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Advanced Wireless & 5G Networks

Prof. Dr. Ir. Michael Peeters — 2023–2024

Topics for today

- **What to do with 20/10?**
- **What are your expectations?**
- **1. Introduction (continued)**
  - Recap of last week
- **2. Technology baselining/refresher**
  - Two formulas

Planning

Session	Date	Topic
1	20231006	~~Introduction, history, market, industry, bands, licensed vs. unlicensed, …~~
2	20231013	Technology baselining (a.k.a. refreshing what you should have known): 2G, WiFi, …
3	20231020	L Cellular/3GPP. 2G as a ”low-complexity” example
4	20231027	L 3GPP 2G-3G-4G-5G architecture evolution. 5G intro
5	20231110	L 5G: Air interface
6	20231117	L Other licensed and special cases (CBRS, LAA, Public Safety, Loon, V2V, Satellite)
7	20231124	U IEEE Wifi Network Architecture: the 802.11 family
8	20231201	U 802.11 abgn
9	20231208	U QoS, 802.11 ac,ax and 802.11 ad,ay
10	20231215	U short range 802.15.4: Zigbee, BLE, and UWB
11	20231222	U Specials: LoRa, Sigfox (perhaps), proprietary, 802.11p
	TBD	Extra: Technology enablers and acronyms you need to be aware of: ADC, FEM, PA, LSA, and other key analog and digital HW blocks, mMIMO, Beam management, 802.11be, AI, 6G, THz and their implications to the network

Your expectations

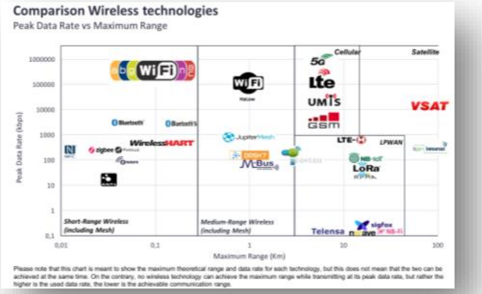
- How it is possible that, in a world where the number of devices continue to grow, every device can get mobile wireless connectivity with the internet without saturating the network.
- How do 4G/5G/... technologies actually work.
- How do you go about designing a good WiFi network, both on the physical end (devices, access point locations, ...) and on the configuration end.
- What are the technologies behind the current advancement in Cellular and Wi-Fi networks?
- Be able to understand the need for improved and efficient networking technologies, and how to approach solving the drawbacks of current technologies.
- What are the limitations of 5G in regard to the latest trends in Ai, AR/VR and technologies that require very low latency.
- What is next?
- How do modern mobile networks work and how have they changed from the previous ones?
- What are the main problems or limitations faced by different types of networks? If it is possible, what are the best ways to solve them?
- How will wireless and mobile networks possibly evolve in the near future?
- To better understand historical challenges in wireless that companies such as blackberry faced.
- To better understand wireless technologies such as Zigbee and LoRaWan and their use in IOT projects.
- What role data science could have in this field?
- Can networks be perfected to the point where we don't need to keep on creating new ones or upgrade the existing ones?
- Can governments stop the development of networks?
- Will connectivity ever be available underwater or underground?

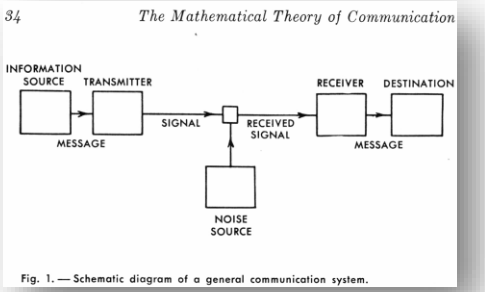
1. Introduction

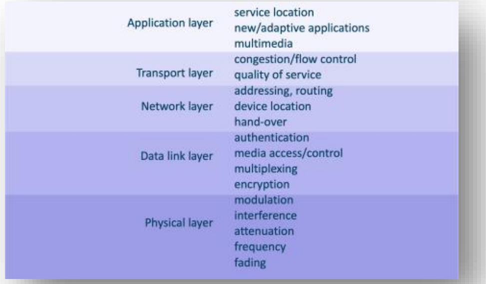
(continued)

Recap

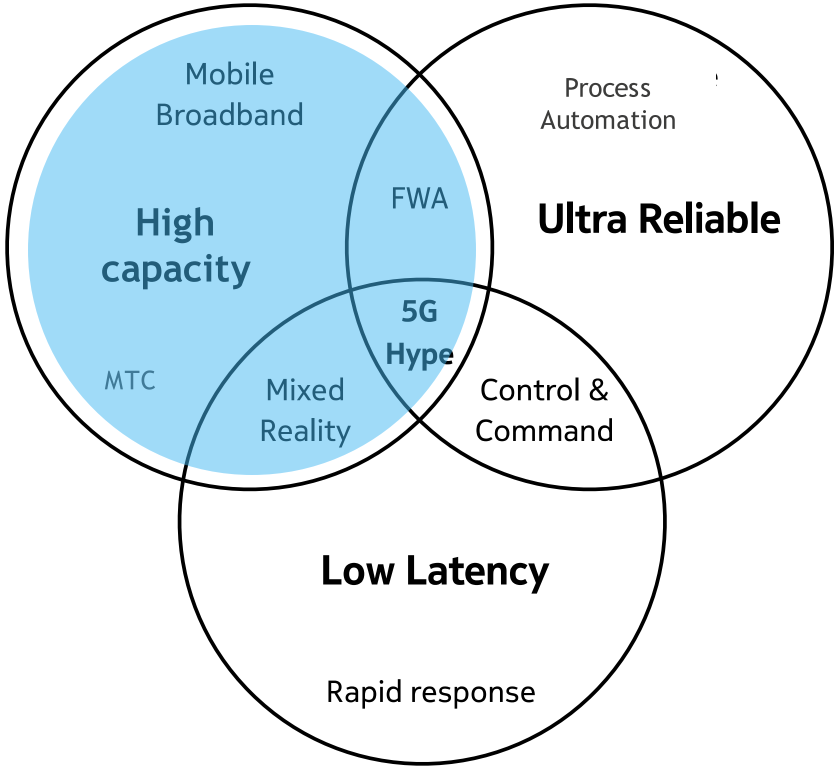
- **What problem are we solving?**
  - Growth of data (transfer)
  - Due to value of sharing data
  - Efficiency bits/€
- **To know how much we can transmit**
  - Capacity
  - Shannon-Hartley
- **Capacity is not the same as throughput**
  - Multiple layers when you look at a network

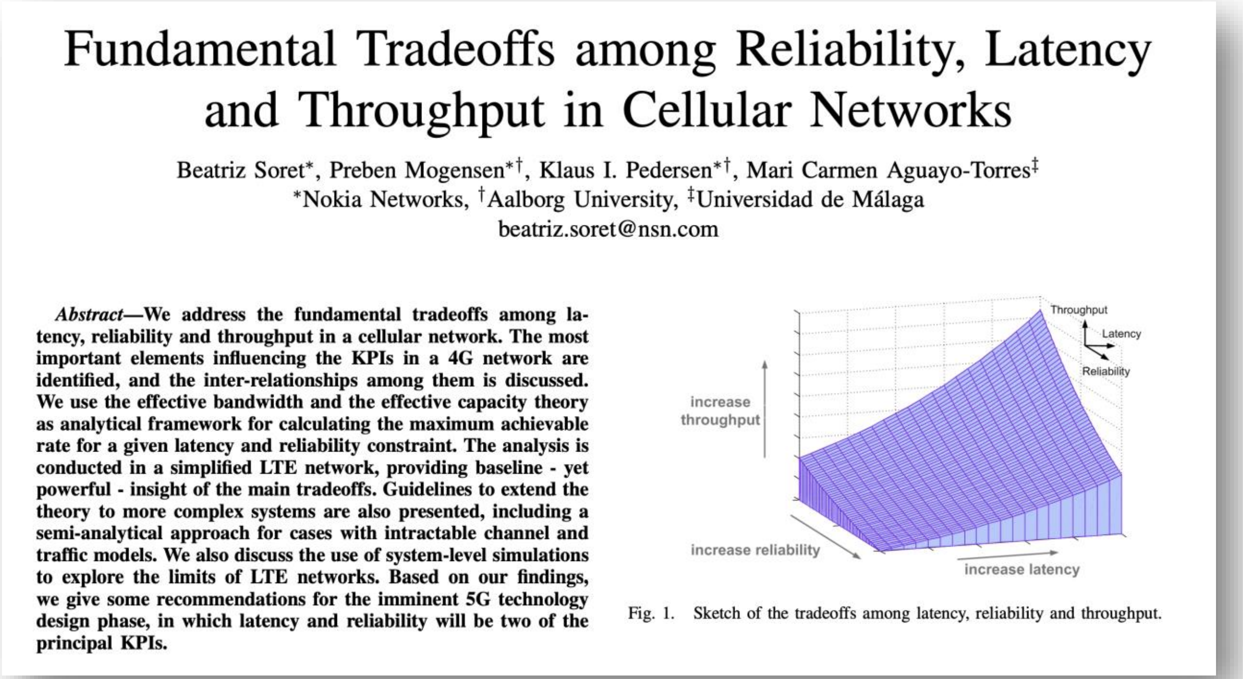






There is no free lunch





Fundamental Tradeoffs among Reliability, Latency and Throughput in Cellular Networks

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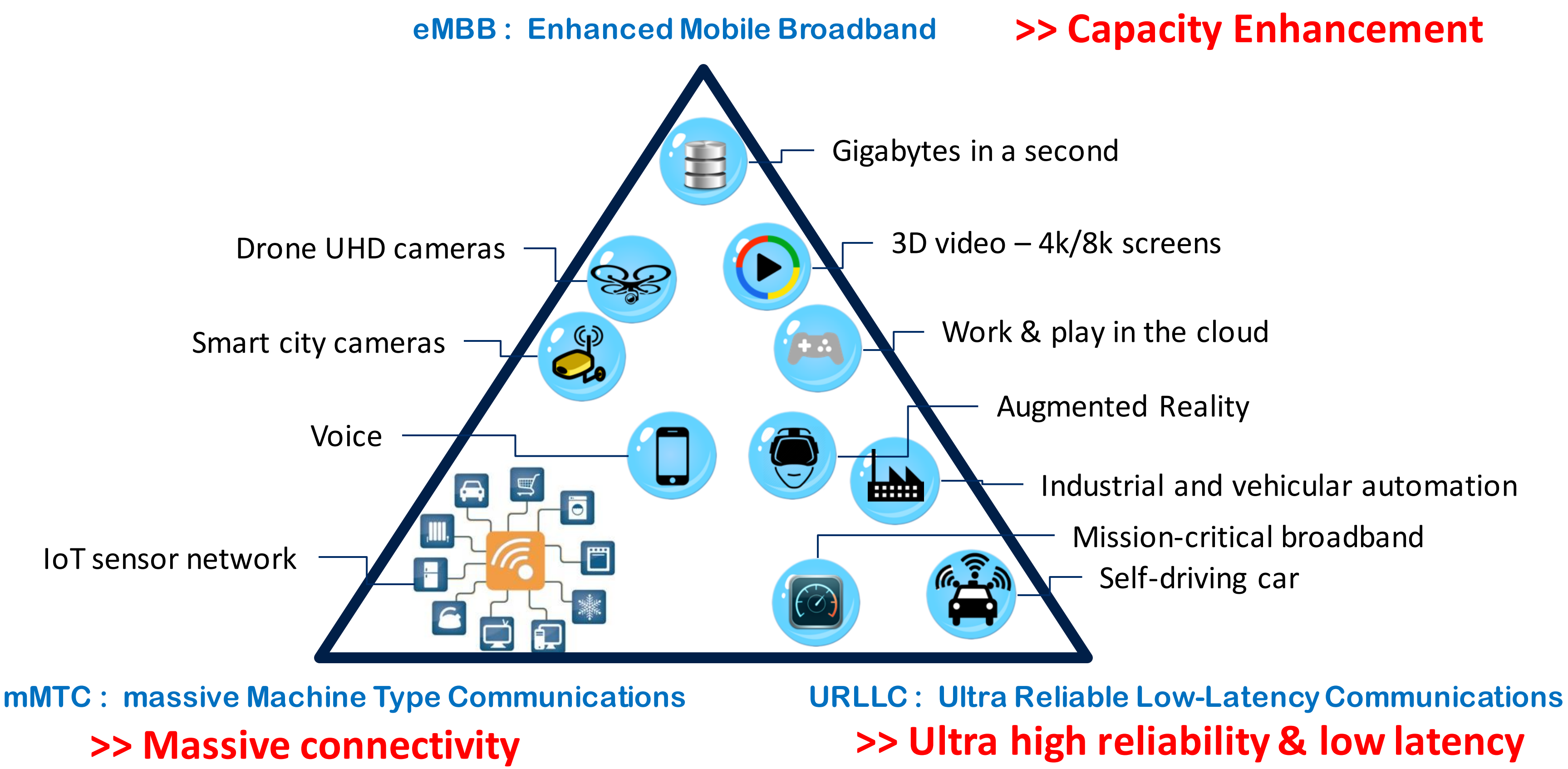
Abstract—We address the fundamental tradeoffs among latency, reliability and throughput in a cellular network. The most important elements influencing the KPIs in a 4G network are identified, and the inter-relationships among them is discussed. We use the effective bandwidth and the effective capacity theory as analytical framework for calculating the maximum achievable rate for a given latency and reliability constraint. The analysis is conducted in a simplified LTE network, providing baseline - yet powerful - insight of the main tradeoffs. Guidelines to extend the theory to more complex systems are also presented, including a semi-analytical approach for cases with intractable channel and traffic models. We also discuss the use of system-level simulations to explore the limits of LTE networks. Based on our findings, we give some recommendations for the imminent 5G technology design phase, in which latency and reliability will be two of the principal KPIs.

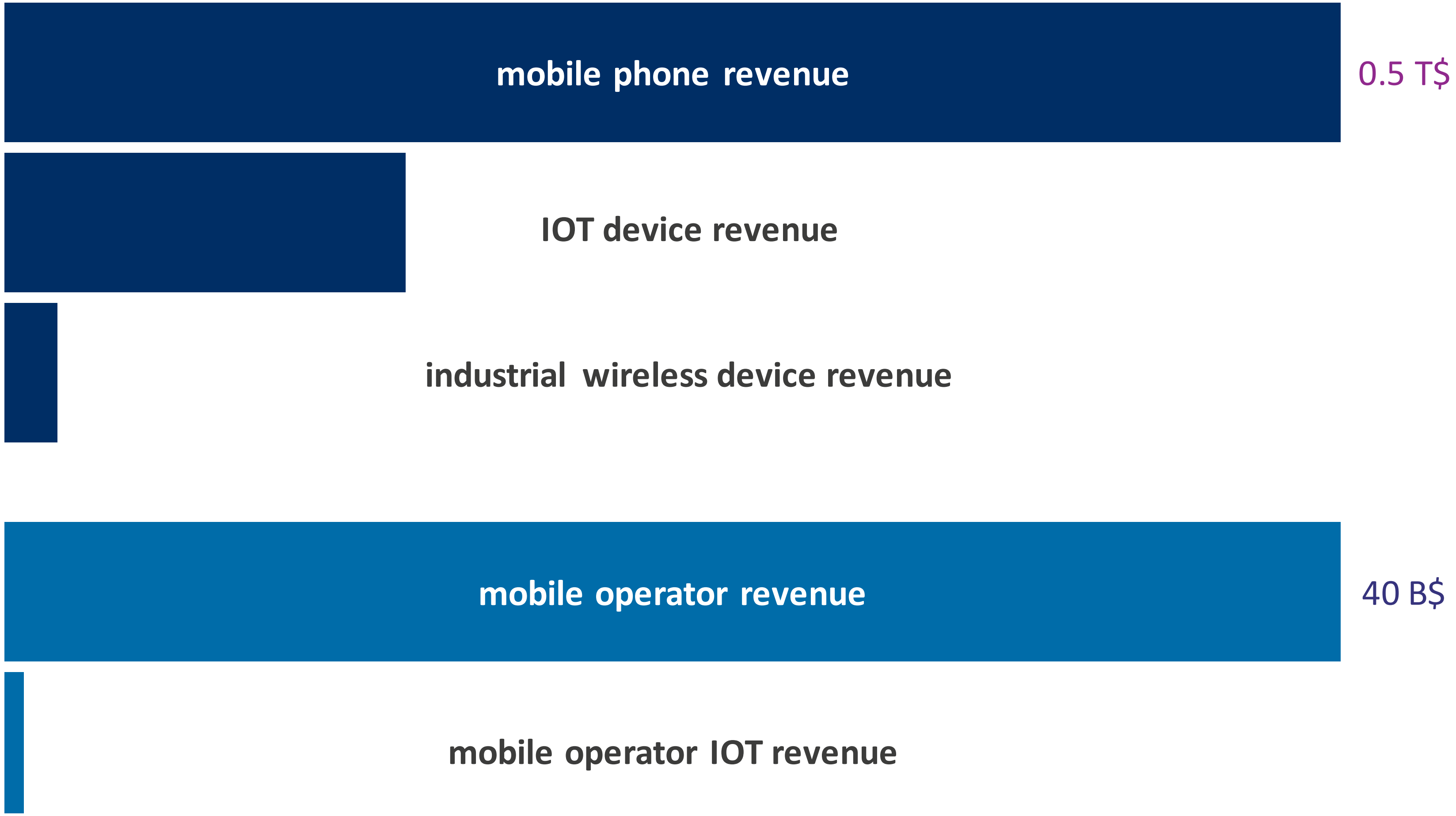
Fig. 1. Sketch of the tradeoffs among latency, reliability and throughput.

5G use cases defined by ITU under IMT-2020



IRG Heads' Workshop 2018, Brussels, 18 October, 2018

eBOS Technologies

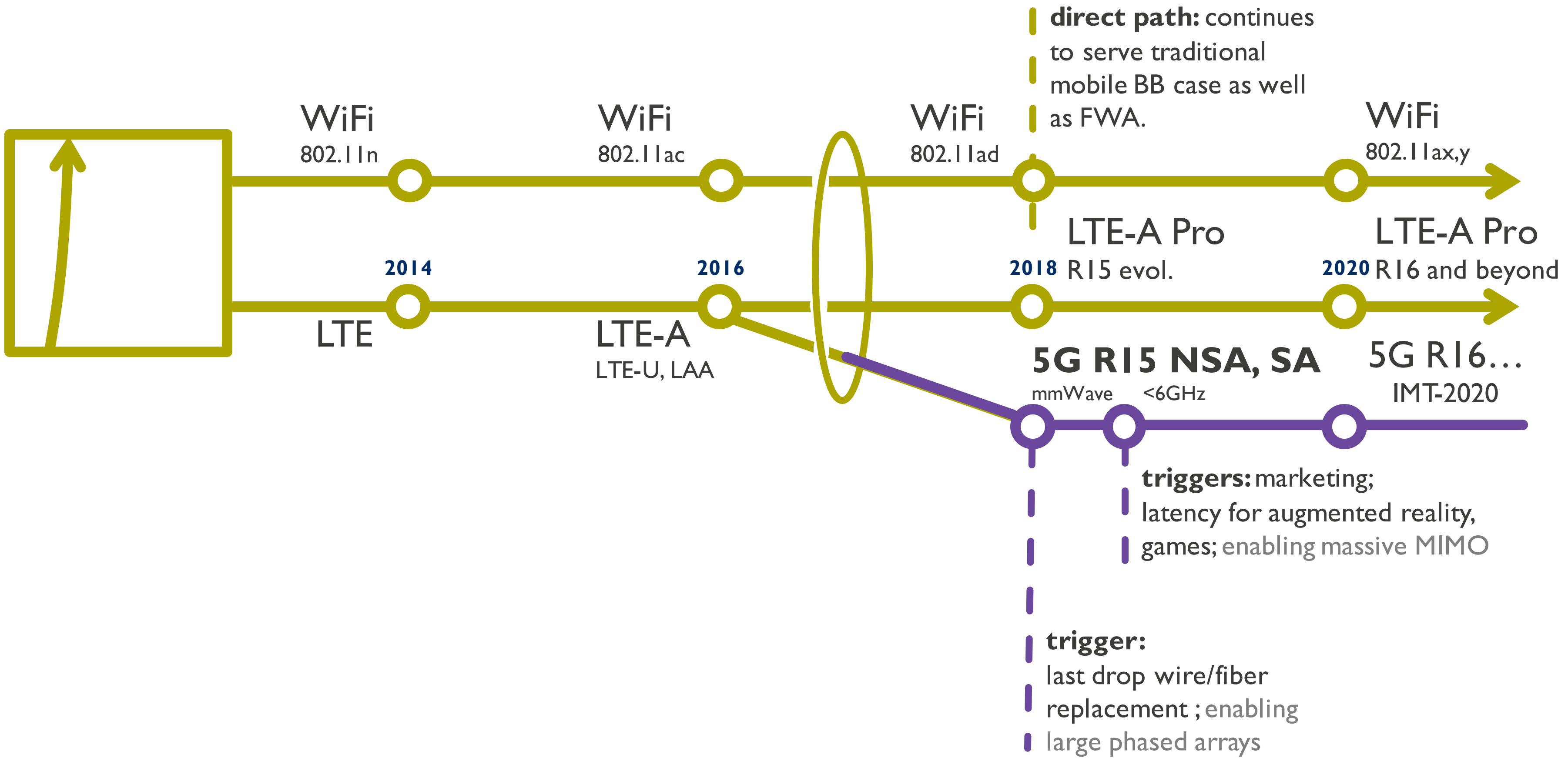

mobile phone revenue
0.5 T$
IOT device revenue
industrial wireless device revenue
mobile operator revenue
40 B$
mobile operator IOT revenue

Or even simpler

2 billion consumers at $250 per year

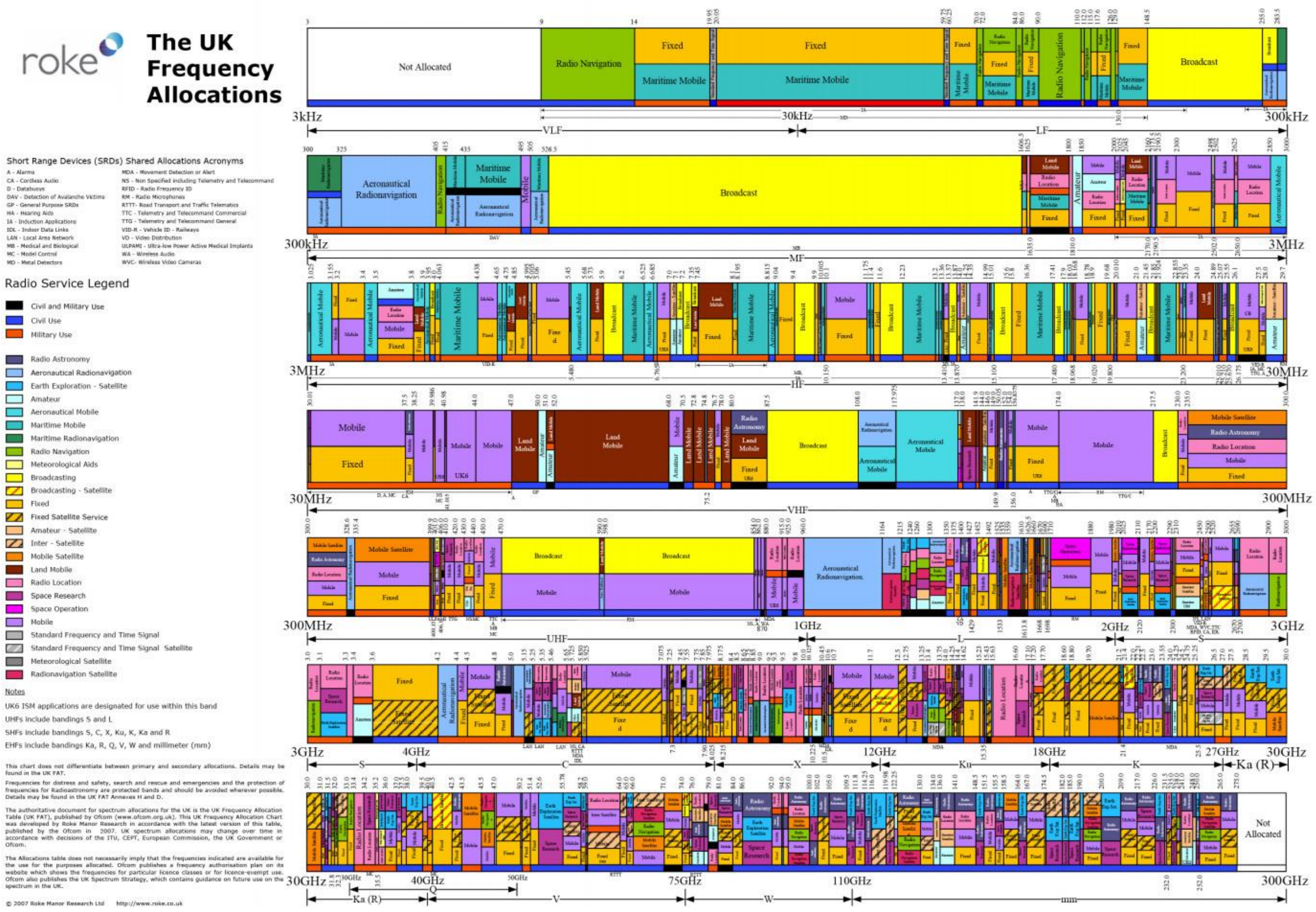
50 billion devices at $1 per year

Wireless & mobile evolution (and some terminology)



Capacity driven (eMBB) development continues to be “clear”.

WiFi vs. 5G? No. Better: licensed vs. unlicensed



- **Bandwith (not frequency) is a scarce commodity**
- **Regulated…**
- **Depending on the frequency, can be**
  - Licensed: you need to get permission and follow certain rules.
  - Unlicensed: you need to follow certain rules.

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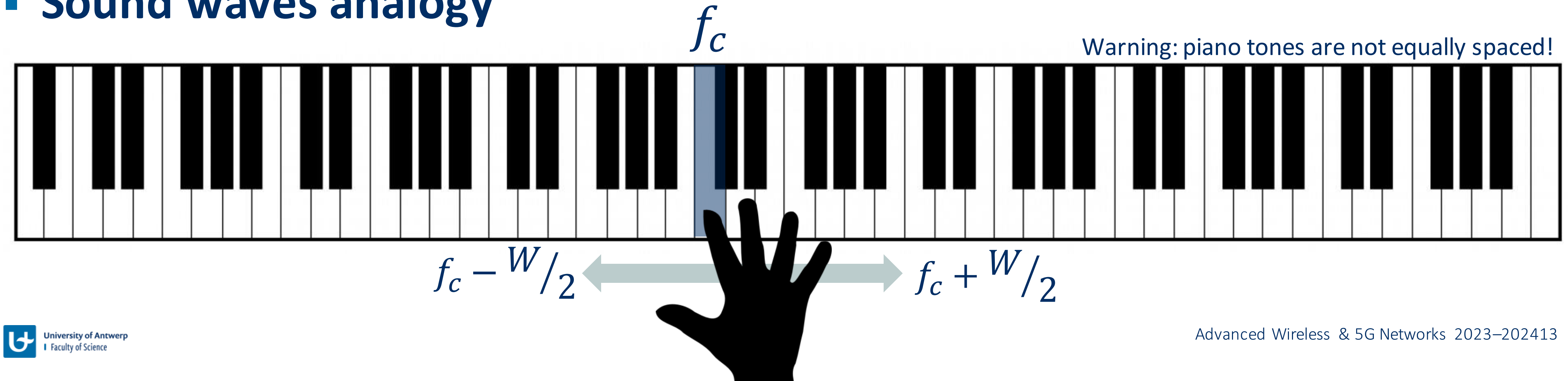
Bandwidth vs. Frequency

- **A piece of spectrum is defined by a center frequency and a bandwidth**
  - Frequency f_c or f, expressed in Hz|MHz|GHz
  - Bandwidth W, also expressed in Hz|MHz|GHz
  - E.g. WiFi 1 (802.11b), channel 11: $f_c = 2462\text{MHz}$ and $W = 22\text{MHz}$
- **These are electromagnetic waves:** $\vec{\boldsymbol{E}} = \boldsymbol{E_W}(\boldsymbol{t}).\cos(kx - 2\pi f_c t).\overrightarrow{\mathbf{1}_{\boldsymbol{y}}}$
- **Sound waves analogy**



Standardization & Regulation

- **Advantages :**
  - creation of large market
  - increase of flexibility (products able to communicate)
- **Disadvantages :**
  - standards freeze the technology
  - gap between technology and standards
  - conflicting standards produced by different bodies
  - *barrier to entry*

Where does it happen?

ITU Telecommunication Standardization Sector (ITU-T) ➔ DSL, GPON

- The international standards (ITU-T Recommendations) developed by Study Group 15 detail technical specifications giving shape to global communication infrastructure. The group’s standards define technologies and architectures of optical transport networks enabling long-haul global information exchange; fibre- or copper-based access networks through which subscribers connect; and home networks connecting in-premises devices and interfacing with the outside world.

ITU Radiocommunication Sector (ITU-R) ➔ Spectrum

- The mission of the ITU Radiocommunication Sector is, inter alia, to ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including those using satellite orbits, and to carry out studies and adopt recommendations on radiocommunication matters.

European Telecommunications Standards Institute (ETSI) ➔ 3GPP (4G, 5G)

- The project covers cellular telecommunications technologies, including radio access, core network and service capabilities, which provide a complete system description for mobile telecommunications.

IEEE Standards Association (IEEE-SA) ➔ WiFi, EPON, Ethernet

- IEEE 802 is a family of IEEE standards dealing with local area networks and metropolitan area networks. The IEEE 802 standards are restricted to networks carrying variable-size packets, unlike cell relay networks, for example, where data is transmitted in short, uniformly sized units called cells. Isochronous networks, where data is transmitted as a steady stream of octets, or groups of octets, at regular time intervals, are also beyond the scope of the IEEE 802 standards.

Ans let’s not gorget: China Communications Standards Association (CCSA) of China, Alliance for Telecommunications Industry Solutions (ATIS), Association of Radio Industries and Businesses (ARIB) of Japan,Telecommunications Industry Association (TIA), Telecommunications Standards Development Society, India (TSDSI), Telecom munications Technology Association (TTA) of Korea, Telecommunications Technology Committee (TTC) of Japan, …

Spectrum: ITU-R

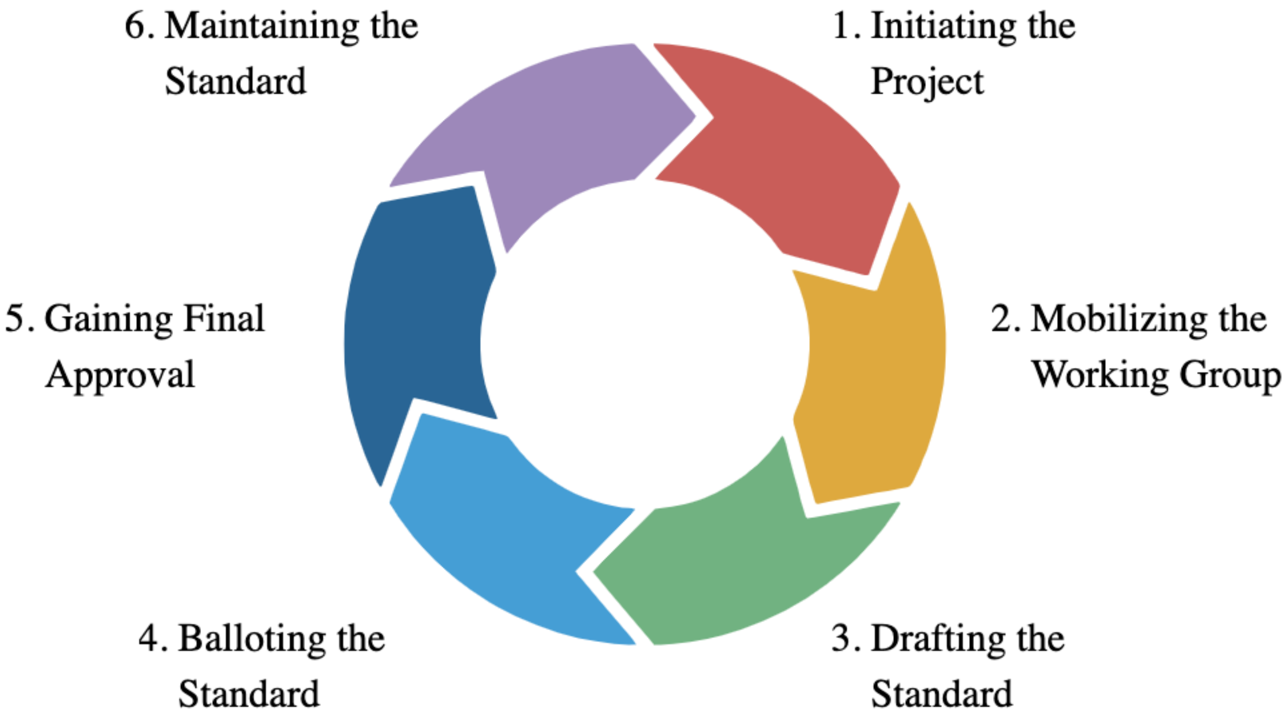
ITU WRC SHARM EL-SHEIKH 2019
28 October - 22 November
Sharm El-Sheikh, Egypt

ITU WRC DUBAI 2023

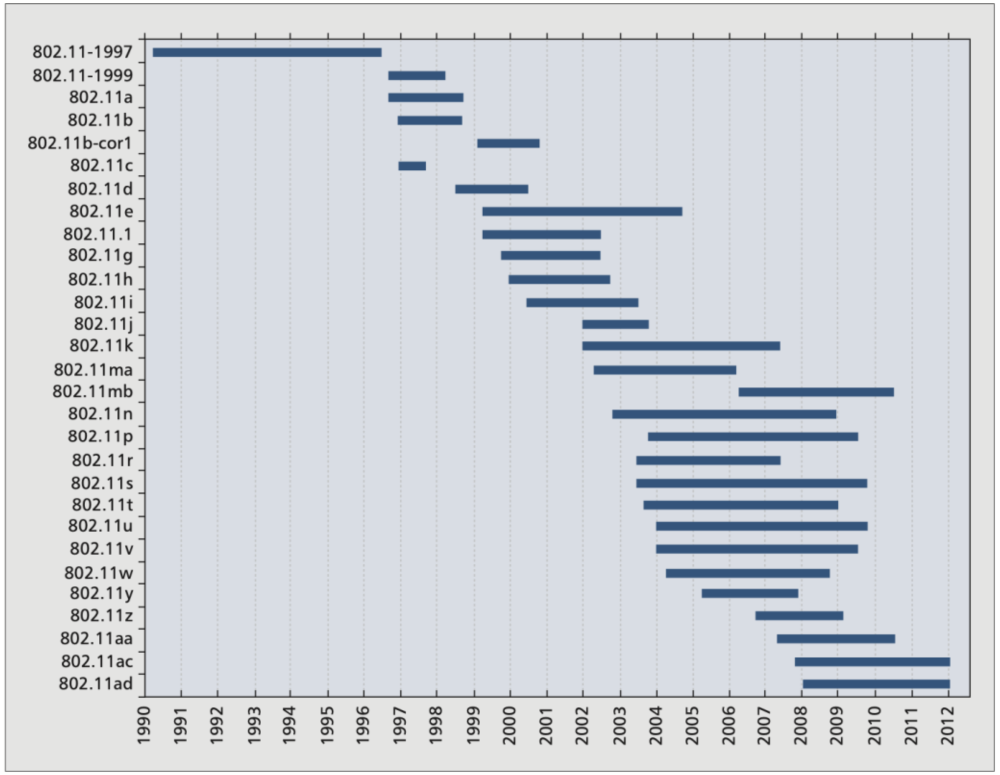
- **Last World Radio Conference WRC-19**
  - World radiocommunication conferences (WRC) are held **every three to four years**. It is the job of WRC to review, and, if necessary, revise the Radio Regulations, the international treaty governing the **use of the radio-frequency spectrum** and the geostationary-satellite and non-geostationary-satellite orbits. Revisions are made on the basis of an agenda determined by the ITU Council, which takes into account recommendations made by previous world radiocommunication conferences.
  - The general scope of the agenda of world radiocommunication conferences is established four to six years in advance, with the final agenda set by the ITU Council two years before the conference, with the concurrence of a majority of Member States.

WiFi: IEEE Standard

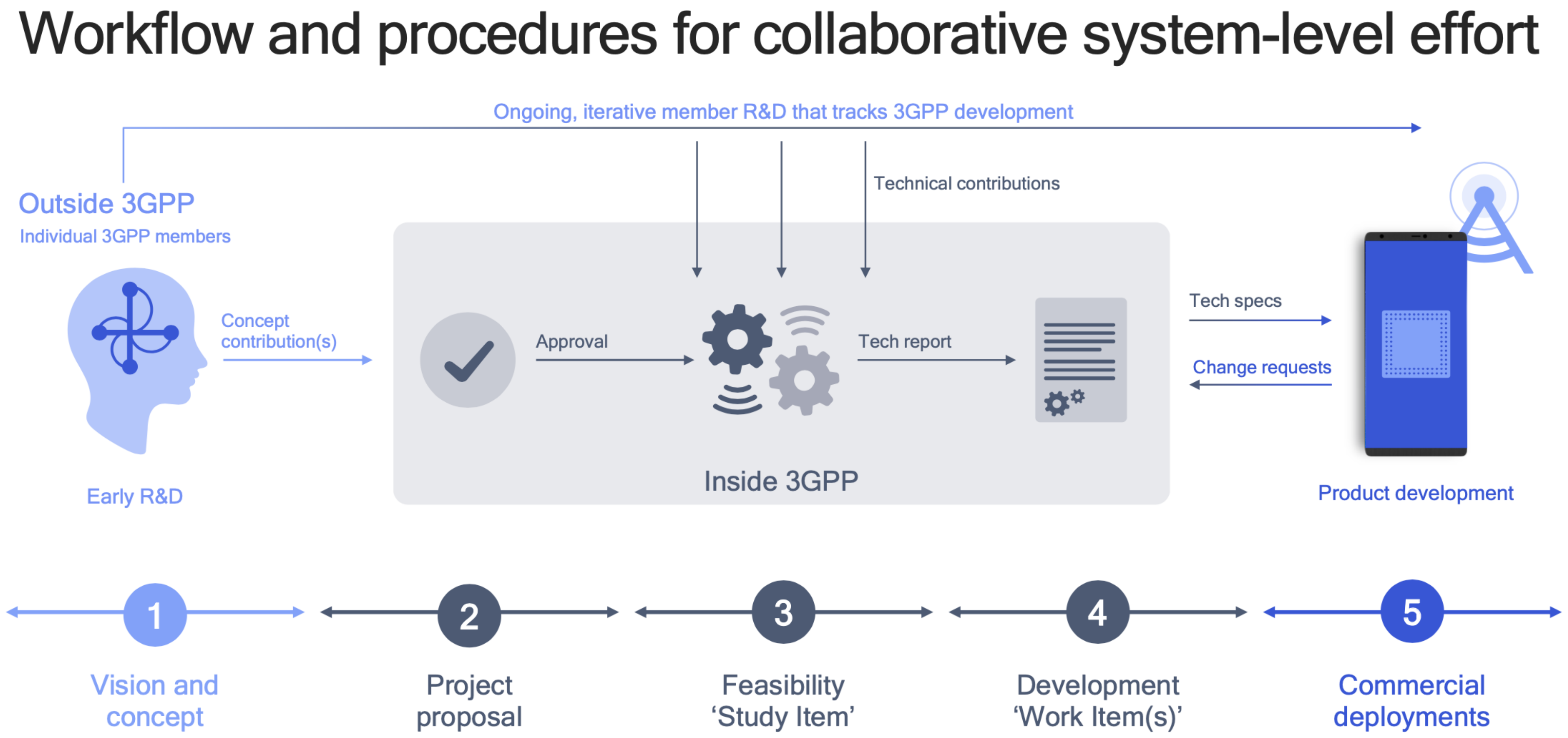
Meritocratic process



G. R. Hiertz, D. Denteneer, L. Stibor, Y. Zang, X. P. Costa and B. Walke, "The IEEE 802.11 universe," in *IEEE Communications Magazine*, vol. 48, no. 1, pp. 62-70, January 2010, doi: 10.1109/MCOM.2010.5394032.



2G, 3G, 4G, 5G: 3GPP



"Meritocratic" process, "specs, not standards"

“Specs, not standards”

Prepares, approves, enhances and maintains globally applicable specifications

Transpose 3GPP specs into standards[2]
also responsible for IPR[3] policy for 3GPP members[4]

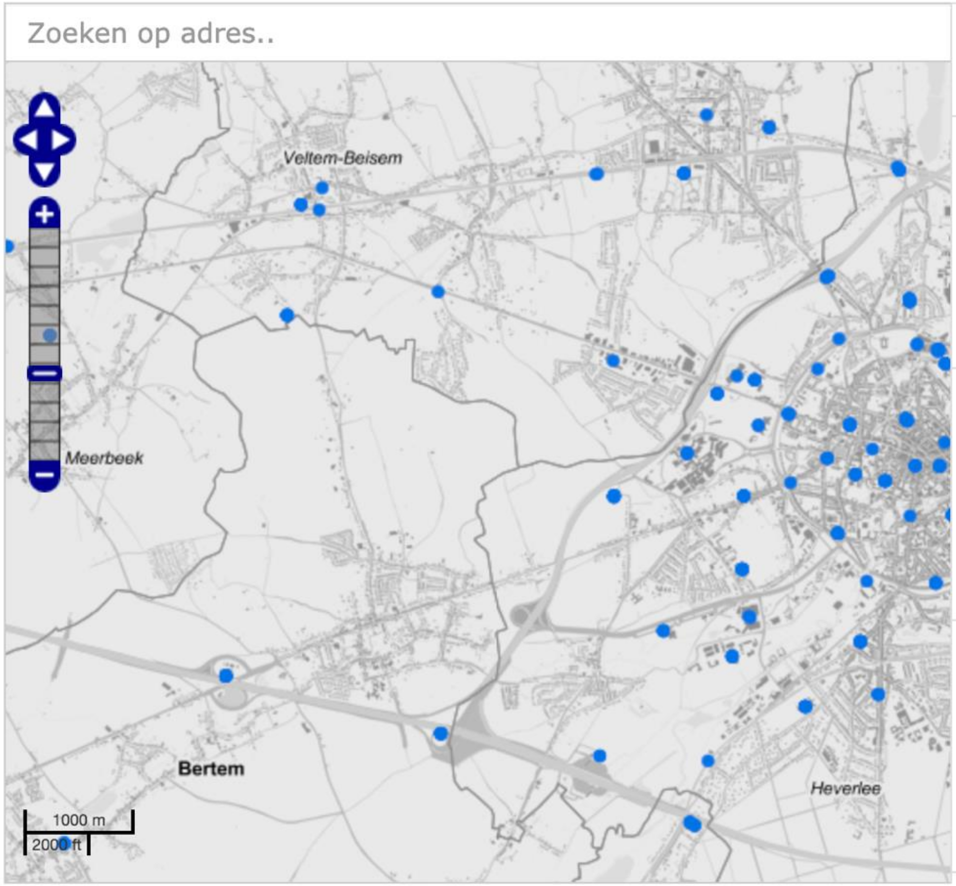
1. Also Market Representation Partners that provide guidance on market dynamics and requirements, e.g. GSMA, NGMN; 2. Regional SDOs transpose 3GPP specs into national standards - ITU responsible for transposing 3GPP specs into international standards; 3. Intellectual Property Rights; 4. In order to participate in 3GPP, individual members must formally join one of SSOs

Biological impact

- **Non-ionizing radiation**
  - Since 1998, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has maintained that no evidence of adverse biological effects of RFR exist, other than tissue heating at exposures above prescribed thresholds.
  - In contrast, in 2011, an expert working group of the International Agency for Research on Cancer (IARC) categorized RFR emitted by cell phones and other WTDs as a Group 2B ("possible") human carcinogen.
    - Group 2B includes: coffee, pickles, talcum powder

Regulation in Belgium

Exposure and health are regional



Resultaten

x

A
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Referentie operator: VB4344A
Attest: link

B
Status: Goedgekeurd (2013-12-31T23:00:00)
Adres: Waversebaan 68, 3001 LEUVEN (HEVERLEE)
Operator: Telenet Group BVBA
Referentie operator: VB4344A_99141910_CON_ZTE
Attest: link

C
Status: Goedgekeurd (2016-10-27T22:00:00)
Adres: Waversebaan 68, 3001 LEUVEN (HEVERLEE)
Operator: Telenet Group BVBA
Referentie operator: _VB4344A_99146910_MOD_M4C
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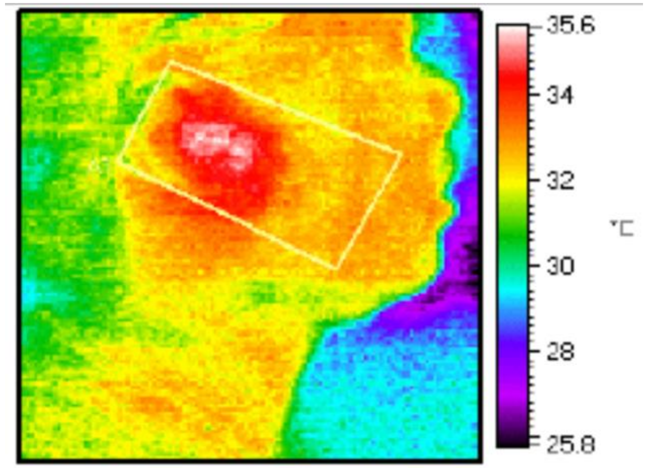
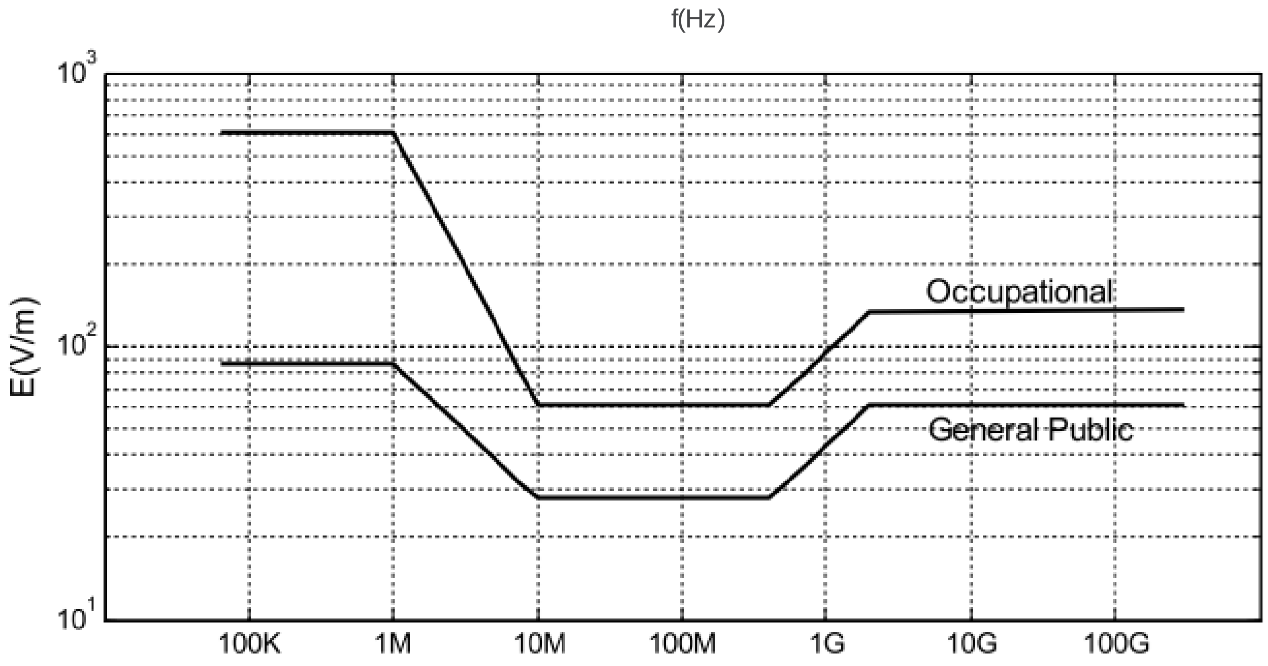
Proven biological impact



- **Posture**
- **Sleep cycle**
- **Notification anxiety**
- **Distracted driving**
- **Warm ears**

ICNIRP limits

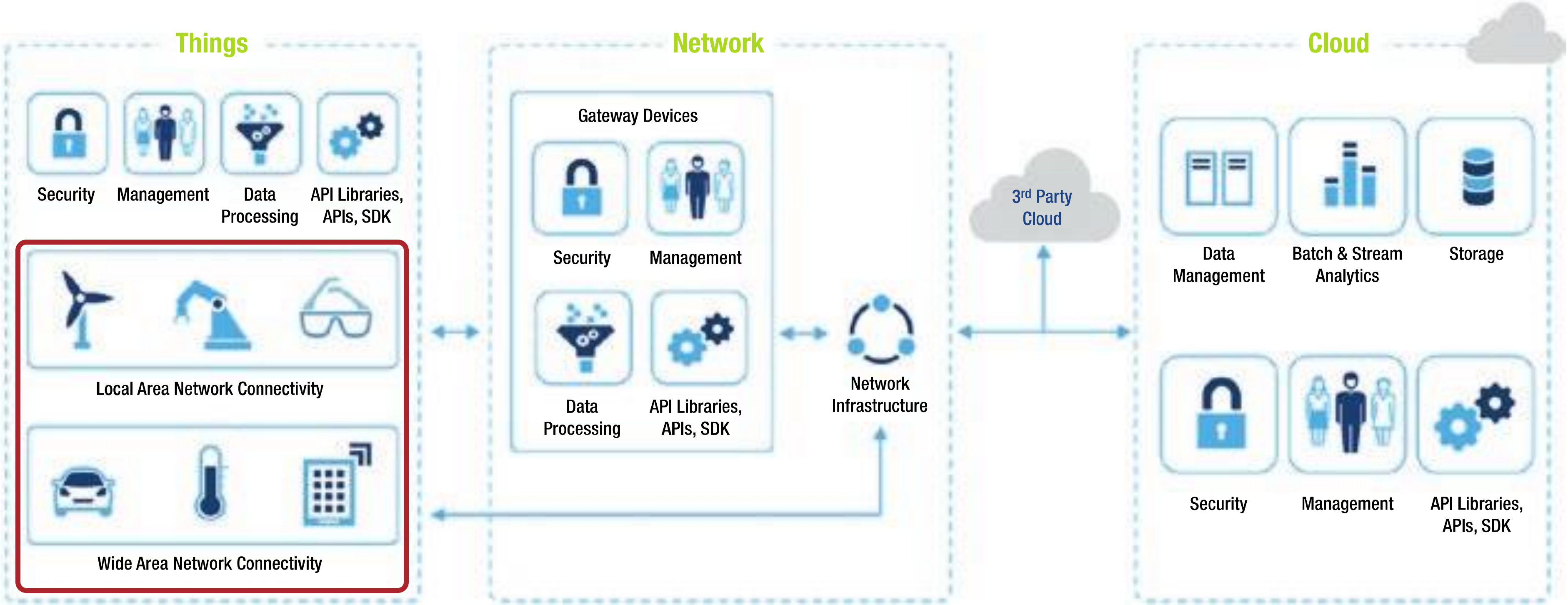


Brussels: 6 V/m

ICNIRP
As an independent organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides scientific advice and guidance on the health and environmental effects of non-ionizing radiation (NIR) to protect people and the environment from detrimental NIR exposure.

NIR refers to electromagnetic radiation such as ultraviolet, light, infrared, and radiowaves, and mechanical waves such as infra- and ultrasound. In daily life, common sources of NIR include the sun, household electrical appliances, mobile phones, Wi-Fi, and microwave ovens.

Wireless is not just wireless connectivity



Cheruvu S., Kumar A., Smith N., Wheeler D.M. (2020) Connectivity Technologies for IoT. In: Demystifying Internet of Things Security. Apress, Berkeley, CA. https://doi.org/10.1007/978-1-4842-2896-8_5

2. Baselining

(concepts & toy examples)

What will we cover

- Mobile vs. Wireless vs. Fixed
- Shannon's law, to calculate capacity and compare technologies
- Friis's equation, to calculate coverage
- 2G as a reference system

Calling a cat a cat

Fixed Networks

- Tied to infrastructure
  - Physical configuration is required
- Reliable
  - Dedicated link
- Robust
  - Scales to high bandwidths
- Powered
  - Mains
  - PoE
- Mostly unicast
  - Highly secured

Wireless Networks

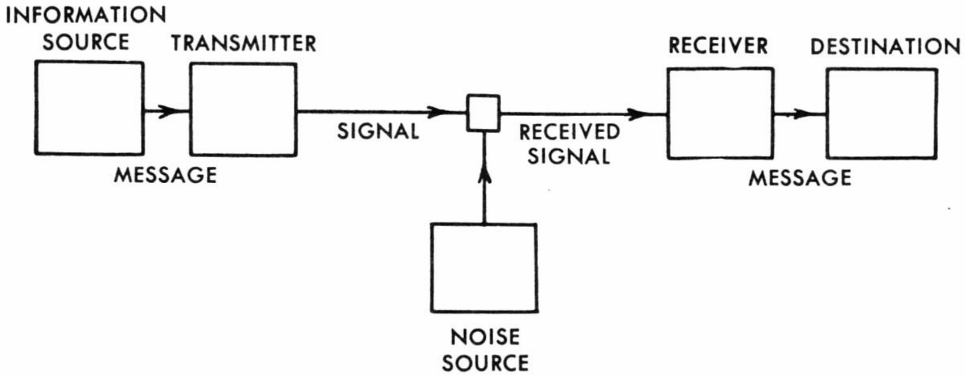
- Not tied to infrastructure/walls
  - Ad-hoc networking
- Error-prone
  - Traffic Management
- Frequent Disconnections
  - Resource Management
  - Quality of Service for multimedia
- Battery operated
  - Media access and networking while sleeping
  - Time synchronization
- Broadcast
  - Security

Mobile Networks

- Location matters
  - And changes dynamically
  - Can be nonlocal (WAN vs. LAN, roaming)
- Movement matters
  - Doppler shift of f due to velocity
- Addressing
  - IP addresses indicate how to get data
  - But they are tied to an entity
- Hand Off/Over
  - Seamless

Shannon's law – Wireless examples

- **A bunch of assumptions**
  - Wireless, not mobile – movement captured in noise
  - All noise is "white"– not frequency dependent, uncorrelated in time
  - All noise is Gaussian - normally distributed
  - All noise is additive – linear combination of noise and transmission
  - Interference from other users is part of overall Gaussian noise – large numbers
  - Signal and noise are uncorrelated – intersymbol interference is extra noise
  - The environment and the noise are stationary – no blocking or fading
- **This is called the AWGN channel**
  - Additive
  - White
  - Gaussian



Shannon-Hartley for AWGN

$$\underset{\text{bits per second}}{C} = \overset{\text{Hertz}}{W} \log_2\left(1 + \boxed{\frac{\overset{\text{Watt}}{P}}{\underset{\text{Watt}}{N_0 W}}}\right)$$

Signal to noise ratio

$$SNR = \frac{P}{N_0 W}$$

- **Shannon-Hartley = maximum bitrate for error-free transmission** **(with assumptions)**
- **C = capacity, the problem to which telecommunication technology is a solution**
- **W = bandwidth, expensive because of**
  - scarcity
  - infrastructure
  - technical implementation (higher switching speeds)
- $^{P}/_{N_0 W}$ **= received signal power vs. noise power, expensive because of**
  - regulation
  - technical implementation (low noise)
  - inside log2, so large changes needed

Key metric:
Spectral Efficiency
$SE = \eta = {}^{C}/_{W}$

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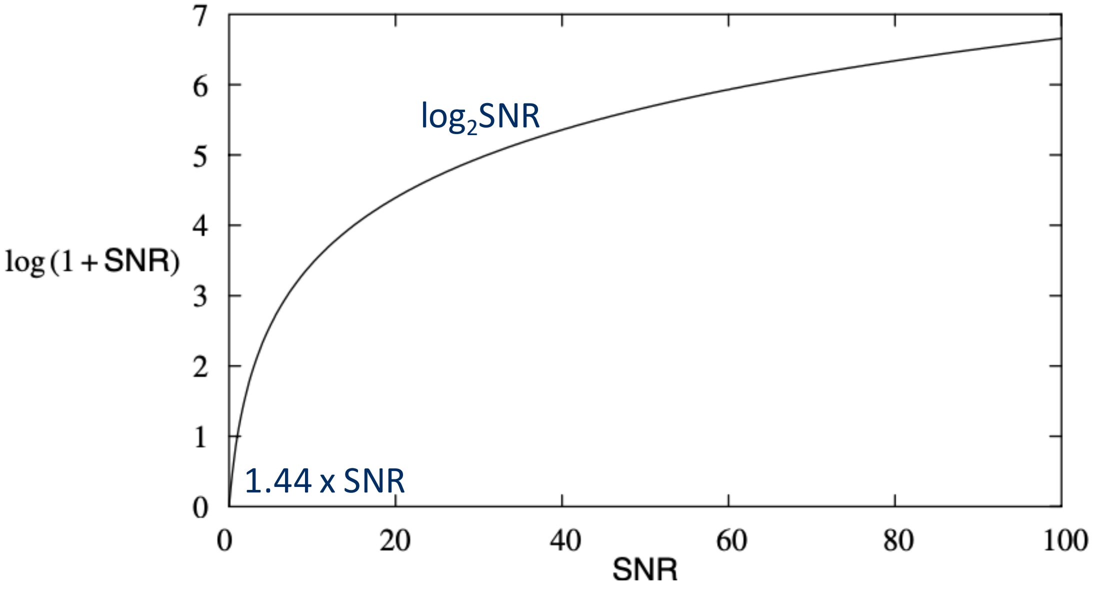
How does this formula behave?

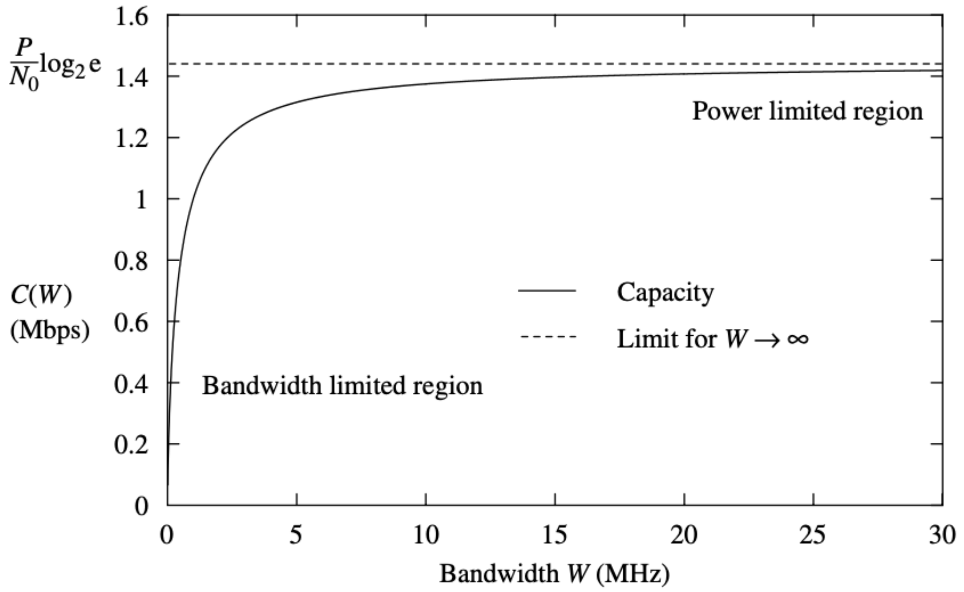
$$C = W \log_2\left(1 + \frac{P}{N_0 W}\right)$$

Dependence on power



$$\log_2(1+x) \approx x\log_2 e \qquad \text{when} x \approx 0,$$
$$\log_2(1+x) \approx \log_2 x \qquad \text{when} x \gg 1.$$

Dependence on bandwidth



$$W\log\left(1+\frac{\bar{P}}{N_0 W}\right) \approx W\left(\frac{\bar{P}}{N_0 W}\right)\log_2 e = \frac{\bar{P}}{N_0}\log_2 e.$$

Blackboard

- **Logarithms**
- **dB, dBm, dBW and dBi**
- **Power levels**
  - Wifi Access Point
  - 5G Small Cell
  - 5G Basestation
  - 5G Cell Phone
- **Power spectral density (PSD)**
- **Noise**
  - Johnson-Nyquist PSD=k_B.T
  - Wifi 1, Wifi 6, 2G, 5G