P&S: Radio Frequency Electromagnetic Fields in our daily Life

FS 2025: Organization and Introduction

Marco Zahner – marco.zahner@fieldsatwork.ch

About Me

- **Name:** Marco Zahner
- **2017: PhD at IEF**
  - Topic: methods and devices for EMF exposure assessment

- **Since 2017: Various activities at IEF (previously IFH)**
  - Practicals, master- and semester projects, research projects
  - Measurements and supervision of anechoic chamber
- **2014: ETH Spin-off Fields at Work**

P&S Electromagnetic Fields: What is it about?

- Electromagnetic fields (EMF) are ubiquitous
- Where and how are they generated?
- How do they propagate?
- How strong is EMF radiation encountered in daily life?
- How can EMF be measured?
- Is it possible to tell where they come from?
- Is EMF dangerous for our health?
- How can exposure to EMF be reduced?

These and other questions will be investigated during the course of this P&S

Goals of this P&S

- **Understand** the basic characteristics of electromagnetic radiation at UHF and microwave frequencies. Discover the variety of RF sources we are exposed to every day and the strength of the fields they radiate.

- Get **practical experience** with RF and microwave measurement equipment, related measurement techniques and methods. You will have the opportunity to use the equipment in our lab.

- **Your Task:** Define and realize your own project: Choose an EM radiation related topic of your interest and perform a **small empirical study**. Feel free to realize you own ideas.

- Have fun ☺

Organisation

General Information, dates and deadlines

Students FS 2025

Last Update: 26. Feb 2025

	Name	Vorname	E-Mail
1	Aksenov	Anahi	aaksenov@student.ethz.ch
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6	Itschner	Ludwig	litschner@student.ethz.ch
7	Kochsiek	Bennet	bkochsiek@student.ethz.ch
8	Lüthi	Nicolas	nlueth@student.ethz.ch
9	Nguyen	Vien Kheo	vienguyen@student.ethz.ch
10	Posada Saiz	Hugo	hposada@student.ethz.ch
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12	Xu	Linqi	linqixu@student.ethz.ch

General Information

- **Time and Location**
  - Every Thursday 09:15 – 11:00 ETZ K 71
- **E-Mail contact**
  - marco.zahner@fieldsatwork.ch My Office: ETZ H 67
- **Slides, reading material, software**
  - P&S Website: http://people.ee.ethz.ch/~mzahner/PPS-EMrad/
  - Download Section: http://people.ee.ethz.ch/~mzahner/PPS-EMrad/material/
  - Content will be updated regularly

P&S Organization

- Plenary sessions (lectures)
  - Introduction
  - Antennas
  - Spectrum analyzer
  - Personal exposure assessment
- Group Project (groups of 3-4)
  - Work shall be related to EMF, but you are free to choose the topic
  - Measurements, experiments, studies
- Presentation & Report
  - Present and explain your work to your classmates and institute members

P&S FS 2025: Timeline

Date	Topic
27. Feb 2025	Lecture: PPS Organization, Introduction, basics and definitions
06. Mar 2025	Lecture: Measuring EM-radiation: Fields, Antennas & Anechoic Chamber
13. Mar 2025	Lecture: Measuring EM-radiation: The Spectrum Analyzer
20. Mar 2025	Lecture: Measuring EM-radiation: Personal exposure assessment using exposimeters Project: Group assignment and choice of the topic
27. Mar 2025	Project: Concretization and writing the research plan Discussion in individual group meetings (outside of usual P&S time slot)
03. Apr 2025	*Individual work* ***Marco not in Zurich from 1. - 6. April***
10. Apr 2025	*Individual work, group meetings as necessary*
17. Apr 2025	*Individual work, group meetings as necessary*
24. Apr 2025	*Individual work, group meetings as necessary* ***Easter Break – no lecture***
01. May 2025	*Individual work, group meetings as necessary* ***Tag der Arbeit – no lecture on Thursday***
08. May 2025	*Individual work, group meetings as necessary*
15. May 2025	*Individual work, group meetings as necessary*
22. May 2025	**P&S Presentations**
29. May 2025	***Auffahrt – no lecture***
06. Jun 2025	**Written report deadline** *(1 week after end of semester)*

Deliverables

- **Presentation at the end of Semester**

You will present your topic and findings in a short presentation at our institute

Duration: 15-20 minutes

Language: English

Date: **Thu, 22.05.2025**

- **Written Report**

Must not be long, but well structured: Goals, Methods, Results, Conclusions….

Extent: 5-10 pages (as many as necessary) – Word Template available

Language: English

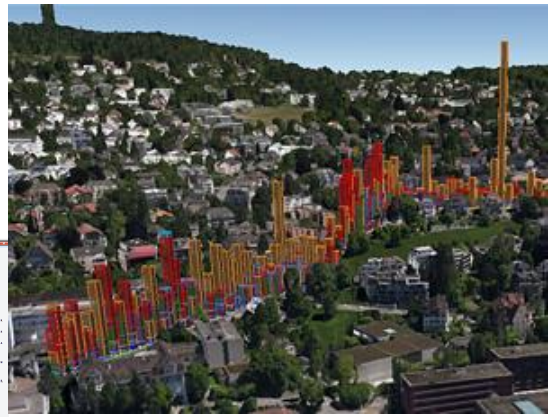
Deadline: Fri, 07.06.2025

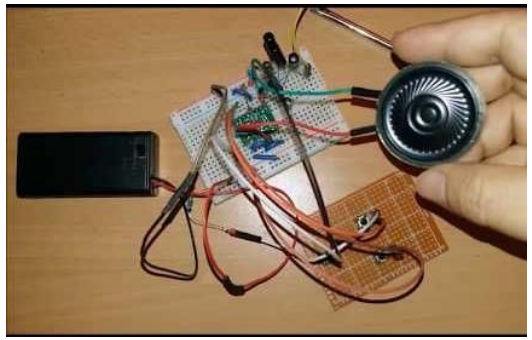
- More information and presentation/report templates in the last lecture

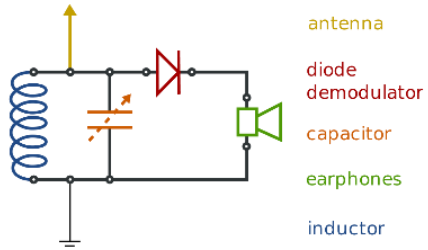
Group project: Examples

Laboratory Experiments

Environmental Exposure Measurements

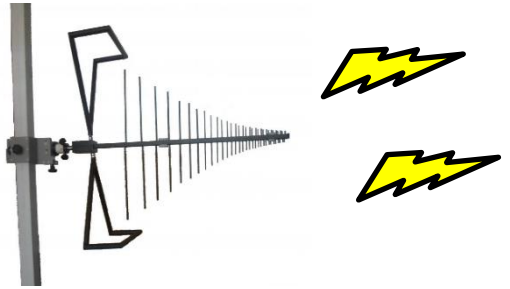






Build your own radio receiver / detector

Provocation studies



Group project: Contribution to ETAIN Project

https://www.etainproject.eu/

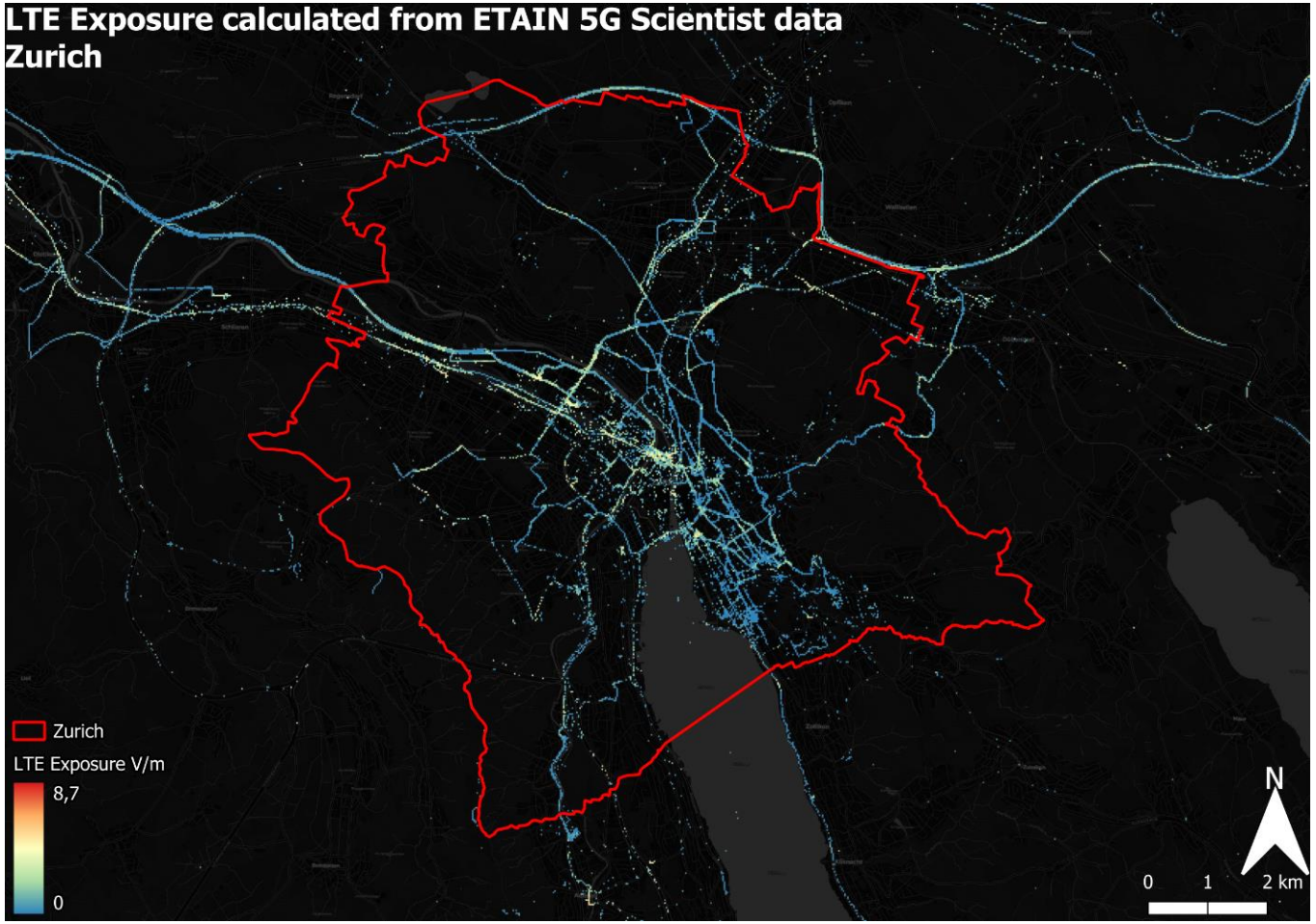
- **What is ETAIN**
  - EU funded Research Project
  - **E**xposure **T**o electrom**A**gnetic f**I**elds and pla**N**etary health
  - Investigates risks and possible effects of RF-EMF on **human health** and **biodiversity**
  - Focus: 5G and mmW frequencies (26 GHz)

- **Activities and Goals**
  - Biological experiments with insects (honeybees, drosophilae and many other)
  - Online portal to identify one's personal exposure to RF-EMF
  - **Mapping outdoor exposure levels across European cities using citizen science approach**

Group project: Contribution to ETAIN Project

ETAIN 5G Scientist App

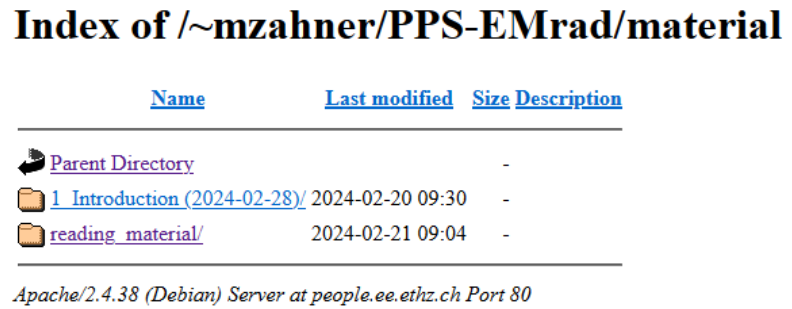
- Estimates RF-EMF level based on Smartphone operational data (RSSI, RSRP etc.)
- Full picture (map) requires data from all service providers (Salt, Swisscom, Sunrise) from all parts of the city
- Comparison with measurements using dedicated RF-EMF measurement device



P&S Download section

people.ee.ethz.ch/~mzahner/PPS-EMrad/material

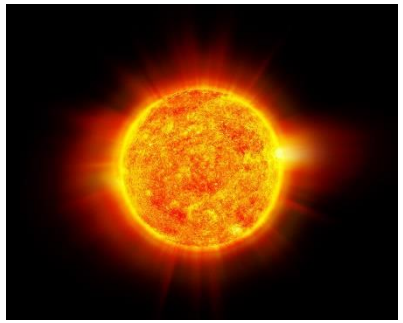
- **Contents of the download section:**
  - Presentation slides
  - Exercise assignments
  - Collection of reading material
  - Software for the measurement devices
  - Additional project specific documents



- **The contents are continuously updated, more files are added during the P&S**
- **You will get the link also via e-mail**

Introduction

Electromagnetics in Everyday Life



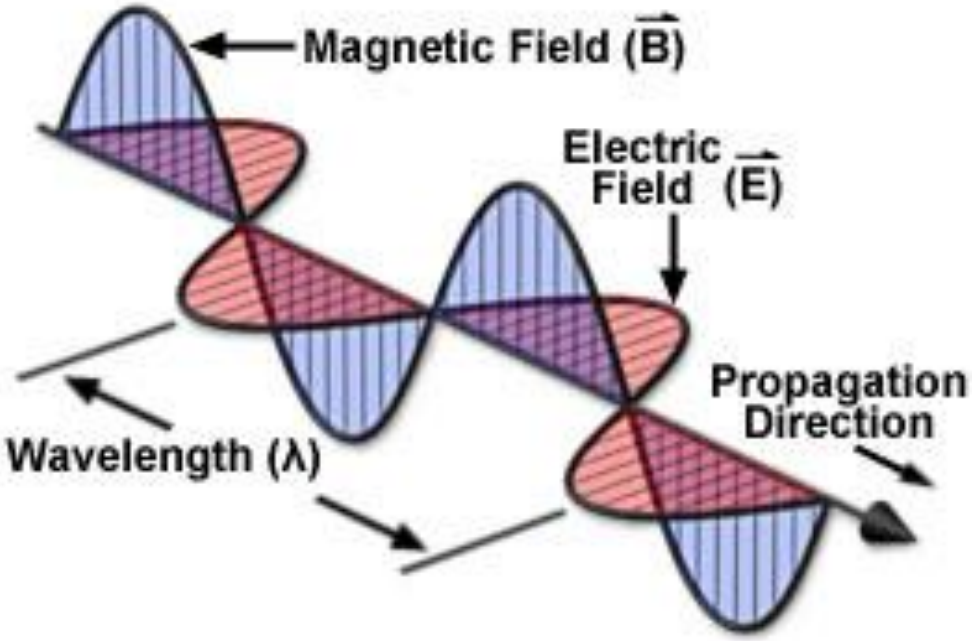
Fields, Radiation, Electromagnetic waves…

Electromagnetic (EM) Fields:

- Time-varying (oscillation)
- Coupled E and H field
- $E/H = Z_0$ (wave impedance, constant)

Radiation

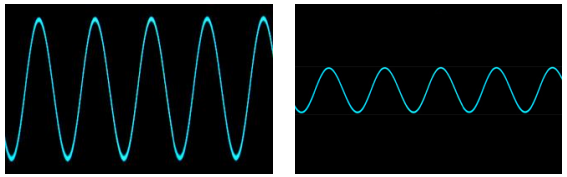
- Wavelength << distance to source
- Freely traveling EM wave
- Requires no medium to propagate
- Transports energy (e.g sunlight)



Fields, Radiation, Electromagnetic waves…

Characterization of EM Fields:

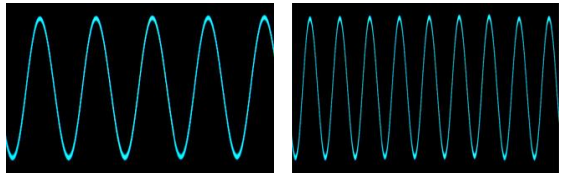
- **Field Strength / Power Density:**



- Electric Field strength **E** [V/m]
- Magnetic Field strength **H** [A/m]
- Intensity **S** [W/m^2] = **E x H**

Free-space: E/H = Z_0 -> it is sufficient to know either E, H or S.

- **Frequency / Wavelength:**



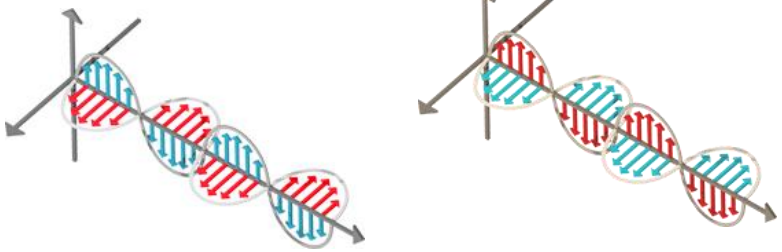
λ: Wavelength [m] **λ=c/f**

f: Frequency [Hz]

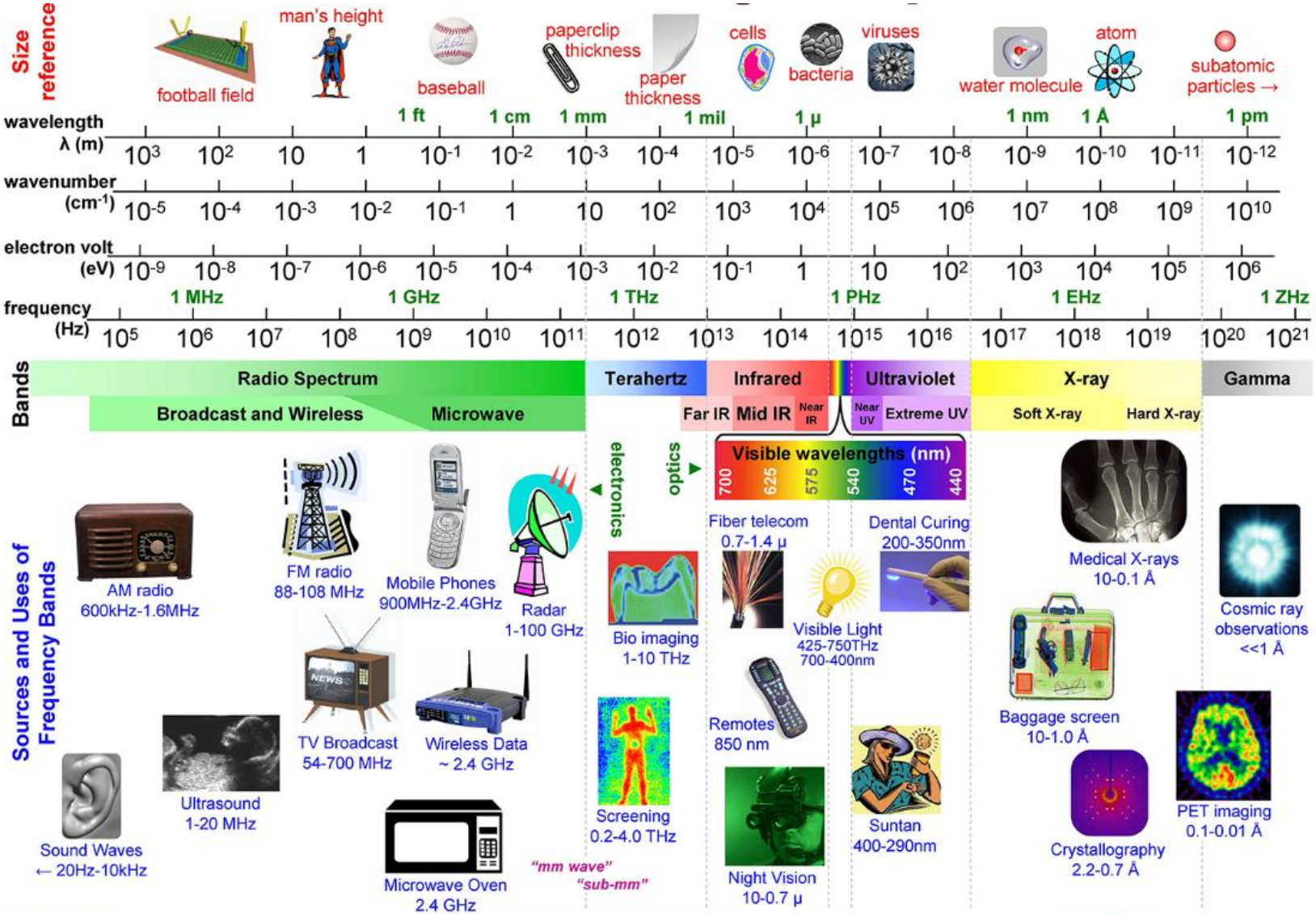
c: Speed of light

- **Polarization:**

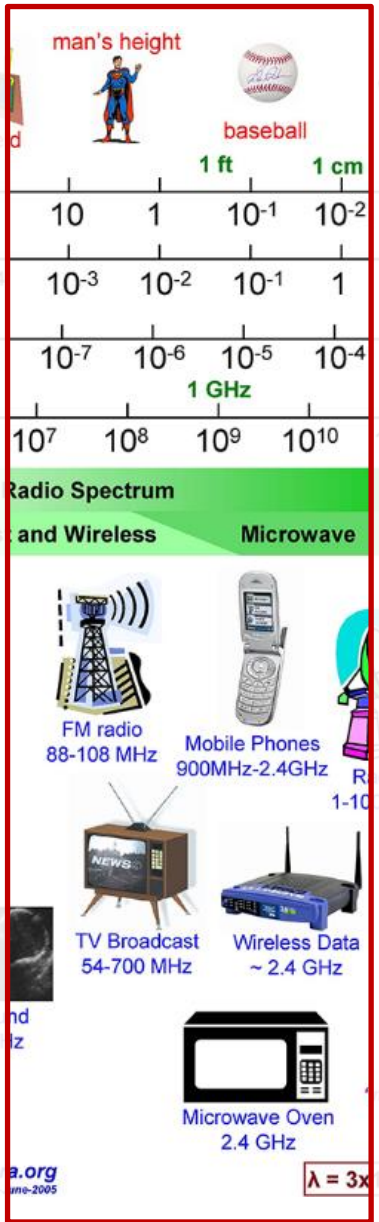
  Orientation of E-field vector



Electromagnetic fields: Frequency Spectrum



Electromagnetic fields: Frequency Spectrum



RF and Microwave Frequency range
~ 30 MHz – 300 GHz

RF and Microwave: Definitions

Nomenclature and (approximate) Definitions:

- **Radio Frequency (RF): VHF:** 30 – 300 MHz **UHF:** 300 MHz - 3 GHz
- **Microwave:** “GHz frequencies”
- **mmW (millimeter waves):** upper part of microwave spectrum; roughly 20 GHz – 300 GHz

Wavelength (free space):

- **UHF:** 10 cm …. 1 m
- **Microwave:** less than 30 cm

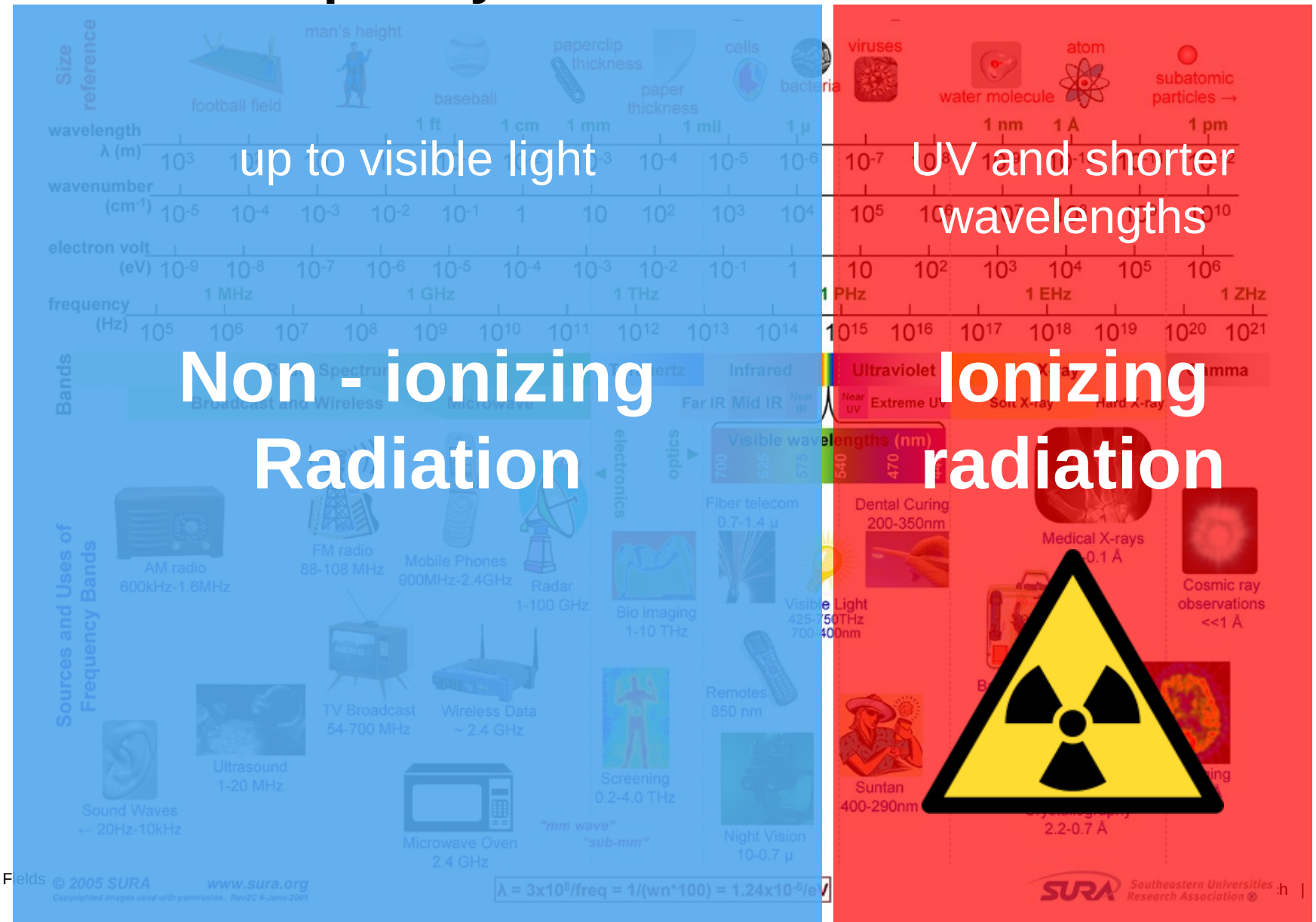
Applications:

- Wireless communication systems: GSM, UMTS, LTE, 5G, WiFi etc…
- Broadcasting: TV, FM radio
- Directional data links (satellites, point-to point radio)
- Heating (microwave oven)

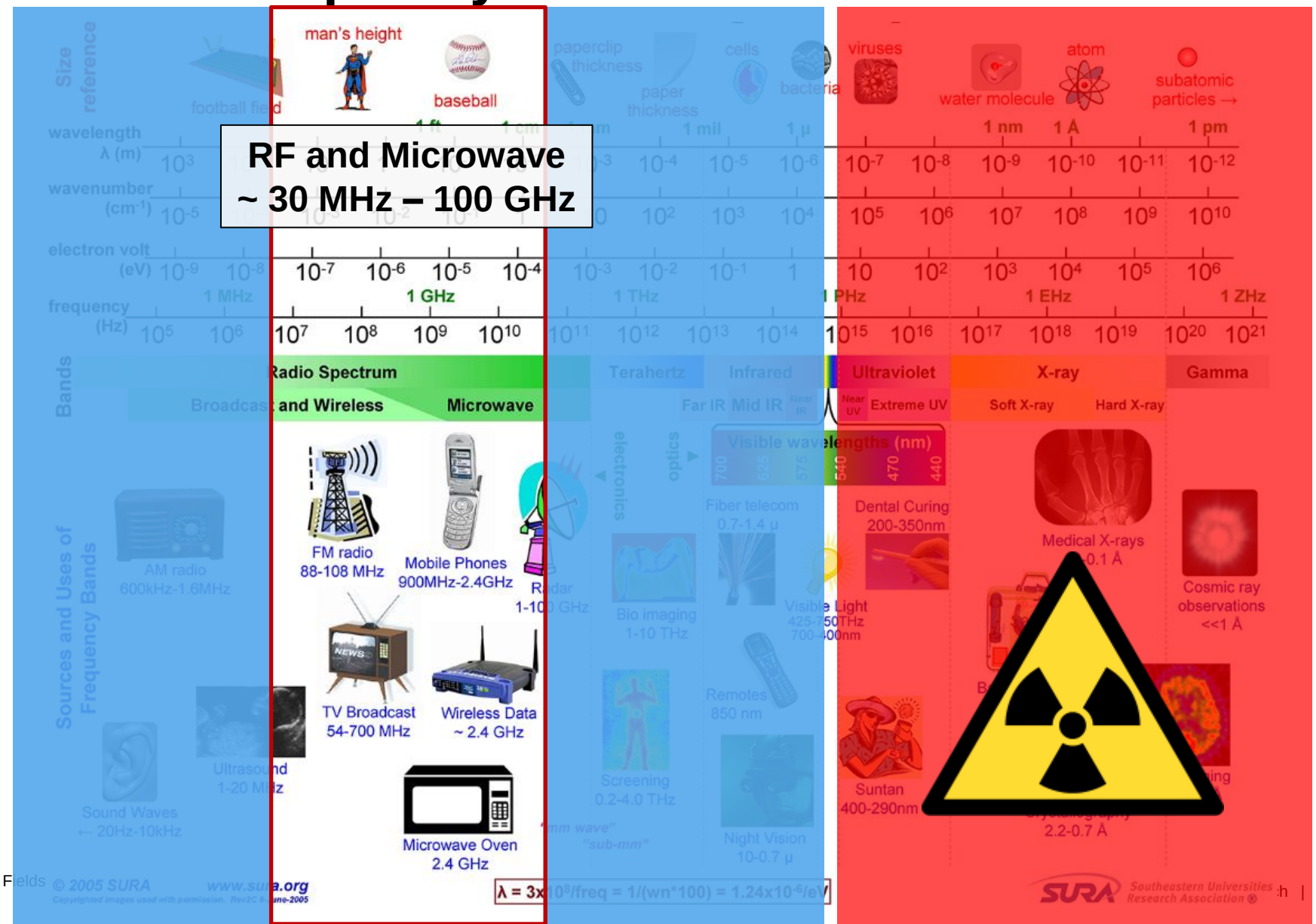
Safety, Limits, Guidelines

Definitions and Quantities

Health effects: Frequency



Health effects: Frequency



Health effects: Frequency, Power & Dose

Ionizing EMF radiation:

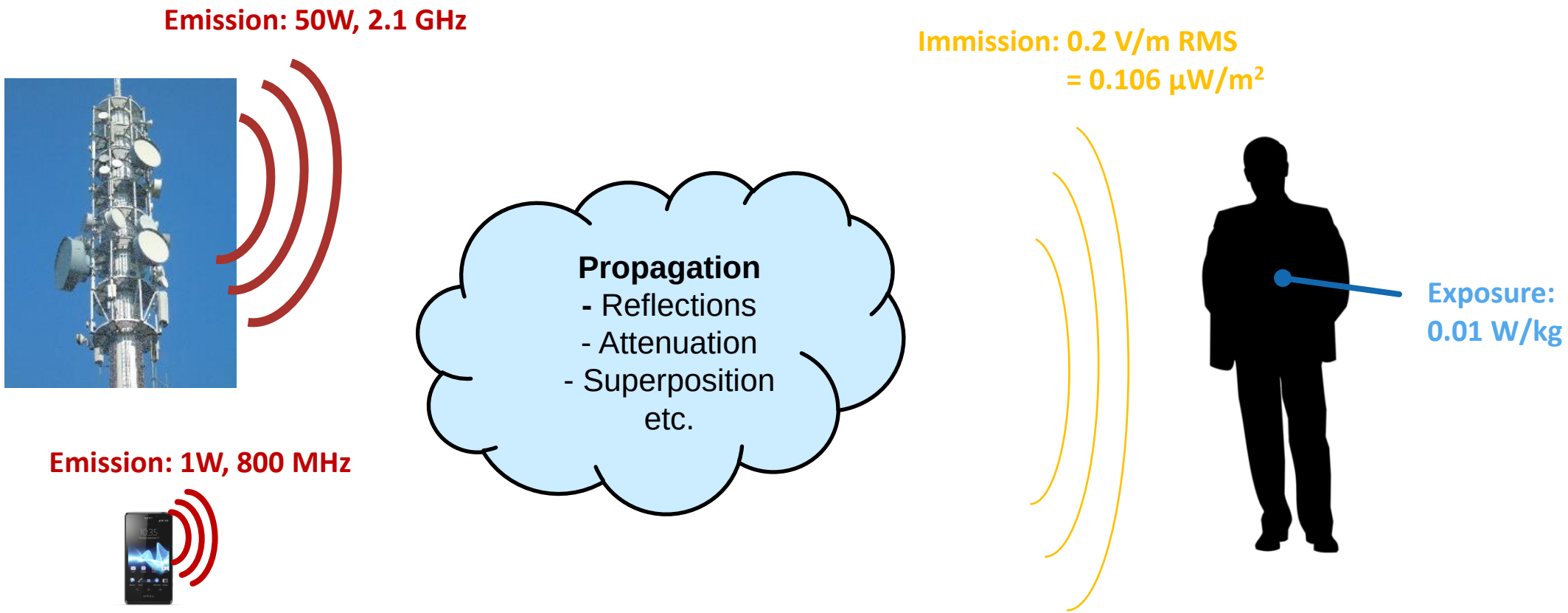
- EMF with extremely short wavelengths (nm…pm): X-Rays, gamma rays
- In general, harmful and even potentially lethal
- Known **dose response:** Probability of cancer and other health effects increases with dose (= time x intensity of exposure)
- Biology adapted to low-level natural radiation (e.g. DNA repair)

Non-Ionizing radiation:

- High power levels: Burns, Cataract etc: **->Thermal effects**
- Low power levels ("*Electrosmog*"): No conclusive evidence of negative **non-thermal effects** in the telecom frequency range
- Long-Term effects still unknown "by definition"

Emission, Immission and Exposure

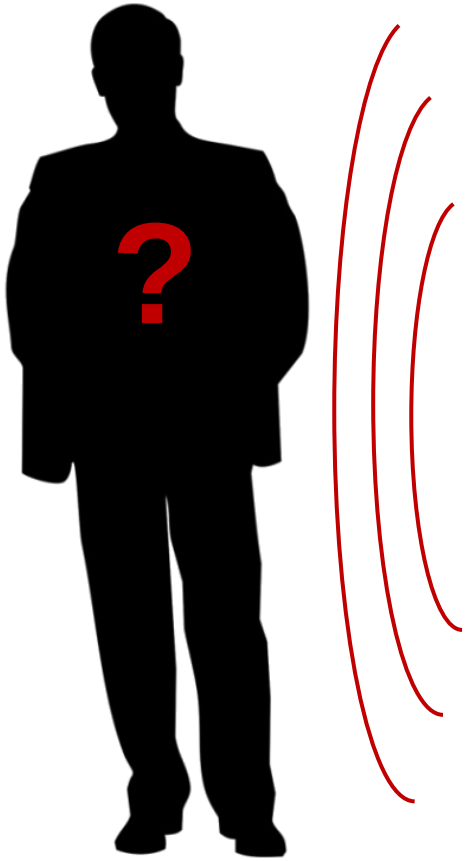
Emissions (e.g. from Antennas) produce **Immissions** at the location of the person and lead to **Exposure**.



Health effects of low-power RF & Microwave radiation

RF EM Field strength limits:

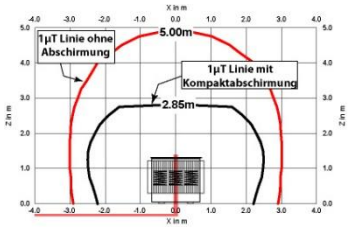
- Effects unknown: Precautionary principle
- RF EMF classed 2B *(“possibly carcinogenic”)* by IARC (coffee is also classed 2B…)
- Guidelines based on scientific results all over the world (plus safety margins)
- Specialty in CH: **Anlagegrenzwert:**
  Lower immission limits in “sensitive” environments



How are the Limits defined ?

ICNIRP Guidelines (International Commission on Non-Ionizing Radiation Protection)

Immission: Can be measured



Reference Levels

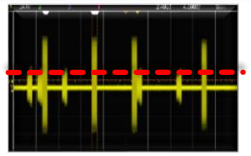
Field Strength
E-Field and B-Field
[V/m], [µT]

Power Density
Radiative Sources
[W/m^2]

Numerical modeling

Geometry
Anatomy
Tissue Properties

Averaging Rules
Time Averaging
Spatial Averaging



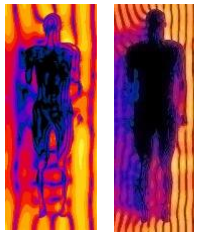
In-body Fields and absorption (Exposure) not directly accessible

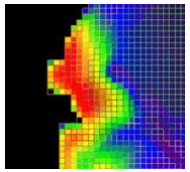
Basic Restrictions

Internal Fields

Induced Currents

Absorbed Power
SAR Value
[W/kg]





Compliance to reference levels ensures compliance to basic restrictions

Limiting values (Switzerland) in the RF range

Verordnung über den Schutz vor nichtionisierender Strahlung (NISV)

Immissionsgrenzwert (IGW):

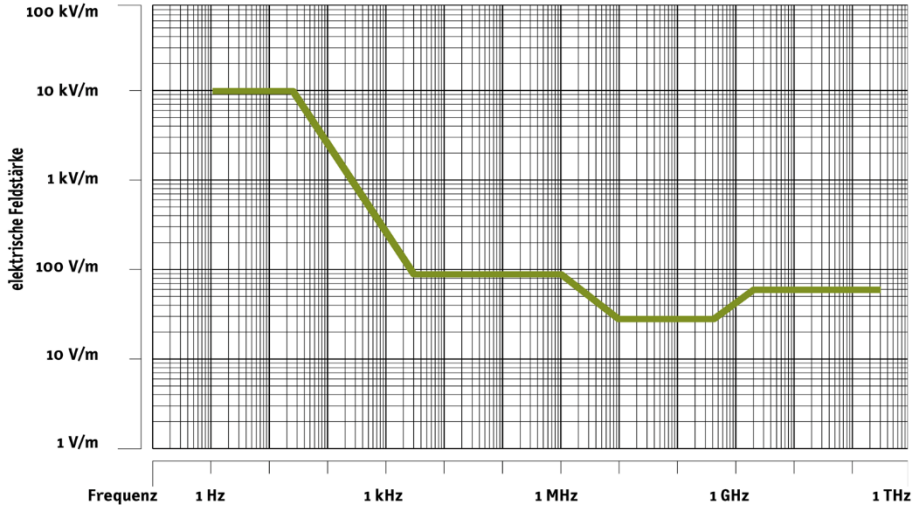
- Must be complied with at any locations, where persons could be present
- Applies to immissions generated by **fixed installations** (antenna towers etc.)
- Portable personal devices (i.e. mobile phone) are **not included**

Anlagegrenzwert (AGW):

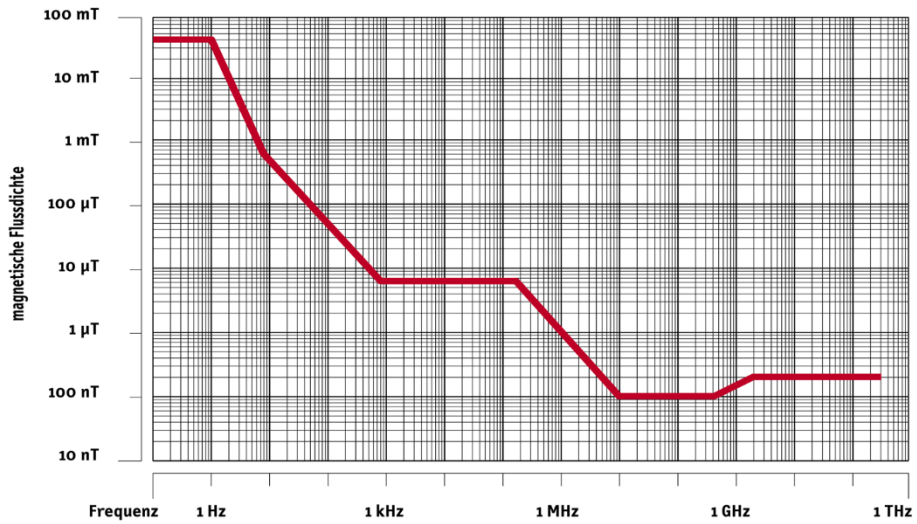
- Much more restrictive (precautionary limit)
- Applies to the total of all immissions generated by **one fixed installation**
- Must be complied with at “sensitive” locations (Orte Mit Empfindlicher Nutzung / “OMEN”)
- OMEN examples: homes, offices, schools, playgrounds…

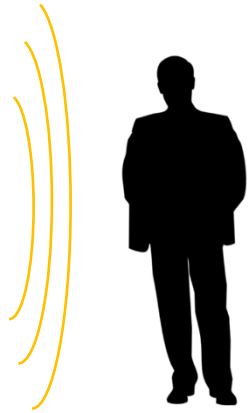
Limiting values in CH (Immissionsgrenzwerte, IGW) vs Frequency

Electric field strength (E)



Magnetic flux density (B)

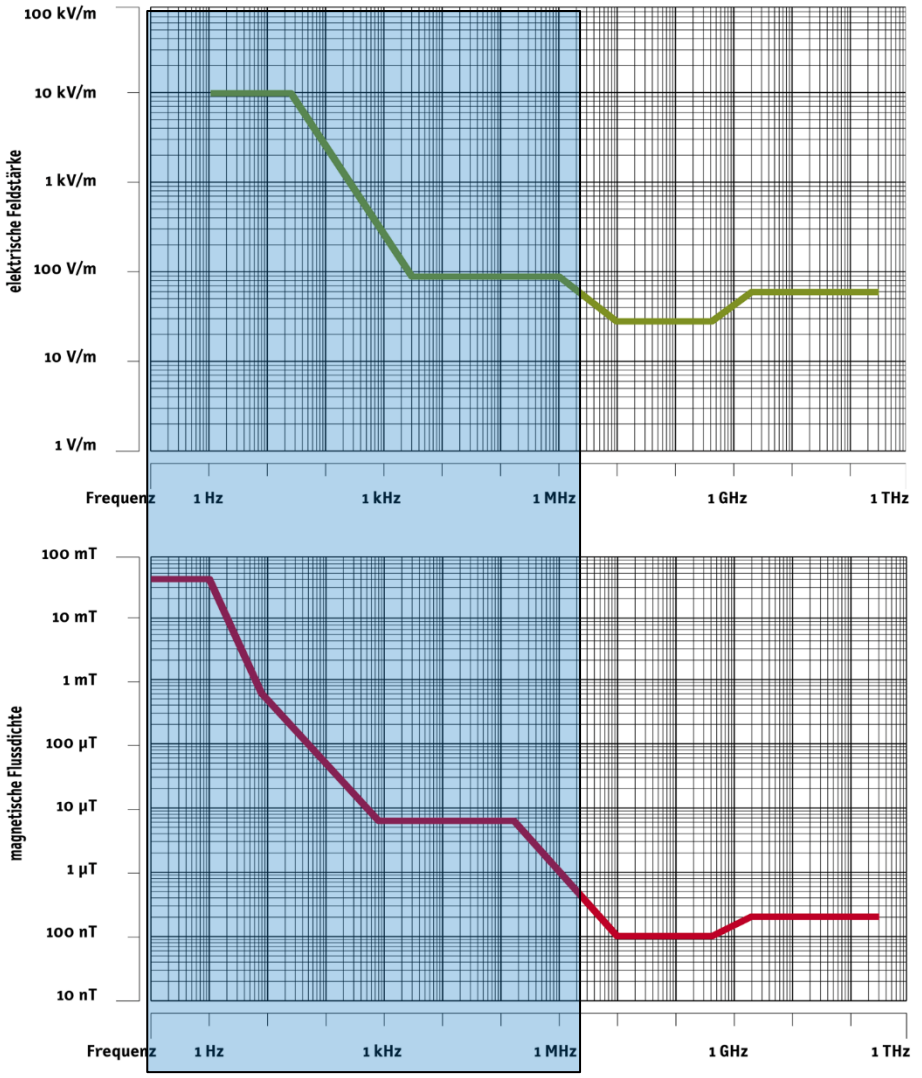




Why is there such strong frequency dependence?

Low frequencies (Hz ~ low MHz)

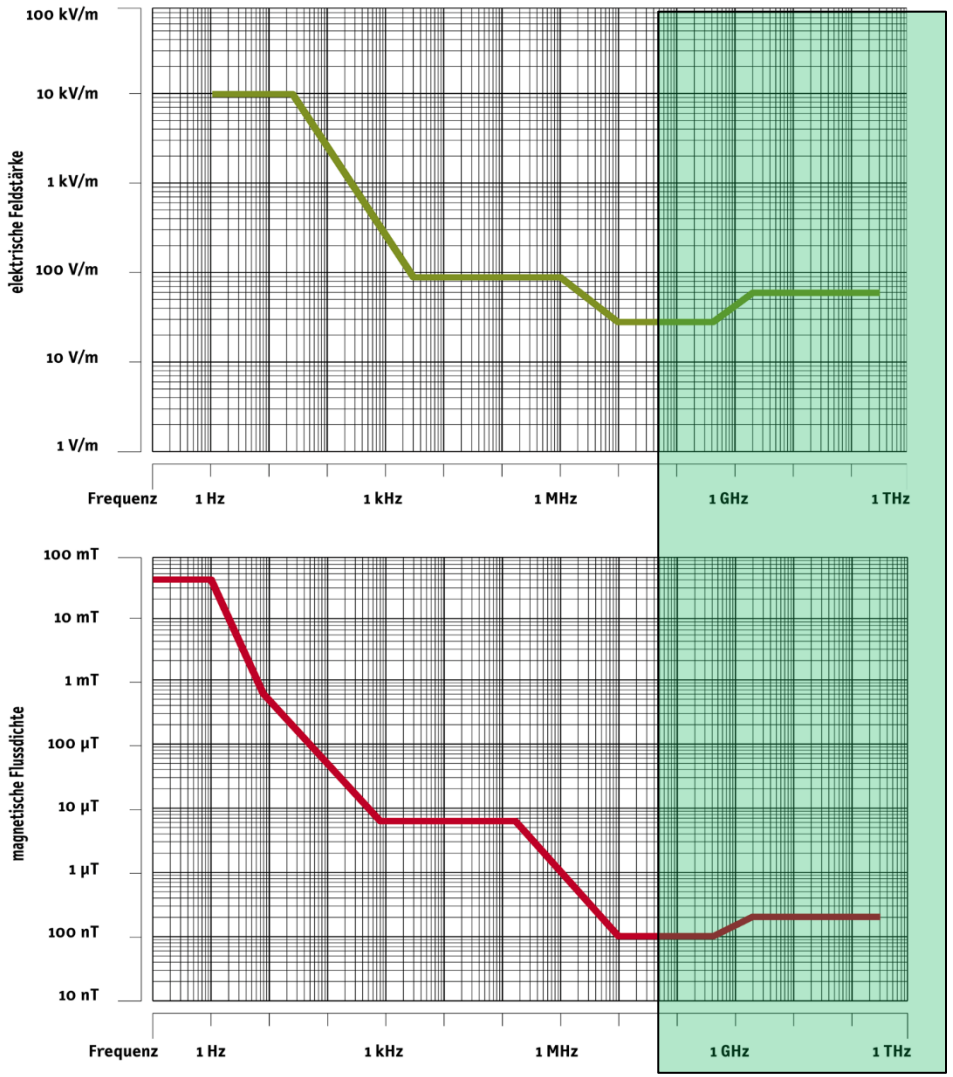
- Large equivalent wavelength
- (almost) **no radiation, mostly localized fields**
- E- and H field sources can be easily distinguished
- Inductive and capacitive coupling to tissue
- High penetration of B-Field
- Induced fields ~dB/dt
- Displacement currents ~dE/dt



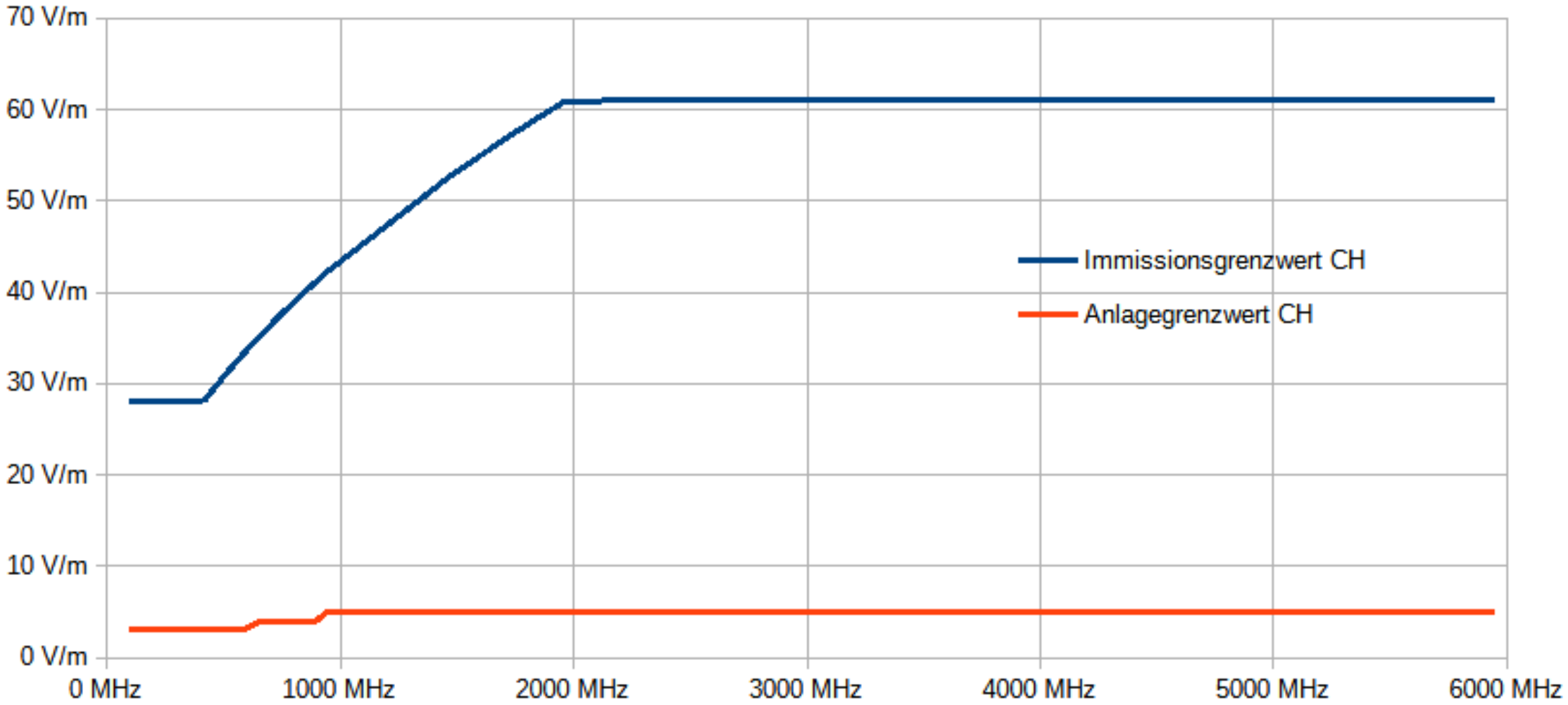
Why is there such strong frequency dependence?

RF & microwave (0.3 to 300 GHz)

- Wavelength of mm - m
- Mostly encountered as **electromagnetic radiation**
- E- and H field components coupled by Z_0
- **Power density** makes more sense than separate E/H measurement
- Penetration depth in tissue decreases with frequency
- Reflection effects
- Physical behavior starts to be more like visible light



Limiting values (IGW) in Switzerland in the RF range up to 6 GHz



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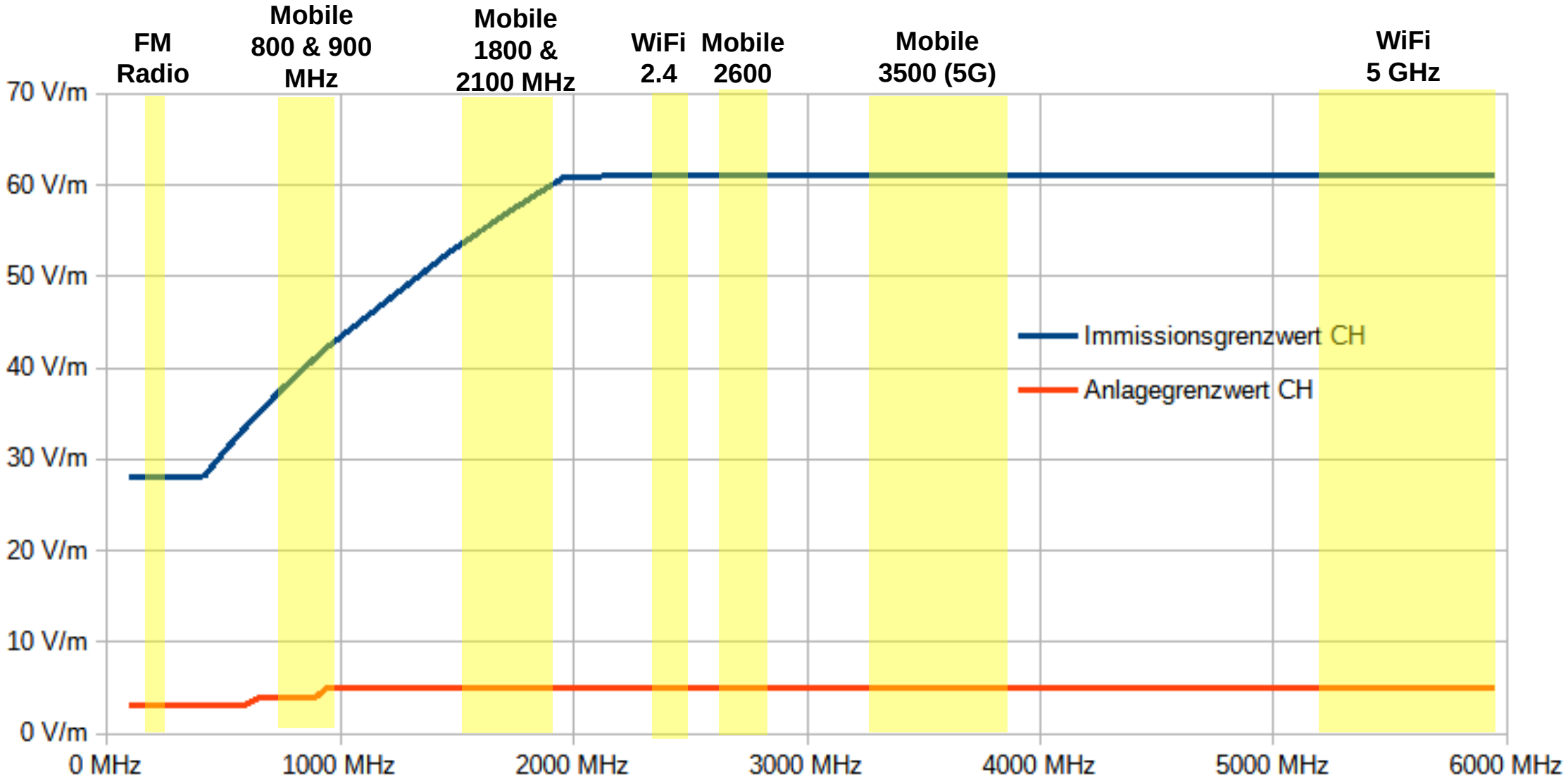


Usage of the RF & Microwave Spectrum

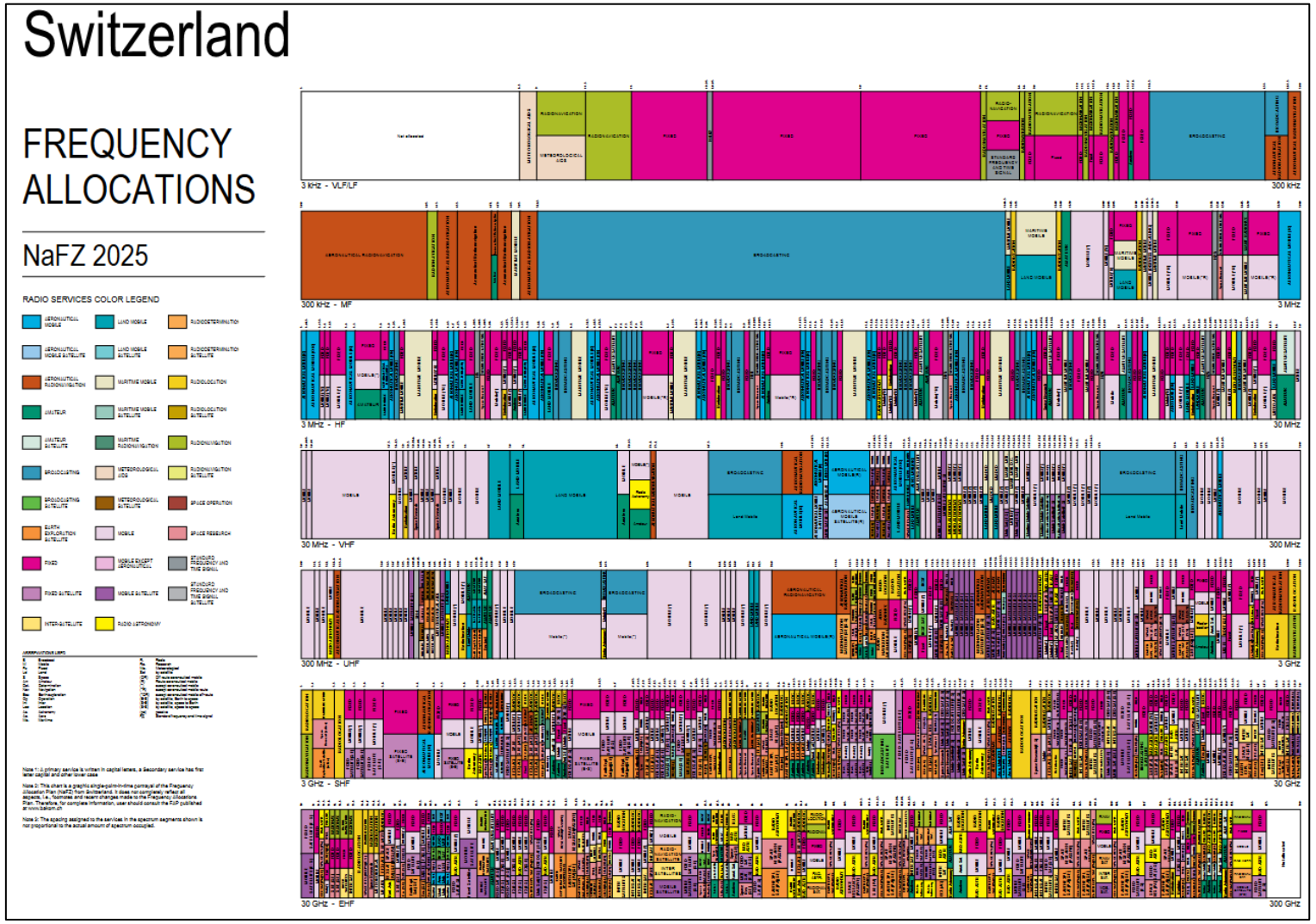
The RF and microwave spectrum is highly regulated

Frequency allocation plan:

- Defines which frequency is reserved for which application
- Avoids interference between users and systems
- Defines priorities in case of multiple use

Examples of usage rules:

- Frequency & bandwidth
- Max. allowed transmit power
- Max. allowed duty cycle
- Indoor / outdoor use
- Mandatory DFS (dynamic frequency selection)



Most active frequency bands (Switzerland)

Service	Frequency [MHz]	Modulations
FM Radio (analog) – *CH: will be shut down by end of 2026*	87.5 – 108	FM
DAB Radio (digital)	174 – 230	ODFM
SRD (short range devices): remotes, weather stations etc	433.05 – 434.79	various
TV broadcasting – *CH: mostly shut down since 2019*	470 – 790	AM/FM, OFDM
Mobile 700 MHz (4G & 5G)	703 – 788	OFDM
Mobile 800 MHz (4G & 5G)	832 – 915	OFDM
Mobile 900 MHz (3G - 5G)	880 – 960	GMSK, QPSK, OFDM, CDMA
Mobile 1800 MHz (3G - 5G)	1710 – 1880	GMSK, QPSK, OFDM, CDMA
DECT (cordless phones)	1880 – 1900	GFSK
Mobile 2100 MHz (3G - 5G)	1920 – 2170	QPSK, OFDM, CDMA
Wi-Fi, Bluetooth, microwave oven, remote controls…	2400 – 2485 (2.4G ISM band)	various
Mobile 2600 MHz (4G & 5G)	2500 – 2690	OFDM
Mobile 3.5 GHz (5G)	3424 – 3800	OFDM
Wi-Fi 5GHz	5150 – 5875	OFDM
Wi-Fi 6 (EU / CEPT countries)	5925 – 6425	OFDM

dB: The Ubiquitous Unit in the World of Radio

Definitions and Usage of dB, dBm, dBuV/m….

dB and dBm … Why use a logarithmic scale?

Power (Watts)	Power (dBm)	Found typically in
		linear particle accelerator Klystron peak power
		Large TV station, Typical RADAR peak power
		FM radio transmitter, microwave oven
		Average cell phone base station TX power
		mobile phone transmit power
		WiFi router TX power (peak)
		Wireless sensor network nodes
		Phone 250m from GSM base station (line of sight)
		Cell phone sensitivity
		GPS signal at receiver

dB and dBm … Why use a logarithmic scale?

Power (Watts)	Power (dBm)	Found typically in
100000000		linear particle accelerator Klystron peak power
1000000		Large TV station, Typical RADAR peak power
10000		
1000		FM radio transmitter, microwave oven
100		Average cell phone base station TX power
10		
1		mobile phone transmit power
0.1		WiFi router TX power (peak)
0.01		
0.001		Wireless sensor network nodes
0.0001		
0.00001		
0.0000001		Phone 250m from GSM base station (line of sight)
0.000000001		
0.00000000001		
0.0000000000001		Cell phone sensitivity
0.000000000000001		
0.00000000000000001		GPS signal at receiver

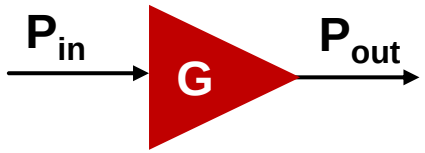
dB and dBm … Why use a logarithmic scale?

Power (Watts)	Power (dBm)	Found typically in
100000000	+110 dBm	linear particle accelerator Klystron peak power
1000000	+90 dBm	Large TV station, Typical RADAR peak power
10000	+70 dBm	
1000	+60 dBm	FM radio transmitter, microwave oven
100	+50 dBm	Average cell phone base station TX power
10	+40 dBm	
1	+30 dBm	mobile phone transmit power
0.1	+20 dBm	WiFi router TX power (peak)
0.01	+10 dBm	
0.001	**0 dBm**	Wireless sensor network nodes
0.0001	-10 dBm	
0.00001	-20 dBm	
0.0000001	-40 dBm	Phone 250m from GSM base station (line of sight)
0.000000001	-60 dBm	
0.00000000001	-80 dBm	
0.0000000000001	-100 dBm	Cell phone sensitivity
0.000000000000001	-110 dBm	
0.00000000000000001	-130 dBm	GPS signal at receiver

dB, dBm … The RF engineer's logarithmic units

dB

- **Relative Power**
- Example: Amplifier gain
- Power / power density comparisons



$$\boldsymbol{G}[dB] = \mathbf{10} \cdot \boldsymbol{log}_{\mathbf{10}} \left(\frac{\boldsymbol{P_{out}}[W]}{\boldsymbol{P_{in}}[W]} \right)$$

dBm

- **Absolute Power**
- **Definition:** 0 dBm = 1 mW
- Example: Transmitter RF Power

$$\boldsymbol{P}[dBm] = \mathbf{10} \cdot \boldsymbol{log}_{\mathbf{10}} \left(\frac{\boldsymbol{P}\ [W]}{\mathbf{1}\ \boldsymbol{mW}} \right)$$

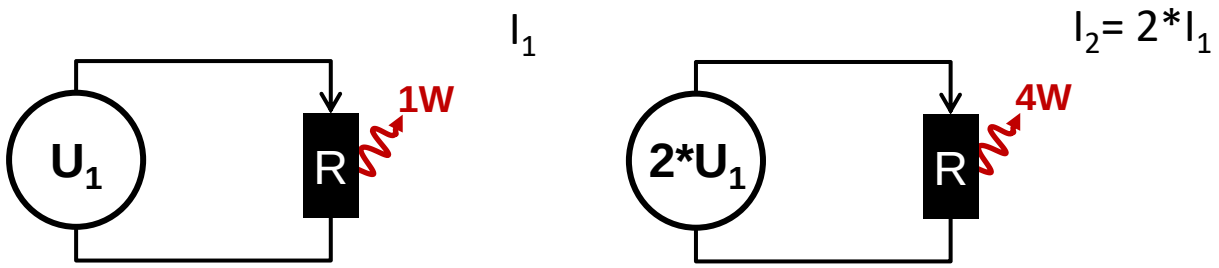
dB, dBm … Power vs Field values

Network theory:

P = U*I [W]

P = U^2/R

P = R*I^2



$$\frac{P_2}{P_1} = \frac{{U_2}^2}{{U_1}^2} = \frac{{I_2}^2}{{I_1}^2}$$

Electromagnetic wave power density:

S = E x H [W/m^2]

P = $|E|^2/Z_0$

P = Z_0*$|H|^2$

$$\text{Difference } [dB] = \mathbf{10} \cdot \boldsymbol{log_{10}}\left(\frac{S_2}{S_1}\right)$$

$$\text{Difference } [dB] = \mathbf{20} \cdot \boldsymbol{log_{10}}\left(\frac{E_2}{E_1}\right)$$

Advantages of using a dB scale

- **Measurements: simultaneous display of strong and very weak signals**
  - Spectrum Analyzer (you will see that later)
  - Comparison of small frequency components in a signal (e.g., harmonic distortion)

- **In RF, ratios are often more useful than absolute values**
  - Gain of amplifiers
  - Attenuation of signals
  - Evaluations in “orders of magnitude”

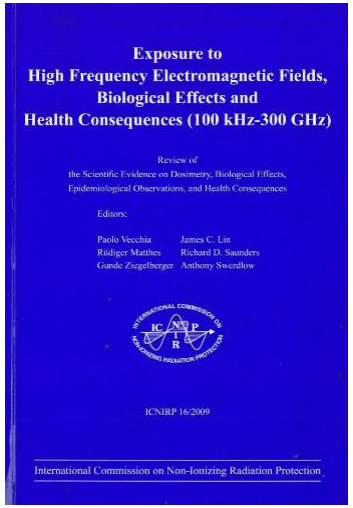
- **In the dB world, a ratio transforms into a difference**
  - E.g.: +3dB = twice the power
  - -30 dB = 1000 times less power
  - Gain of complex signal chains is easier to characterize

Task for next lesson

- **Get familiar with topic: Reading material:**

BAFU Brochure

ICNIRP publications
EMF & Health



ICNIRP
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NON-IONIZING RADIATION PROTECTION

- **Answer questionnaire that I will send you per E-Mail**

Reading Material, Exercises, etc.

P&S homepage:

people.ee.ethz.ch/~mzahner/PPS-EMrad/material

Next Meeting:
Wed, 06.03.2025 at 09:15 in ETZ K71