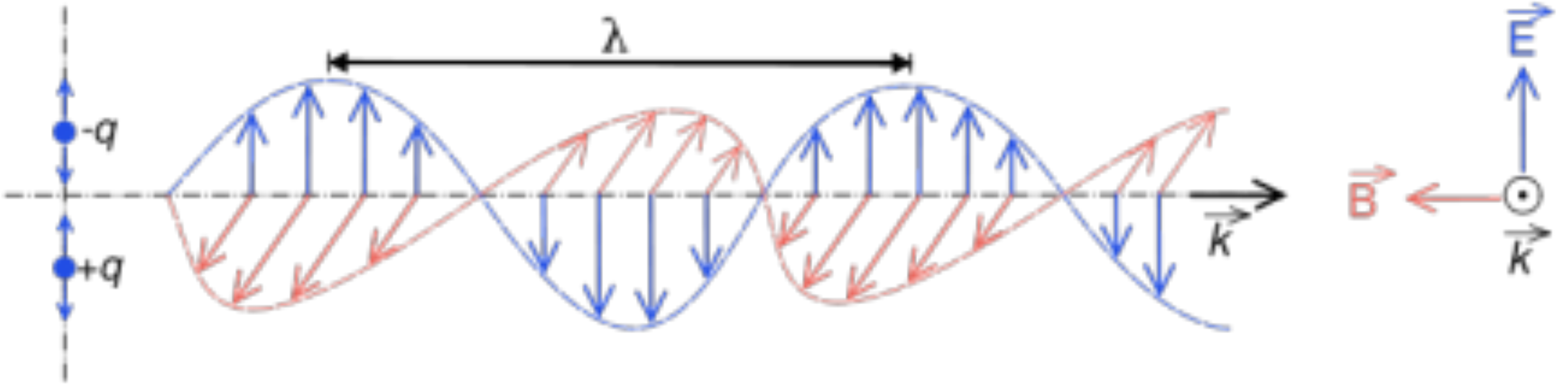
Band	Frequency	Wavelength	Propagation via
Very low frequency, VLF	3-30 kHz	100 - 10 km	Guided between the earth and the ionosphere.
Low frequency, LF	30 - 300 kHz	10 - 1 km	Guided between the earth and the D layer of the ionosphere. Surface waves.
Medium frequency, MF	300 - 3000 kHz	1000 - 100 m	Surface waves.E, F layer ionospheric refraction at night, when D layer absorption weakens.
High frequency, HF (short wave)	3-30 MHz	100-10 m	E layer ionospheric refraction. F1, F2 layer ionospheric refraction.
Very high frequency, VHF	30-300 MHz	10-1 m	Sporadic E propagation Extremely rare F1,F2 layer ionospheric refraction during high sunspot activity up to 80 MHz. Generally direct wave.
Ultra high frequency, UHF	300-3000 MHz	100-10 cm	Line-of-sight propagation. Sometimes tropospheric ducting.
Super high frequency, SHF	3-30 GHz	10-1 cm	Direct wave.
Extremely high frequency, EHF	30-300 GHz	10-1 mm	Direct wave limited by absorption.

Electromagnetic signals

dielectric constant ε_r
permeability μ_r

- Prerequisite: Ohm's law, current, dielectric constant , conductivity
  - "Pappa, what is voltage?"
  - Alternating electric and magnetic field
- Direction of wave from "right-hand rule"

$$\overrightarrow{B} = \mu_0 \mu_r \overrightarrow{H}$$



[Source:Magne Pettersen, Wikipedia]

[Source: unknown]

Maxwell, Wave equation

- see: http://its-wiki.no/wiki/B1-Free_Space_Propagation

Source free environment and free space:

$$\nabla \cdot \vec{E} = 0 \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

$$\nabla \times \vec{B} = \mu_0\epsilon_0 \frac{\partial}{\partial t}\vec{E} \quad (4)$$

yields the wave equation:

$$\frac{\partial^2 \vec{E}}{\partial t^2} - {c_0}^2 \cdot \nabla^2 \vec{E} = 0$$

$$\frac{\partial^2 \vec{B}}{\partial t^2} - {c_0}^2 \cdot \nabla^2 \vec{B} = 0$$

with $c_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.99792458 \times 10^8$ m/s

[Source: Wikipedia]

Homogeneous electromagnetic wave

- Questions/Tasks:
  - Group velocity for n=2
  - from where do you know n?
  - Show that for a plane wave:

$$\frac{E_x}{H_y} = Z_0 = \sqrt{\mu_0/\varepsilon_0}$$

A single frequency electro (E)-magnetic (B) wave is described by

$$\vec{E}(\vec{r}) = E_0 e^{j(\omega t - \vec{k}\cdot\vec{r})},$$

$$\vec{B}(\vec{r}) = B_0 e^{j(\omega t - \vec{k}\cdot\vec{r})},$$

[Source: Wikipedia]

where

- $\vec{r} = (x, y, z)$ and $\vec{k} = (k_x, k_y, k_z)$ so?
- j is the imaginary unit
- $\omega = 2\pi f$ is the angular frequency, [rad/s]
- f is the frequency [1/s]
- $e^{j\omega t} = \cos(\omega t) + j\sin(\omega t)$ is Euler's formula

with the group velocity (free space = speed of light) $c = \frac{c_0}{n} = \frac{1}{\sqrt{\mu\varepsilon}}$ and

the refraction index $n = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}}$

Free space propagation

- ➡ Questions/Tasks:
  - Propagation equation in dB
  - provide examples for *f = 10* MHz, 1 GHz, 100 GHz

Power received in an area in a distance R from transmitter:

- area of a sphere is $A_s = 4 * \pi * R^2$
- power transmitted from isotropic antenna is P_t
- antenna area of receiver is $A_r =^2 /4\pi$
- power received in A_r = P_r

$$P_r = P_t * A_r / A_s = P_r = P_t * A_r / (4 * \pi * R^2)$$

thus

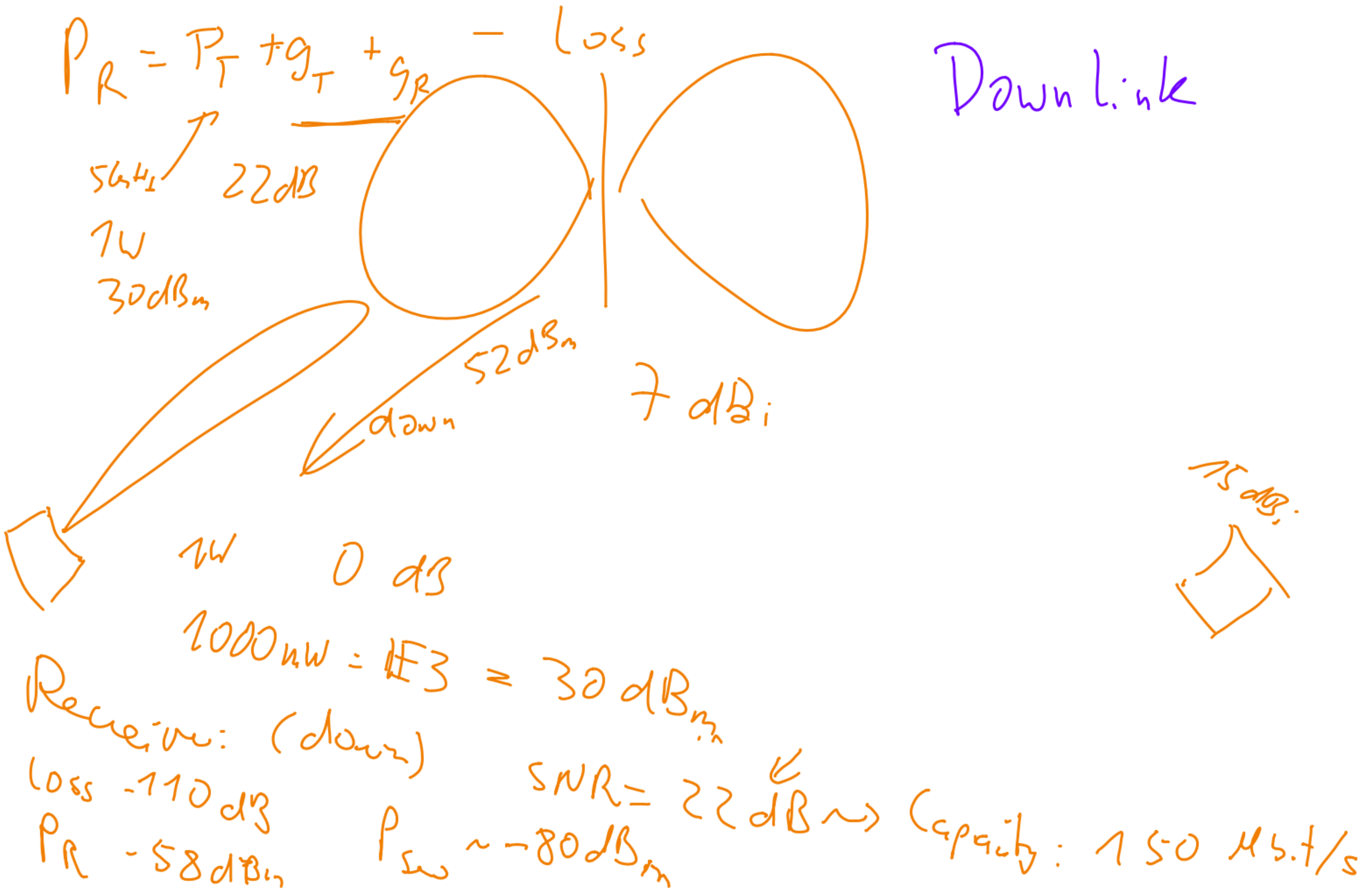
$$P_r = P_t \, G_t \, G_r \, \left(\frac{\lambda}{4\pi r}\right)^2.$$

- 0 dBm = 10^(0/10) = 1 mW
- 10 dBm = 10^(10/10) = 10 mW

Free space attenuation $L = 92,4 + 20\log(d[\text{km}]) + 20\log(f[/\text{GHz}])$

see (http://www.antenna-theory.com/basics/friis.php)

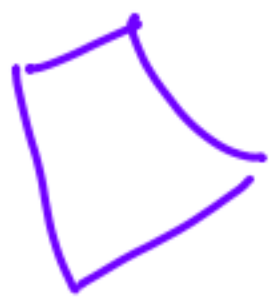
Now you can calculate



what is different in uplink?

7 dBi

17 dBi



P_T < 0 dBm (1 mW)
~~20 dBm~~ (100 mW)

EU: $P_T + G_T < 20\,dBm$ ← 2.4 GHz

Regul

EU 2.4 GHz

There exists two EIRP power limits for the 2.4 GHz band, one for 802.11b rates with CCK modulation (1, 2, 5.5 and 11 Mbps) and one for 802.11g/n rates with OFDM modulation. **The limit is set to 20 dBm (100 mW) for OFDM and 18 dBm (63 mW) for CCK.**

The spectral power limitation of 10 dBm/MHz (10 mW/MHz) causes the lower power limit for 802.11b.

EU 5 GHz

23dBm

Indoor only sub-band I (5150 – 5250 MHz)

The first RLAN sub-band includes the channels 36 to 48 and has an EIRP power limit to **23 dBm (200 mW)**. These channels are considered for indoor only usage and do not require any Dynamic Frquency Selection (DFS) or Transmit Power Control (TPC) features. It is comparable to FCC U-NII-1.

23dBm

Indoor only sub-band II (5250 – 5350 MHz)

In the second sub-band of the RLAN band 1 with channels 52 to 64, the ETSI has set the EIRP power limit to **23 dBm (200 mW)** for devices with TPC and 20 dBm (100 mW) for devices without TPC. For a device with TPC, the mean EIRP at the lowest power level of the TPC range must not exceed 17 dBm (50 mW). This band requires DFS support and is comparable to FCC U-NII-2.

30dBm

RLAN band 2 (5470 to 5725 MHz)

Channels from 100 to 140 are part of the second RLAN band and have an EIRP power limit of **30 dBm (1000 mW)** for TPC and 27 dBm (500 mW) for non-TPC devices or 20 dBm (100 mW) for devices without any TPC or DFS support. The mean EIRP power level for a slave device with TPC must not exceed 24 dBm at the the lowest TPC power level if the device is also capable of radar detection or 17 dBm otherwise. This band can be used for in- and outdoor deployments as well and is comparable to FCC U-NII-2e.

36dBm

Broadband Radio Access Networks (BRAN) (5725 – 5875 MHz)

Comparable to the FCC U-NII-3 (5725 – 5825 MHz) band with a higher upper frequency range, the ETSI has defined the channels 155 to 171 (155, 159, 163, 167, 172)

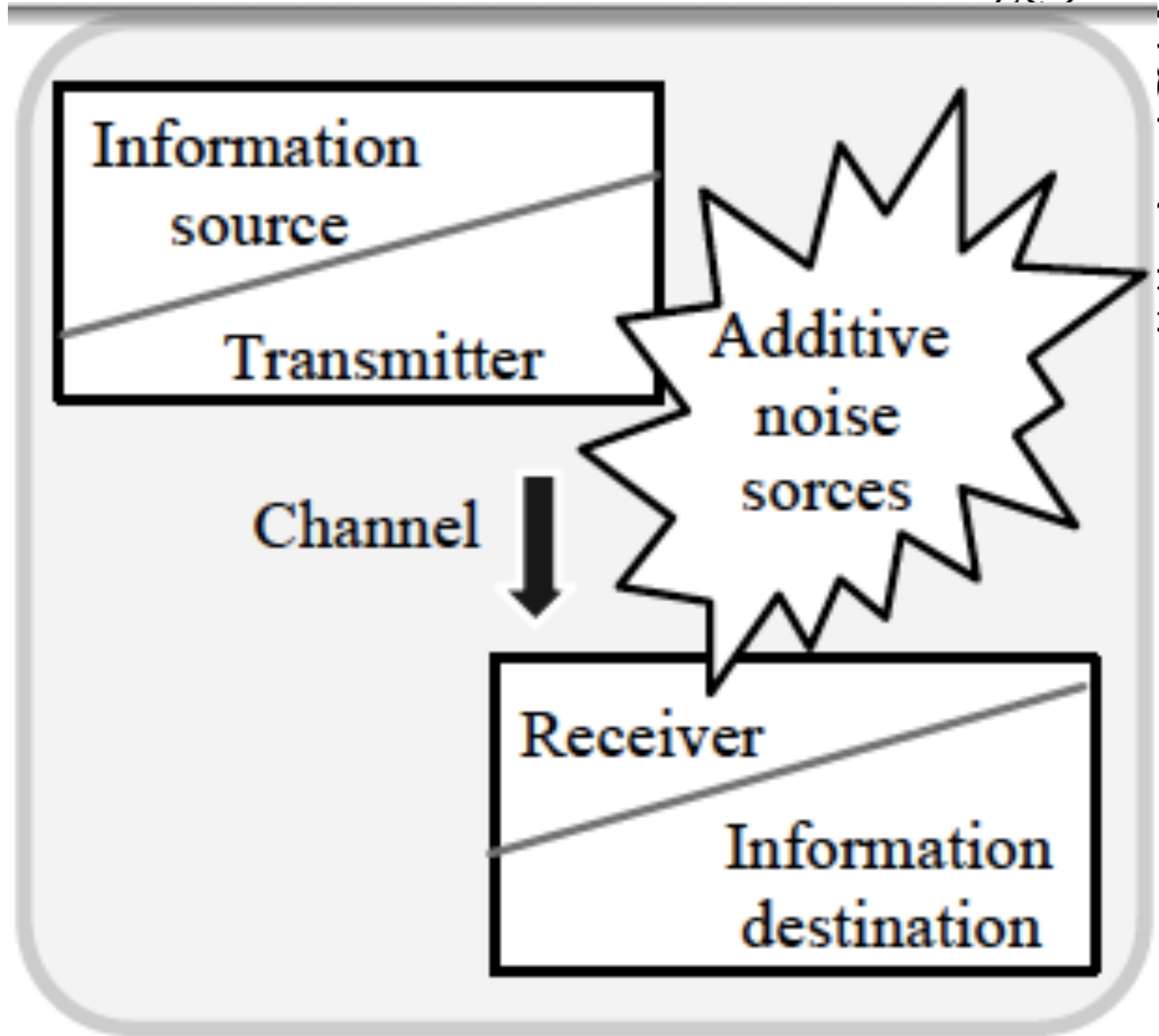
https://wlan1nde.wordpress.com/2014/11/26/wlan-maximum-transmission-power-etsi/

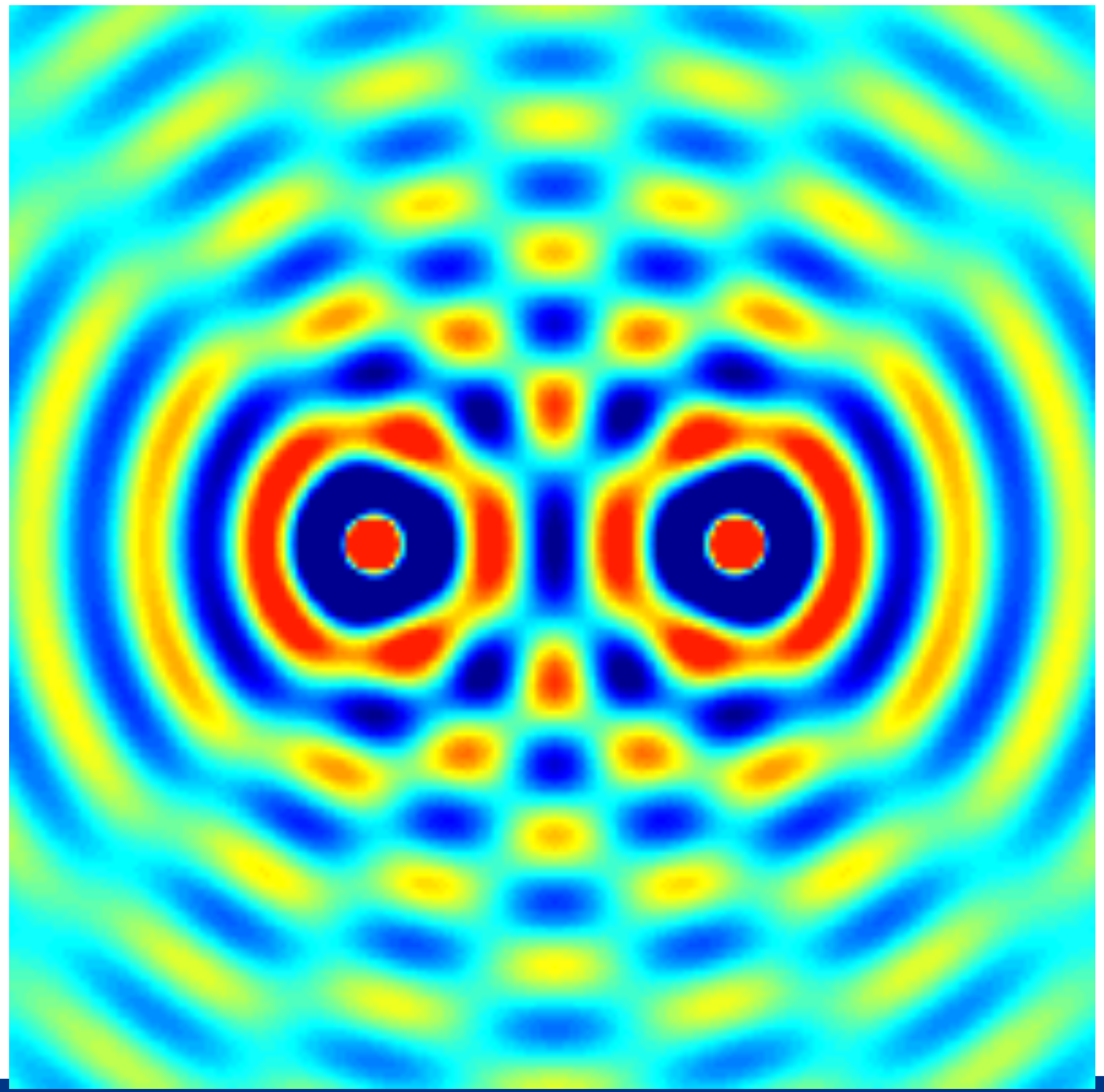
Digital Communications

Nyquist Theorem

- Shannon: If a function *f(t)* contains no frequencies higher than *W* [cycles/s], it is completely determinded by giving its ordinates at series of points spaced *1/2W* seconds apart
- band-limitation versus time-limitation
- Fourier transform

- Questions/Tasks
  - Channel versus Frequency Band

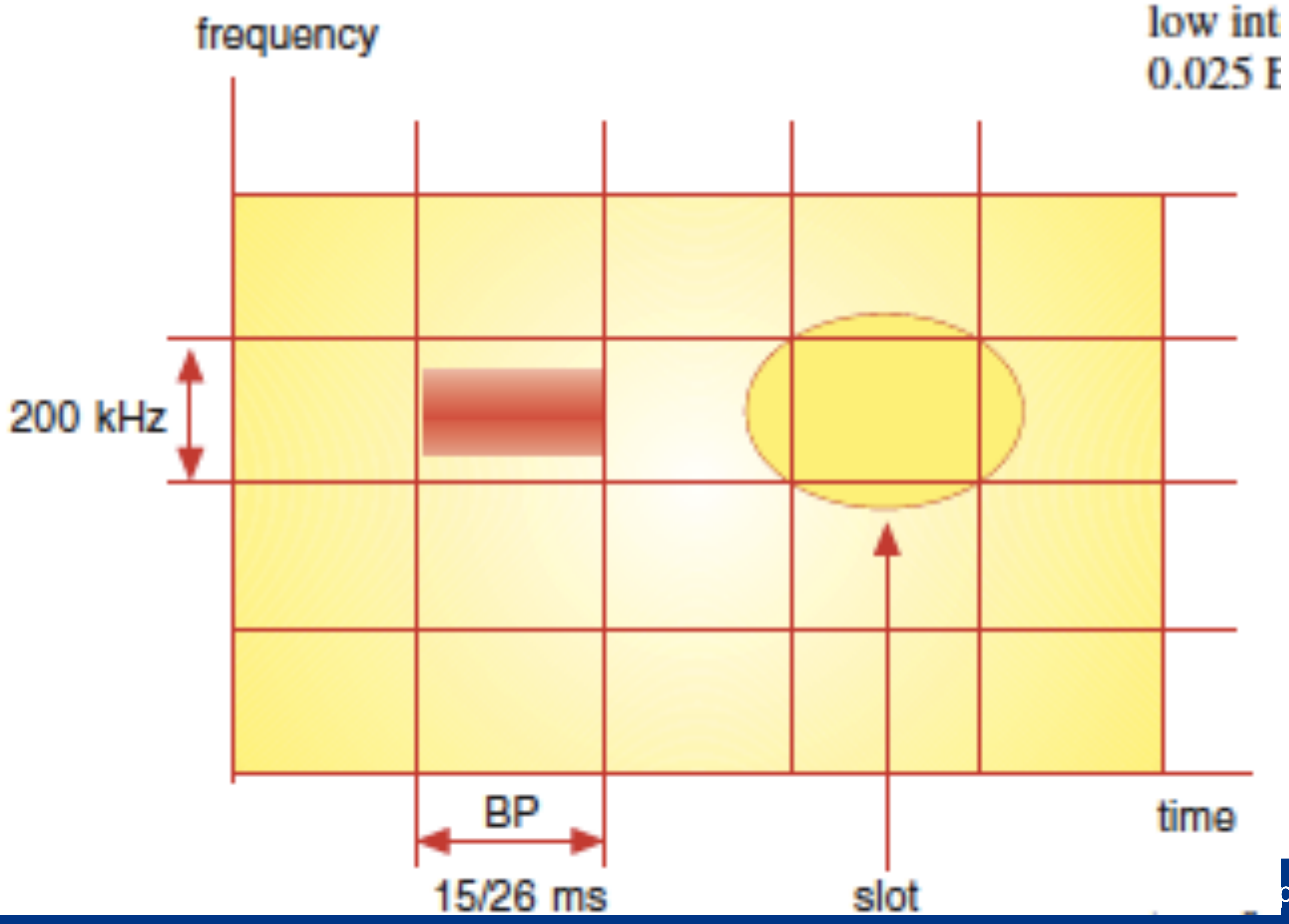


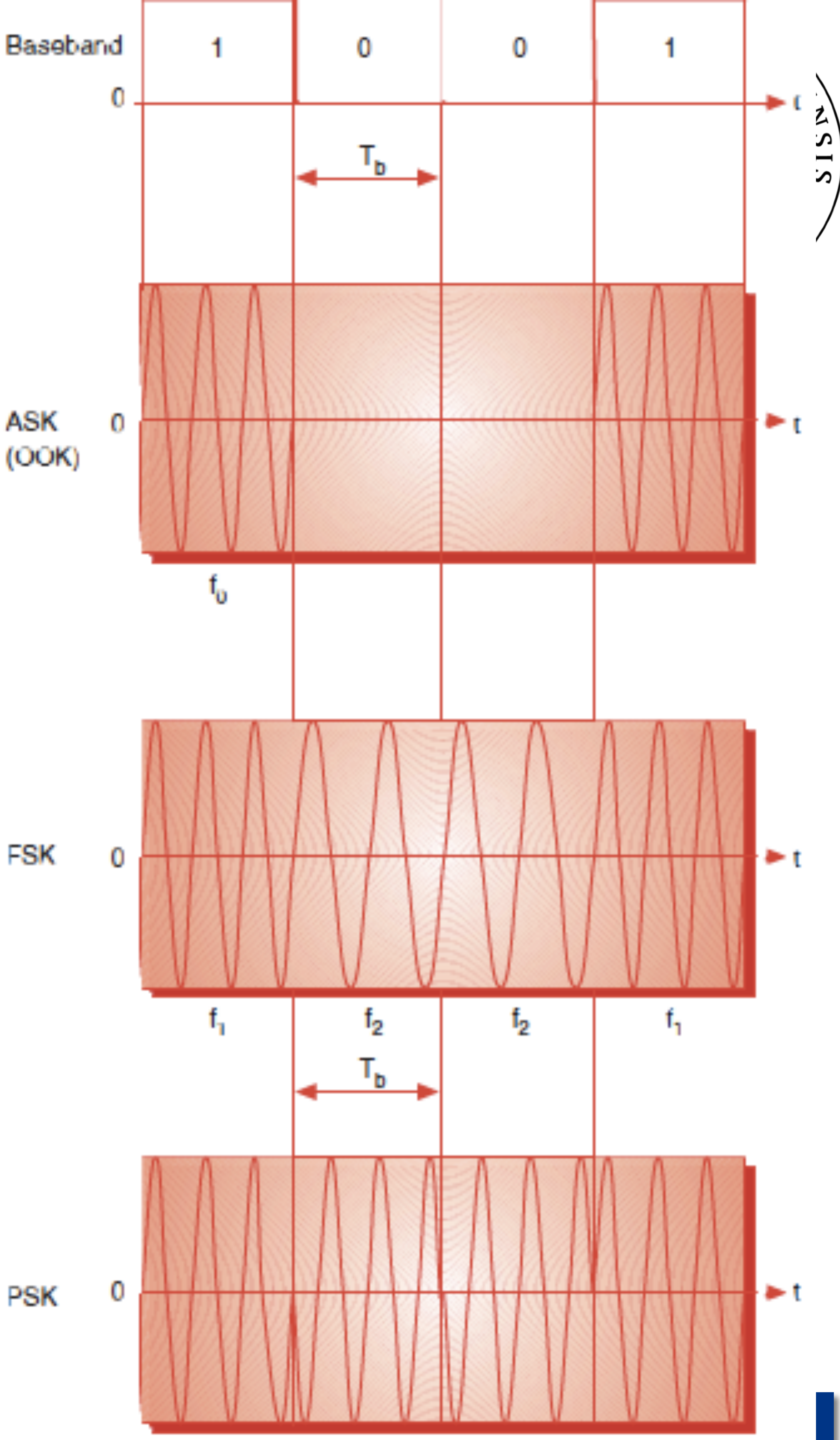


- [source: Shannon, 1948]

Modulation in GSM

- Principle: ASK (AM), FSK (FM), PSK
- Applied as time, frequency, or code





Signal to Noise, Shannon

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}}$$

$$\text{SNR(dB)} = 10\log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right),$$

- in-band vs out-of-band noise
- interference vs noise

- Shannon theorem (1948)
  - almost 30 years after Hartley $C \sim W$

$$C = W \log_2(1 + P/N) \text{ [bit/s]}$$

  - interference free environment: $P/N = \frac{P}{N_0 W}$
  - with Interference

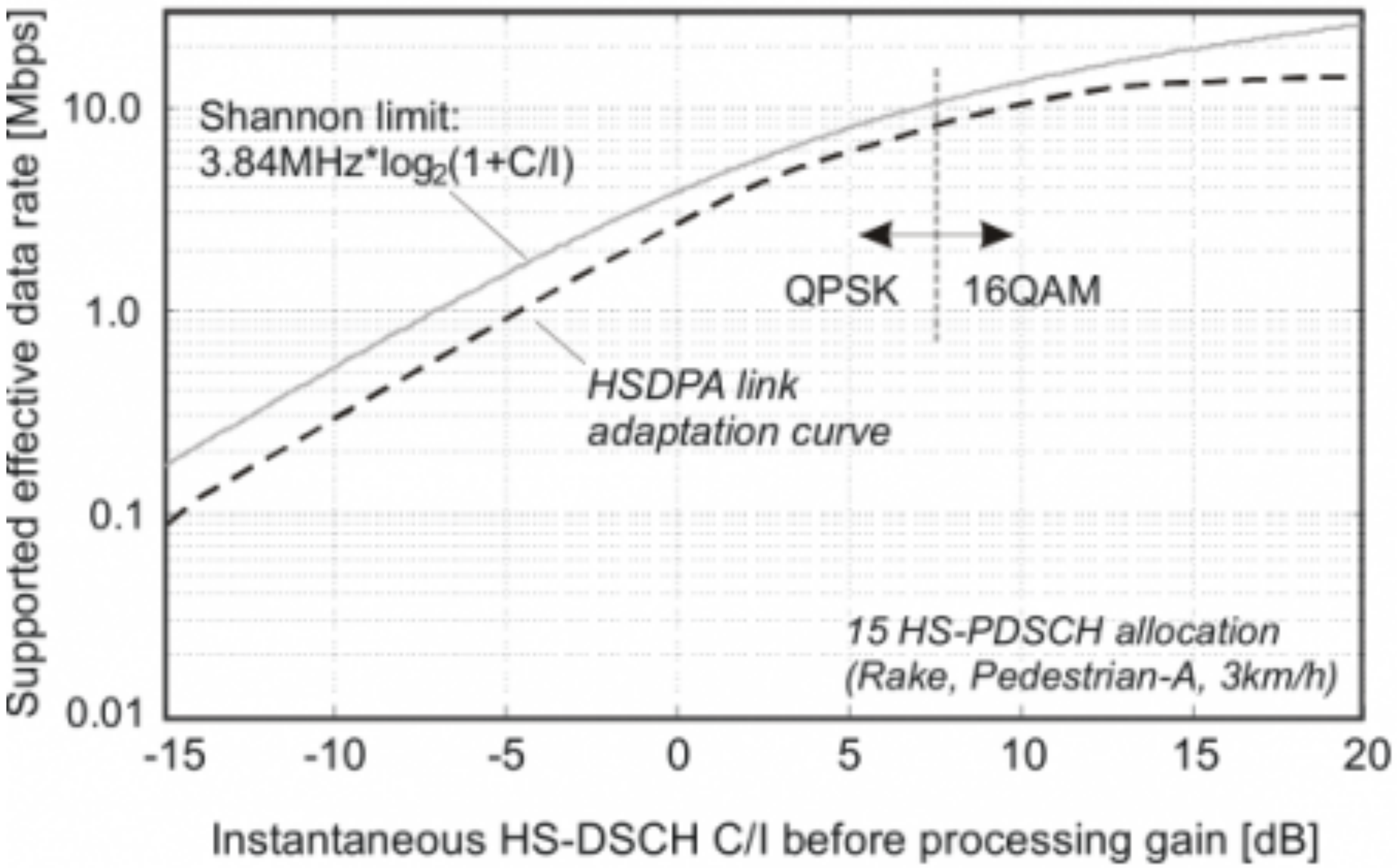
$$N_0 W + N_{\text{interference}}$$

Shannon - Excercises

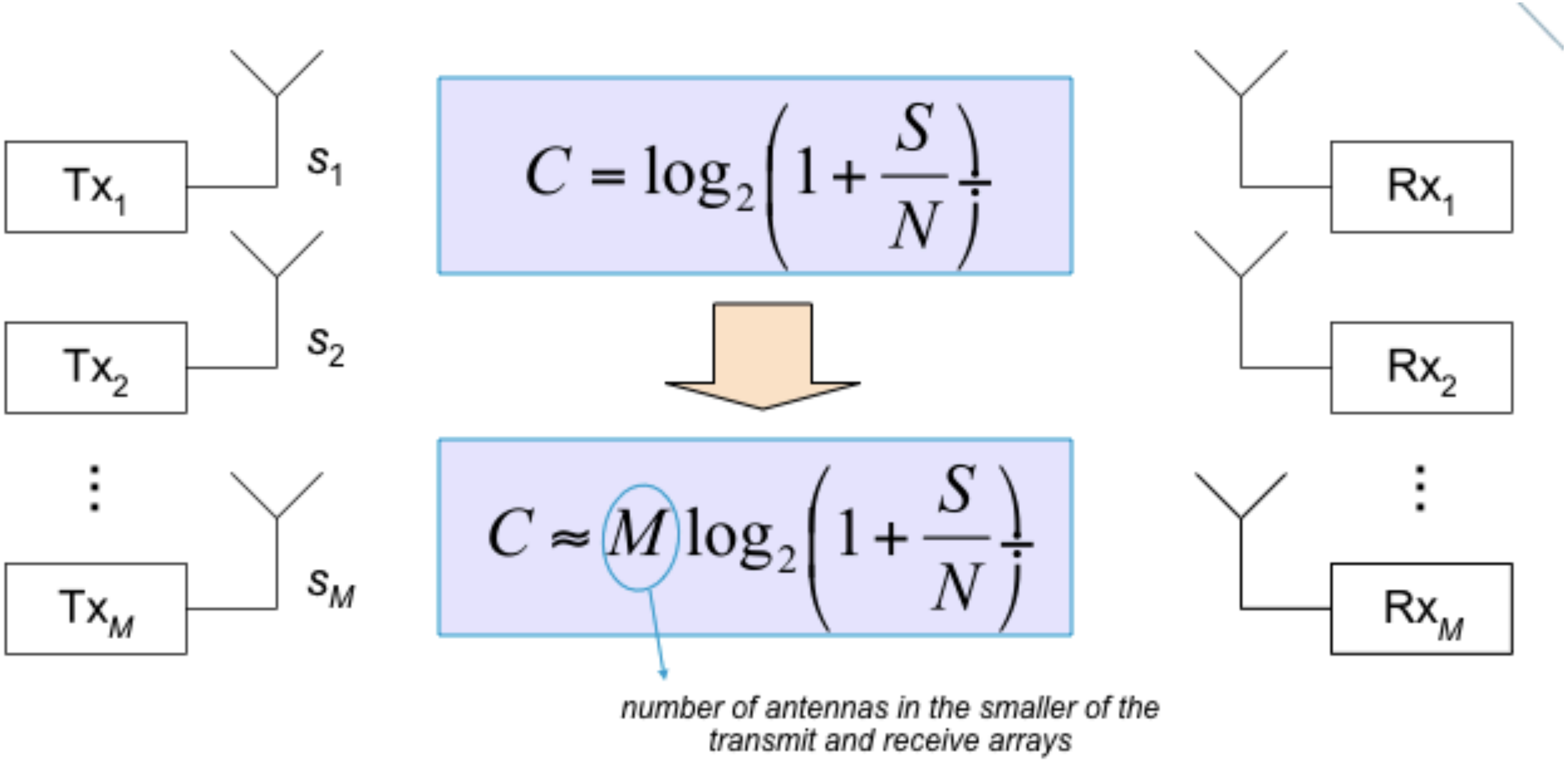
- calculate capacity for W= 200 kHz, 3.8 MHz, 26 MHz, (all cases P/N = 0 dB, 10 dB, 20 dB)
- If the SNR is 20 dB, and the bandwidth available is 4 kHz, what is the capacity of the channel?
- If it is required to transmit at 50 kbit/s, and a bandwidth of 1 MHz is used, what is the minimum S/N required for the transmission?

Cell capacity

- UMTS has already good spectrum efficiency with respect to Shannon.
- Modulation schemes like QPSK and 16-QAM are applied to achieve higher bandwidth.
- Higher modulation schemes need a higher signal to noise ration, Why?



Multiple-Input, Multiple-Output (MIMO)



source: Reinaldo Valenzuela, Lucent Technology

MIMO laptop

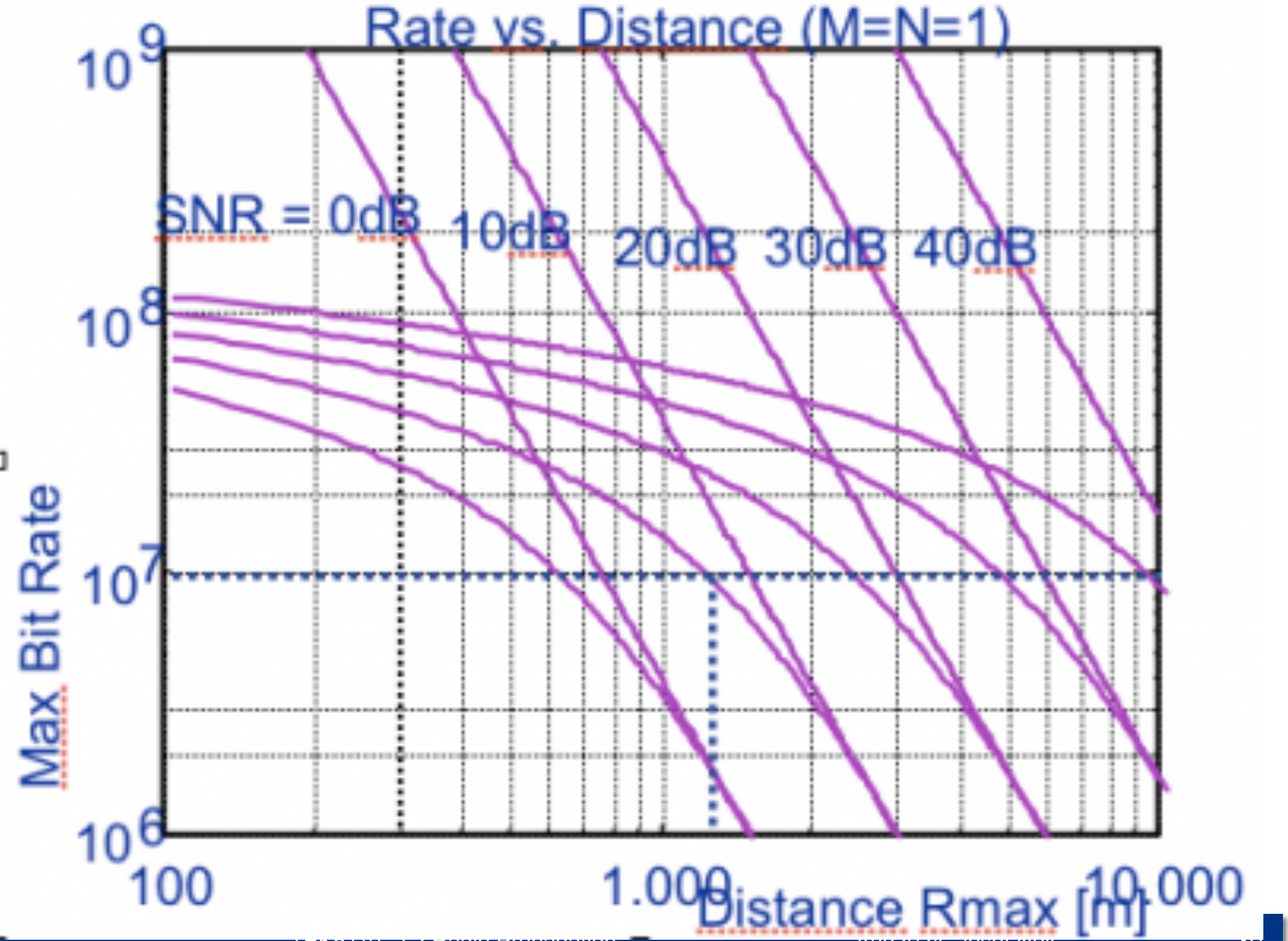
Range versus SNR

- max range

$$R_{max} = \log_2(1 + SNR)$$

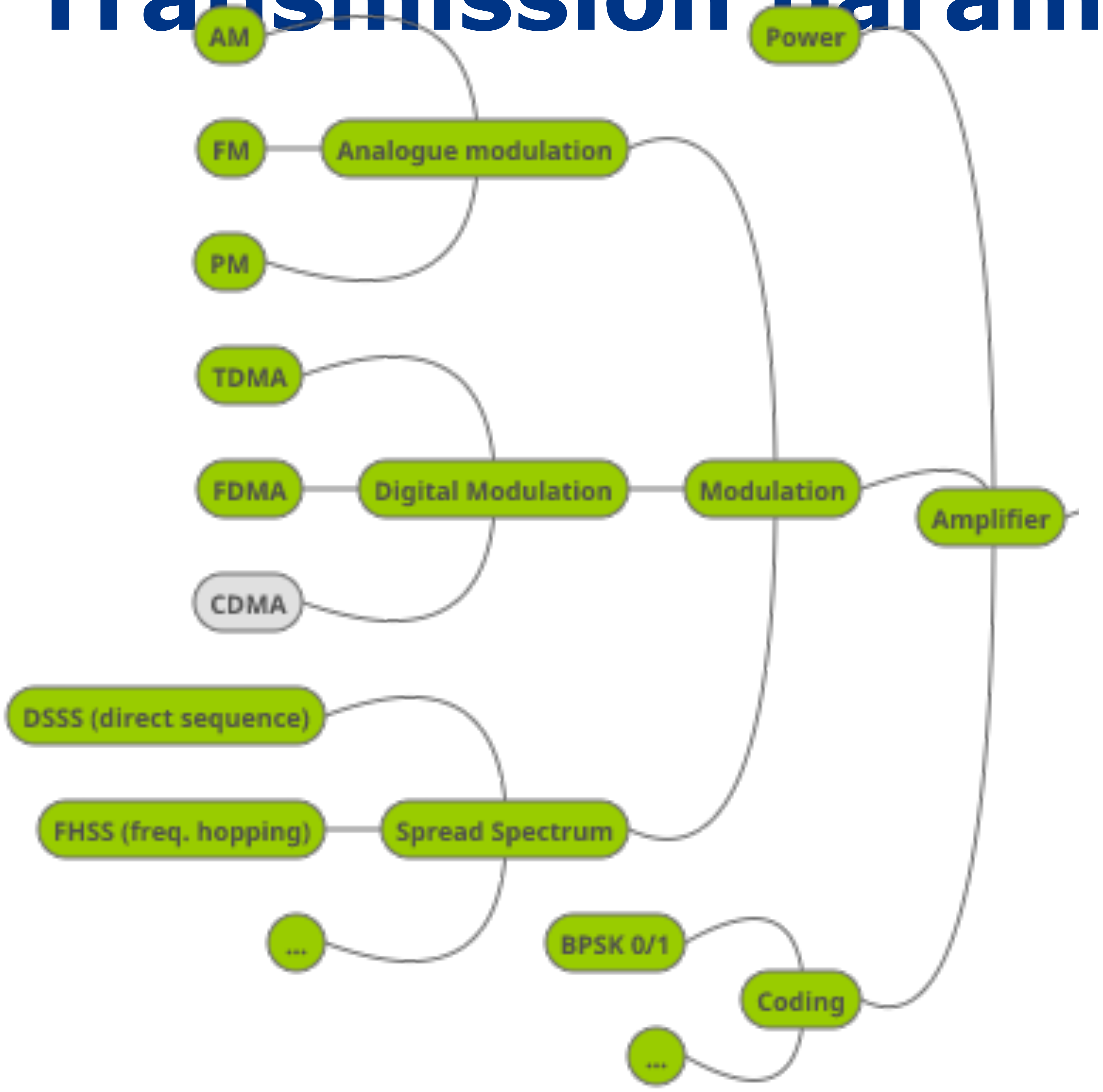
Real system

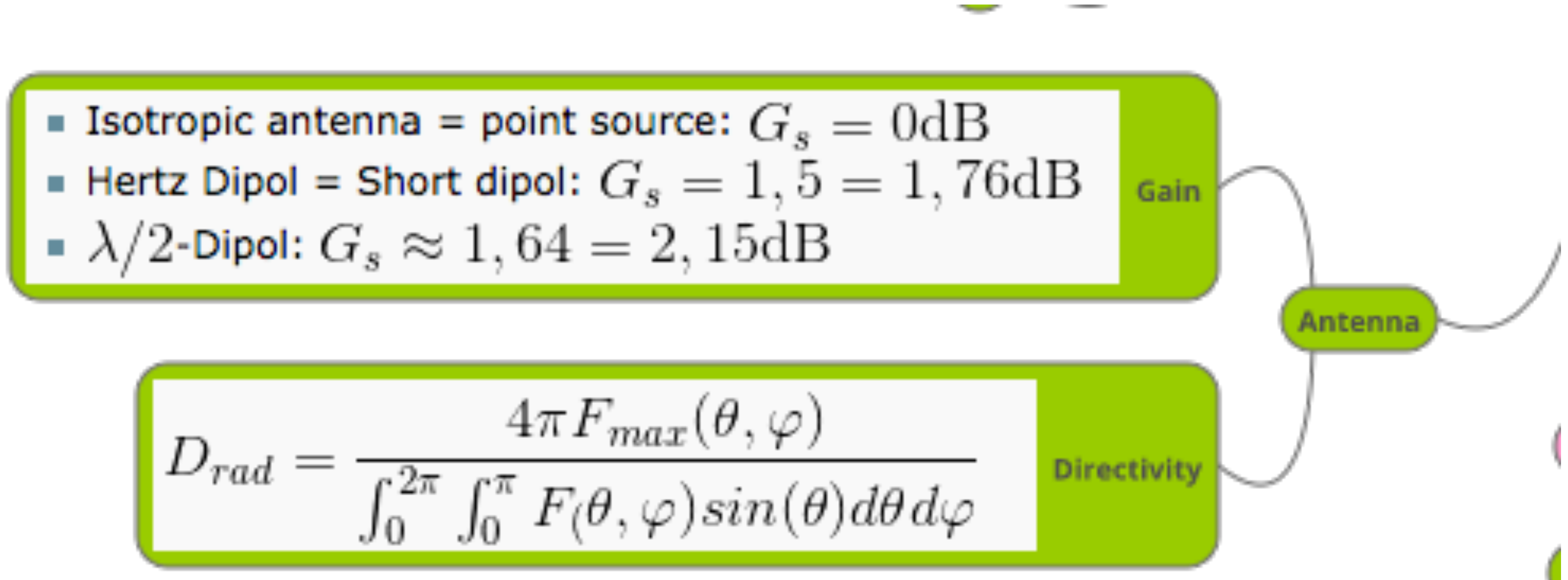
SNR	Range	Capacity
0	600 m	10 Mbit/s
30	300 m	60 Mbit/s
10	3 km (?)	1 Mbit/s (UMTS all capacity)



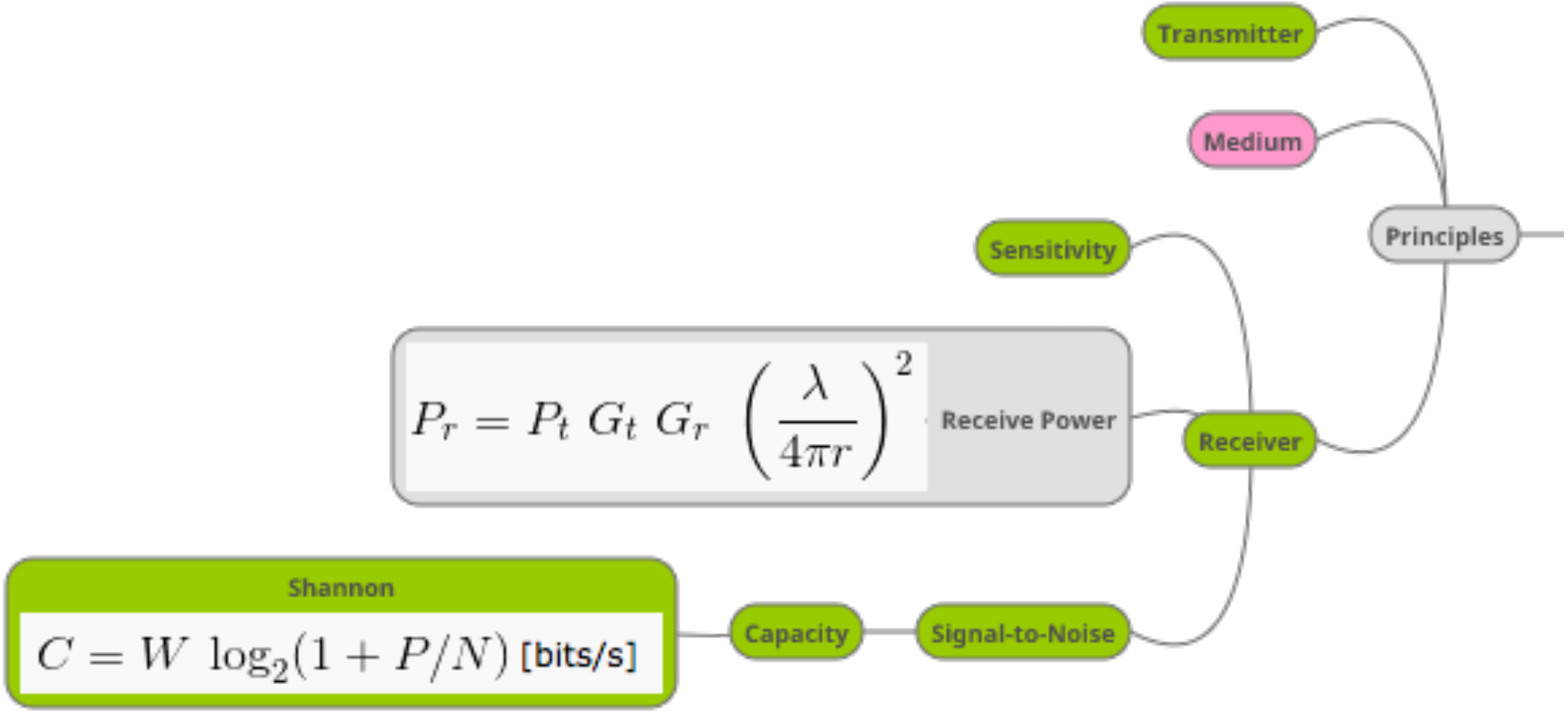
Radio Topics: Antennas, Propagation

Transmission parameters





Receiver


Transmitter
Medium
Principles
Sensitivity
$P_r = P_t \, G_t \, G_r \left(\frac{\lambda}{4 \pi r} \right)^2$
Receive Power
Receiver
Shannon
$C = W \, \log_2(1 + P/N)$ [bits/s]
Capacity
Signal-to-Noise

Upcoming Topics

Upcoming Topics / To do for next week

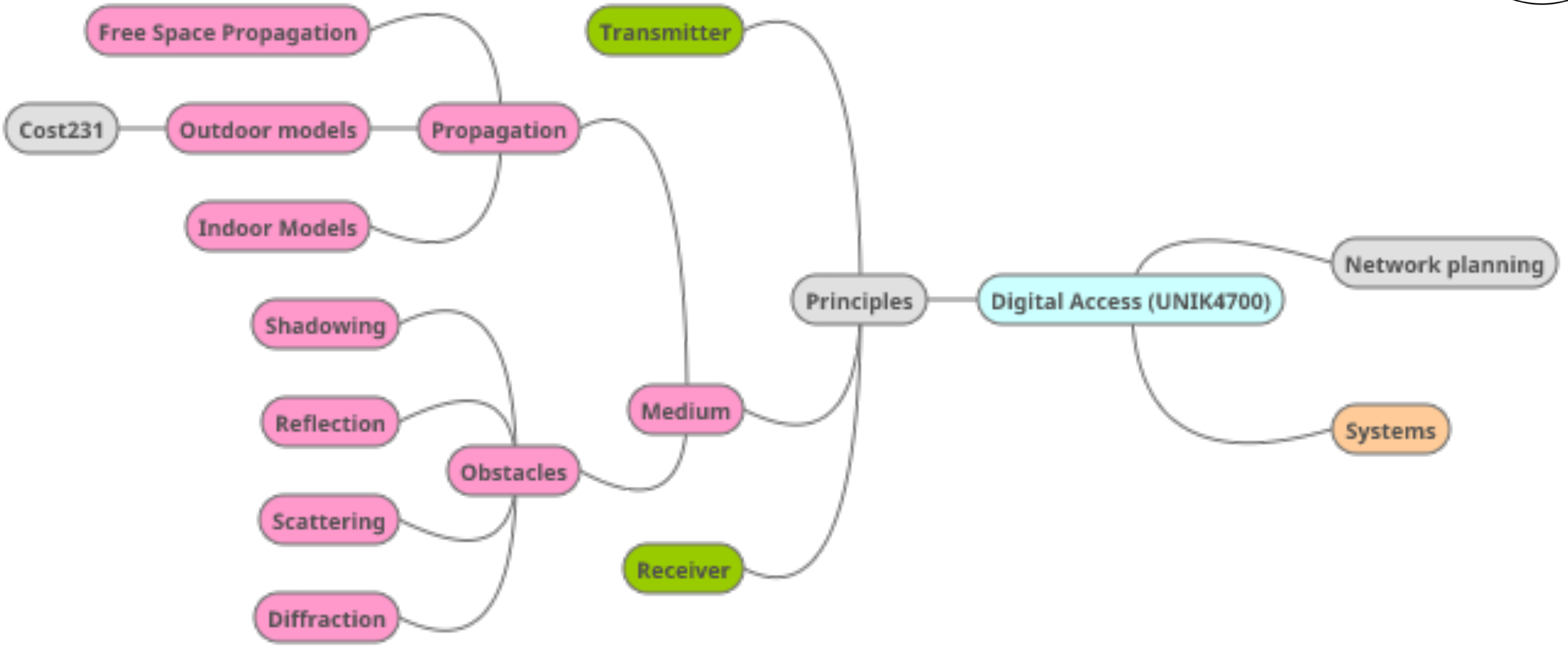
Upcoming Topics

- ➡ Propagation specifics
- ➡ Communication systems

To Do:

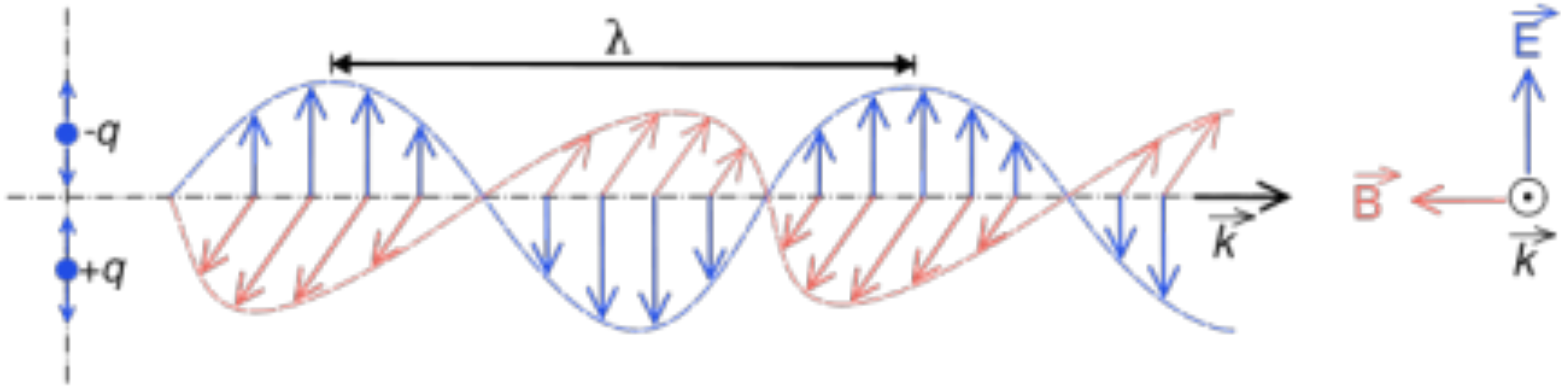
- ➡ Prepare questions to your papers http://its-wiki.no/wiki/TEK5110/List_of_papers

Propagation



Main Take-away L2 Propagation

- Power transport
  - $P_r = P_t g_t g_r L_{oss}$ and $P_{dB} = 10 log(P[W])$
- Electro-magnetic field



- Capacity enhancement
  - Bandwidth, $C = B_w log_2(1 + SNR)$
  - MIMO $C = NB_w \ldots$ where $N = min(A_{number-antennas-receive}, A_{transmit})$
- Typical values