University of Antwerp

2023-2024 2001WETMWN

Advanced Wireless & 5G Networks

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

University of Antwerp

Chapter 0

Setup & Scope

VUB VRIJE UNIVERSITEIT BRUSSEL

Alcatel·Lucent Bell Labs

OnGo Powered by the CBRS Alliance

NOKIA

imec

barkhausen institut

KU LEUVEN

Your baseline and expectations (2023)

Baseline

- …

Expectations

- …

Homework for next week: 3 questions that you expect to be able to answer at the end of the course

Advanced Wireless & 5G Networks

Eternal BETA

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

University of Antwerp

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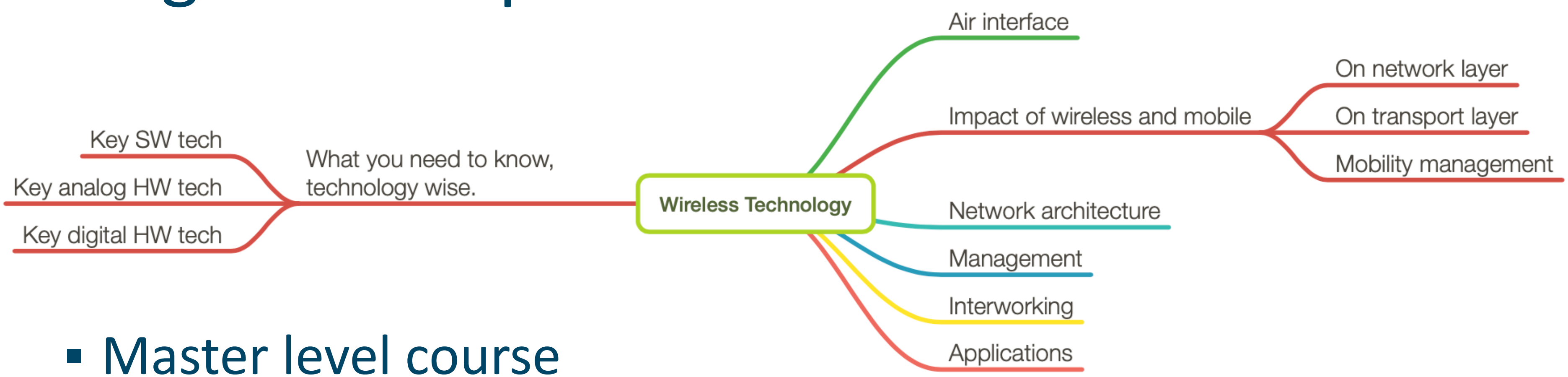
Faculty of Science

Advanced Wireless & 5G Networks

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

Target and Expectations



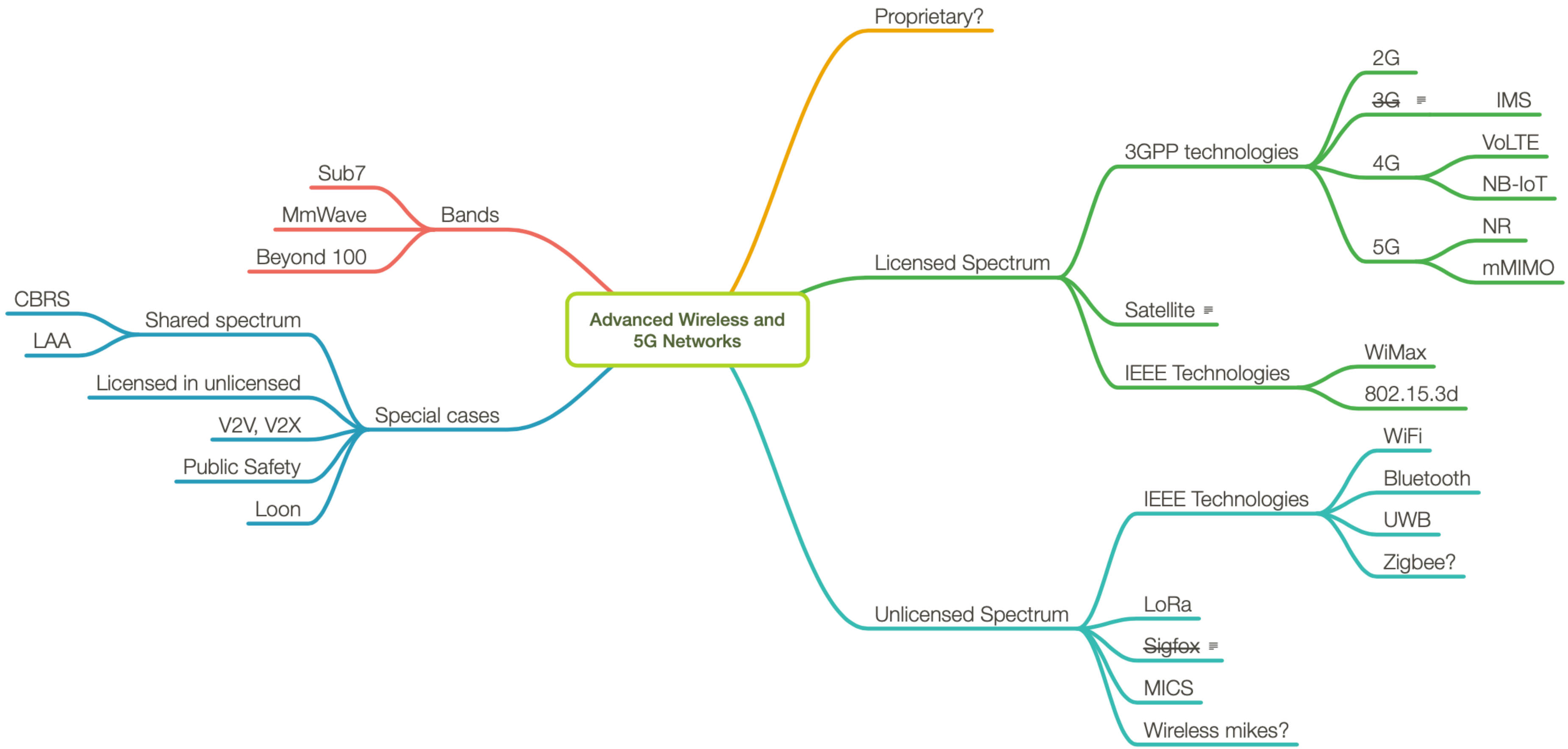
- Master level course
  - know + understand + implement + discover
  - top-down, not bottom-up
- Real world and market, not just theory
  - regulatory impact
  - cover future, not just past & present
  - relations between heterogeneous technologies
- Ideally, combined with hands-on lab (2nd semester)
  - UA2001WETLMW: Advanced networking lab

CS Competences ?

Computer Networks

- Design of protocols
  - [+++] Design, analysis and **implementation** is a central theme and is the **main component** of the **accompanying labs**
  - [++] During this course, the **design** of numerous algorithms and **protocols** is **explained** and (often) attention is also paid to their corresponding software implementation
  - [+] The design and analysis of algorithms (and their software implementations) is covered rather sporadically during this course
- Modeling and simulation
  - [+++] Modeling and simulation is a central theme and an important part of the accompanying labs
  - [++] **Modeling** and simulation is an important part of this course
  - [+] Modeling and **simulation is covered rather sporadically as a topic during this course**
- Mathematical modeling (of telecom and distributed systems):
  - [+++] the course covers each of the 3 skills (designing, modeling, simulating).
  - [++] **the course covers at least 2 skills.**
  - [+] the course covers at least 1 skill

Structure



Advanced Wireless and 5G Networks
Proprietary?
Licensed Spectrum
3GPP technologies
2G
~~3G~~
IMS
4G
VoLTE
NB-IoT
5G
NR
mMIMO
Satellite
IEEE Technologies
WiMax
802.15.3d
Unlicensed Spectrum
IEEE Technologies
WiFi
Bluetooth
UWB
Zigbee?
LoRa
~~Sigfox~~
MICS
Wireless mikes?
Bands
Sub7
MmWave
Beyond 100
Special cases
Shared spectrum
CBRS
LAA
Licensed in unlicensed
V2V, V2X
Public Safety
Loon

Planning ("guideline")

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

Homework for next week: suggestions for dates to replace the red ones

Baseline: Computer Networks 2BA, Telecom Systems 3BA

Logistics

Where

- Campus Middelheim M.G.00x
- Blackboard (course material to be provided after class)
- ? ~~Online classes: Teams or BB Ultra (TBD)~~
- Discussions: Teams

? When

- See planning, until Xmas

Contact (in order of preference)

- Teams
- michael.peeters2@uantwerpen.be
- michael.peeters@imec.be

Even though this is a wireless course

Examination

Not about what you know and can reproduce.

You need to be able to think things through.

! Remember vs. Know vs. Understand !

⇒ written, open book exam, where you will get one or more questions based on a real-world problem.

Grading will be based on:

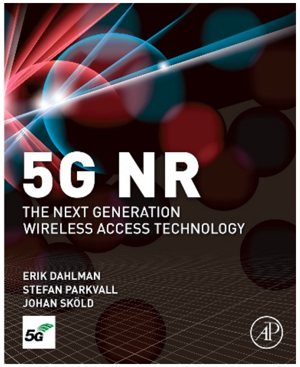
20% Context and your understanding of the problem

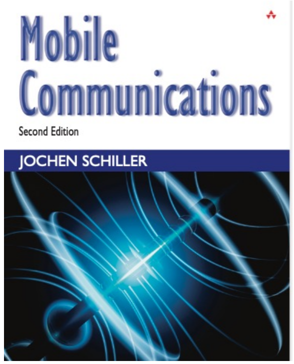
40% Description of the approach to solve it

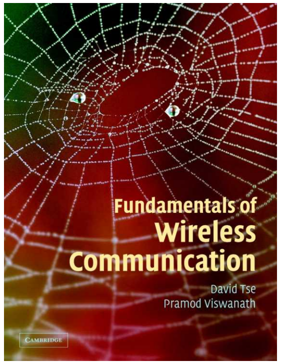
40% Implementation/Solution

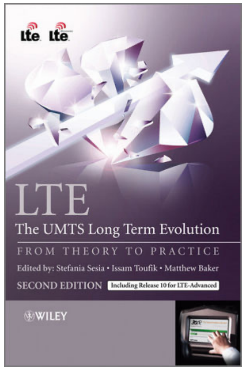
Books and references

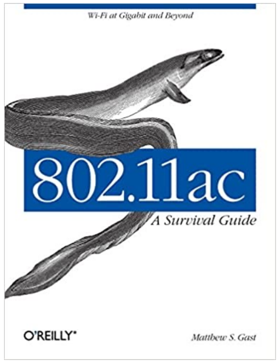
- Where possible, online resources will be provided, which are either accessible as a UA student, or public domain
- Recommended references

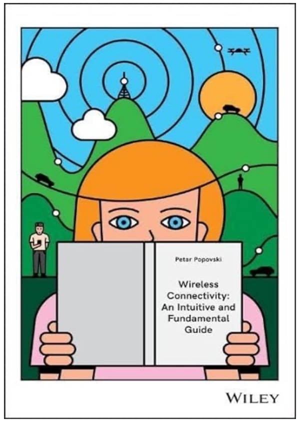


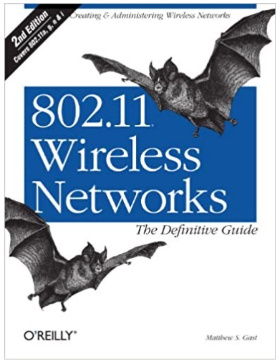












Note: you do **not** need to buy these.

Chapter 1

Introduction to the wireless market

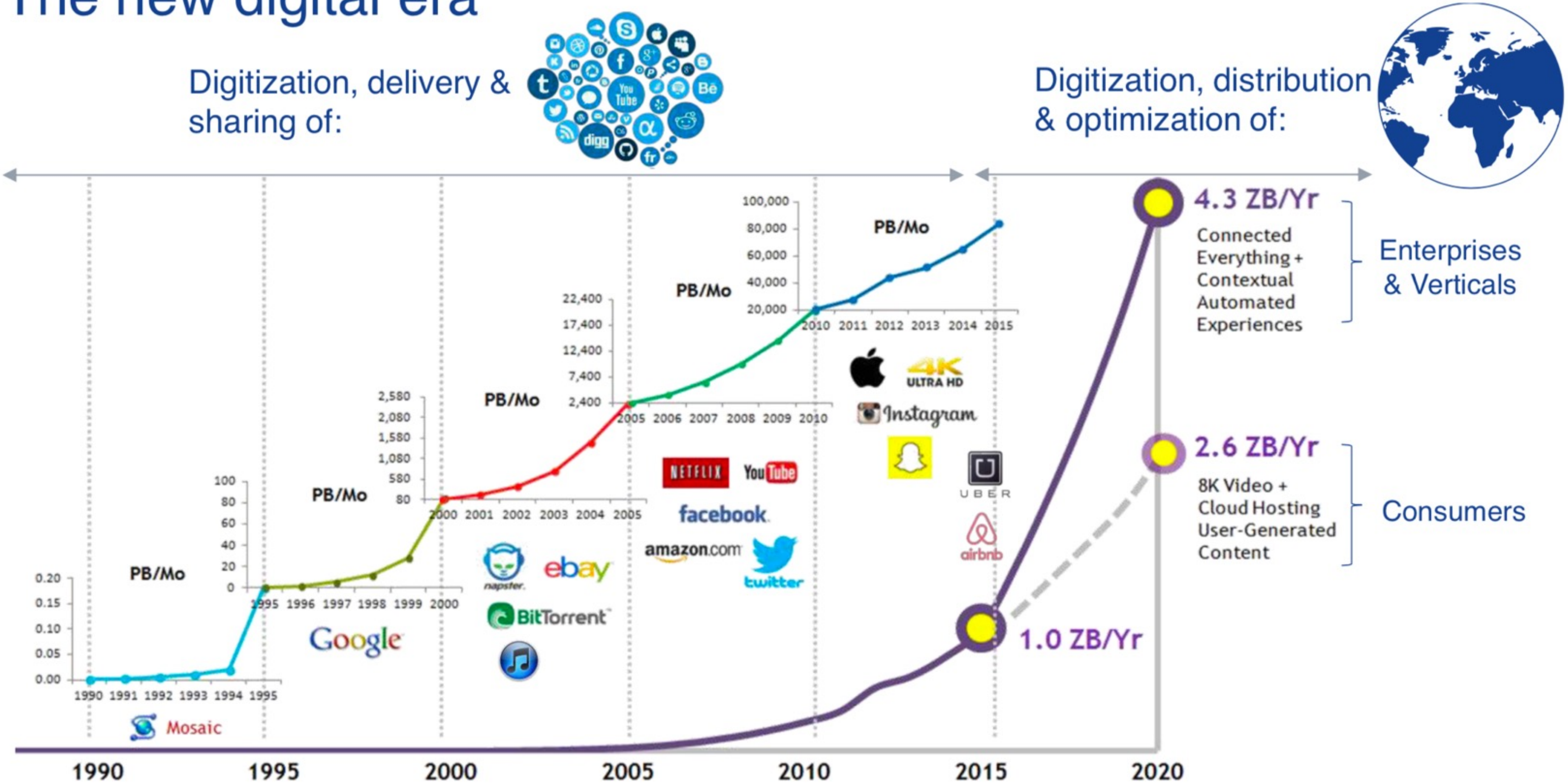
Good questions to ask yourself

Neil Postman: “"Information has become a form of garbage, not only incapable of answering the most fundamental human questions but barely useful in providing coherent direction to the solution of even mundane problems.”

- What is the problem to which this technology is a solution?
- Whose problem is it?
- By solving this problem, what new problems may be created?
- Why did we pick this solution?


JUST FOLLOW THE MONEY.

The new digital era



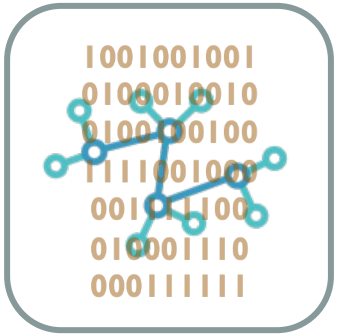
5 © Nokia 2016

Connectivity problems

“If I had asked people what they wanted, they would have said faster horses.” — Henri Ford

In 1910 […] the biggest worry in cities was what to do with all the horse manure that was piling up.
— The Economist 2017.09

“People worry that computers will get too smart and take over the world, but the real problem is that they're too stupid and they've already taken over the world.”
— Pedro Domingos



“Data is not information, information is not knowledge, knowledge is not understanding, understanding is not wisdom.” — Clifford Stoll

Organisms communicate to improve their chances of achieving their goals

THE ROYAL SOCIETY

doi 10.1098/rspb.2000.1140

On the advantages of information sharing

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[2]*School of Mathematics, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel*
[3]*Cohn Institute for the History and Philosophy of Science and Ideas, Tel-Aviv University, Tel-Aviv 69978, Israel*

During the evolution of life, there have been several transitions in which individuals began to cooperate, forming higher levels of organization, and sometimes losing their independent reproductive identity. For example, multicellularity and insect societies evolved independently multiple times. Several factors that confer evolutionary advantages on higher levels of organization have been proposed. In this paper we highlight one additional factor: the sharing of information between individuals. Information sharing is not subject to the intrinsic conservation laws that characterize the sharing of physical resources. A simple model will illustrate how information sharing can result in aggregates in which the individuals both receive more information about their environment and pay less for it. This may have played a role in the evolution of higher levels of organization.

Keywords: information sharing; multicellularity; ensociality; public goods; evolution

COMMUNICATION SATURATION

GENERIC USECASES THAT WILL (ALWAYS?) DRIVE THE MARKET

communication at a distance	People	Pretend-People	Machines	Organisms
People	voice, video calls	entertainment, gaming, bots MR	body-machine interfaces	voice commands, sensing
Pretend-People		conversation bots, training	neural network training	pet bots? Robotic garderer?
Machines			FWA automation, AI-2-AI	control & command, biological IO
Organisms				molecular IO

today & tomorrow | 3–5 years out | 10 years out sense centric

human centric

(10 Gbps retina) (30 Mbps cochl.)

10 Mbps 2 Mbps 100 kbps 100 kbps 135 Mbps

(10 kbps layer IV)

note: conscious awareness ~ 100bps

SRC, “Decadal Plan for Semiconductors”

Fundamental trends

But be careful of aggregated numbers

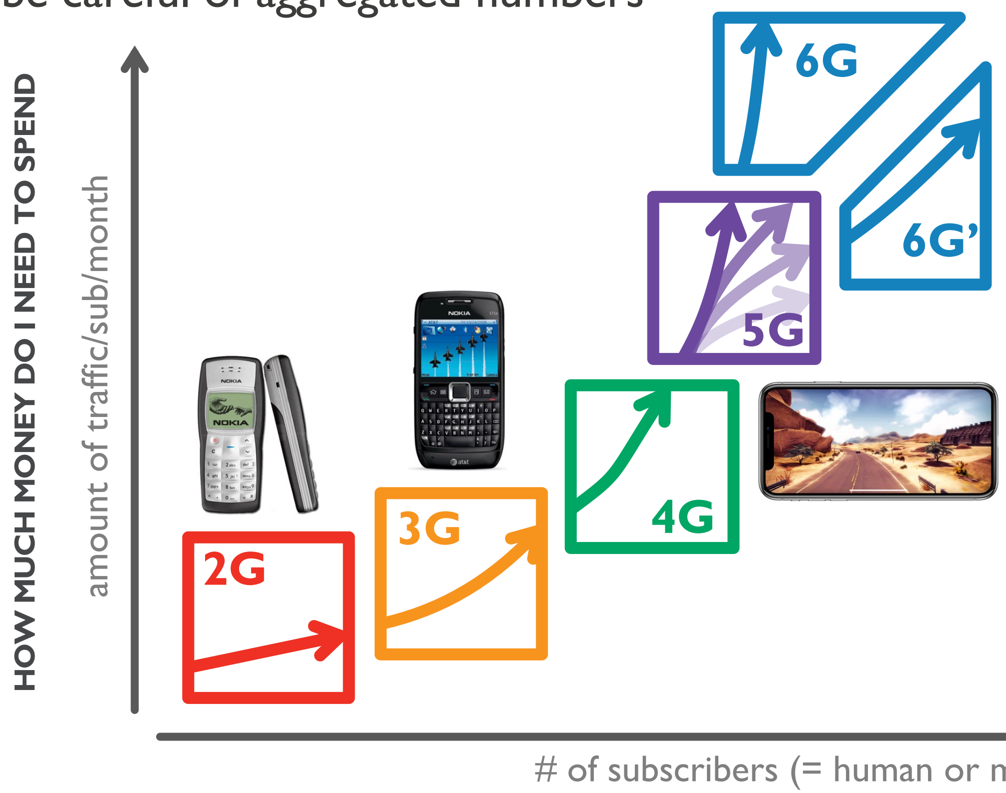
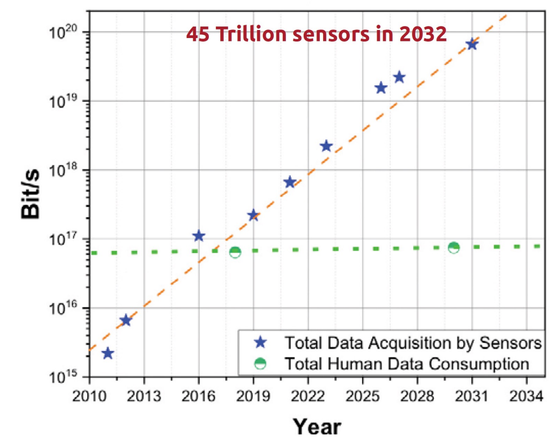
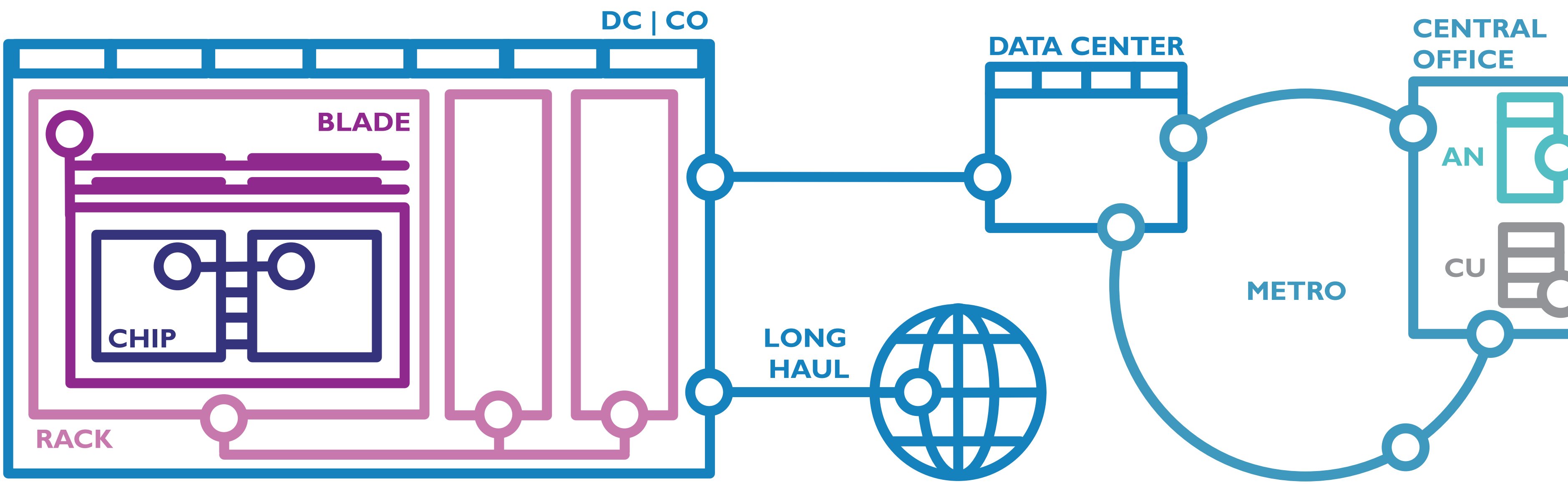


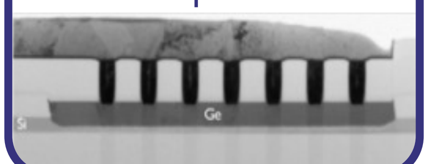
Figure 3: Trend in world’s installed sensing capacities



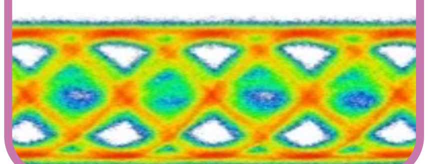
HOW MUCH MONEY CAN I MAKE?



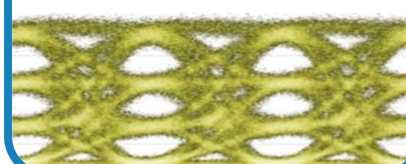
Chip level



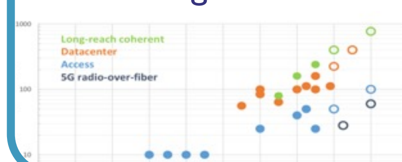
Board and rack level

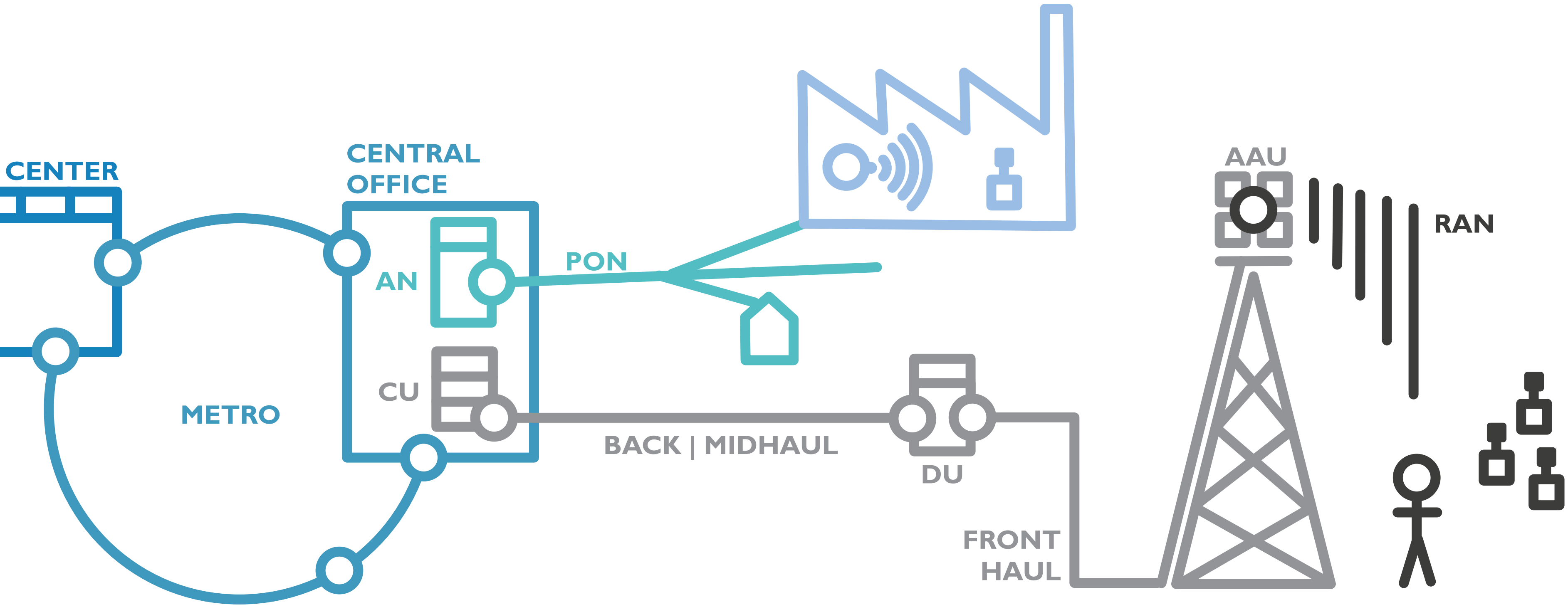


Data centers

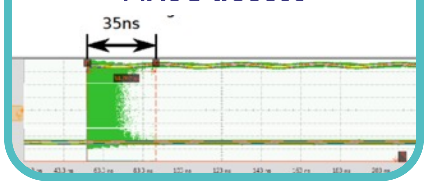


Long reach

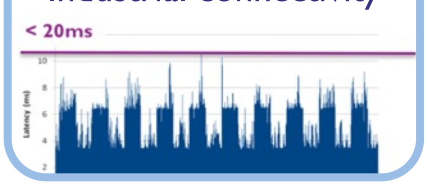




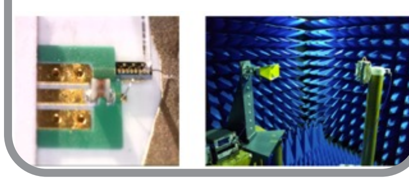
Fixed access



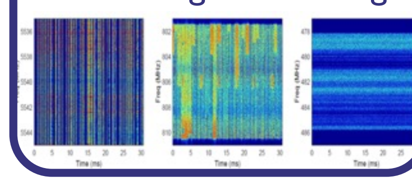
Industrial connectivity



Wireless & cellular



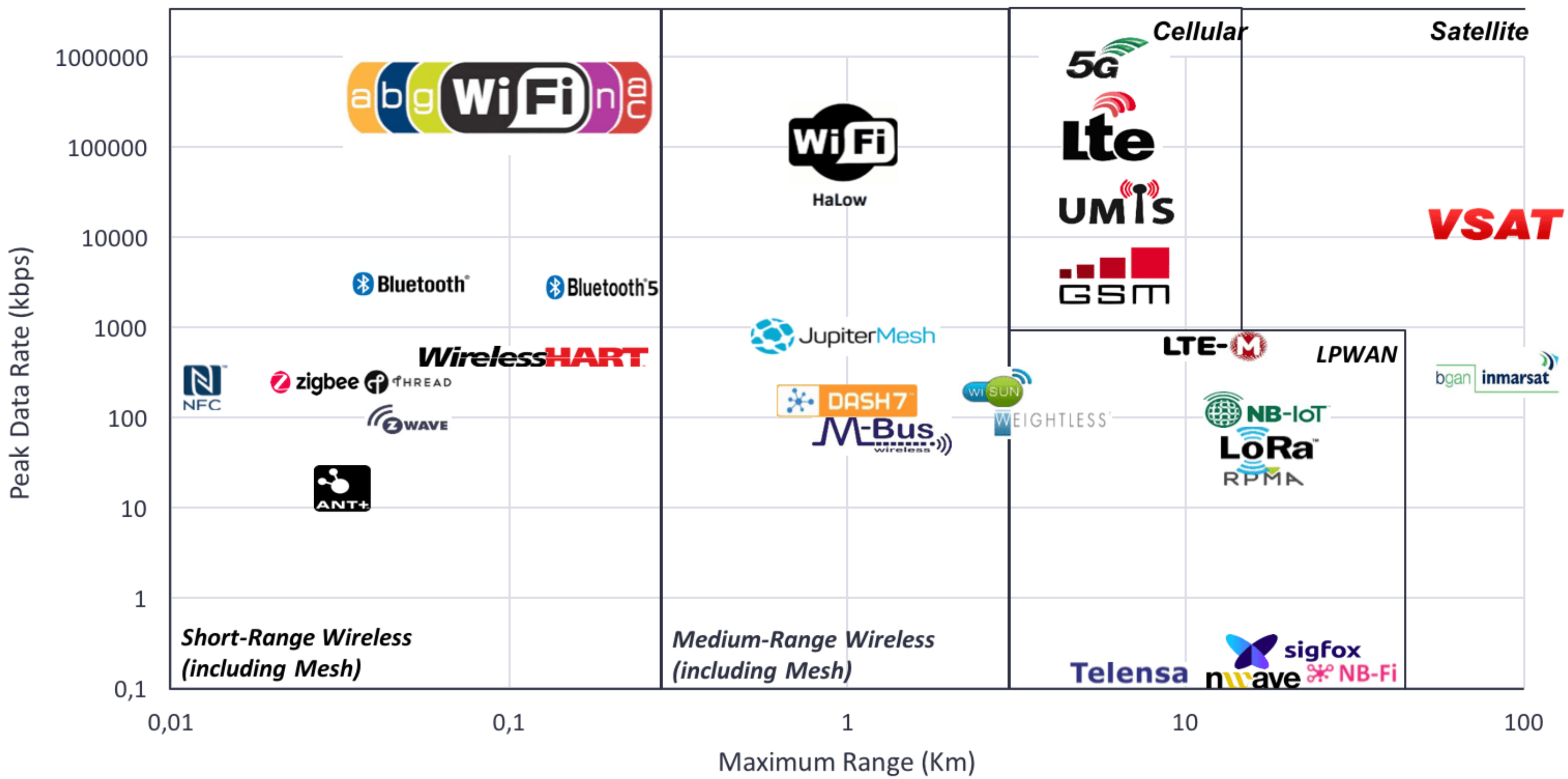
Measuring & modeling



So many choices

Comparison Wireless technologies

Peak Data Rate vs Maximum Range



Please note that this chart is meant to show the maximum theoretical range and data rate for each technology, but this does not mean that the two can be achieved at the same time. On the contrary, no wireless technology can achieve the maximum range while transmitting at its peak data rate, but rather the higher is the used data rate, the lower is the achievable communication range.

https://iot-analytics.com/iot-segments/iot-connectivity/

Similarities and differences

	Power	Range	Data rate	Latency	Spectrum
Wi-Fi HaLOW	Low	Long	Moderate	Low	Unlicensed
Wi-Fi 5 and 6	Moderate	Moderate to long	High	Low	Unlicensed
LTE Cat-M	Low	Moderate to long	Moderate	Low	Licensed
LTE Cat-IoT	Very low	Long	Low	Very low	Licensed
LoRa	Very low	Long	Low	Low	Unlicensed
Sigfox	Very low	Long	Very low	Very low	Unlicensed
Bluetooth Low Energy	Very low	Short	Low	N/A	Unlicensed
802.15 – ZigBee, Thread, 6LoWPAN	Very low	Short	Low	N/A	Unlicensed

Source: Maravedis-Rethink

Communication model

Shannon & Weaver 1948

34 *The Mathematical Theory of Communication*

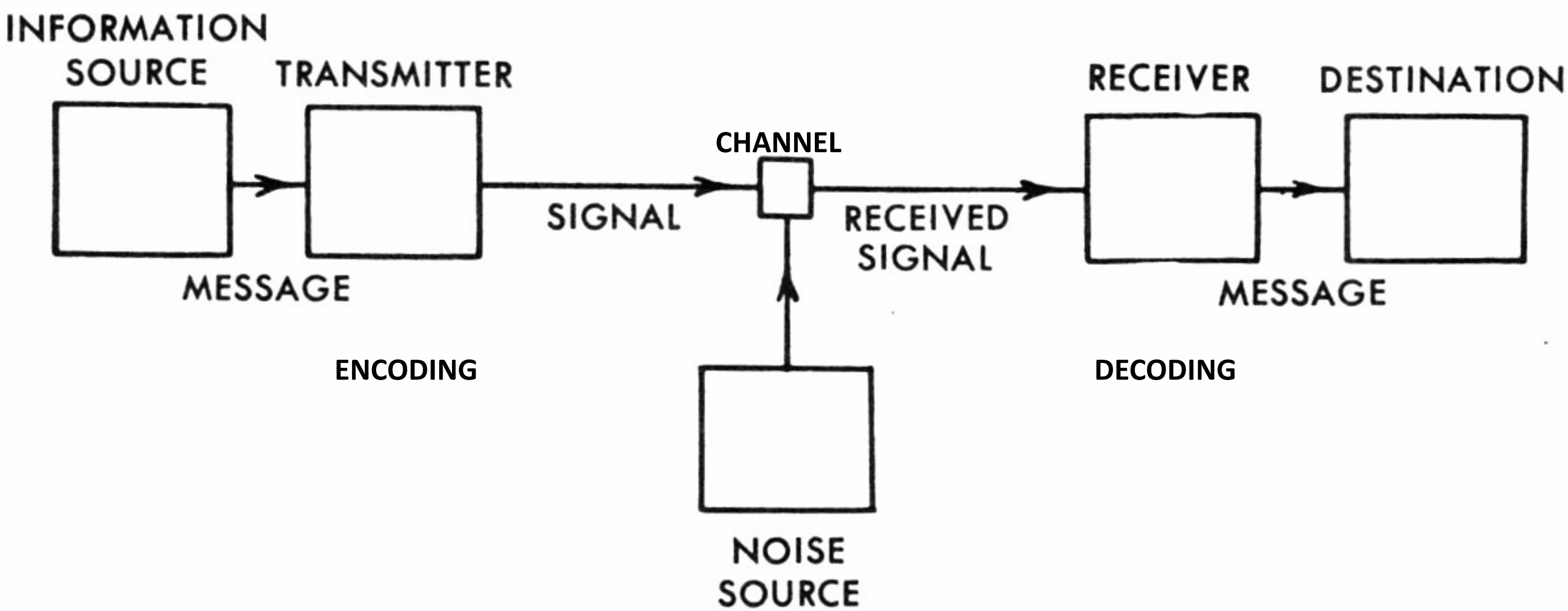


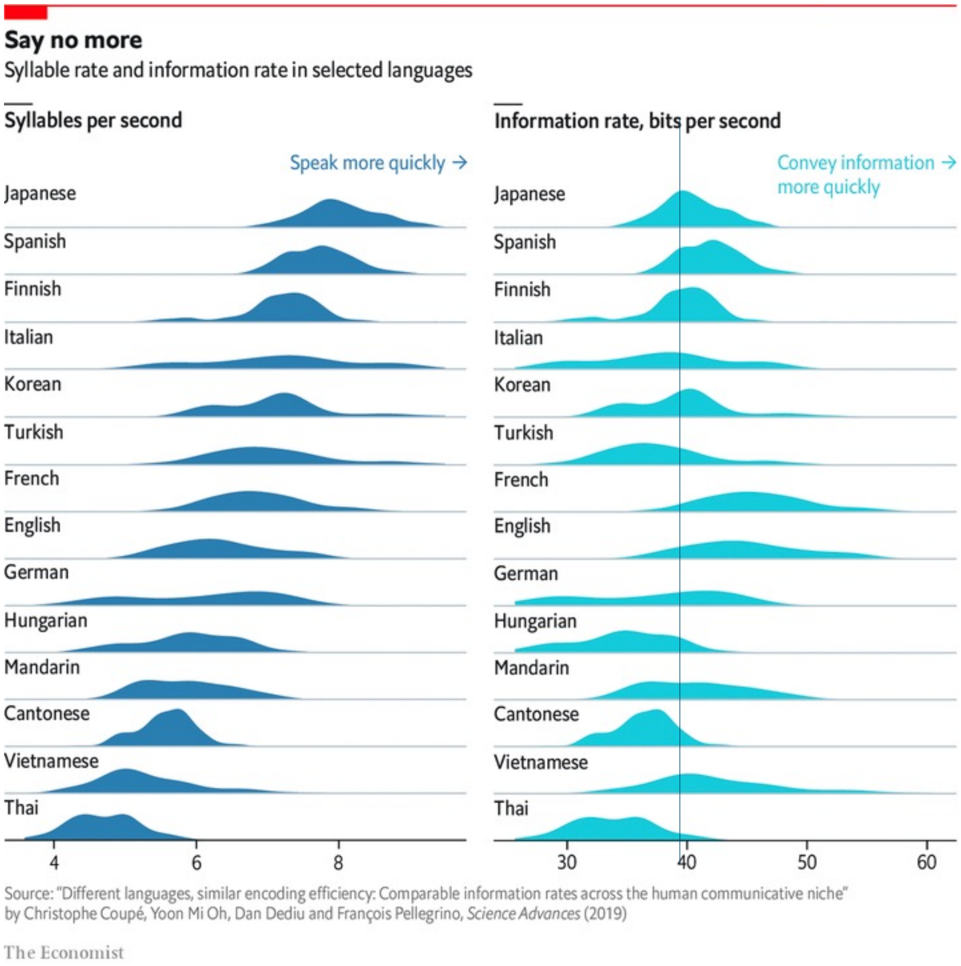
Fig. 1. — Schematic diagram of a general communication system.

CAPACITY, BITRATE

Human languages

- While the number of syllables/s may vary significantly, the number of bits/s has a tighter grouping.
- Shannon–Hartley theorem tells the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the presence of noise

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



SHANNON-HARTLEY

Drives not just research, but also techno-economics

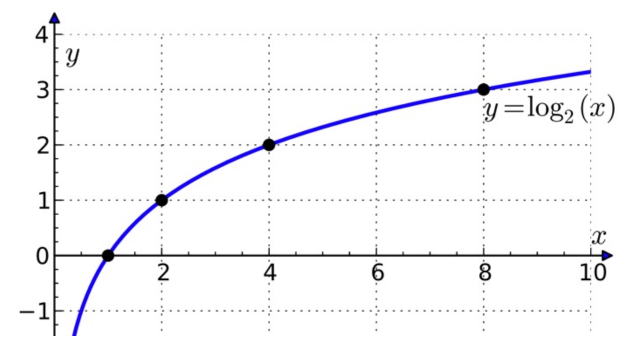
$$\underset{\text{bits per second}}{C} = \overset{\text{hertz}}{W} \log_2\left(1 + \frac{\overset{\text{watts}}{P}}{\underset{\text{watts}}{N_0 W}}\right) \Big\} \begin{array}{c}\text{SNR}\\ \text{Signal to noise ratio}\end{array}$$

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)

$P/_{N_0 W}$ = signal power vs. noise power, expensive because of

- regulation
- technical implementation (low noise)
- inside log2, so large changes needed



To be revisited next week…

Capacity ≠ Throughput ≠ Goodput

? Difference

Capacity ≠ Throughput ≠ Goodput

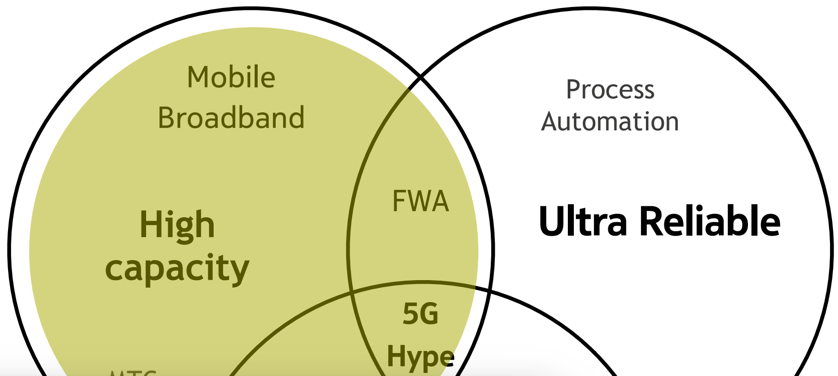
Physical layer | Network layer or below | Application

$\langle C \rangle$ | $T=\eta_{coding}\langle C \rangle$ | $G=\eta_{protocol}\langle T \rangle$

? <x>

Application layer	service location new/adaptive applications multimedia
Transport layer	congestion/flow control quality of service
Network layer	addressing, routing device location hand-over
Data link layer	authentication media access/control multiplexing encryption
Physical layer	modulation interference attenuation frequency fading

There is no free lunch



Fundamental Tradeoffs among Reliability, Latency and Throughput in Cellular Networks

Beatriz Soret*, Preben Mogensen*†, Klaus I. Pedersen*†, Mari Carmen Aguayo-Torres‡
*Nokia Networks, †Aalborg University, ‡Universidad de Málaga
beatriz.soret@nsn.com

***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.**

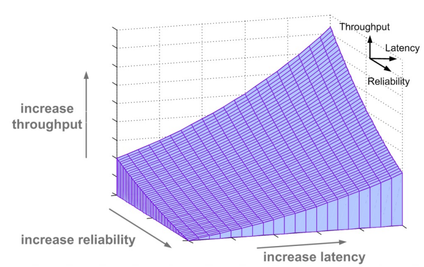


Fig. 1. Sketch of the tradeoffs among latency, reliability and throughput.

Acronyms

4G to CDF

4G/5G	4th (LTE) and 5th (NR) generation mobile technology
AAA	access authorization authentication
AAU	active antenna unit
AC	alternating current
ADSL	asymmetric DSL
AN	access node
AP	Access point
AR	augmented reality
BBU	baseband unit
BH	busy hour
BIPT	Belgisch instituut voor Post en Telecom
Bit	unit of information, corresponding to a 1 or a 0
BSC	basestation controller
BTS	base station transceiver
BW	bandwidth
Byte	8 bits
CAGR	compound annual growth rate
CAPEX	capital expenditure
CCAP	converged cable access platform
CDF	cumulative distribution function

CO to FDX

CO	central office
Coax	Coaxial
CPE	Customer premise equipment
CTO	Chief Technology Officer
CU	central unit
DA	distribution area
dBm	decibel-milliwatt referenced, logaritmic unit of power. 0 dBm equals 1 milliwatt; 10 dBm equals 10 mW; 20 dBm equals 100 mW
DC	datacenter
DNS	Domain Name System
DOCSIS	Data Over Cable Service Interface Specification
DPU	distribution point unit
DS	downstream
DSL	digital subscriber line
DSLAM	DSL Access Multiplexer
DU	distributed unit
eMBB	enhanced mobile broadband
eNB	eNodeB, a basestation
eNodeB	evolved NodeB
EPON	Ethernet PON
FDX	full duplex

FN to HW

FN	fiber node
fps	frames per second
FR1/2	frequency range 1/2
FTTC	fiber-to-the-curb or fiber-to-the-cabinet
FTTdp	fiber-to-the-distribution point
FTTH	fiber-to-the-home
FTTN	fiber-to-the-node
FWA	fixed wireless access
GaAs	Gallium Arsenide, a semiconductor
GaN	Gallium Nitride, a semiconductor
GHz	Gigahertz, one billion cycles per second, or one cycle per nanosecond
gNodeB	next generation eNodeB
GPON	Gigabit PON
GSM	Global system for mobile communications (“2G”)
HFC	Hybrid Fiber Coax
HH	household
HHC	household connected
HHP	household passed
HSS	home subscriber server
HW	hardware

Hz to mmtc

Hz	Hertz, unit of frequency, cycles of a wave per second
I-CCAP	integrated CCAP
IARC	International Agency for Research on Cancer
ICIC	inter-carrier inter-cell interference
ICNRIP	International Commission on Non-Ionizing Radiation Protection
IMS	ip multimedia subsystem
IMT-2020	International Mobile Telecommunications-2020 standard
IOT	internet of things
IP	Intellectual Property
IP	Internet protocol
ISD	inter-site distance
ISDN	integrated services delivery network
LLU	local loop unbundling
LoS	line of sight
LTE	Long term evolution
MAC	medium access control
MDU	multiple dwelling unit
MIMO	multiple input multiple output
MME	mobility management entity
mMTC	massive machine type communication

MO TO POUT

Mo	Month
MS	mobile station
MSC	mobile switching center
NIR	non ionising radiation
NR	New radio
OLT	optical line termination
ONF	Open Networking Foundation
ONT	optical network terminal
ONU	optical network unit
OPEX	operational expenses
OSP	outside plant
PA	power amplifier
PB	petabyte = a unit of information equal to one thousand million million (10 to the 15) or, strictly, 250 bytes.
PCRF	policy control resource function
PDN	packet data network
PHY	Physical layer
PON	passive optical network
PoP	point of presence
POTS	plain old telephony service
Pout	output power

PPP TO UE

PPP	public private partnership
PSTN	packet switched transmission network
PtP	Point-to-point
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying, a form of modulation
R-MAC	remote MAC
R&D	Research and Development
RAN	radio access network
RF	radio frequency
RISS	radio infrastructure site sharing
RRH	remote radio head
RX	reception
S-GW	serving gateway
SDU	single dwelling unit
SiGe	Silicon-Germanium, a semiconductor
sub	subscriber
SW	software
TCO	total cost of ownership
TX	transmission
UE	user equipment, a mobile phone

URLLC to WRC

URLLC	ultra reliable low latency communication
US	upstream
vDAA	virtualized Distributed Access Architecture
VDSL	very high speed DSL
VoIP	voice-over-IP
VR	virtual reality
W	Watt, unit of power
WiFi	wireless fidelity
WiGig	Wireless Gigabit (802.11.ad)
WiPON	Wireless PON
WRC	world radio communication conference

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