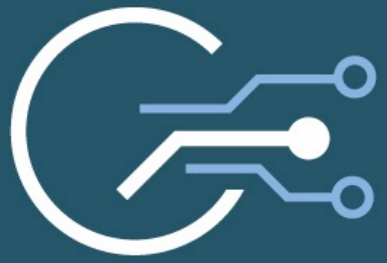

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Researching the Internet of the Future

Networking II

On the need for Computing in Communication Networks

Prof. F. Granelli

University of Trento, Italy

fabrizio.granelli@unitn.it granelli-lab.org

Goal of the first part

- Motivating Computing in Communication Networks
- You should learn about:
  - In-network computing is tackling the propagation delay problem
  - In-network computing can reduce the data rate by in-network operations:
    - Network coding
    - Compressed sensing
  - In-network computing can cause extra costs:
    - Energy
    - Price
    - Latency

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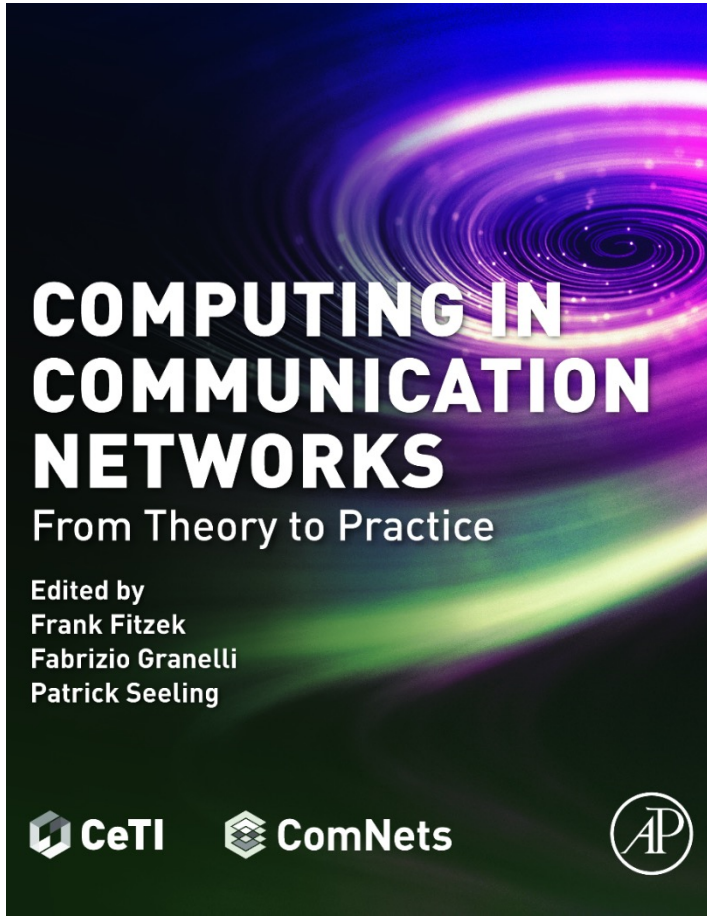
Computing in Communication Networks

- PART 1 FUTURE COMMUNICATION NETWORKS AND SYSTEMS
- PART 2 CONCEPTS
- PART 3 ENABLING TECHNOLOGIES
- PART 4 INNOVATION TRACK
- PART 5 BUILDING THE TESTBED
- PART 6 EXAMPLES
- PART 7 EXTENSIONS
- PART 8 TOOLS

SCAN ME



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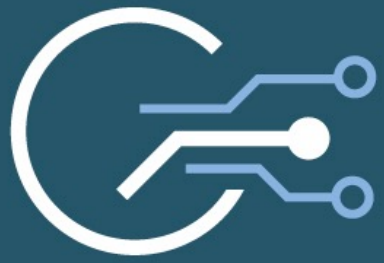

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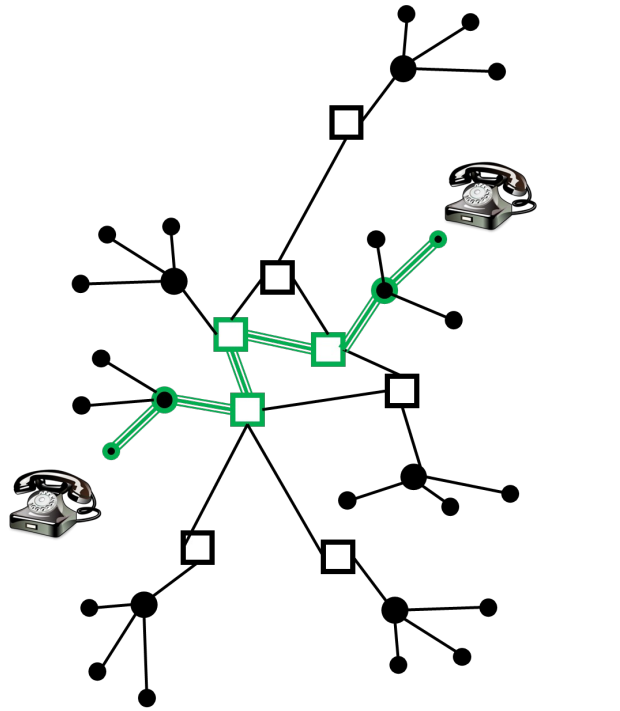
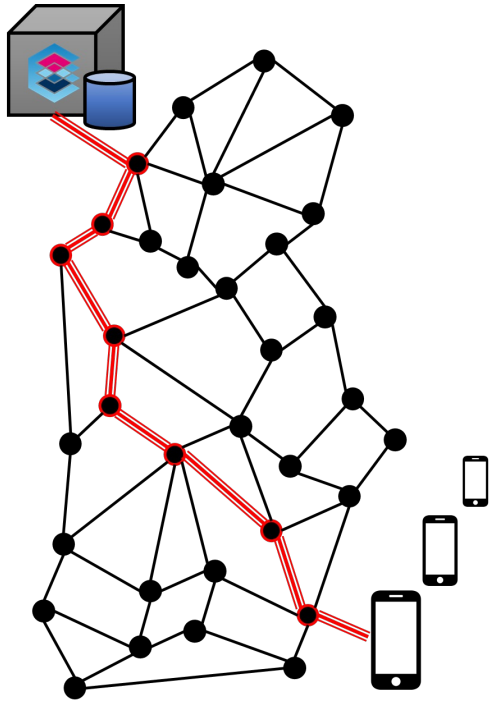
5G Communication System & The Need for Computing

Evolution of Communication Networks



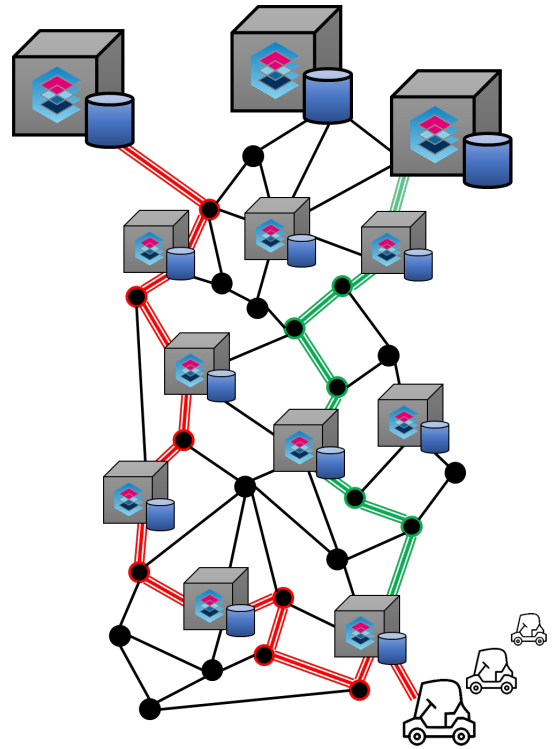
Places

Voice



People

Voice | Data



Things

Voice | Data | Control

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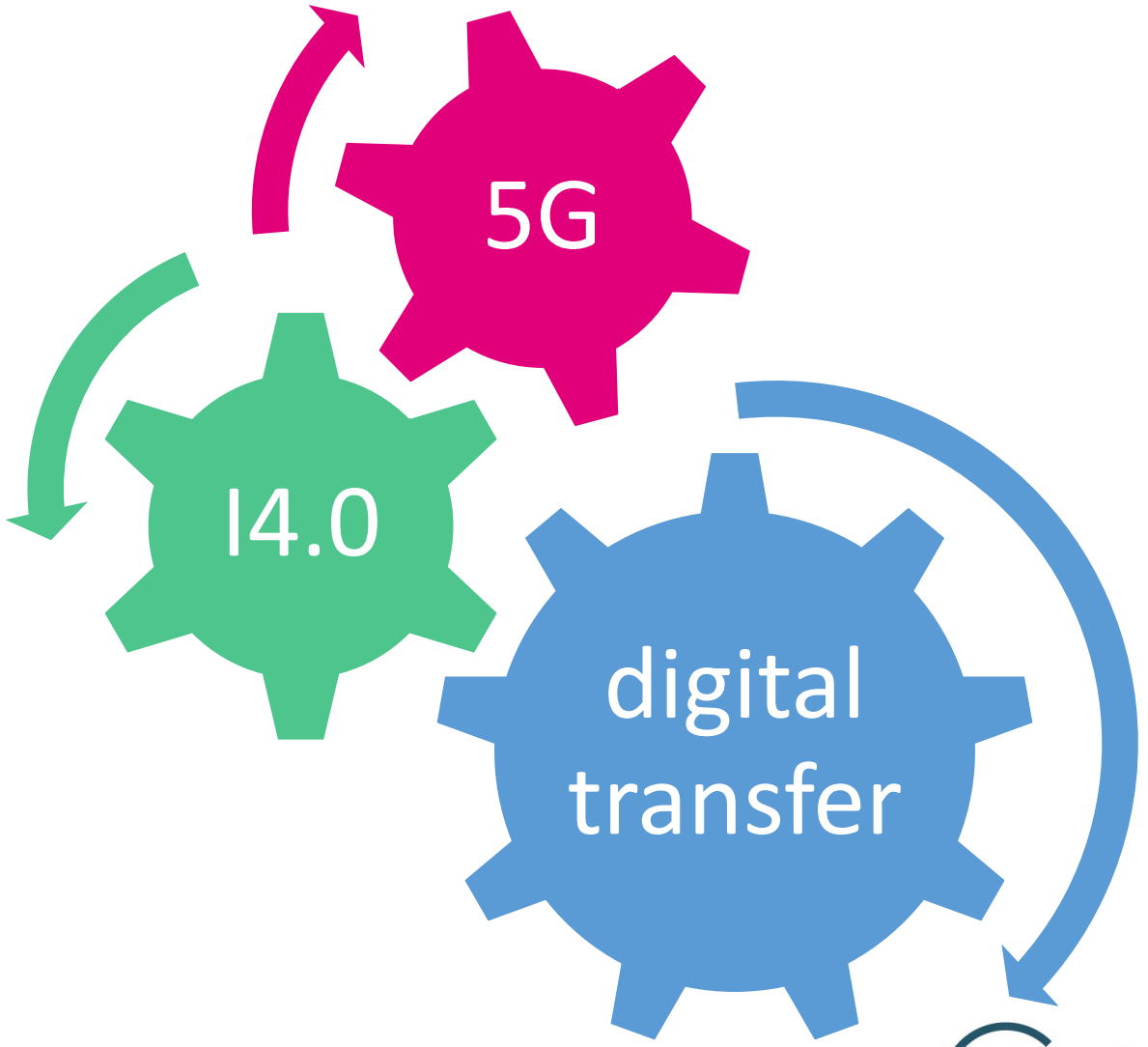
What makes 5G so important?



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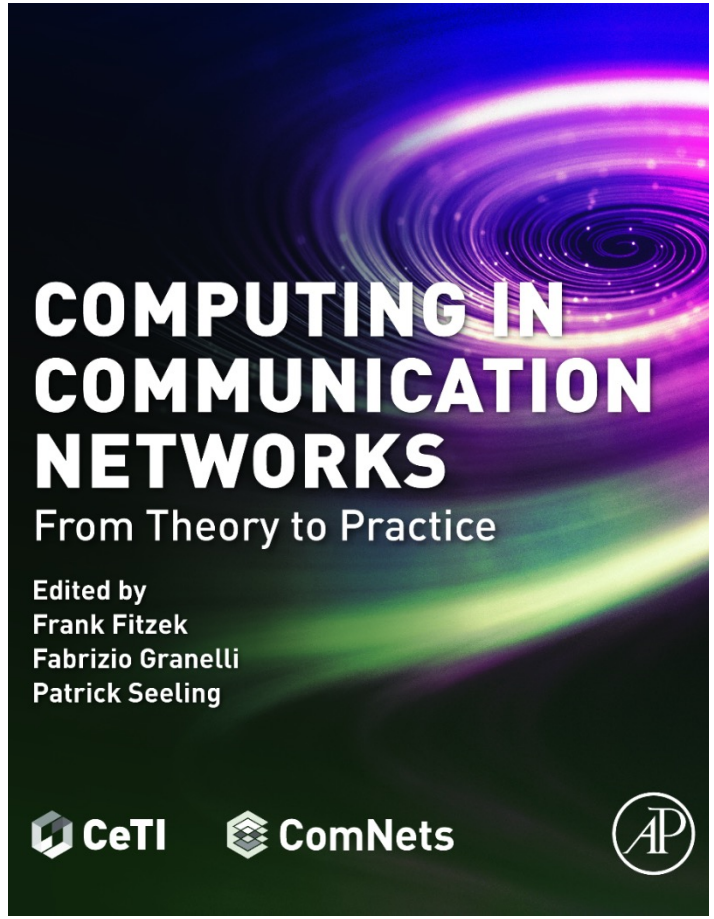
Computing in Communication Networks



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5G (r)evolution

wireless world

You don't know where you're going until you know where you've been.

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5G (r)evolution

wireless world

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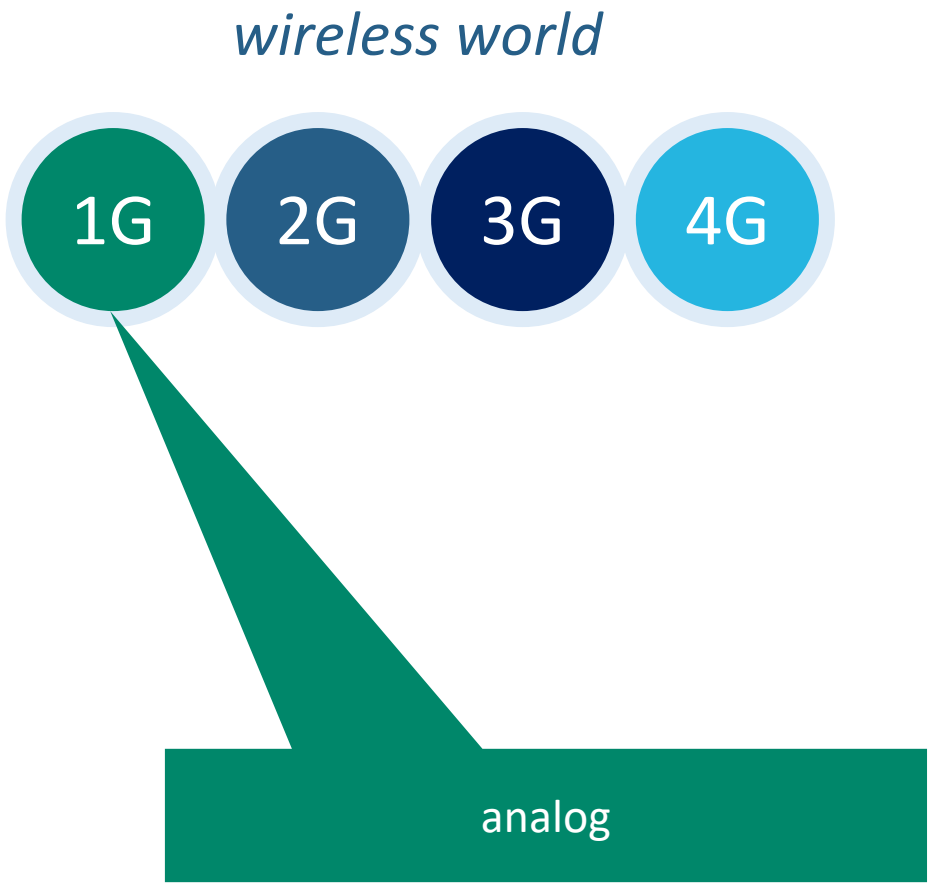
5G (r)evolution



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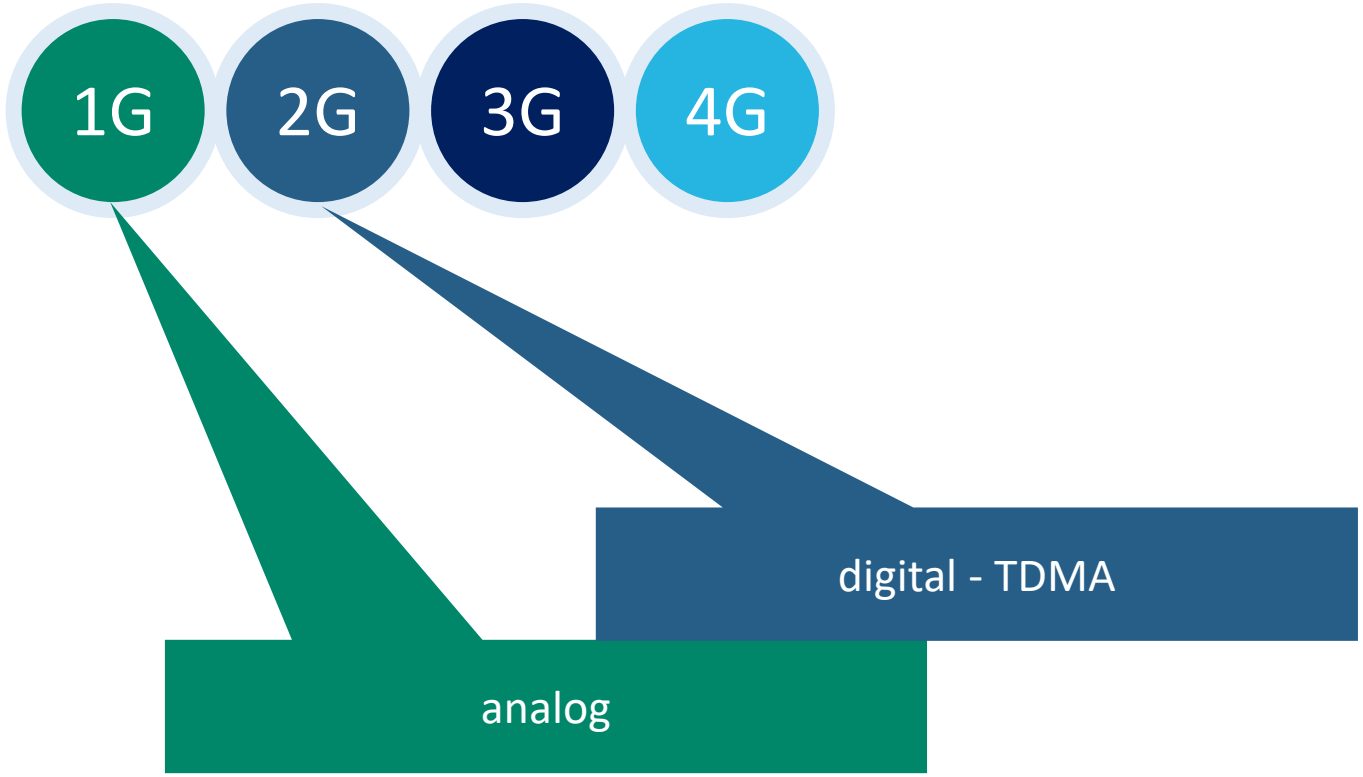
5G (r)evolution

wireless world



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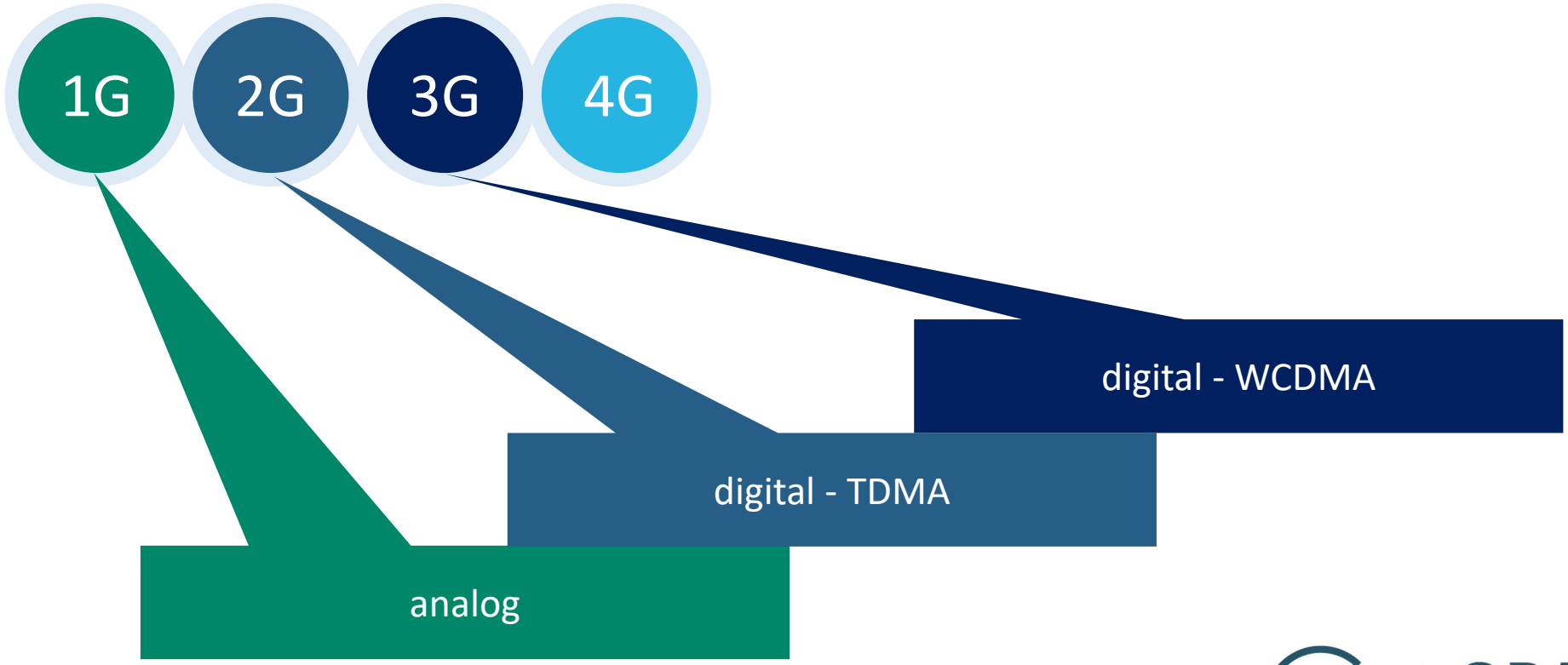
5G (r)evolution

wireless world



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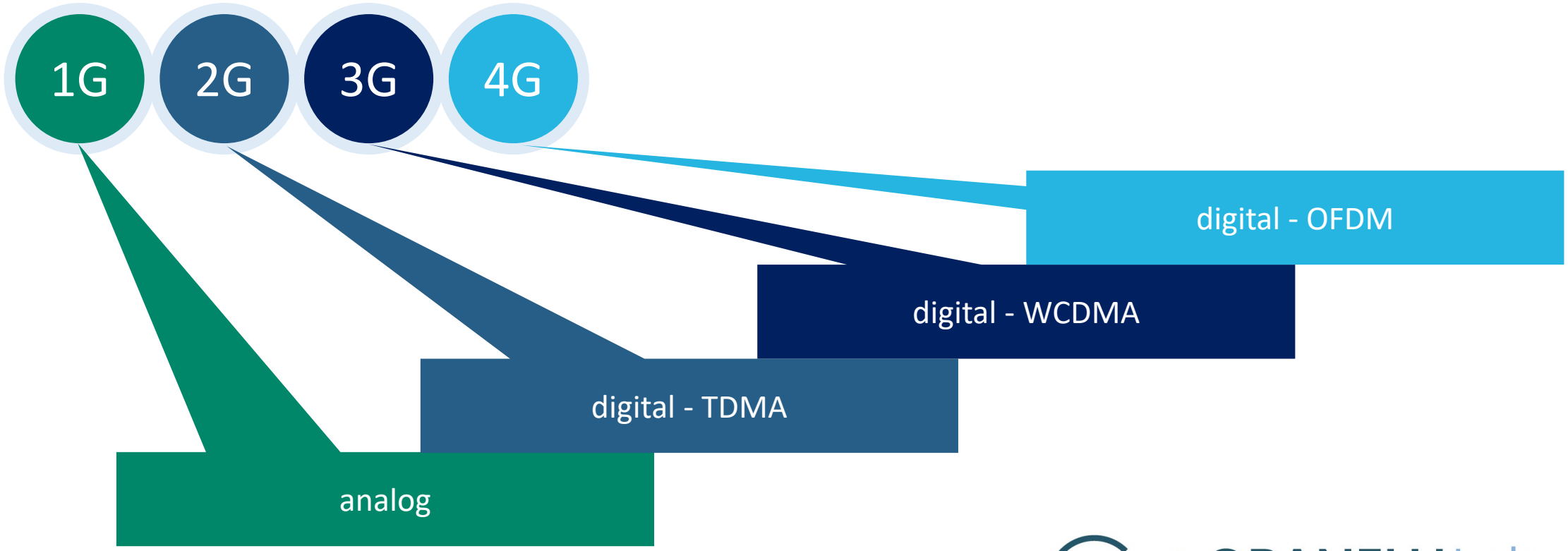
5G (r)evolution

wireless world



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5G (r)evolution

wireless world

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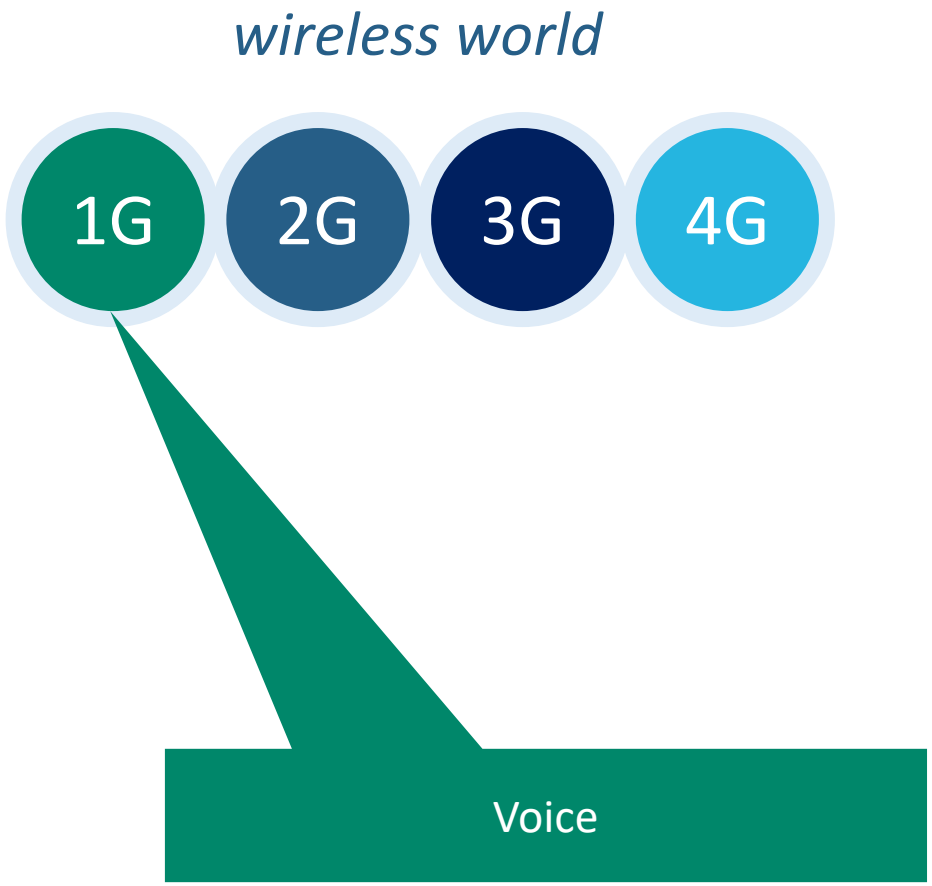
5G (r)evolution



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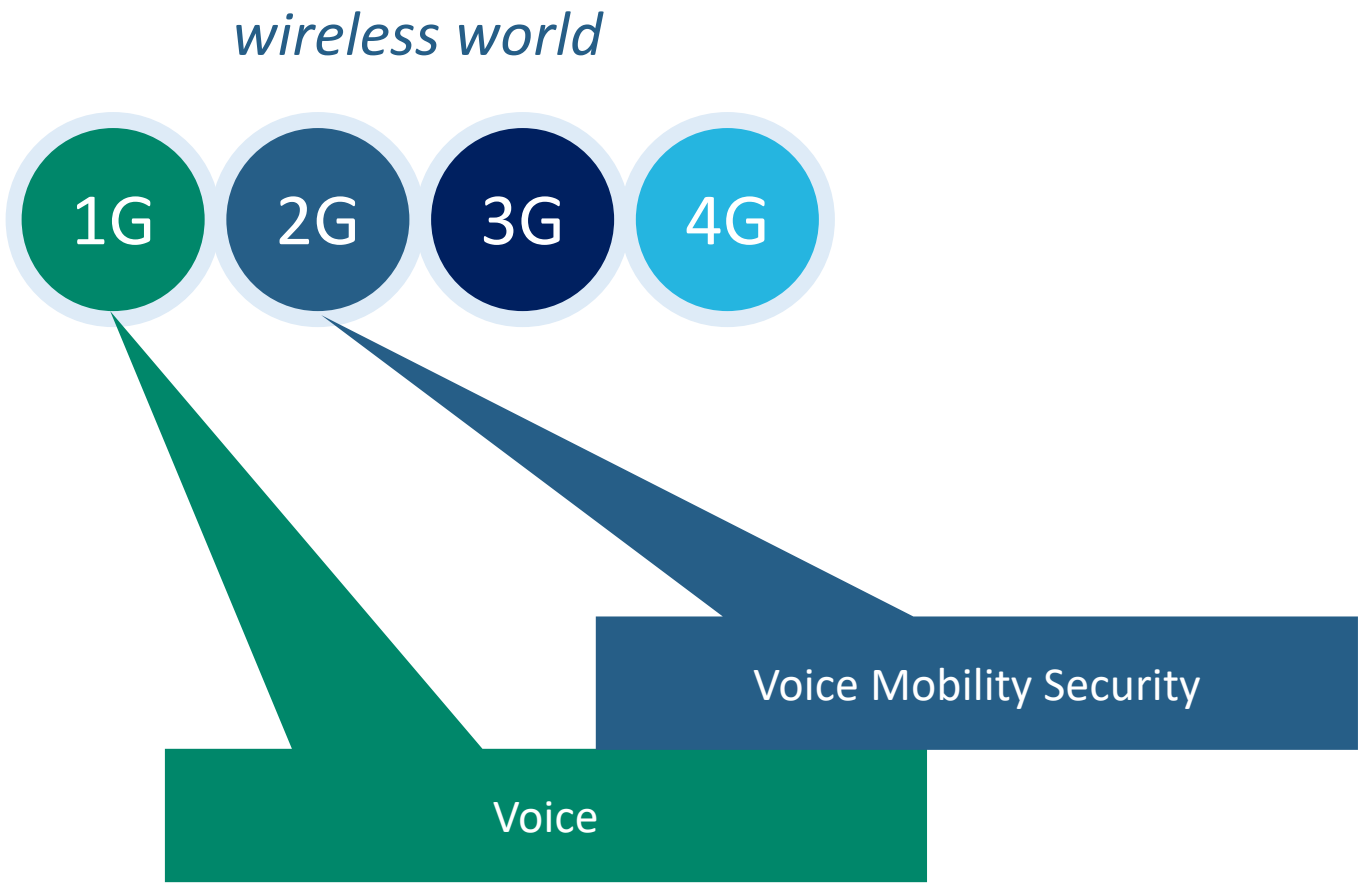
5G (r)evolution



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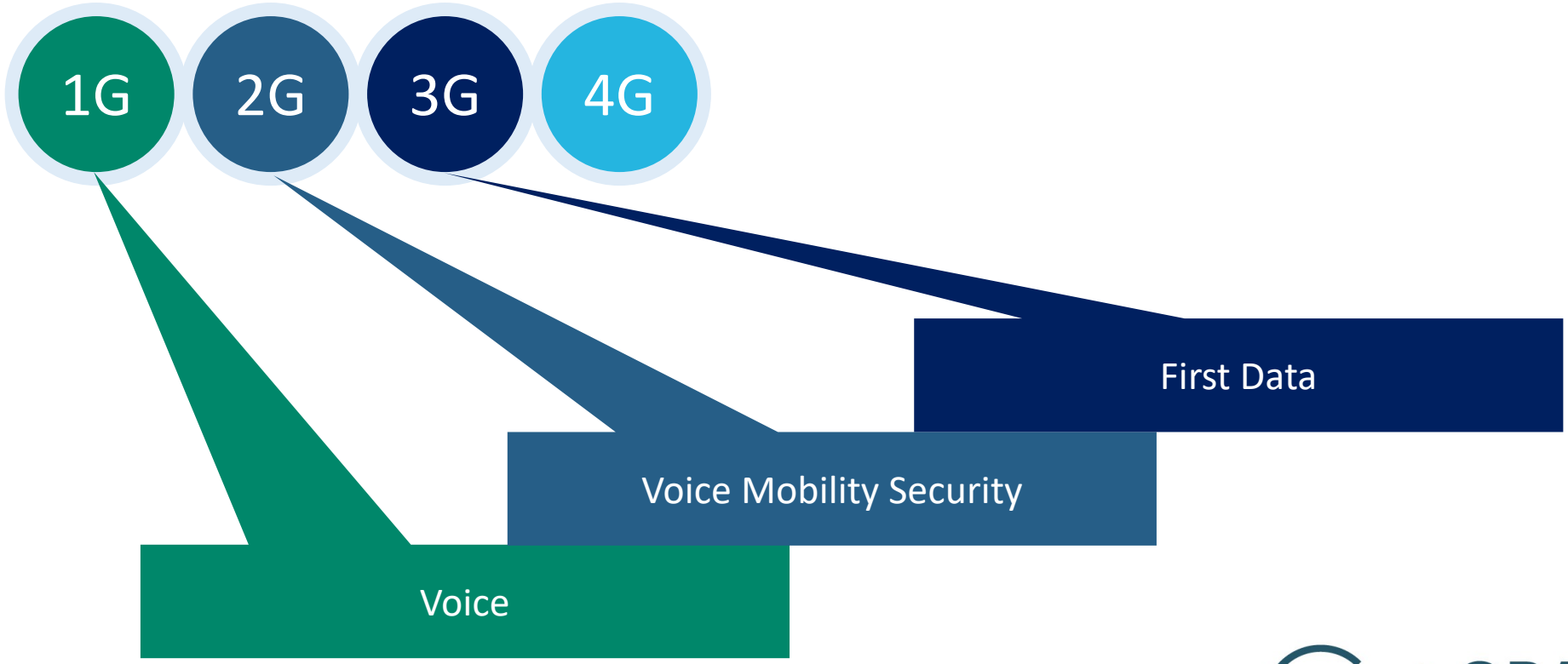
5G (r)evolution

wireless world



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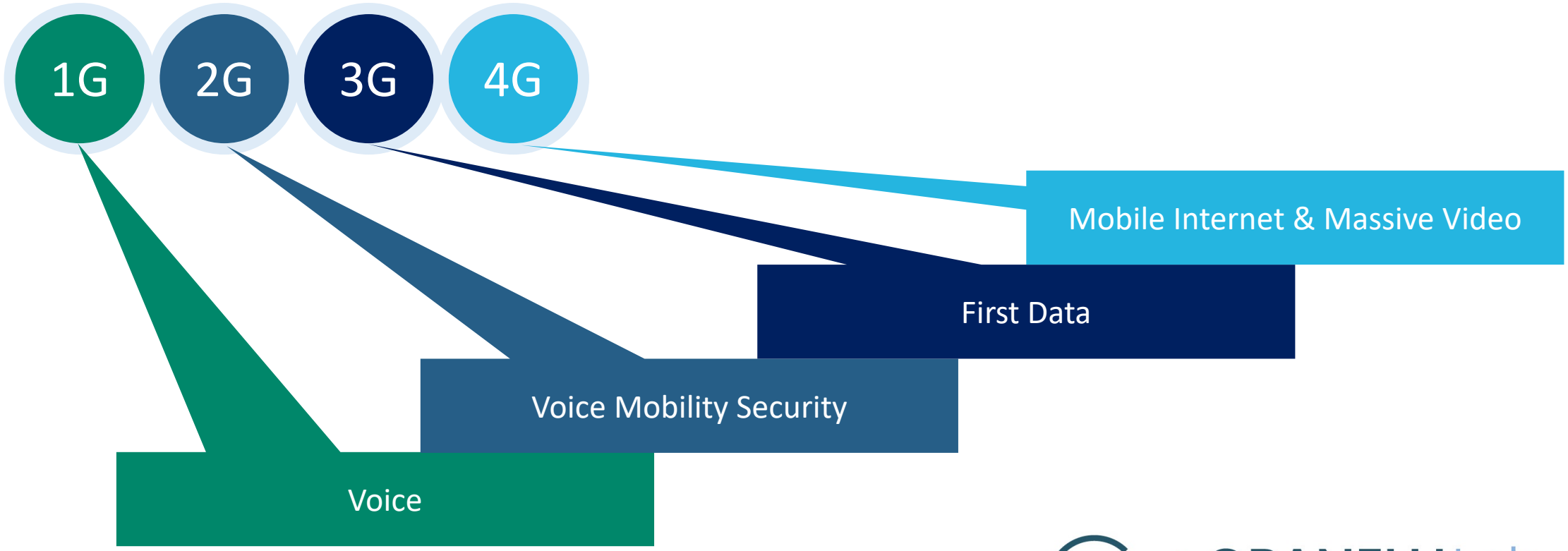
5G (r)evolution

wireless world



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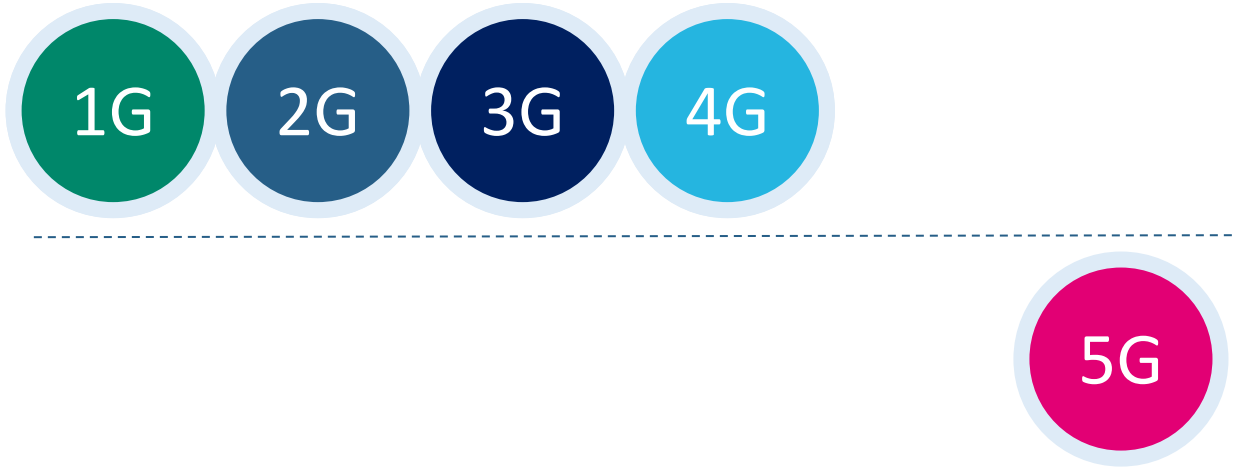
5G (r)evolution

wireless world



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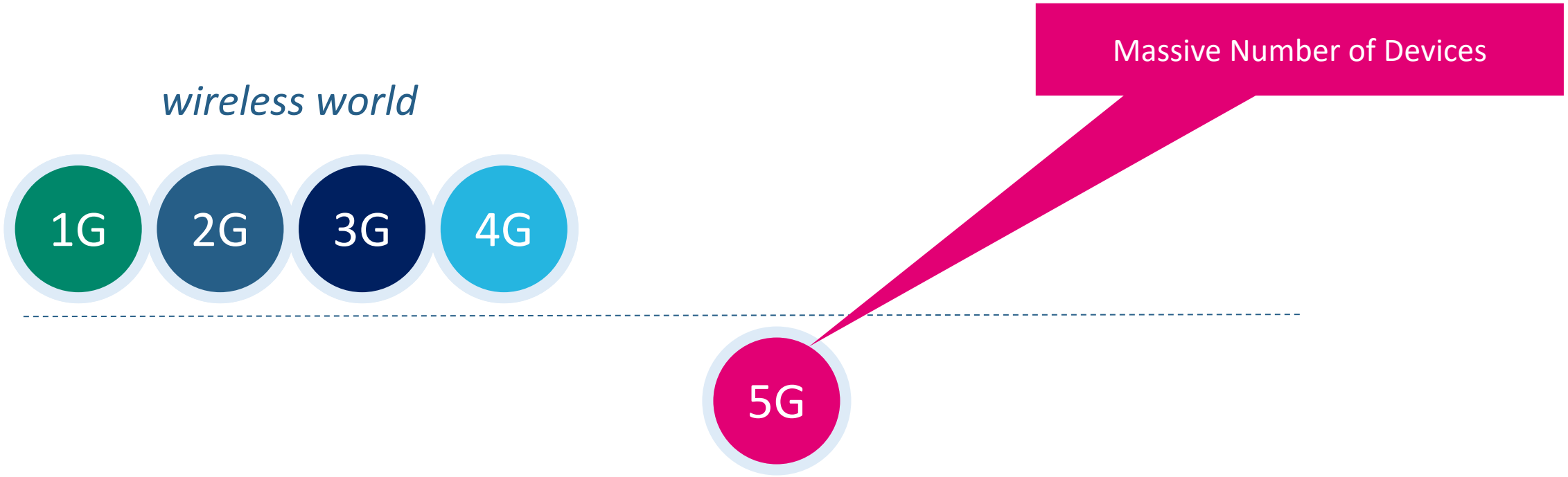
5G (r)evolution



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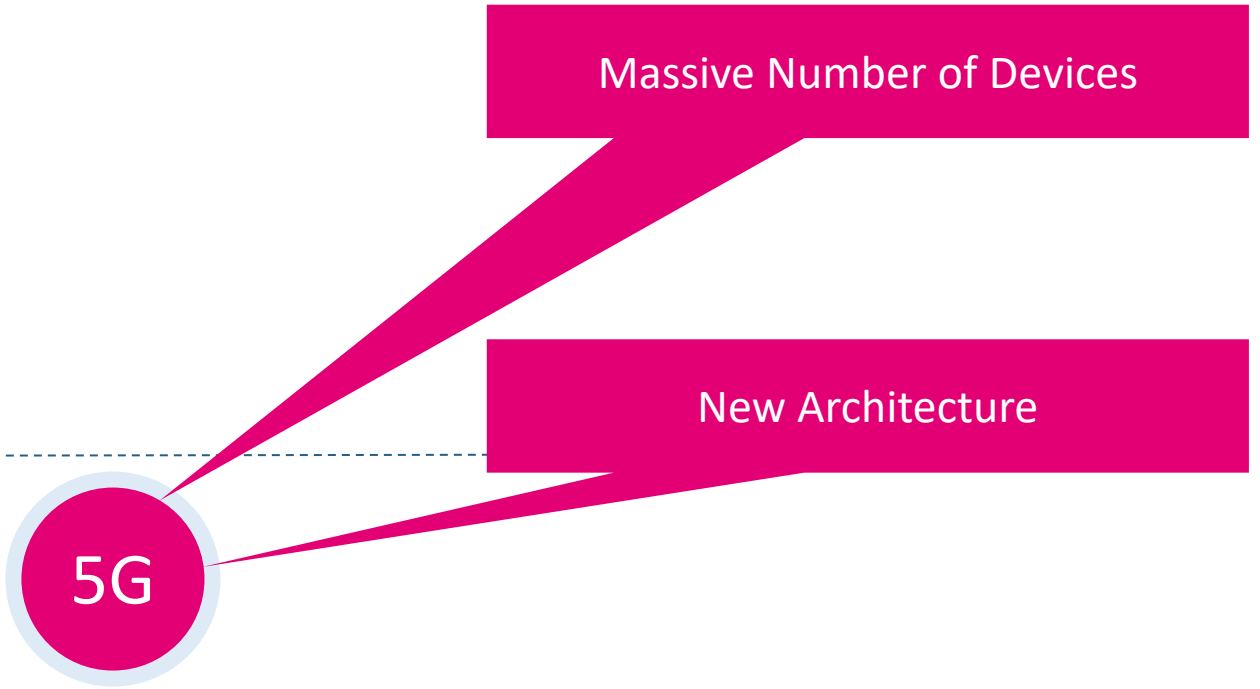
5G (r)evolution

wireless world



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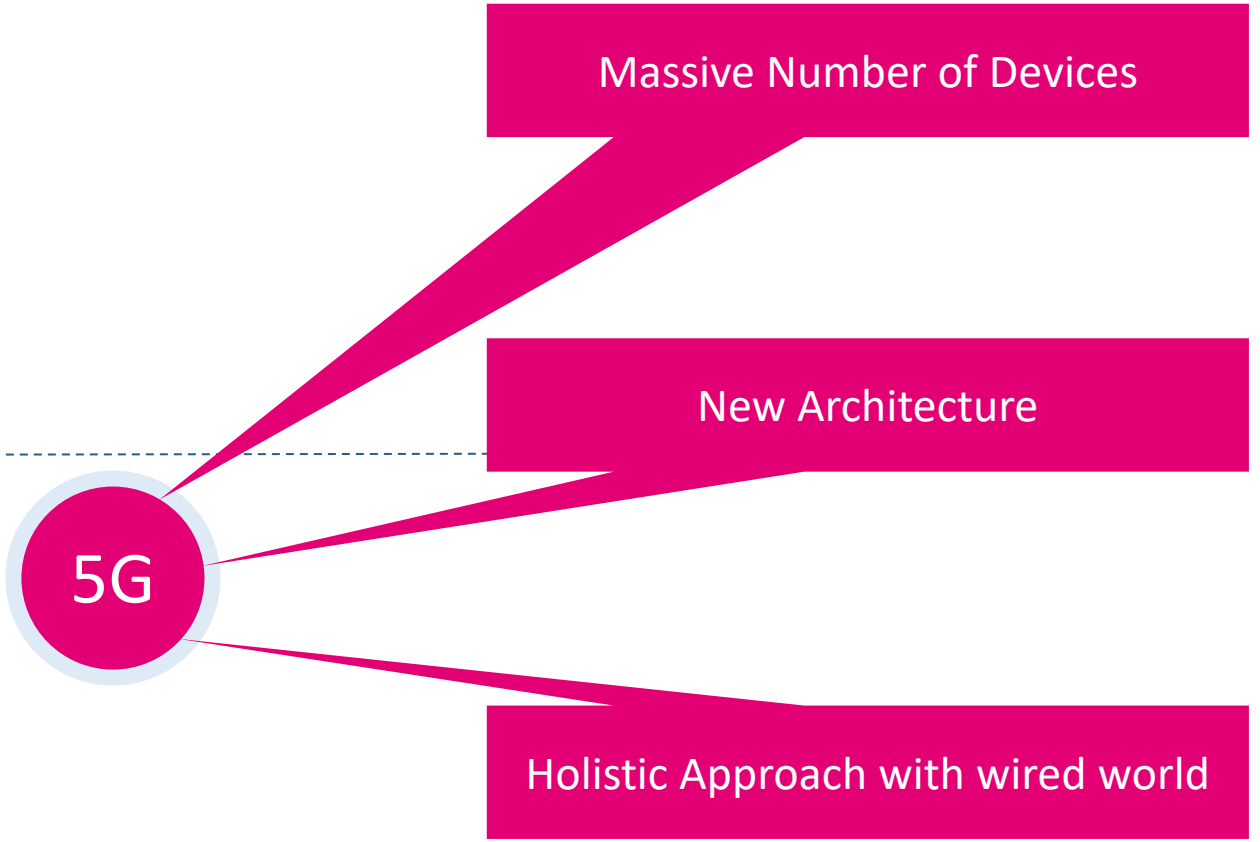
5G (r)evolution

wireless world



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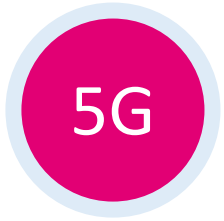
5G (r)evolution

wireless world

communication for consumers



communication for things/control

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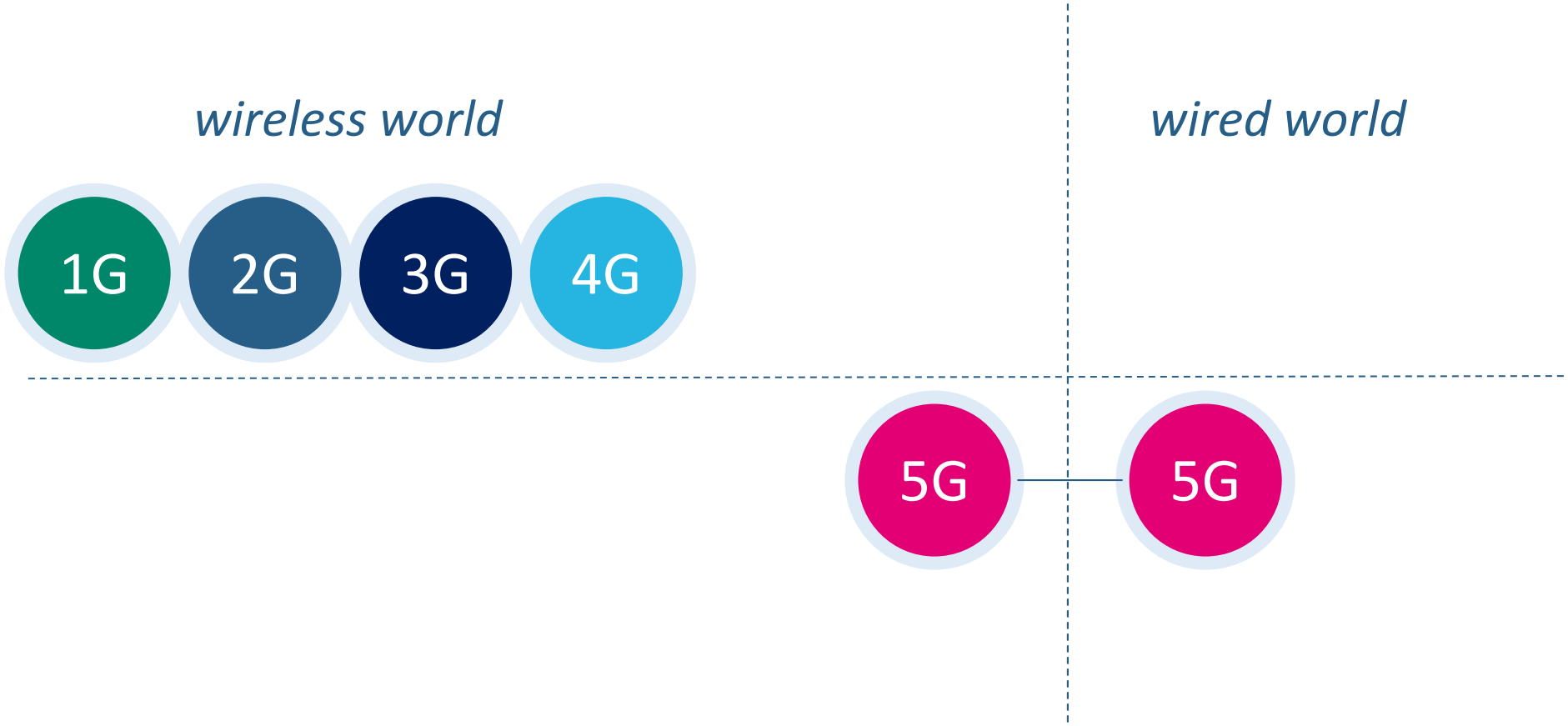
5G (r)evolution



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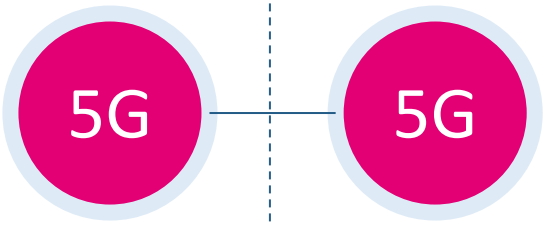
5G (r)evolution

wireless world

wired world



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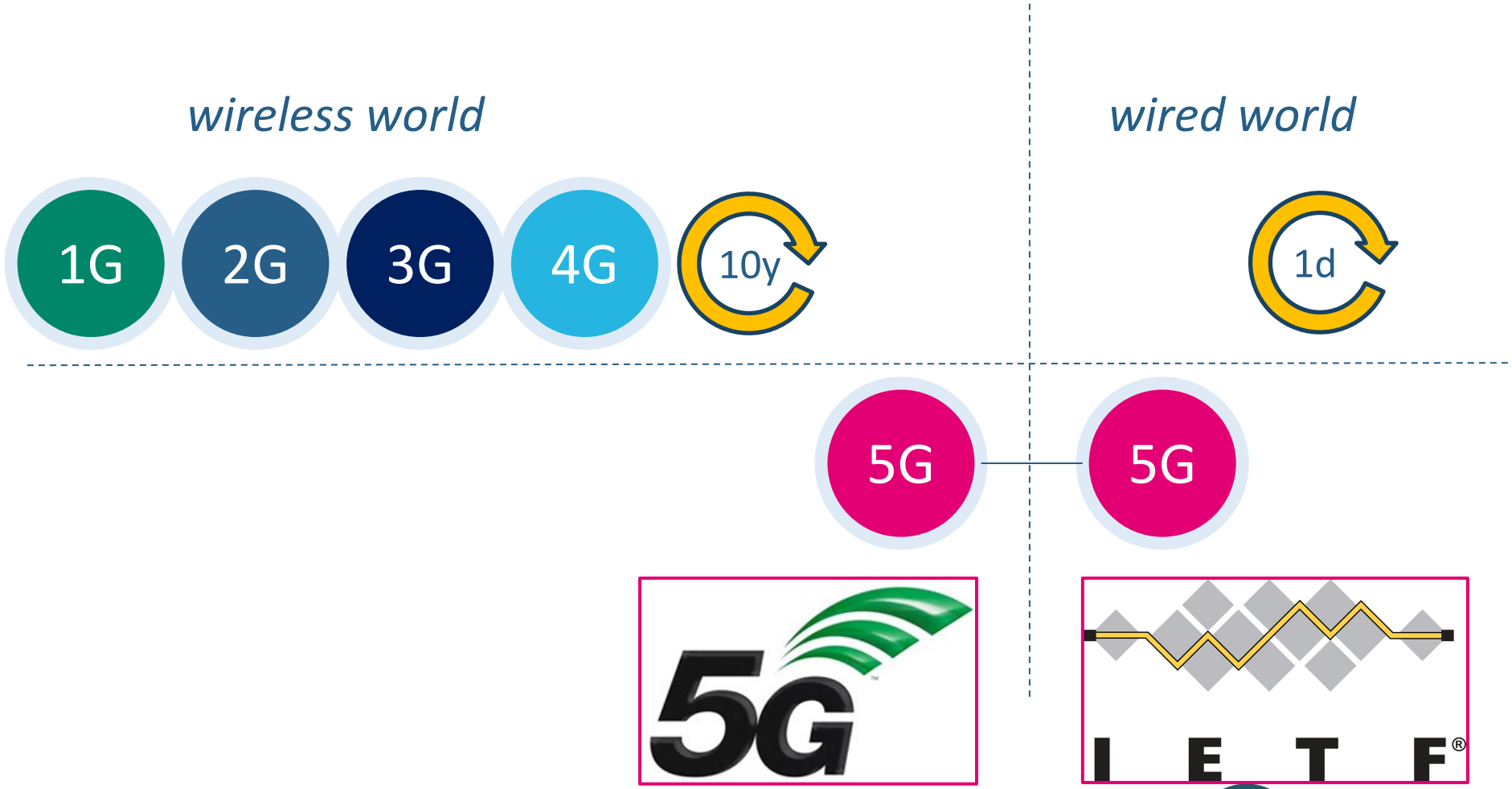
5G (r)evolution



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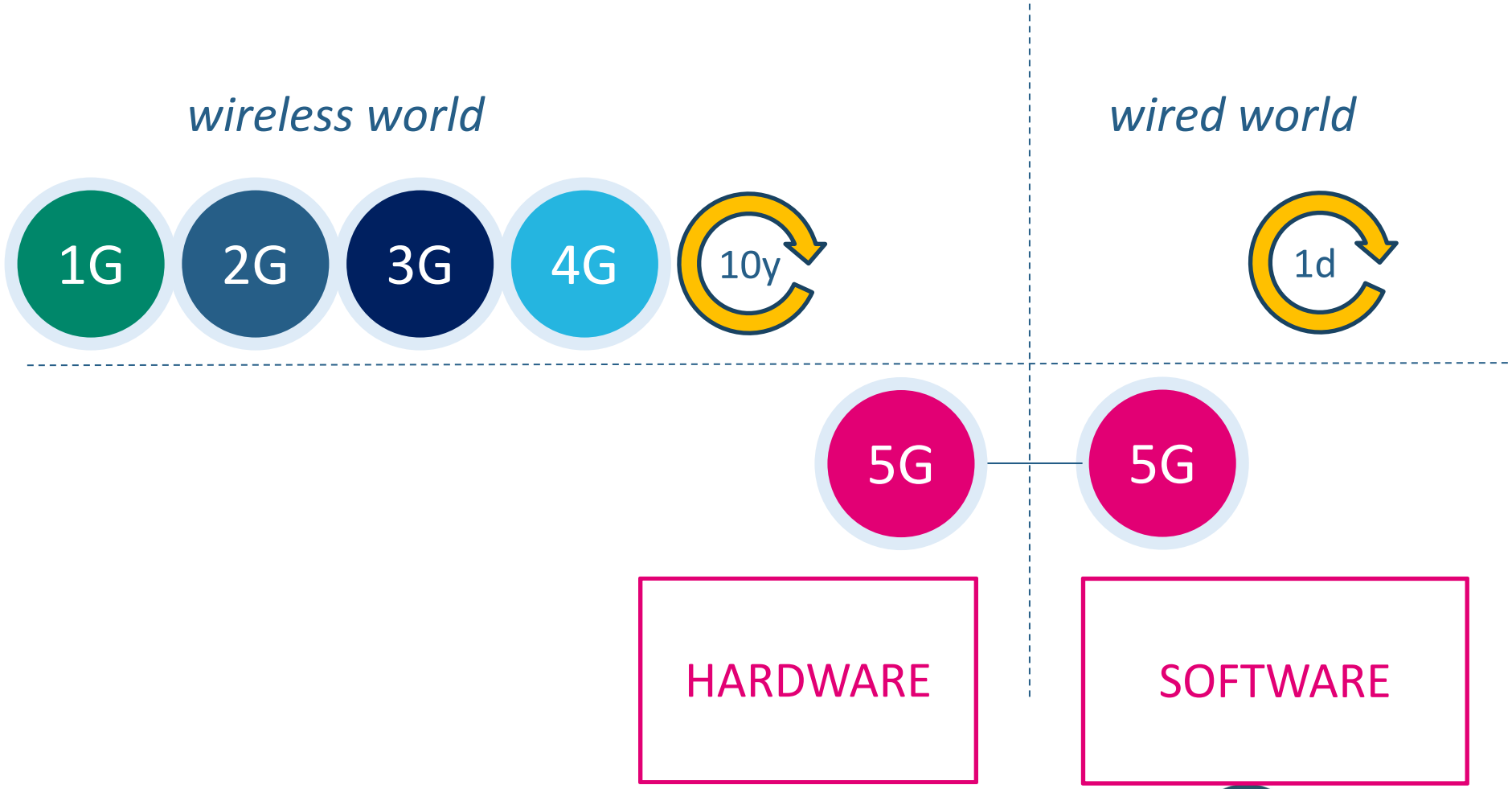
5G (r)evolution



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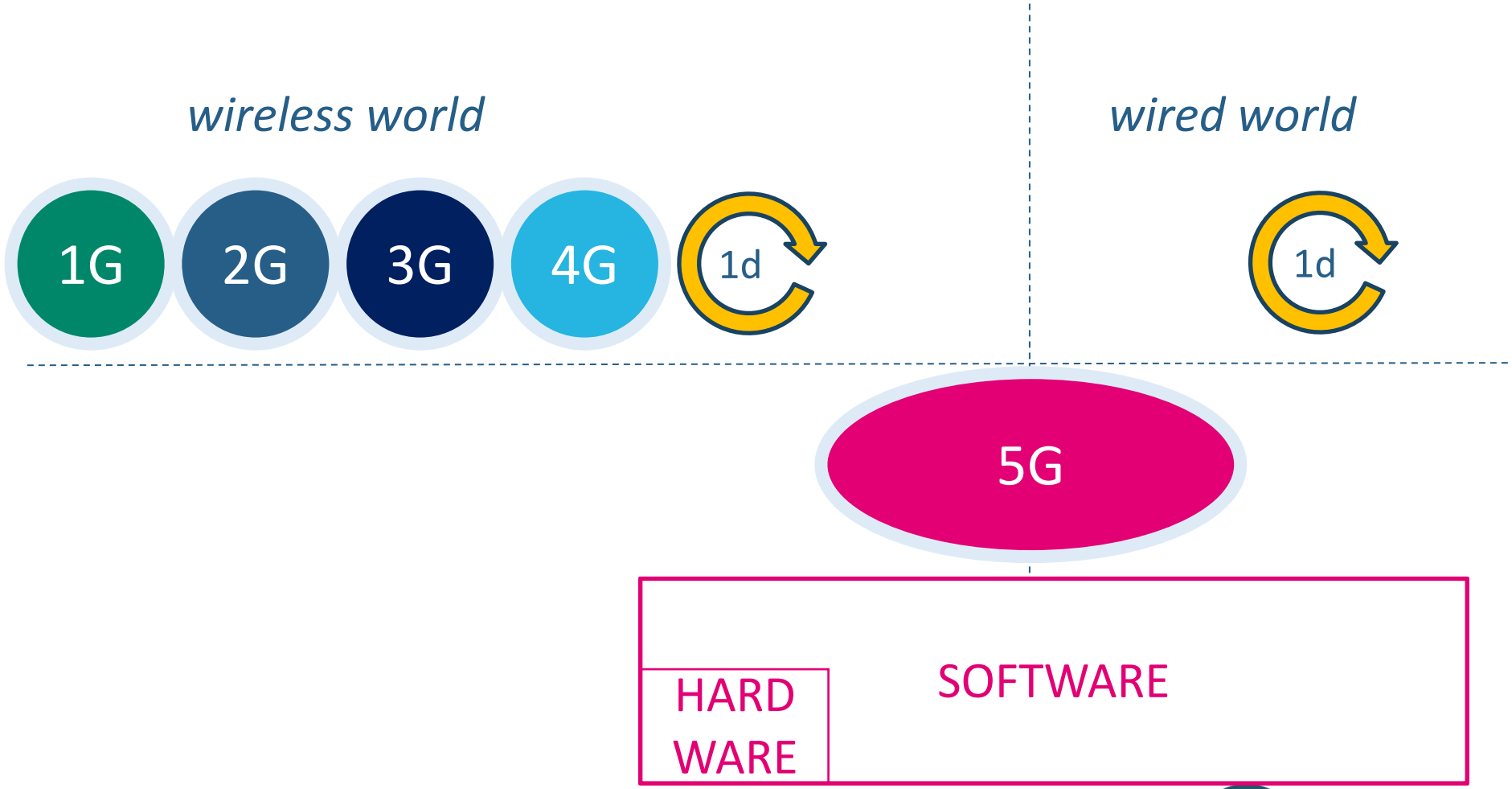
5G (r)evolution



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5G (r)evolution

Computing in Communication

5G

HARD WARE

SOFTWARE

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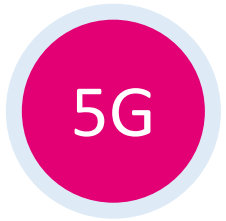
5G (r)evolution

Communication = Transport



Communication = Transport
Storage
Computing

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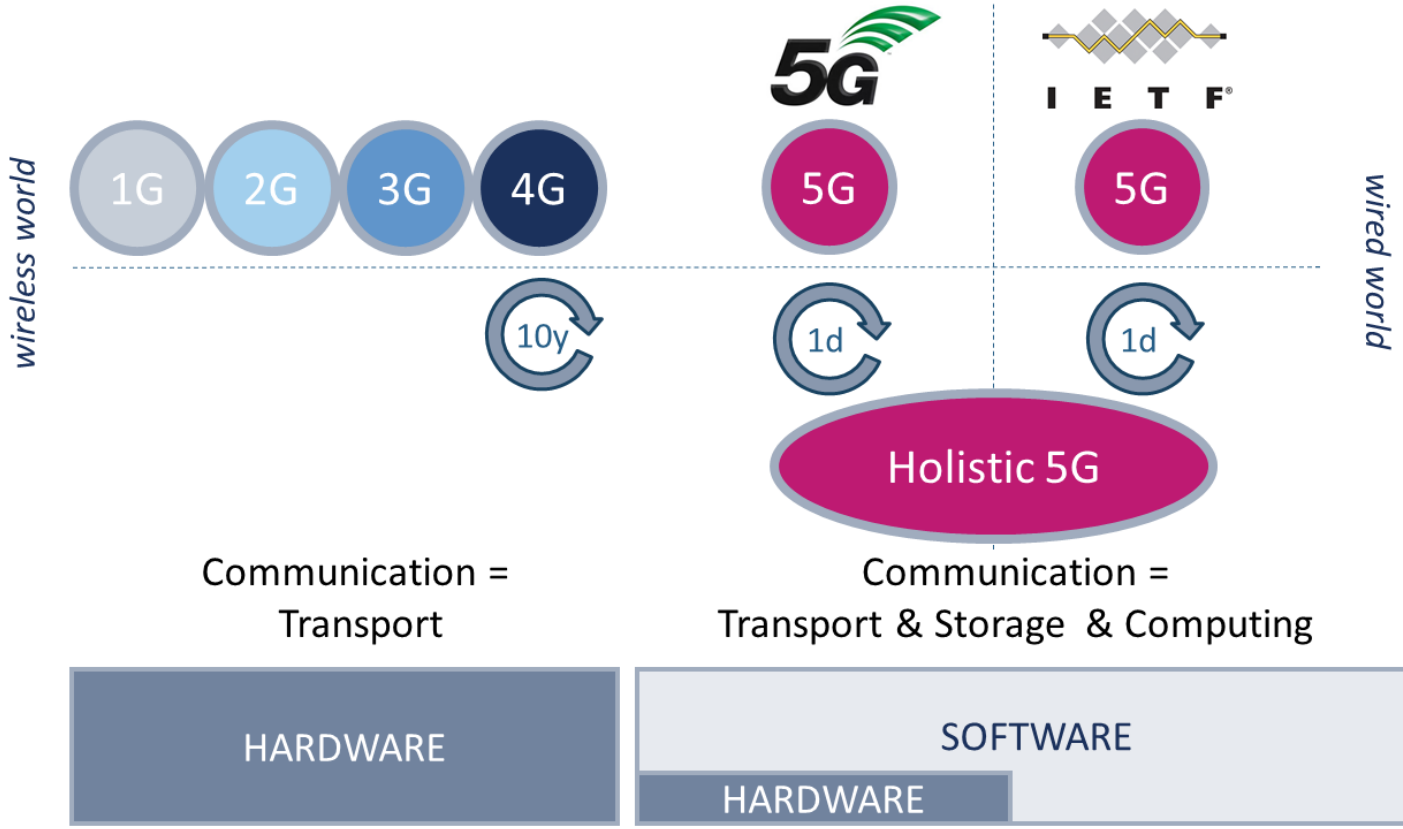
The evolution of cellular communication systems



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What defines 5G?

Massive Number of Devices

7

Billion Devices

2014

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Massive Number of Devices

7

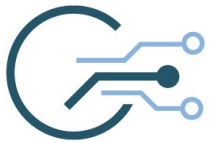
Billion Devices

2014

500

Billion Devices

2022



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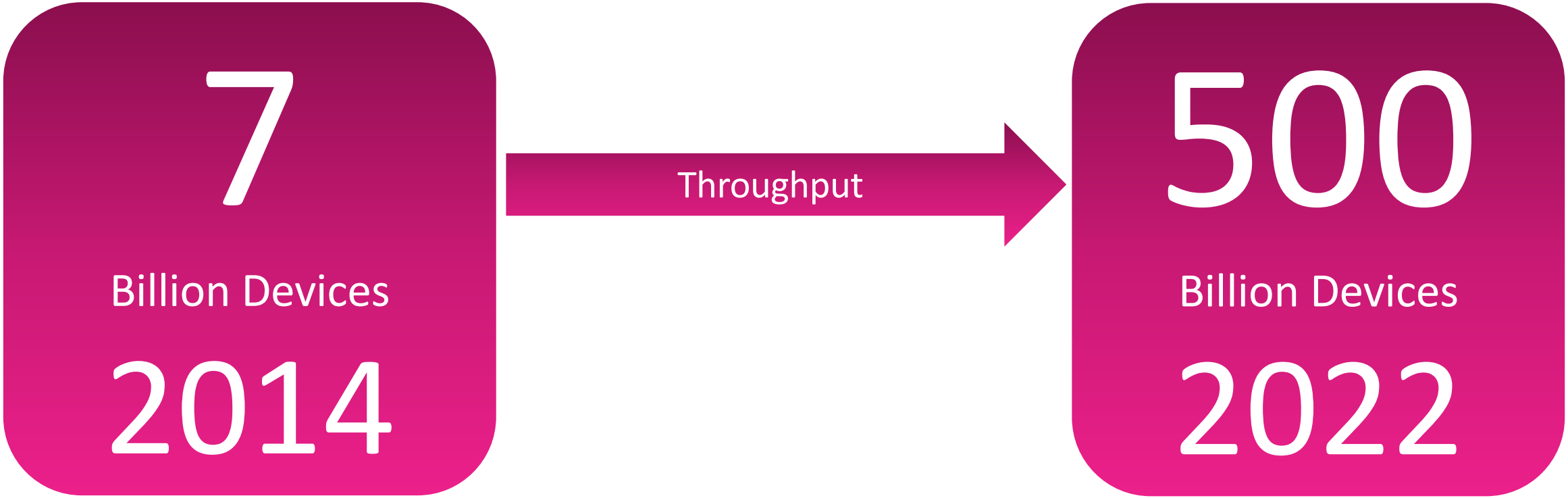
Massive Number of Devices



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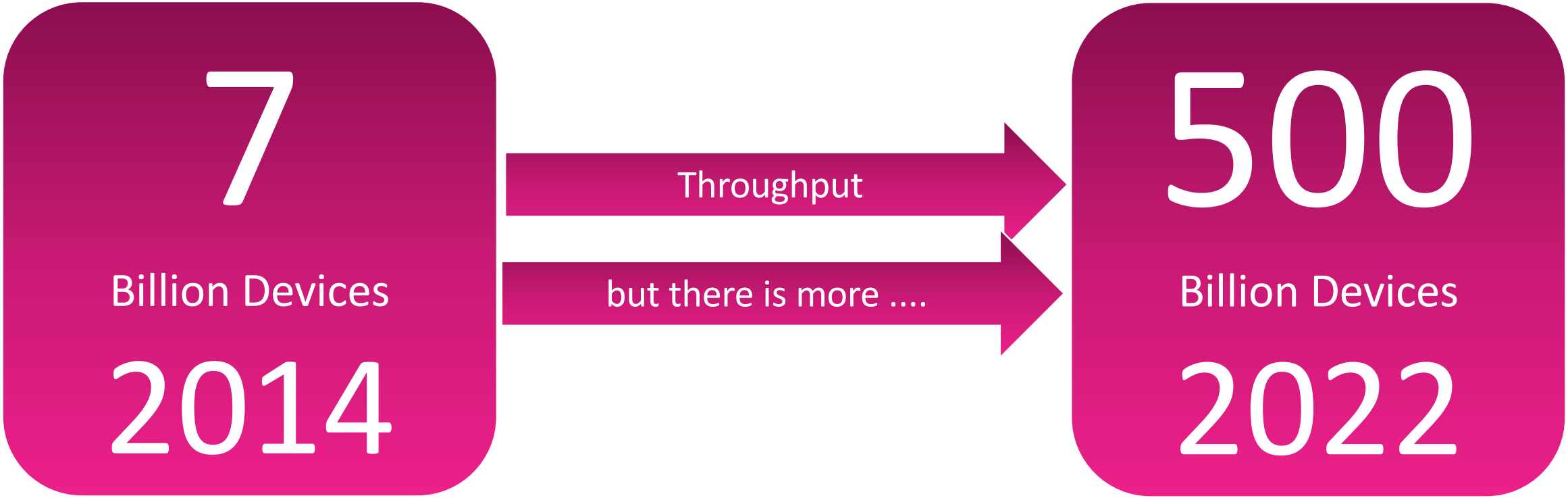
Massive Number of Devices



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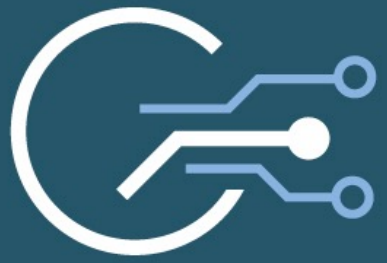

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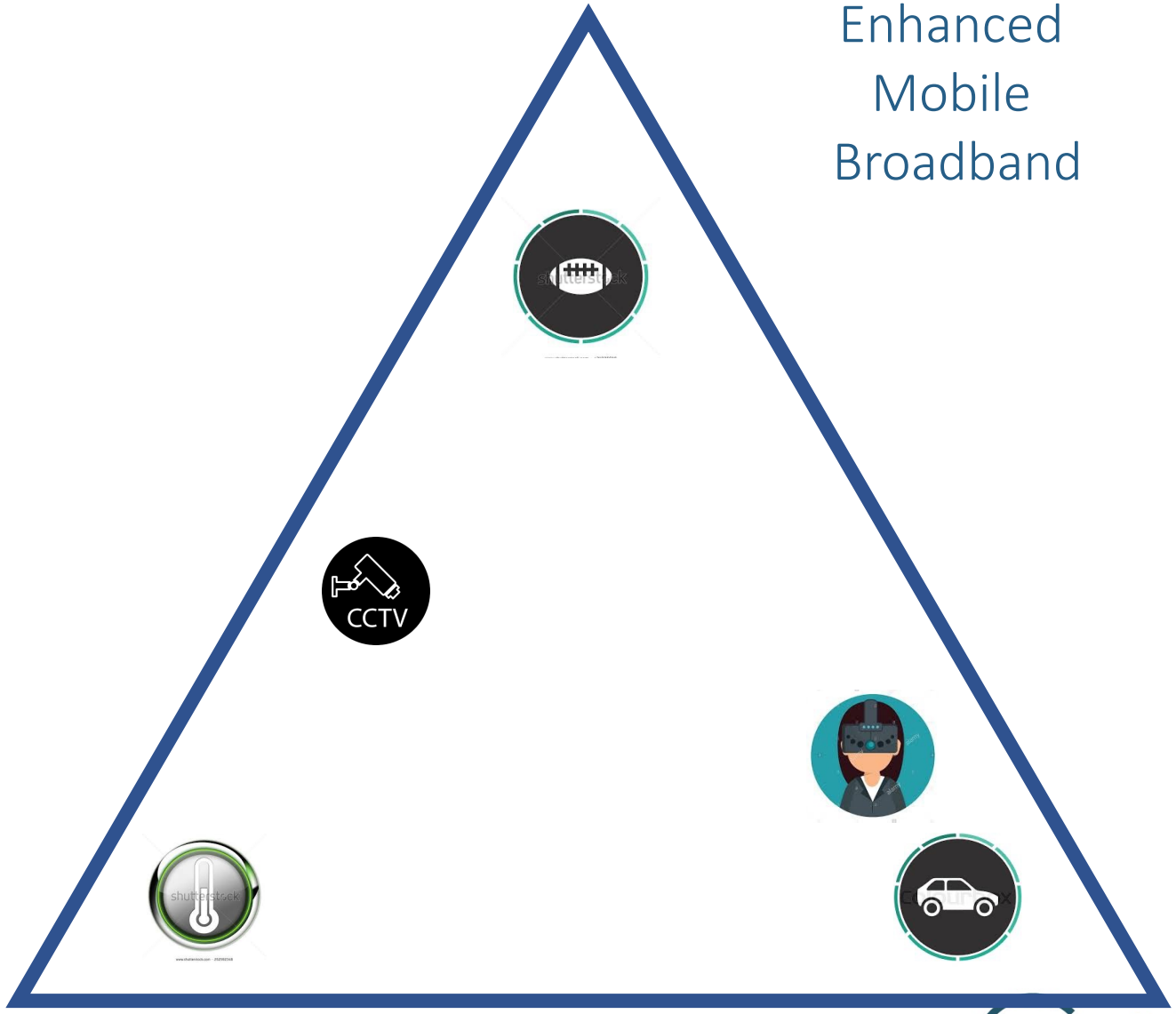
What defines 5G?
IMT 2020

General 5G Definition ITU-R IMT 2020



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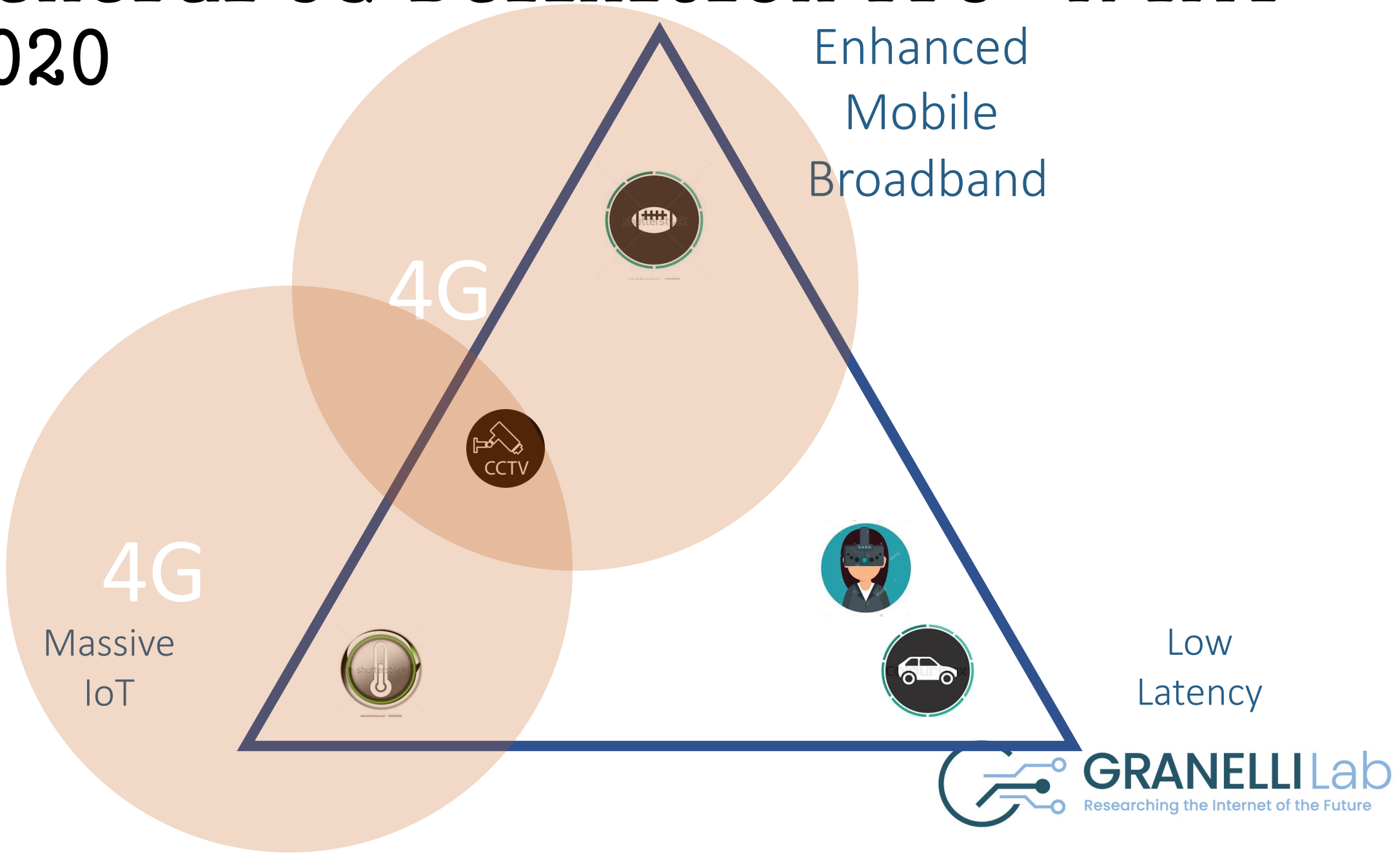
General 5G Definition ITU-R IMT 2020



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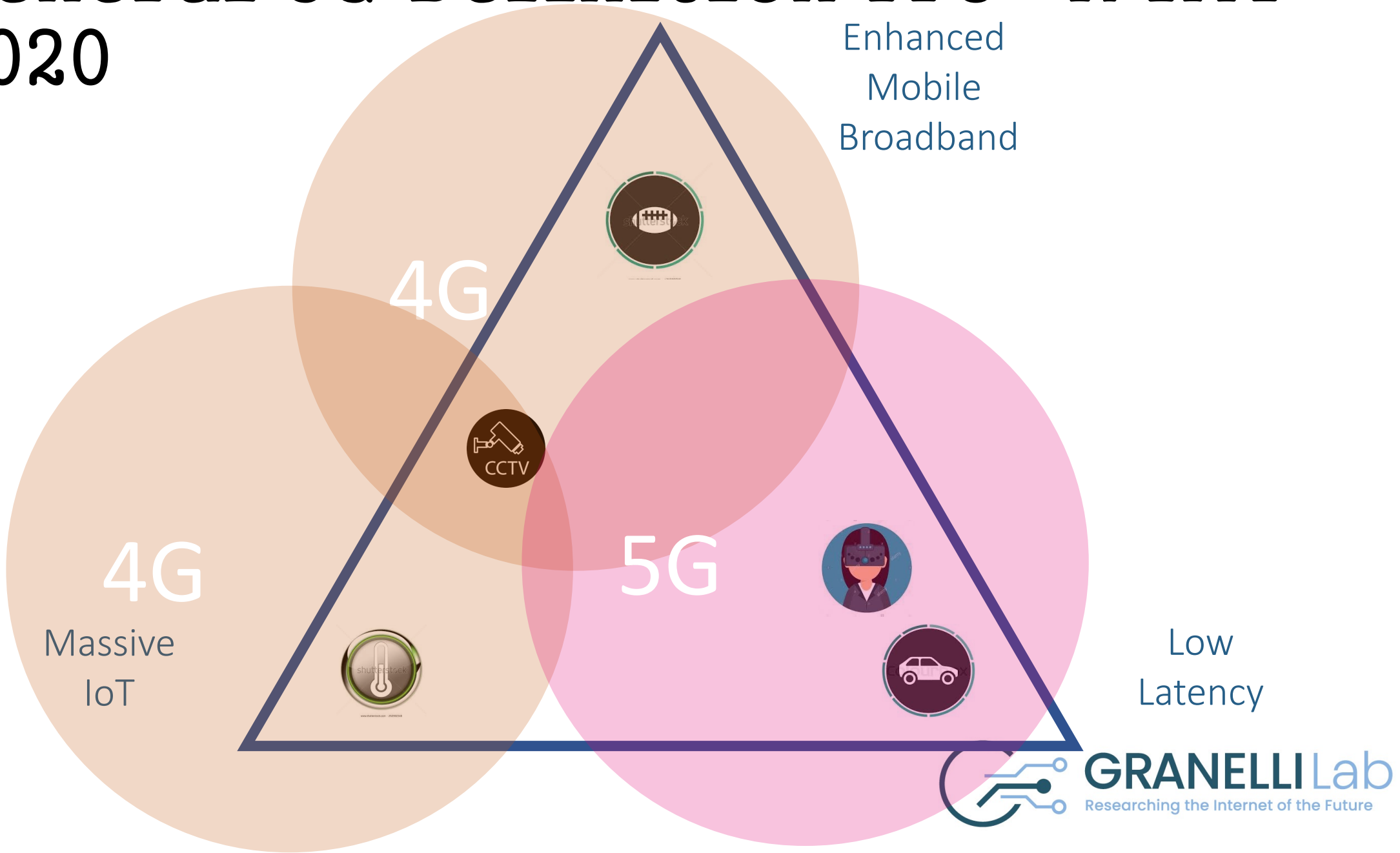
General 5G Definition ITU-R IMT 2020



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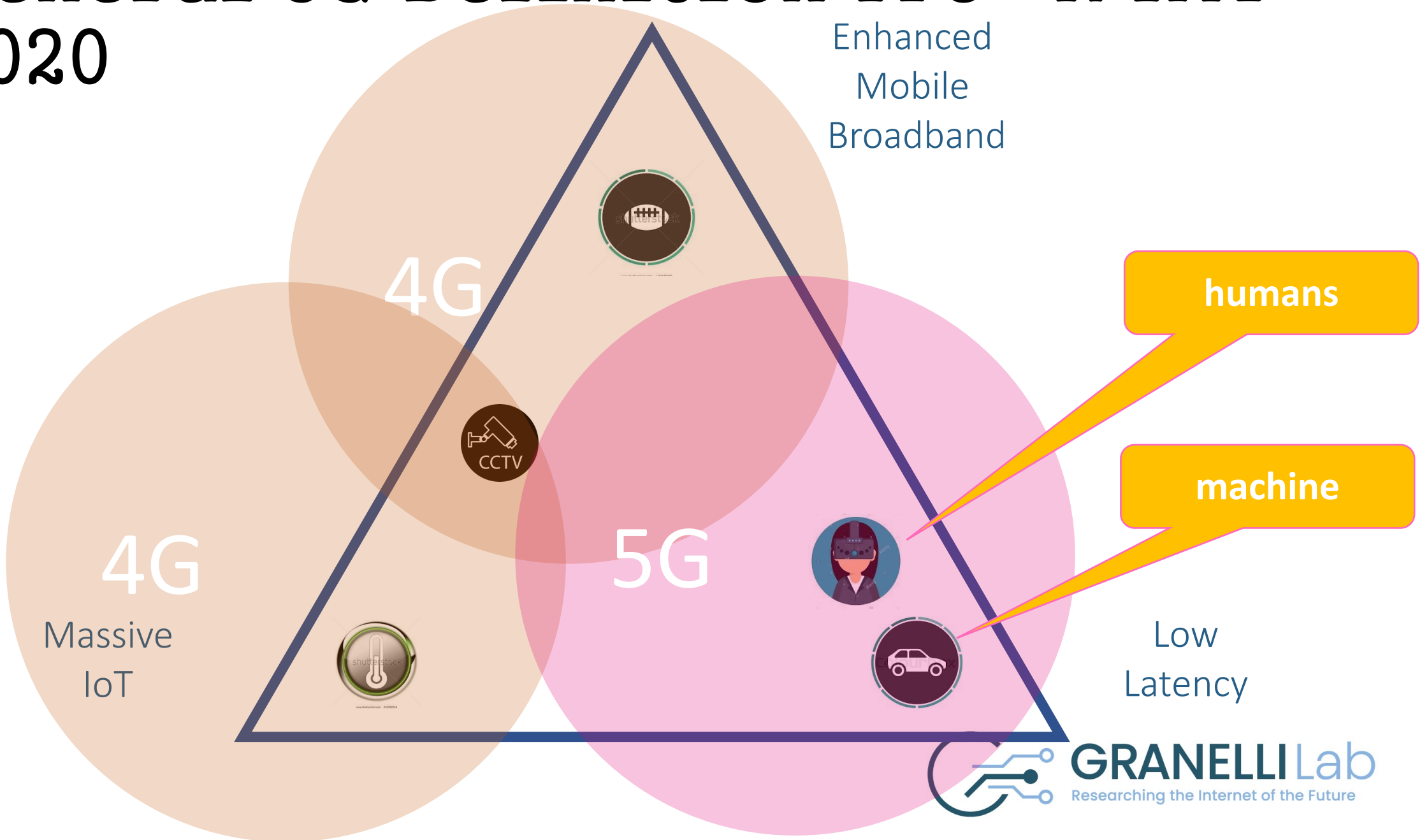
General 5G Definition ITU-R IMT 2020



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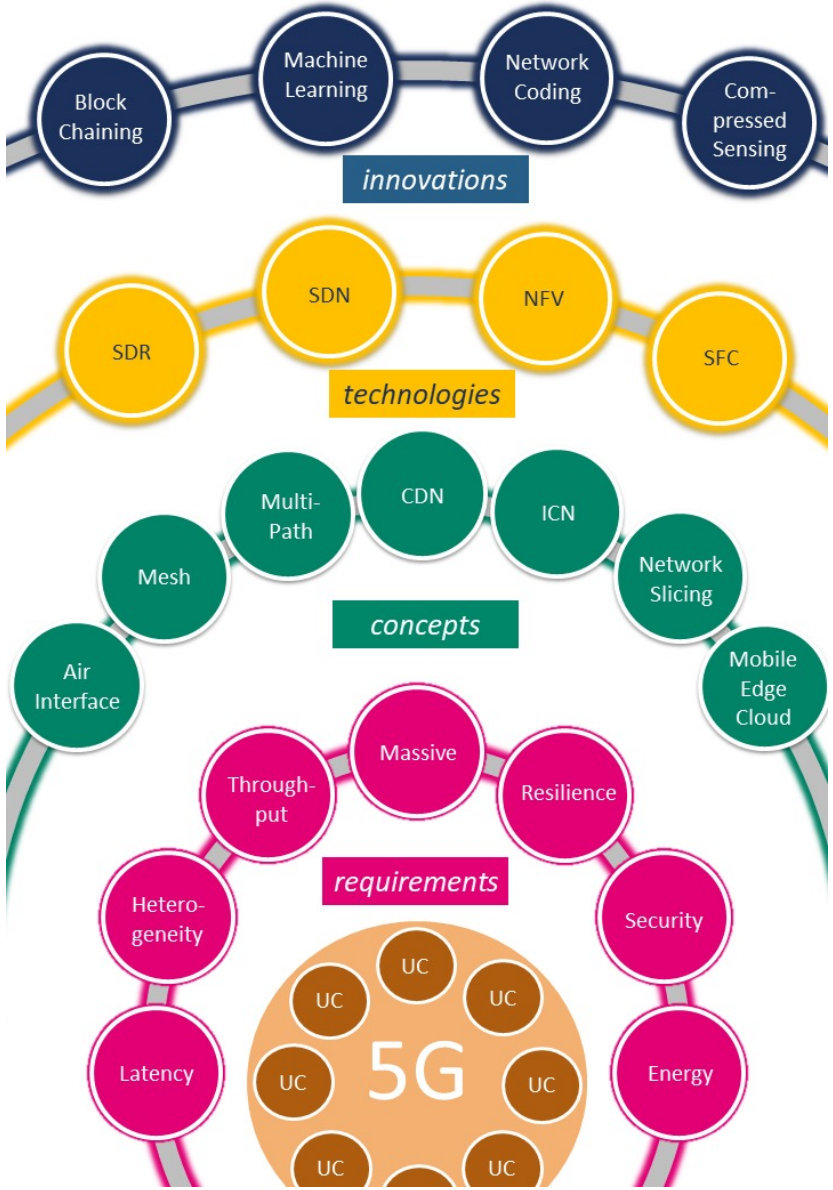
What defines 5G?
The 5G atom

The 5G Atom

- Our definition of 5G by atom
  - Core → Use Cases
  - Electrons → Elements



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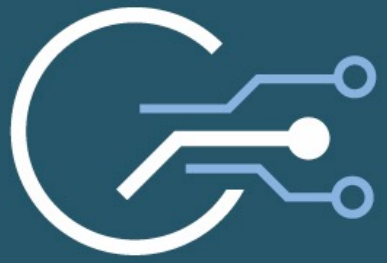

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5G Use Cases

5G atom definition

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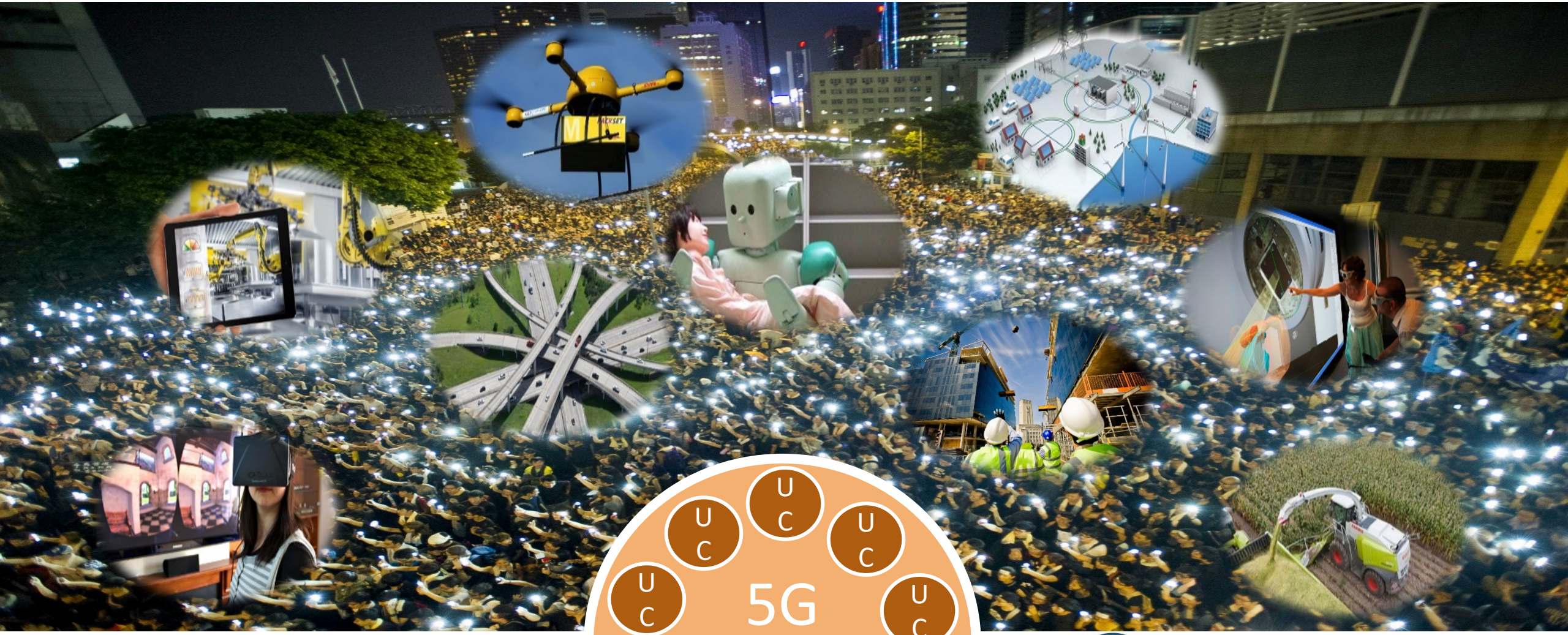
5G atom definition



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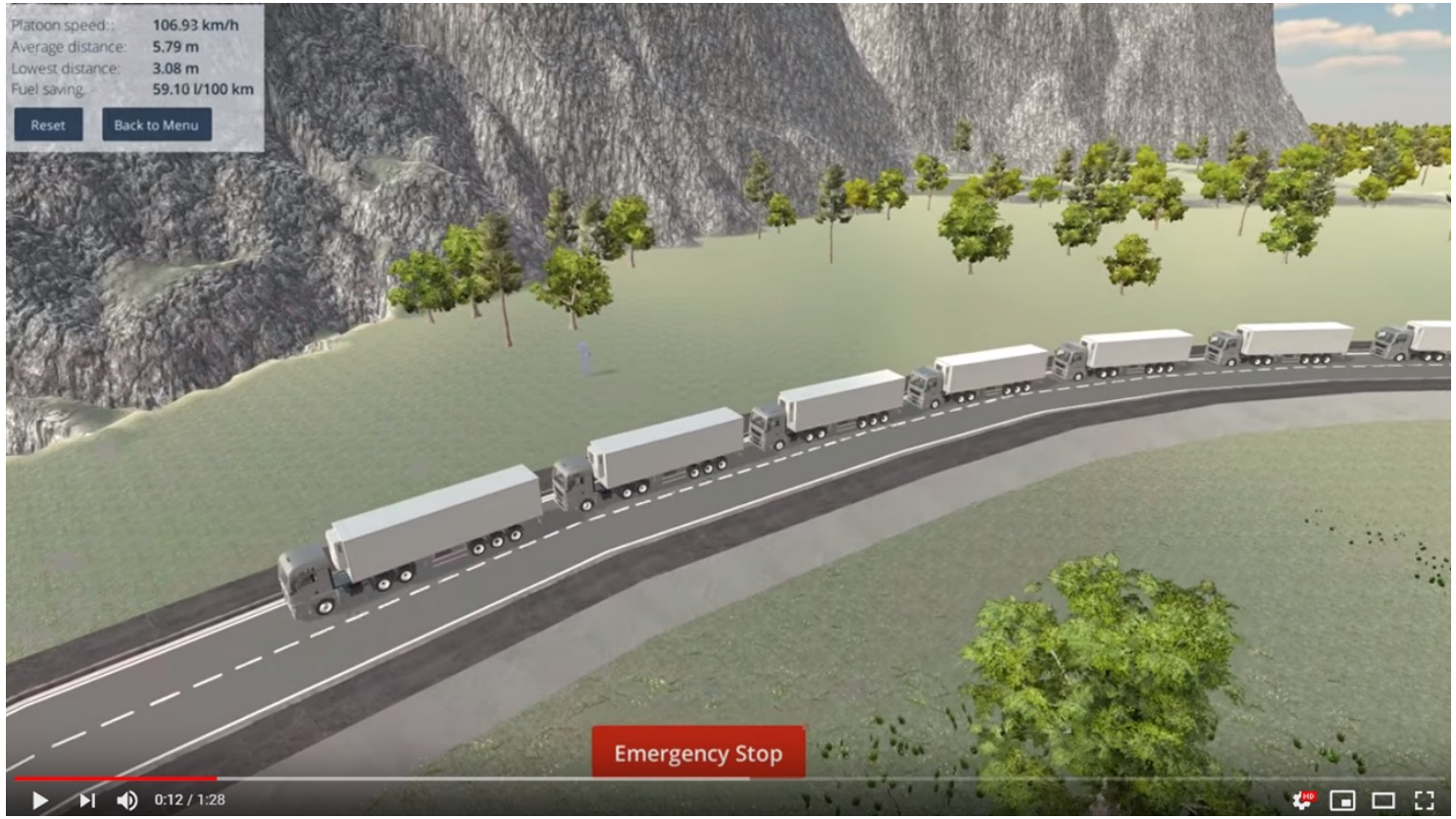
The 5G Atom use cases: Connected autonomous cars platooning example



https://www.youtube.com/watch?v=3R3t_hVsj9c

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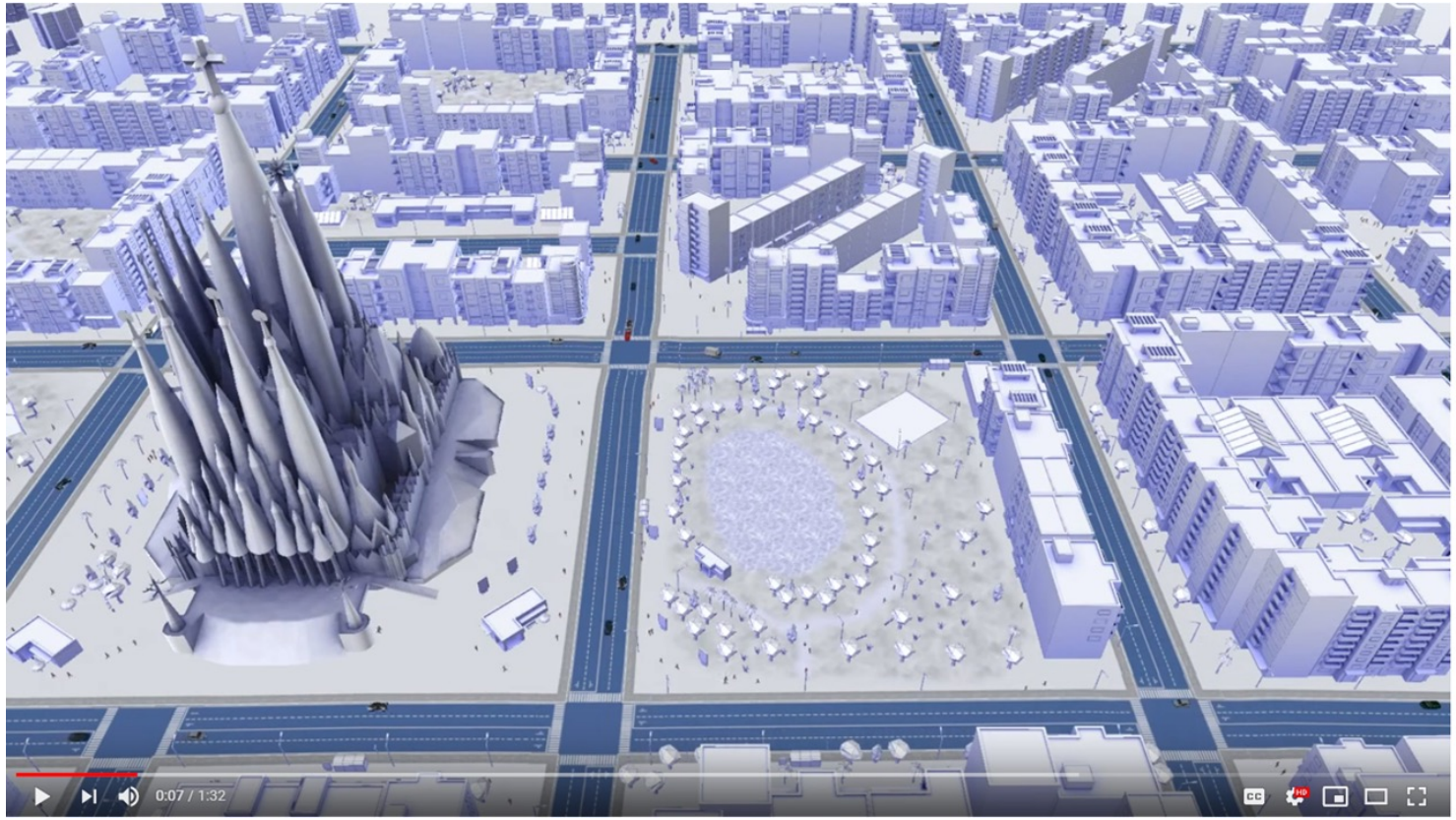
The 5G Atom use cases: Connected autonomous cars Barcelona example



https://www.youtube.com/watch?v=C8fy3IIVlB0&t=27s

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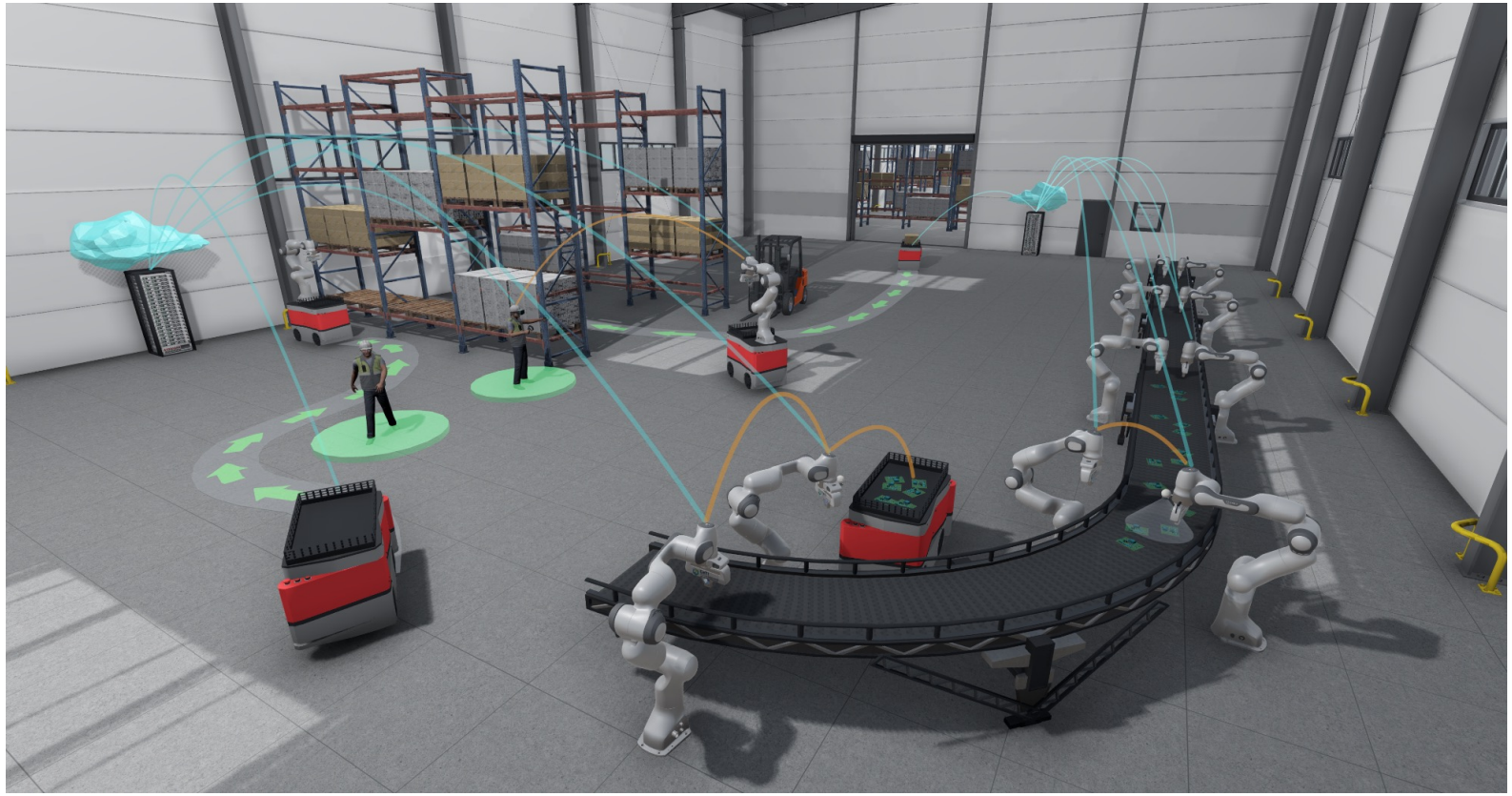
The 5G Atom use cases: Example network architecture in Industry 4.0



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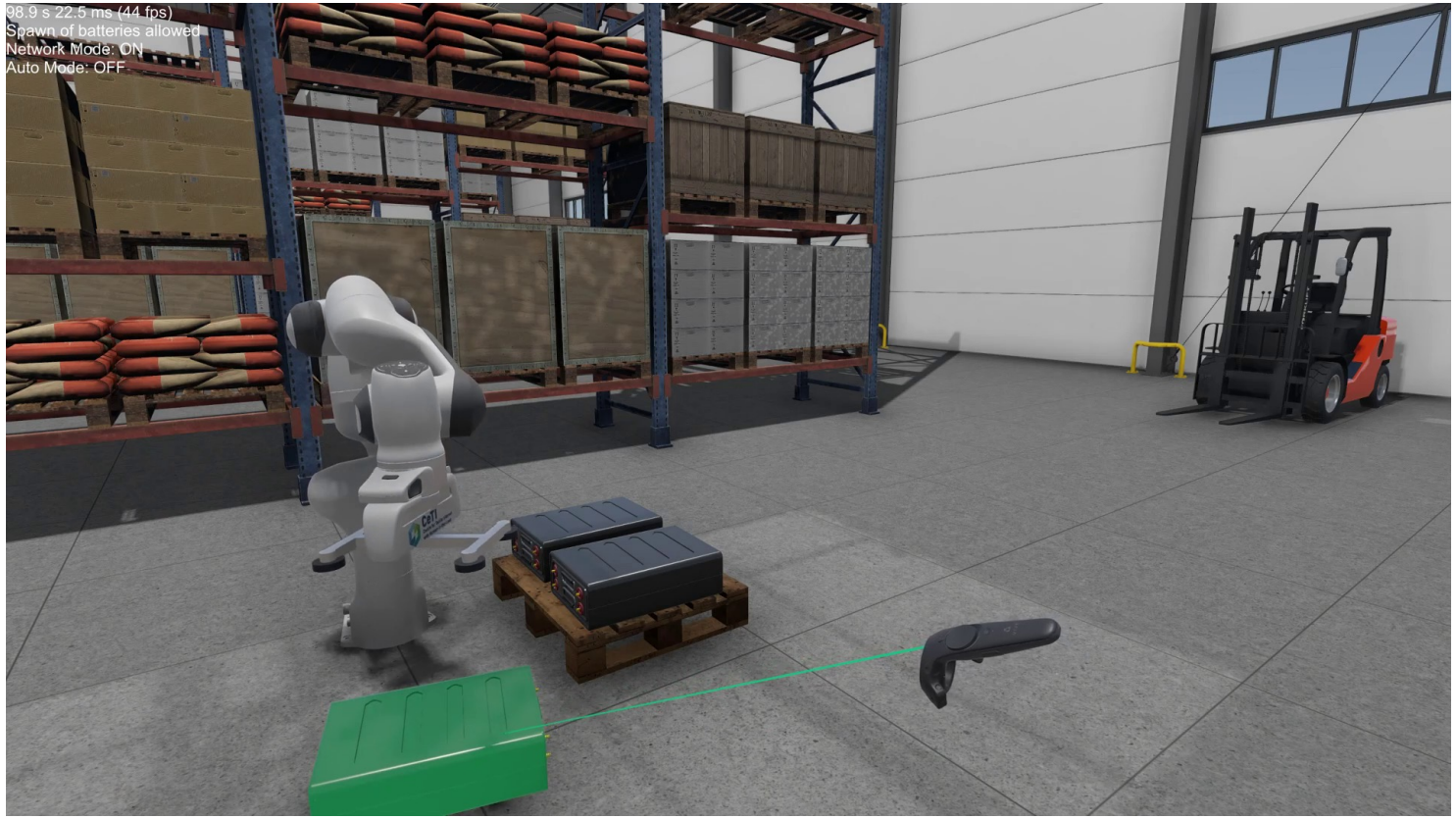
The 5G Atom use cases: Industry 4.0 training or remote control of robots in a virtual room



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The 5G Atom use cases: Agriculture 4.0 machinery platooning with small machines

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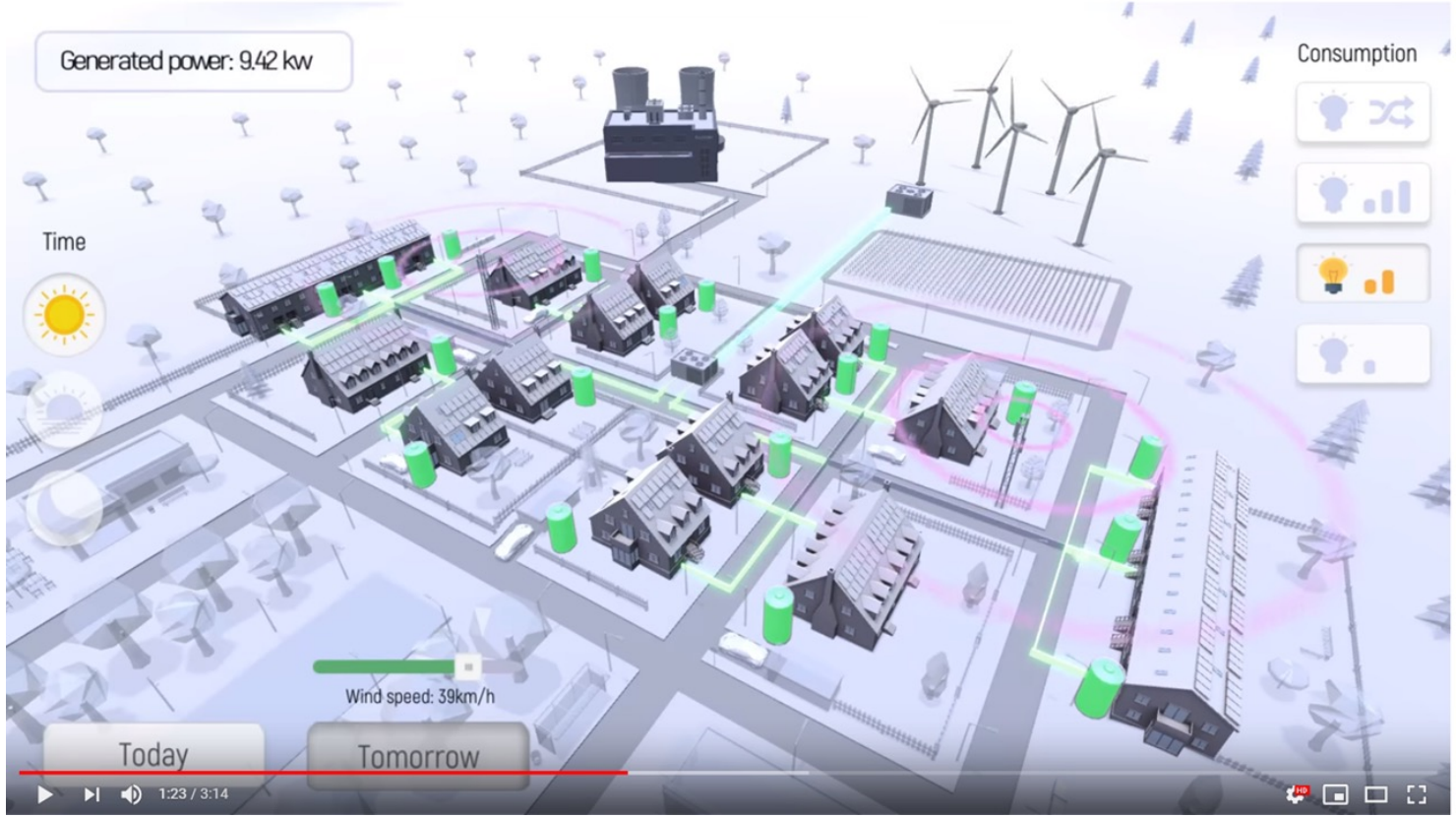
The 5G Atom use cases: Virtual power plant model for the smart energy grid



https://www.youtube.com/watch?v=WqaZly_1LRg&t=8s

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The 5G Atom use cases: Tactile Internet

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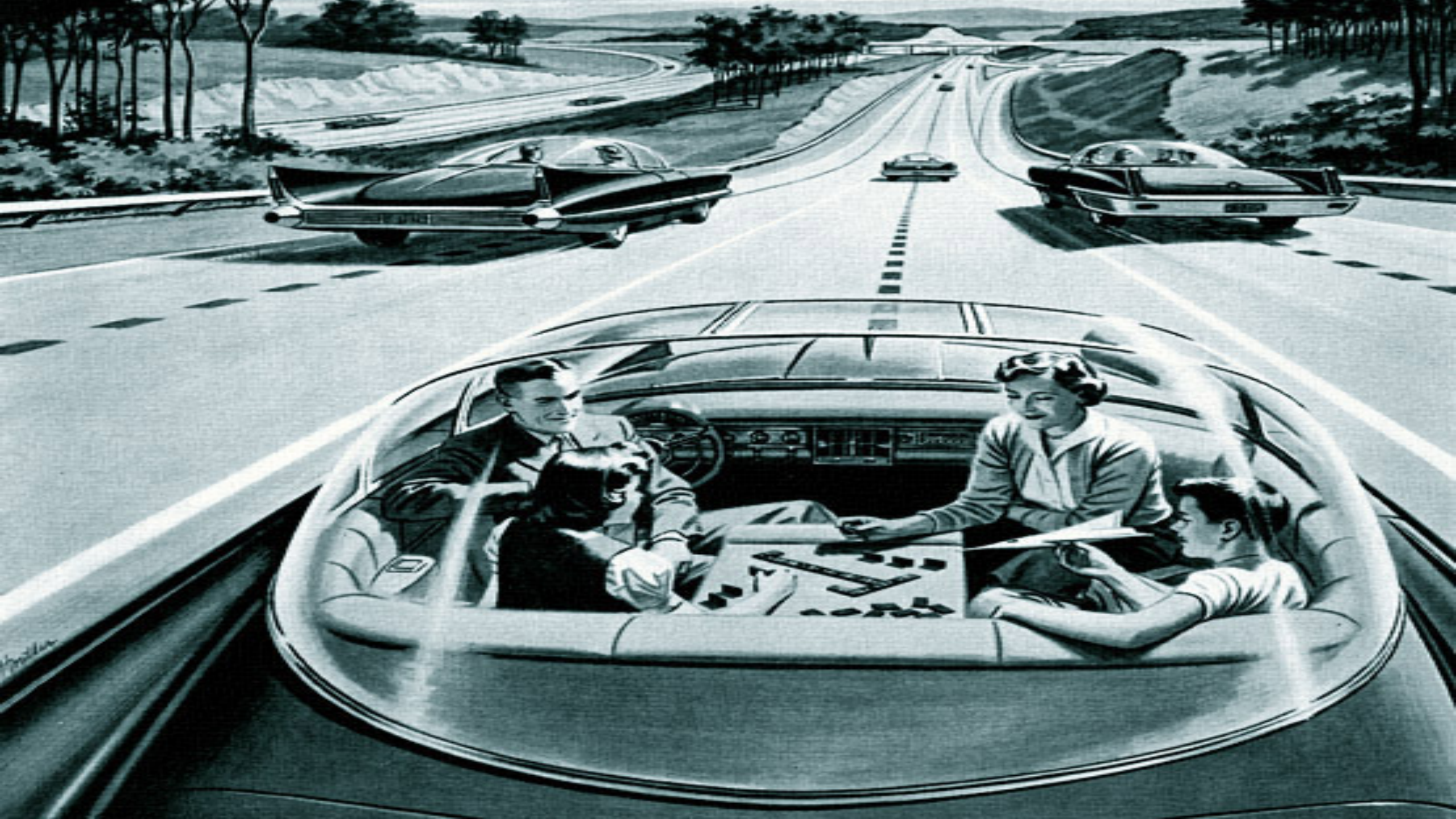

Platooning

- 1–2 ms: ESC, ABS

- Platooned ESC & ABS

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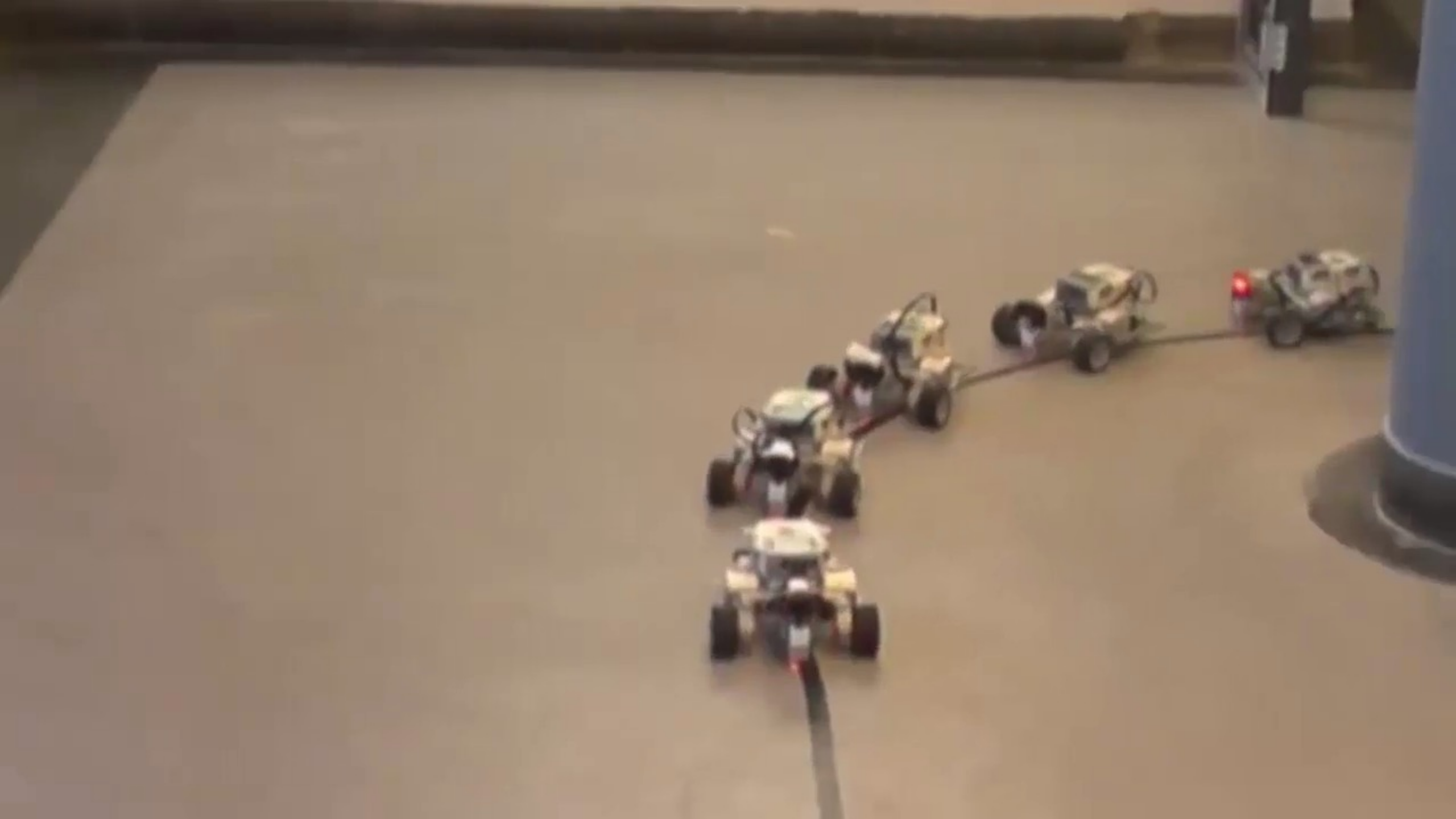
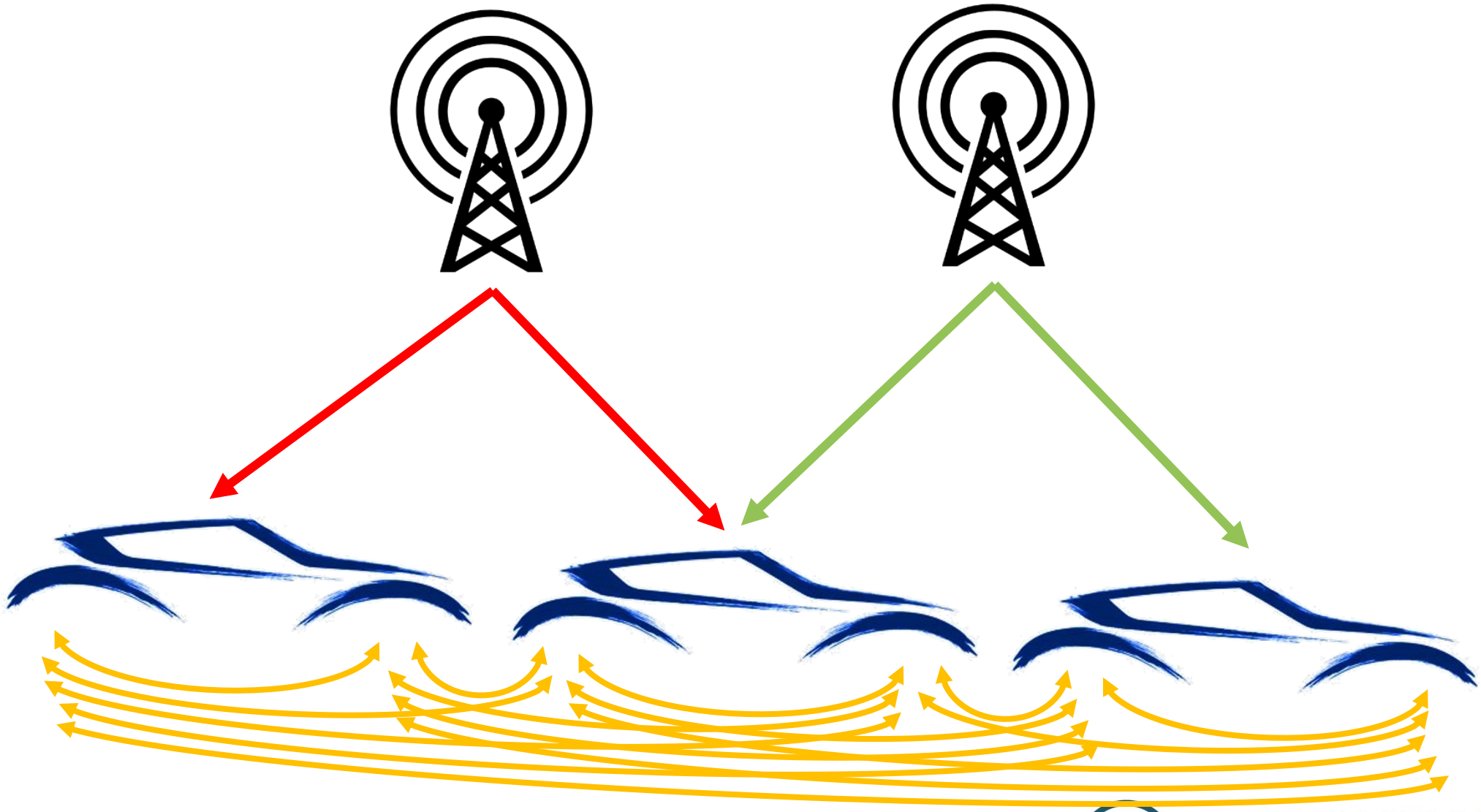


Car Communication Networks



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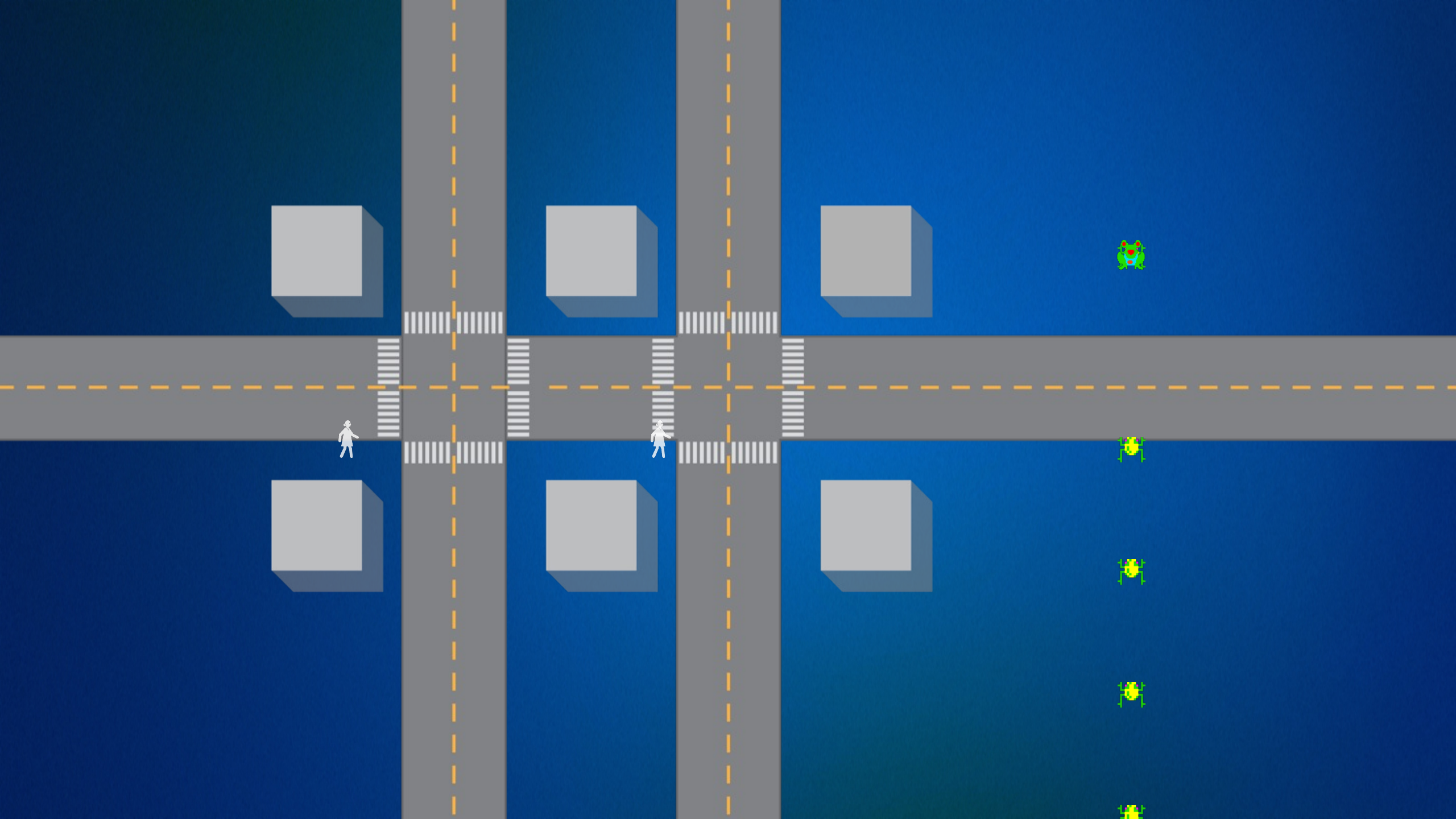


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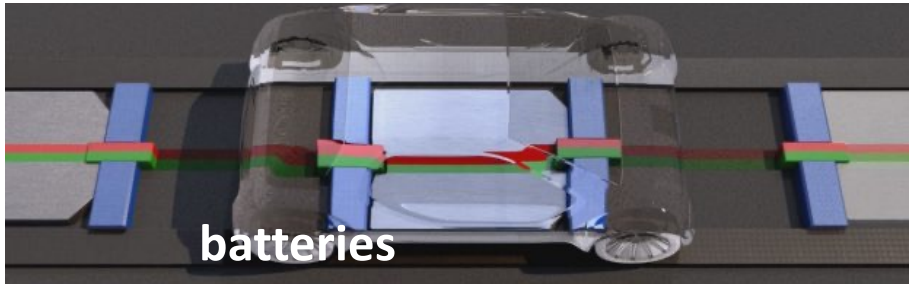
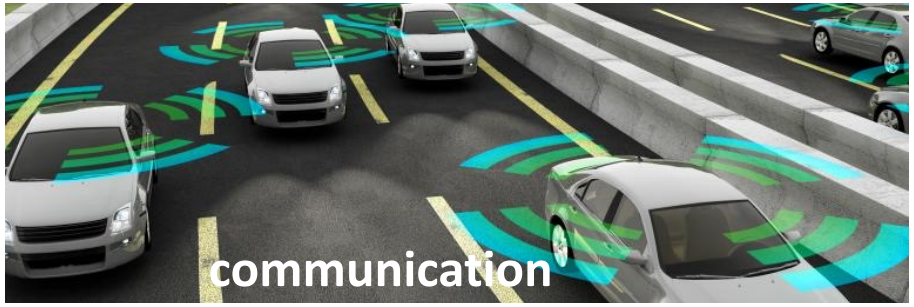
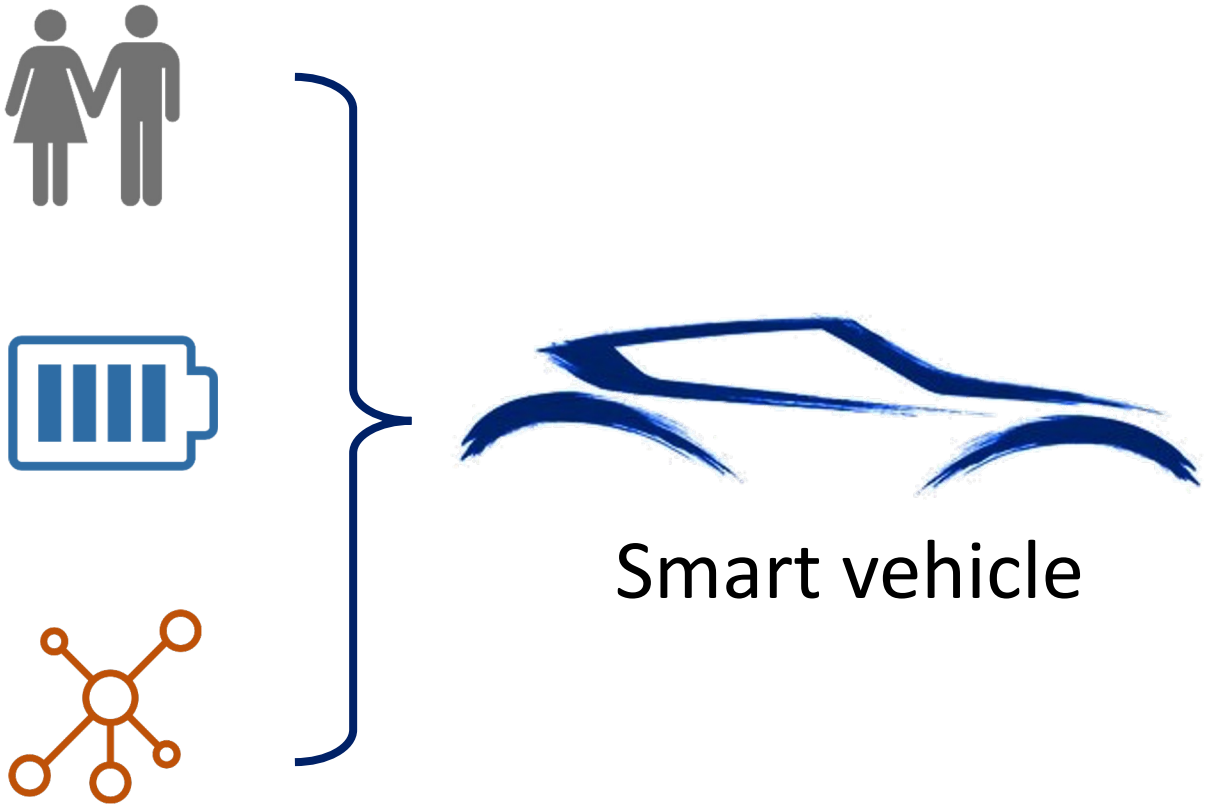
BARCELONA 22-25 FEB 2016

Digital Transfer







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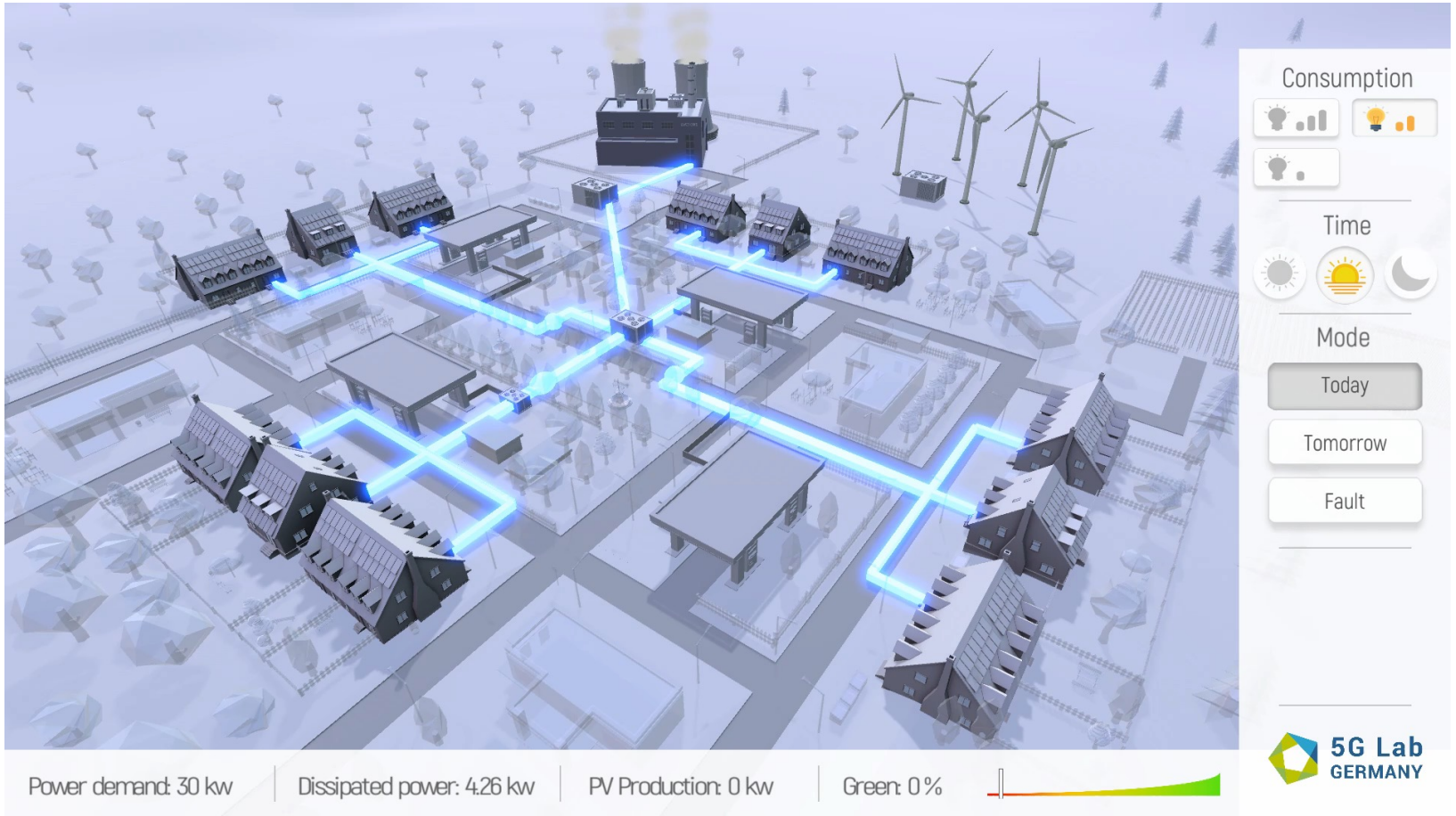
Consumption
Time
Mode
Today
Tomorrow
Fault
5G Lab
GERMANY
Power demand: 30 kw
Dissipated power: 4.26 kw
PV Production: 0 kw
Green: 0 %

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5G Technical Requirements

5G atom definition

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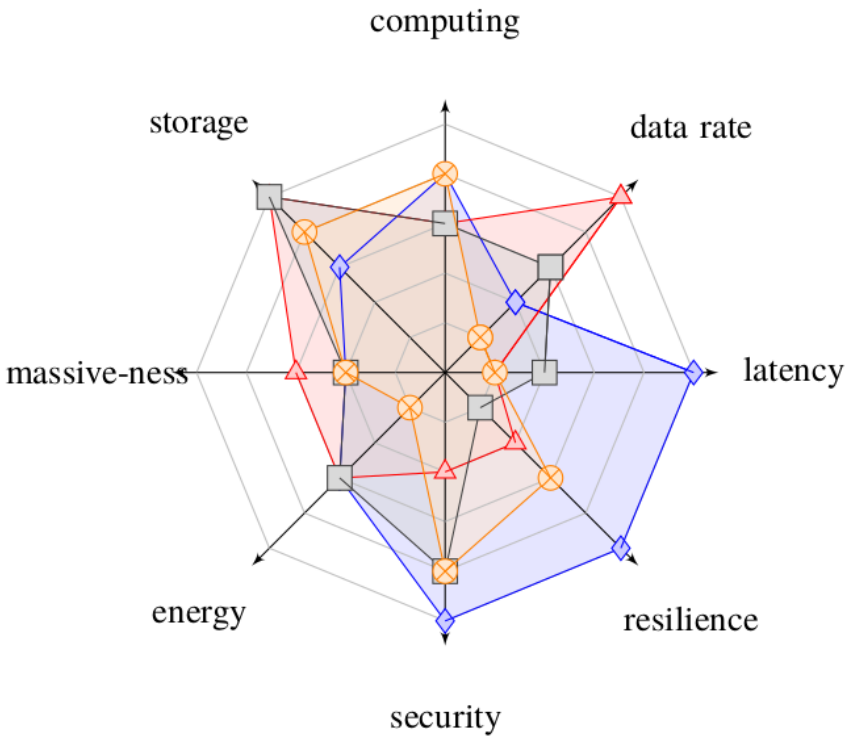
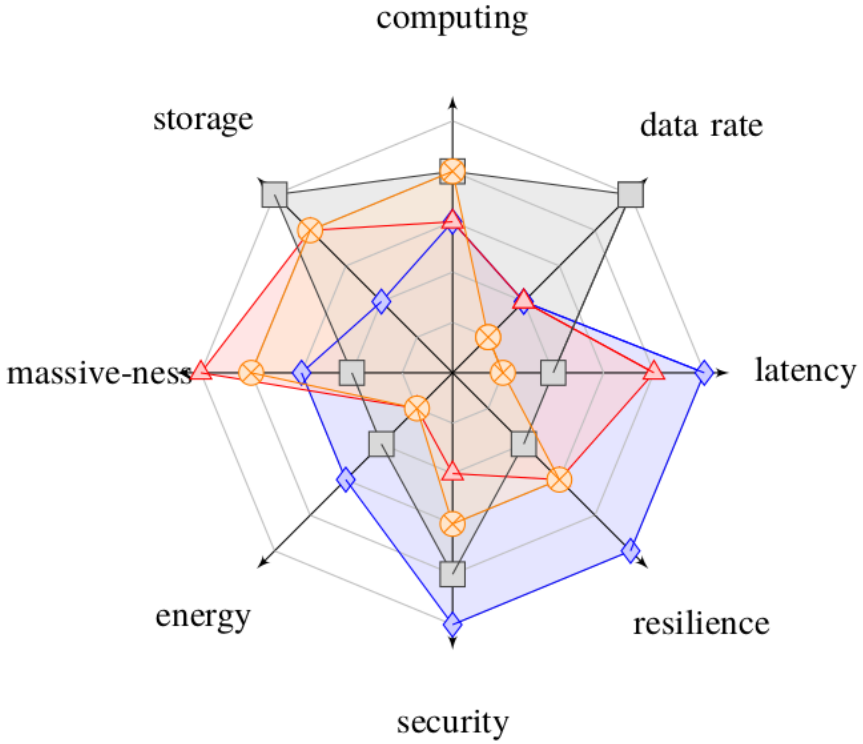
5G atom technical parameters and use cases

Connected Cars



◇ car control △ in-car entertainment
□ car navigation ⊗ predictive maintenance

Industry 4.0



◇ machine control △ massive sensors
□ camera data ⊗ predictive maintenance

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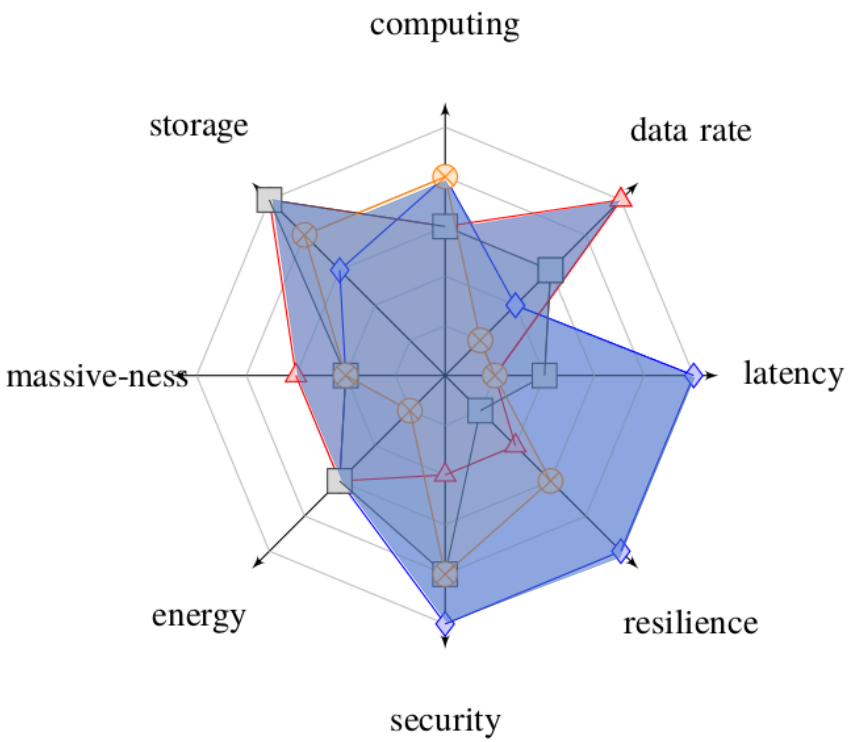
5G atom technical parameters and use cases

Connected Cars



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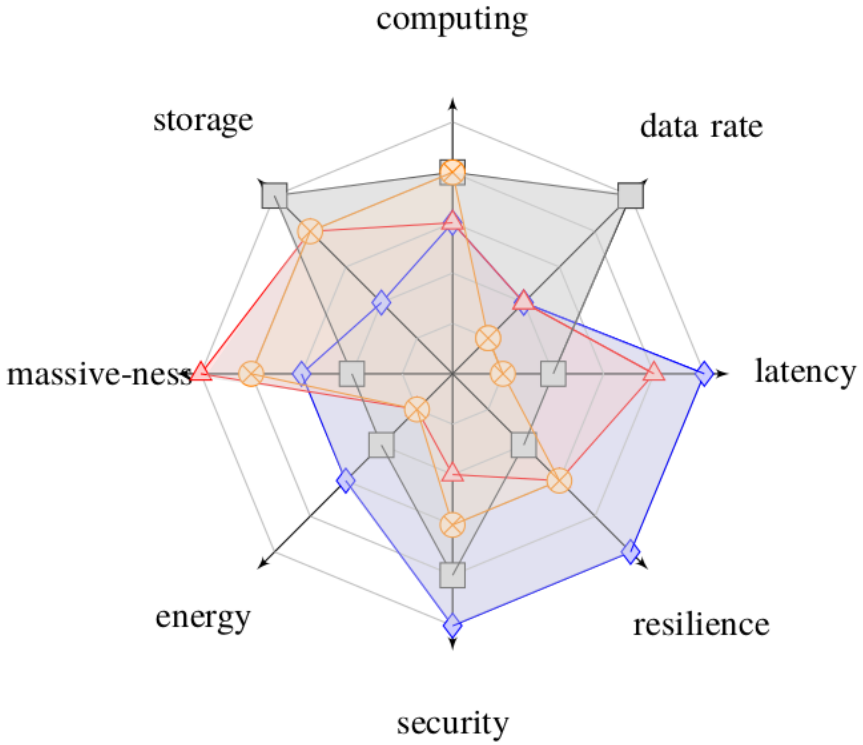

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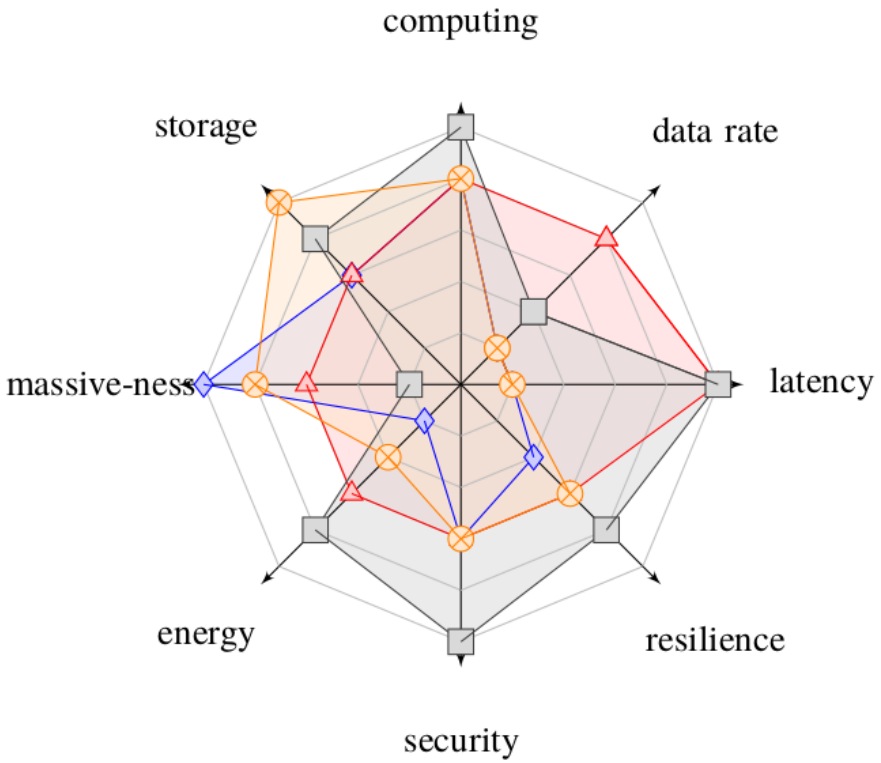
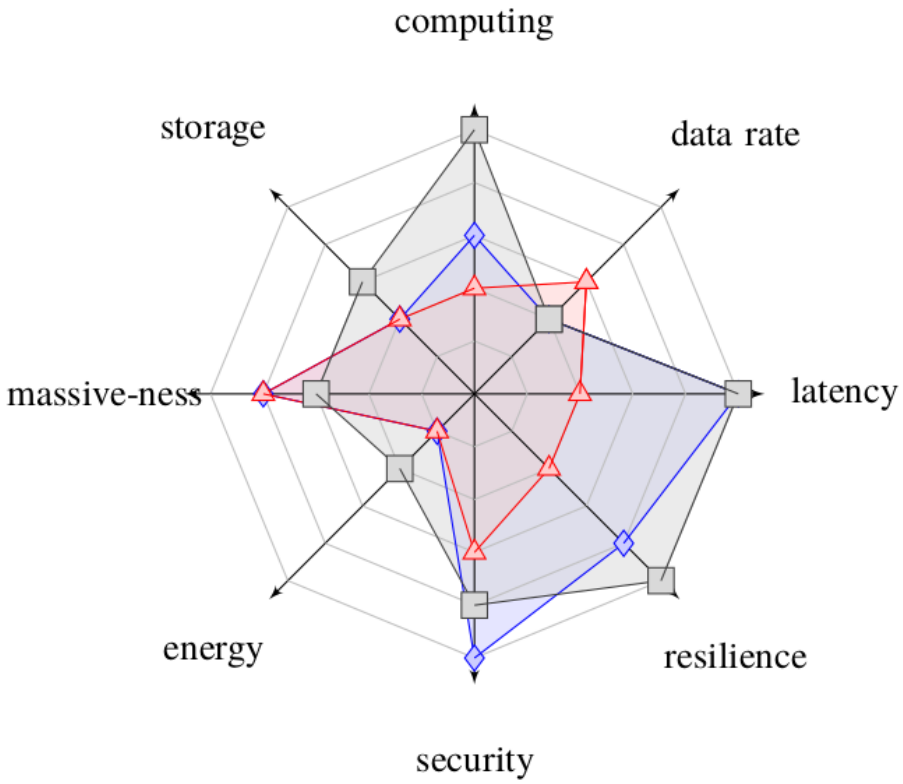
5G atom technical parameters and use cases

Farming



◇ ground sensing △ farm imaging
□ agricultural machine automation ⊗ predictive maintenance

Smart Grids



◇ self organizing virtual power △ smart home □ fault detection

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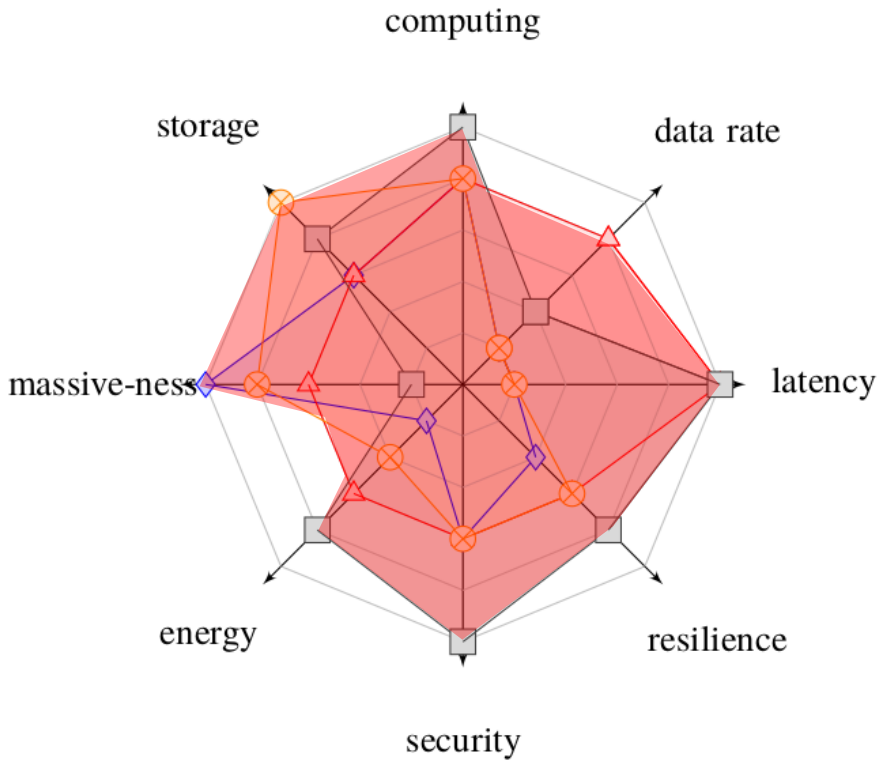
5G atom technical parameters and use cases

Farming



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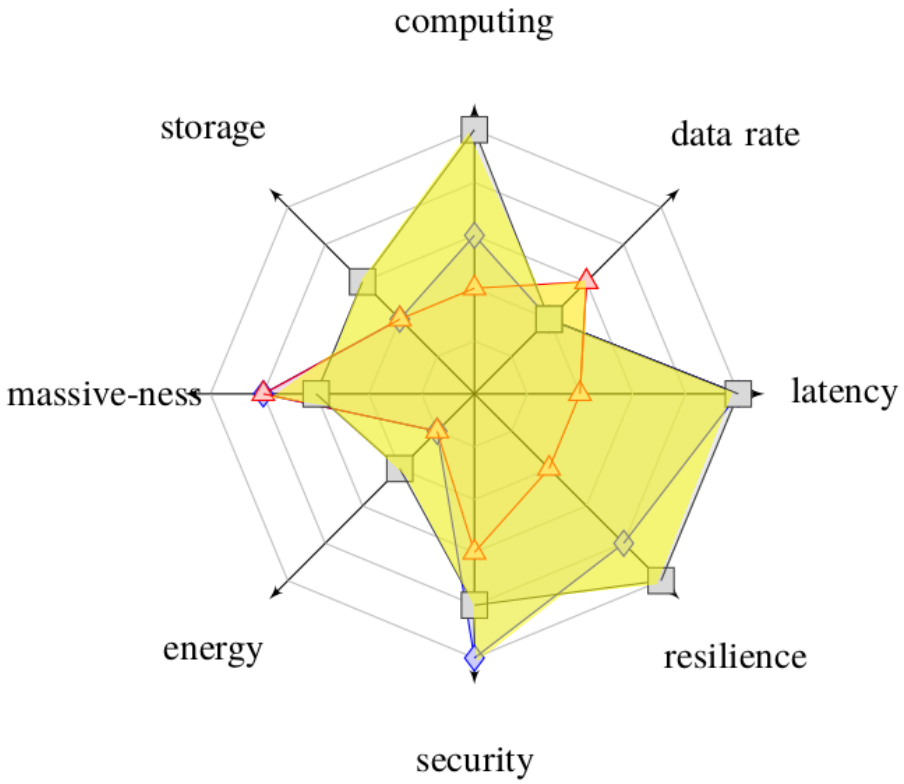

◇ self organizing virtual power △ smart home □ fault detection

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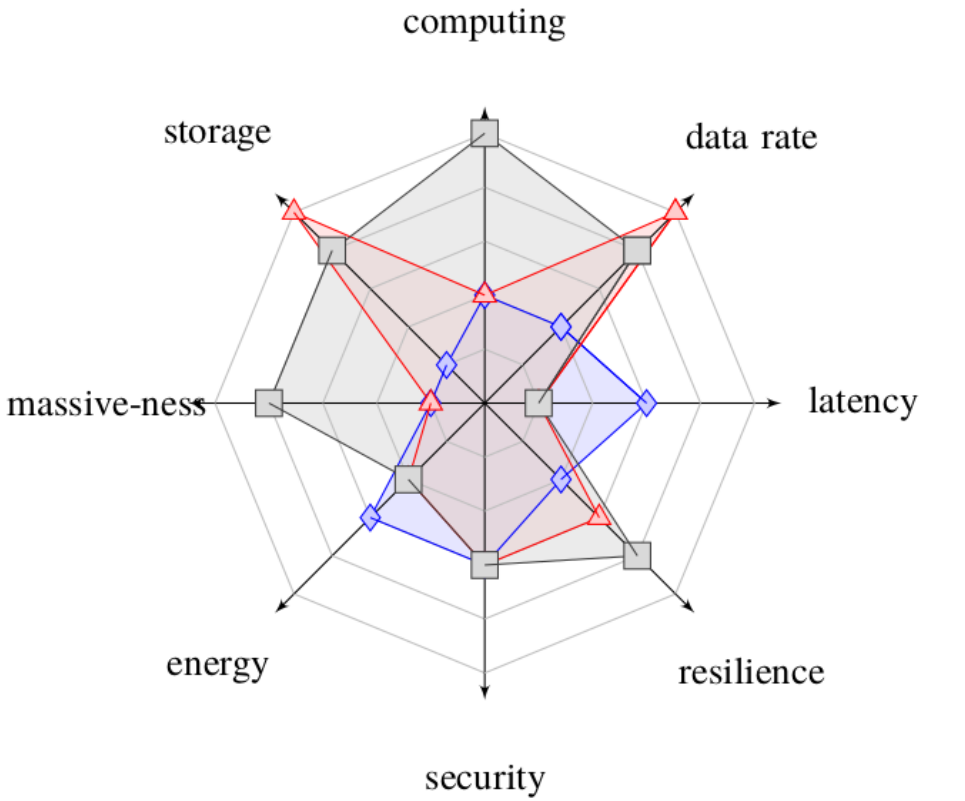
5G atom technical parameters and use cases

Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

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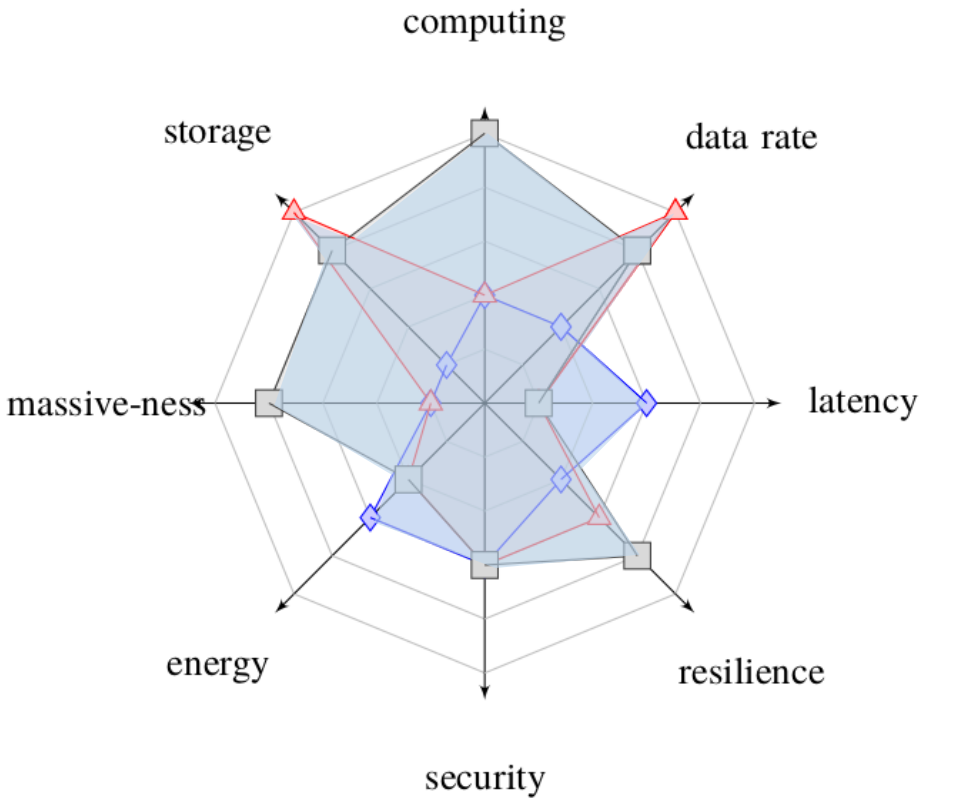
5G atom technical parameters and use cases

Tactile Internet



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5G atom technical parameters and use cases

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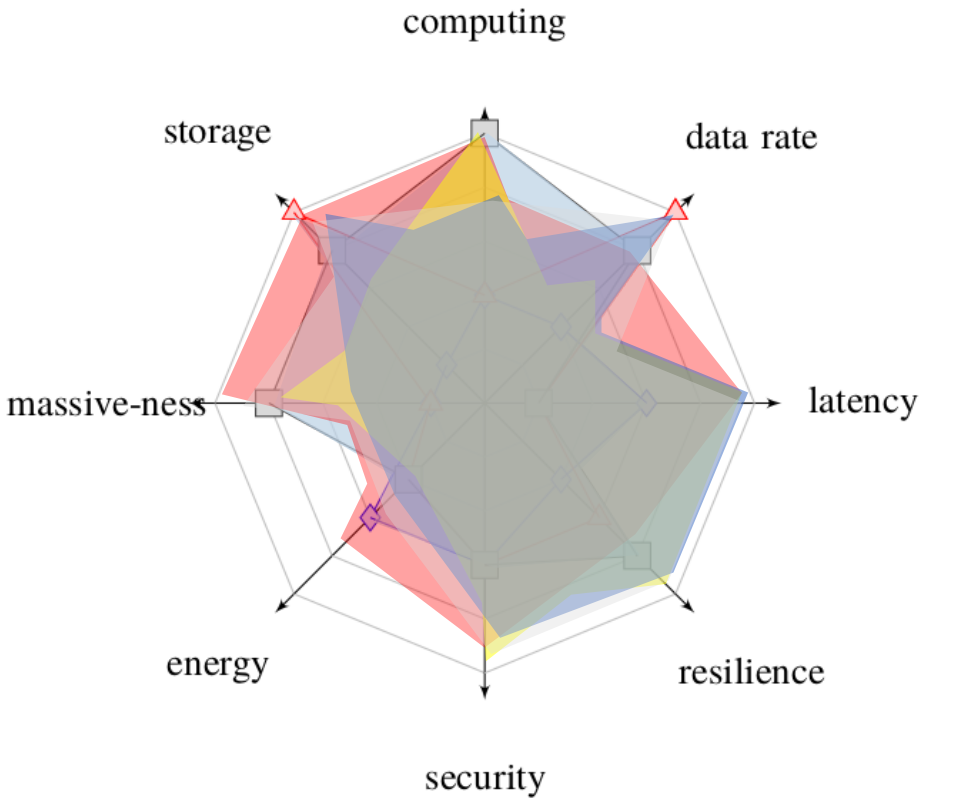

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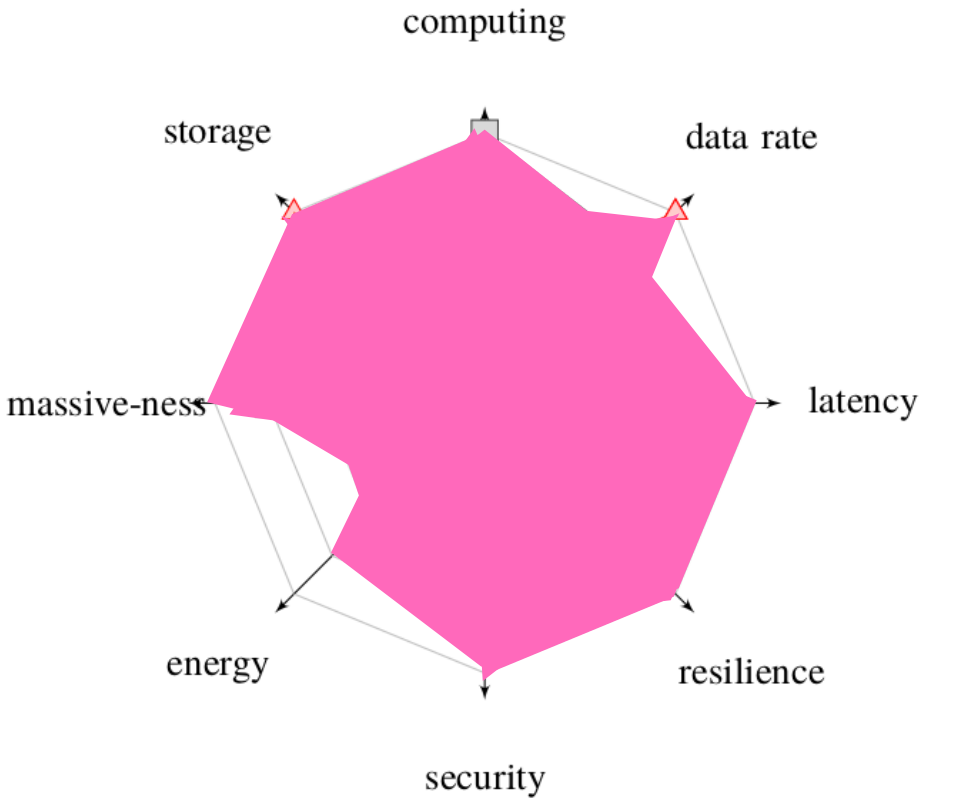
5G atom technical parameters and use cases

Tactile Internet



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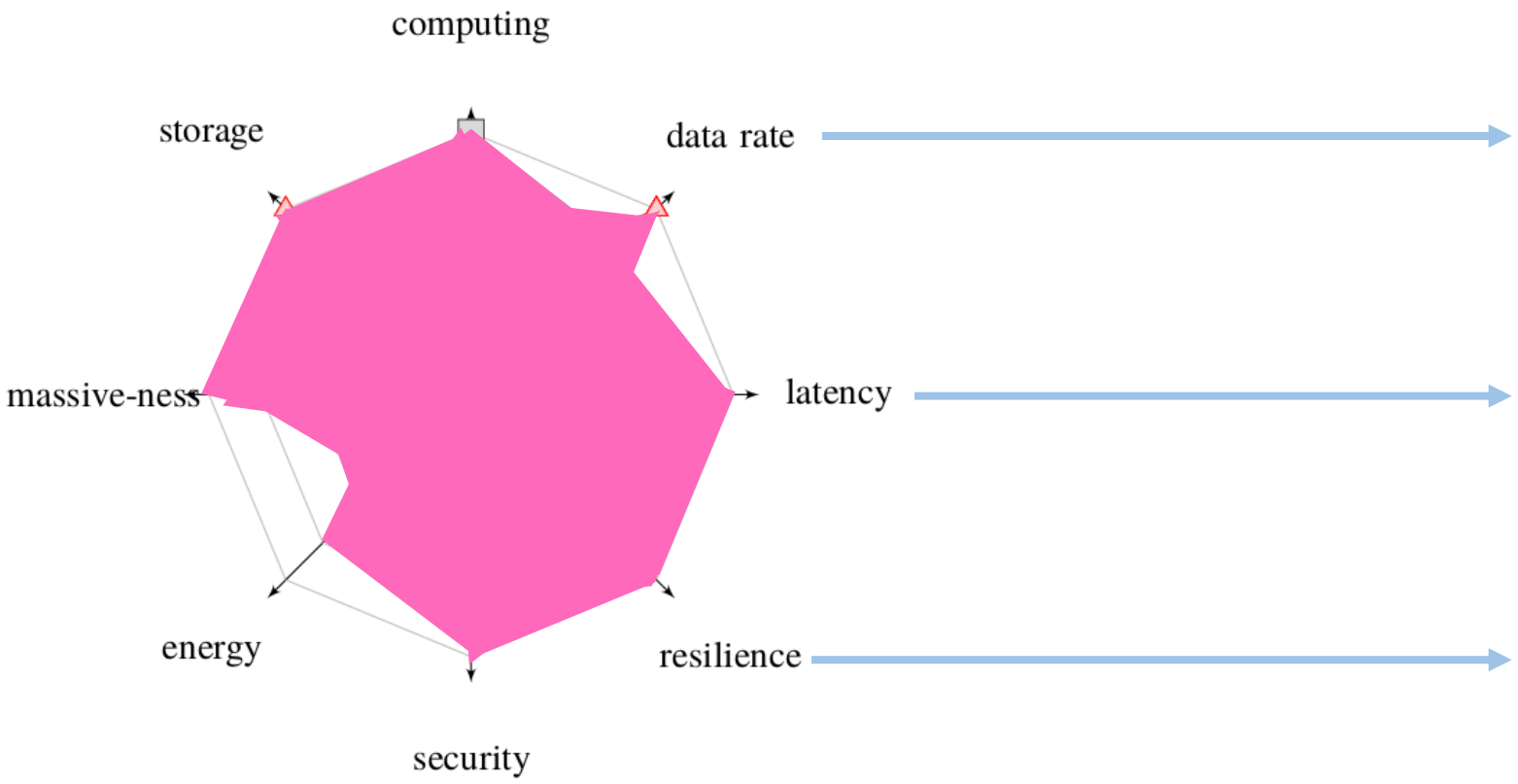
5G atom technical parameters and use cases

Tactile Internet



These three alone, how should this be realised?

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5G atom definition

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The gamers were the first …

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CeTI latency challenge (TU Munich – Prof. Steinbach)

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CeTI latency challenge

Impact of latency on task performance and learning (here: 40 ms LTE network latency one way)

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Human Machine Interaction

- Latency matters!

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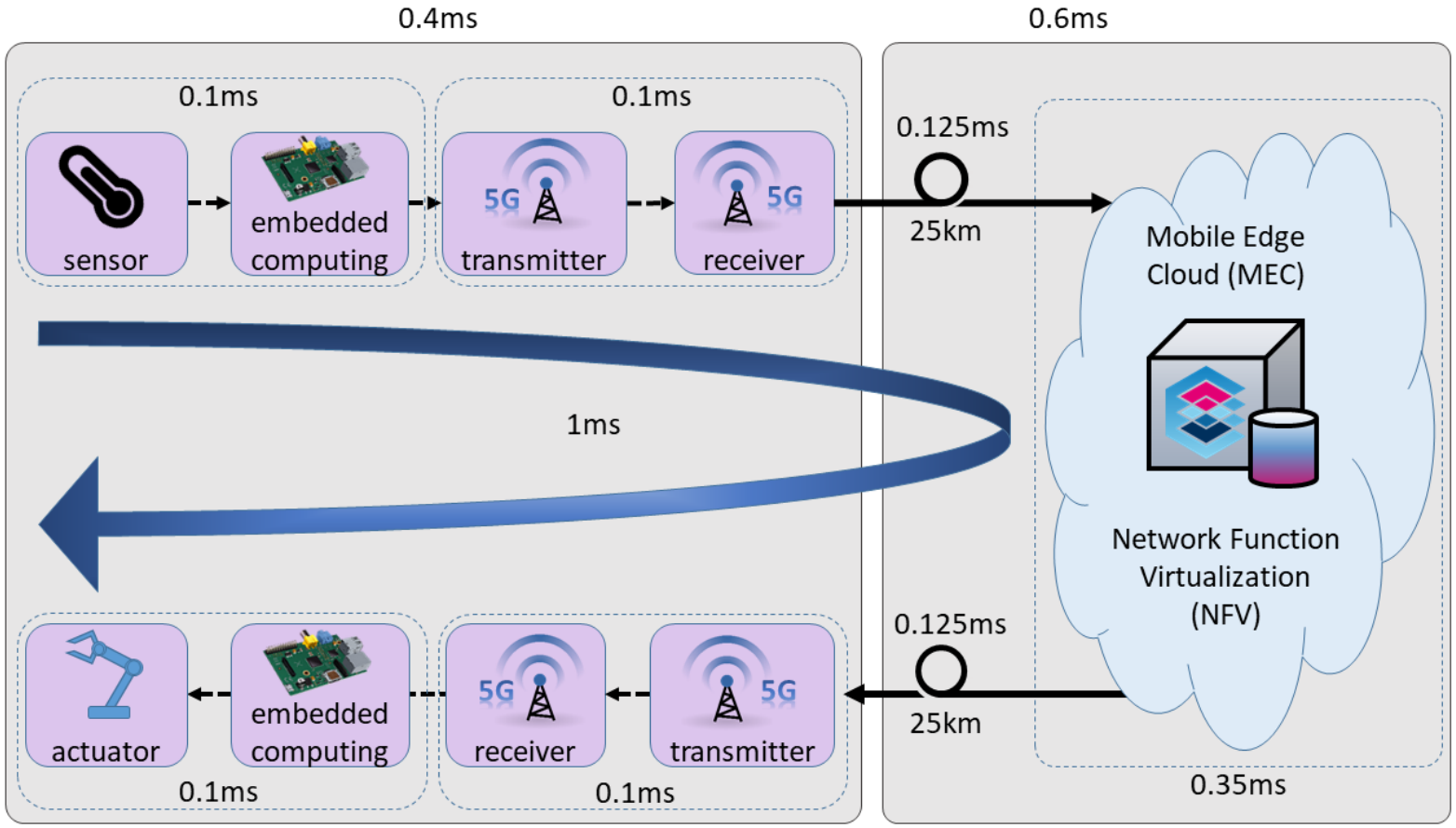
5G atom definition



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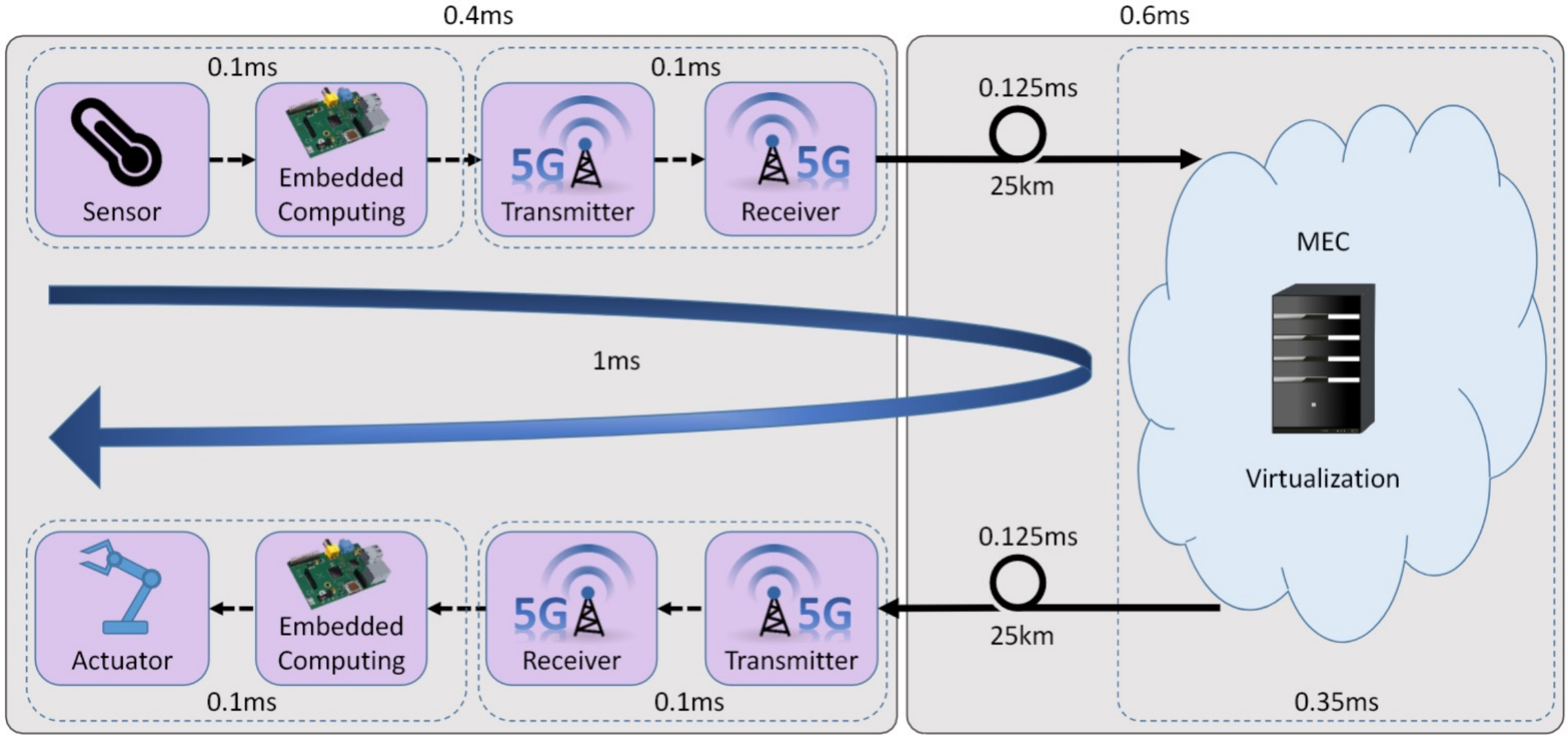
5G atom definition



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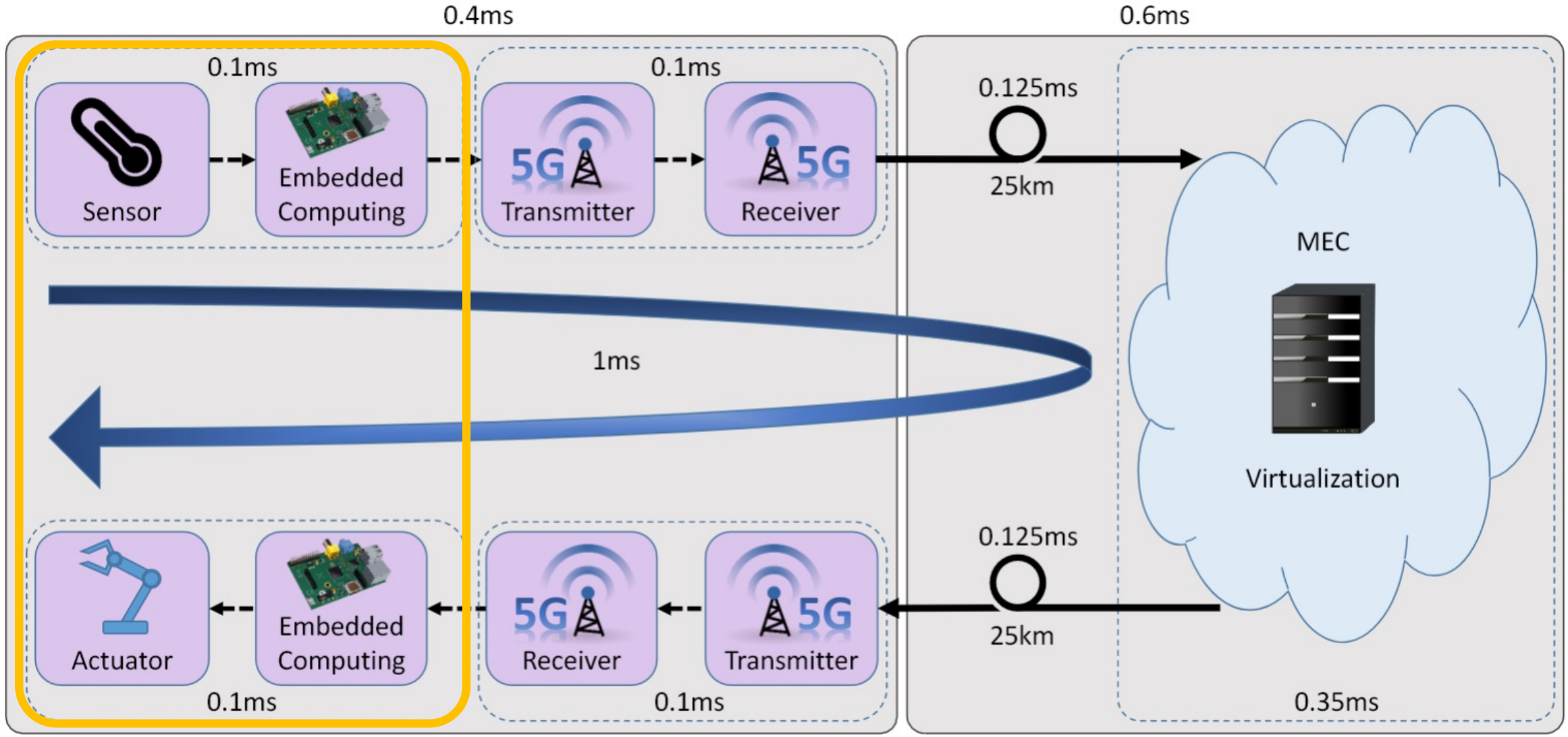

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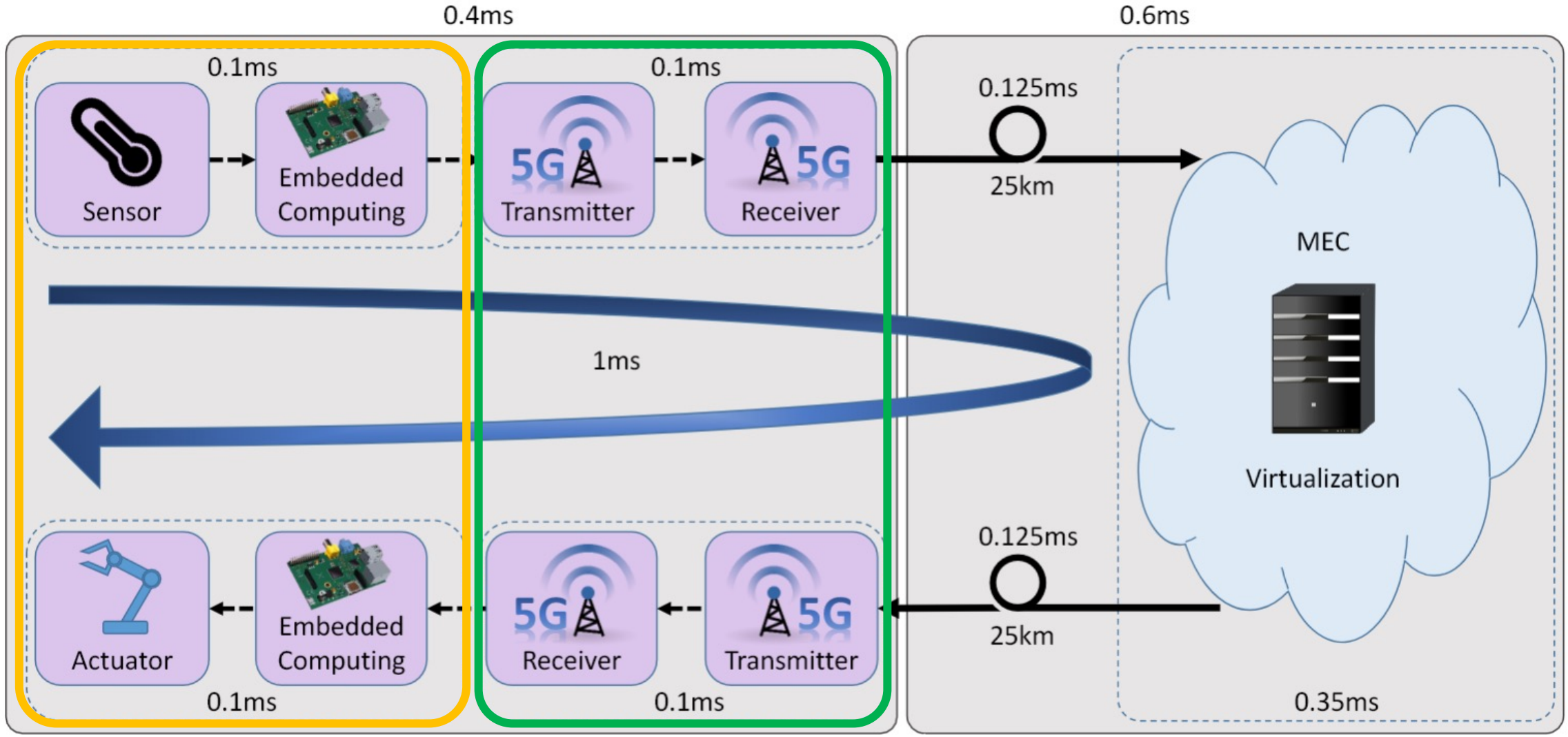

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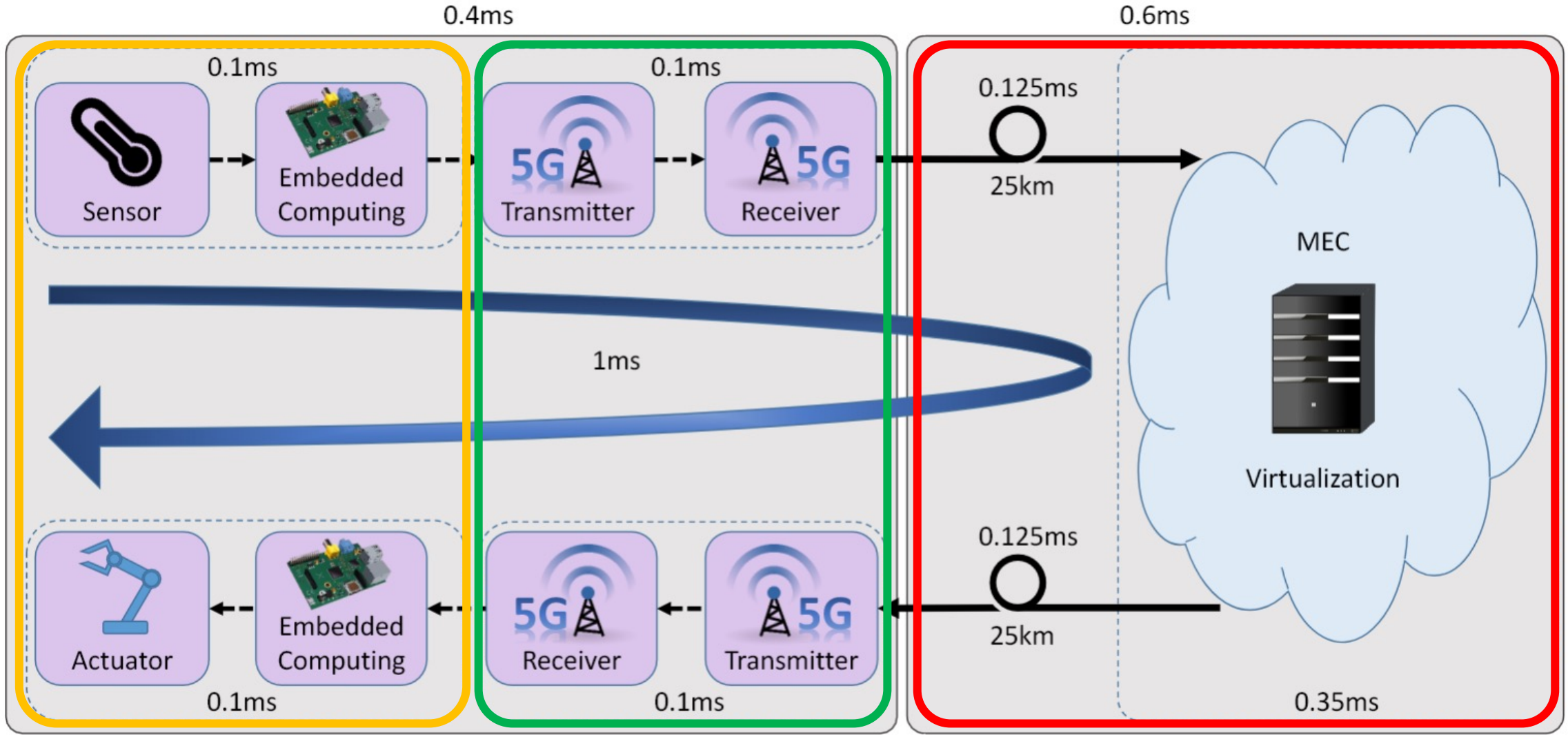
5G atom definition



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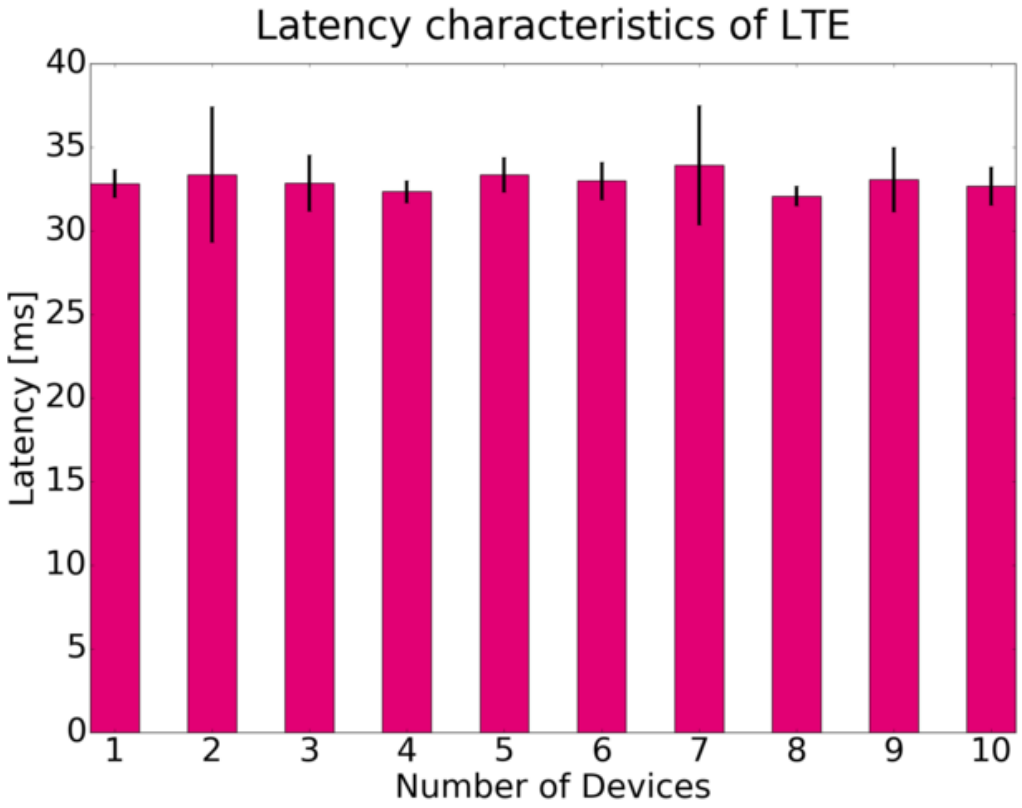
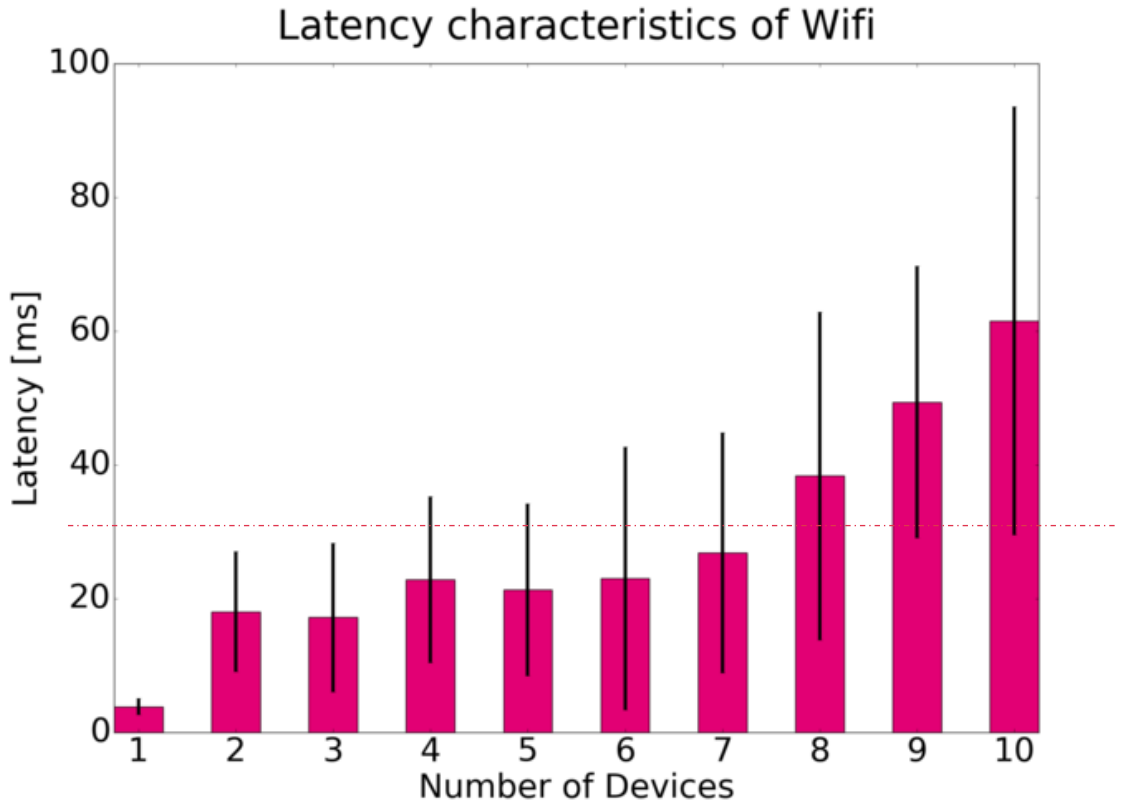
SoA Latency Values





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Latency definition: General view

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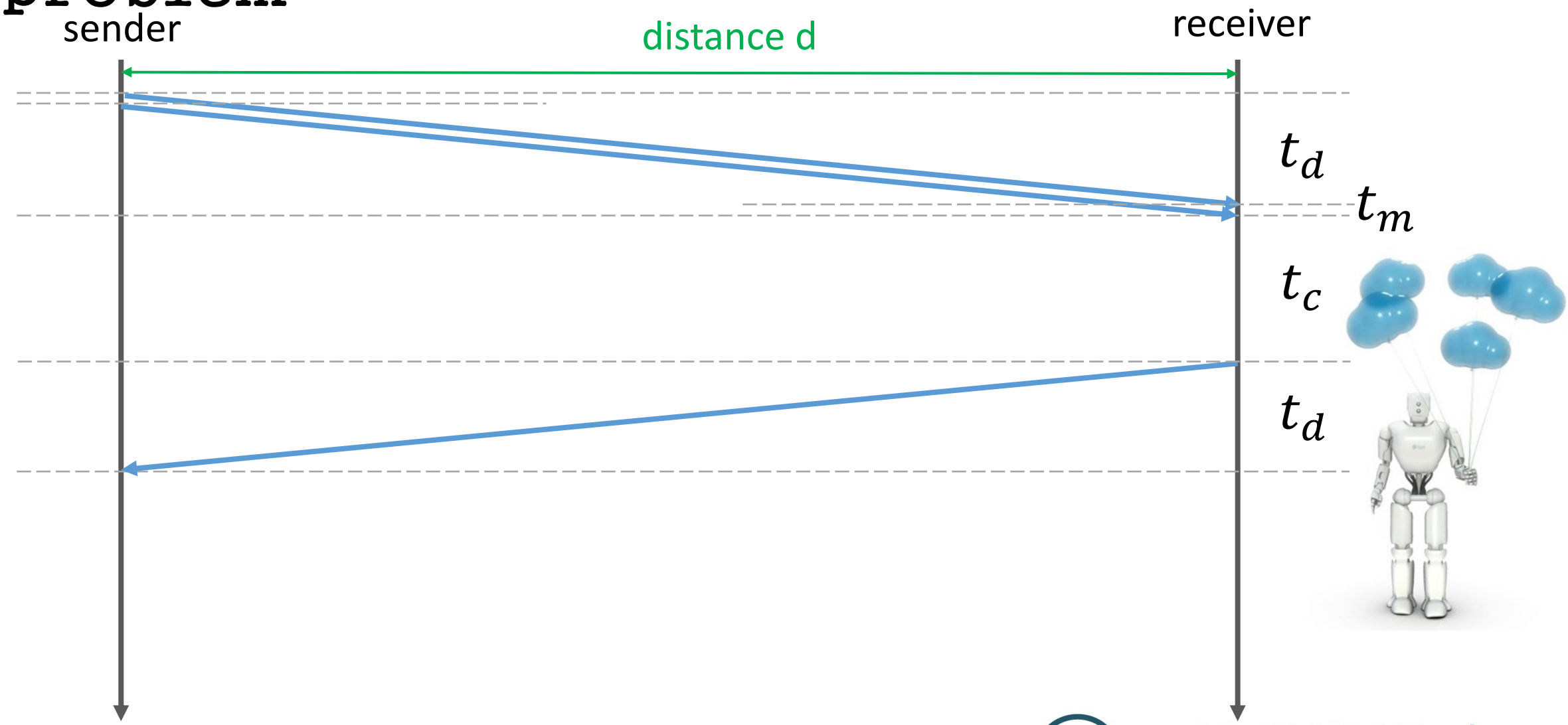
Latency definition: Data rate is not the problem



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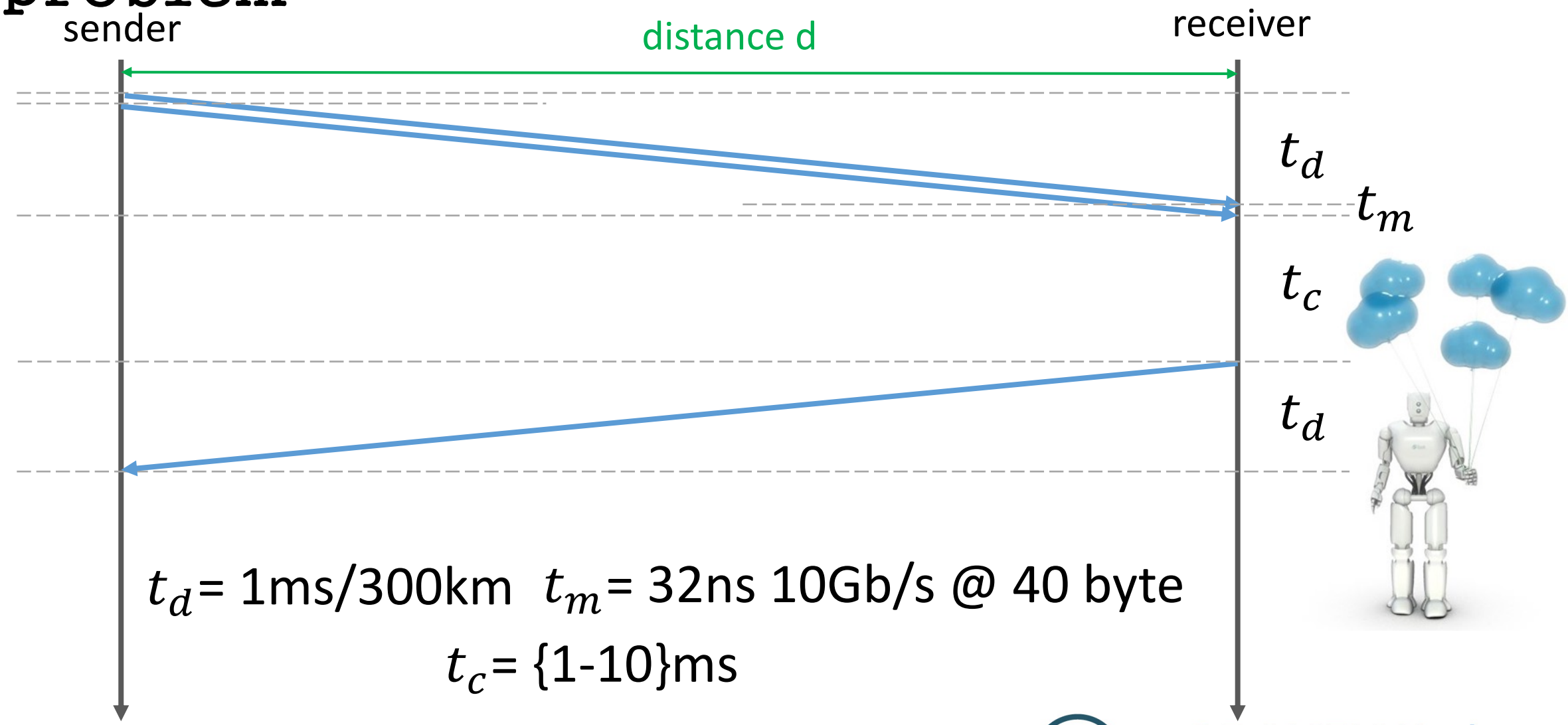
Latency definition: Data rate is not the problem



t_d= 1ms/300km t_m= 32ns 10Gb/s @ 40 byte

t_c= {1-10}ms

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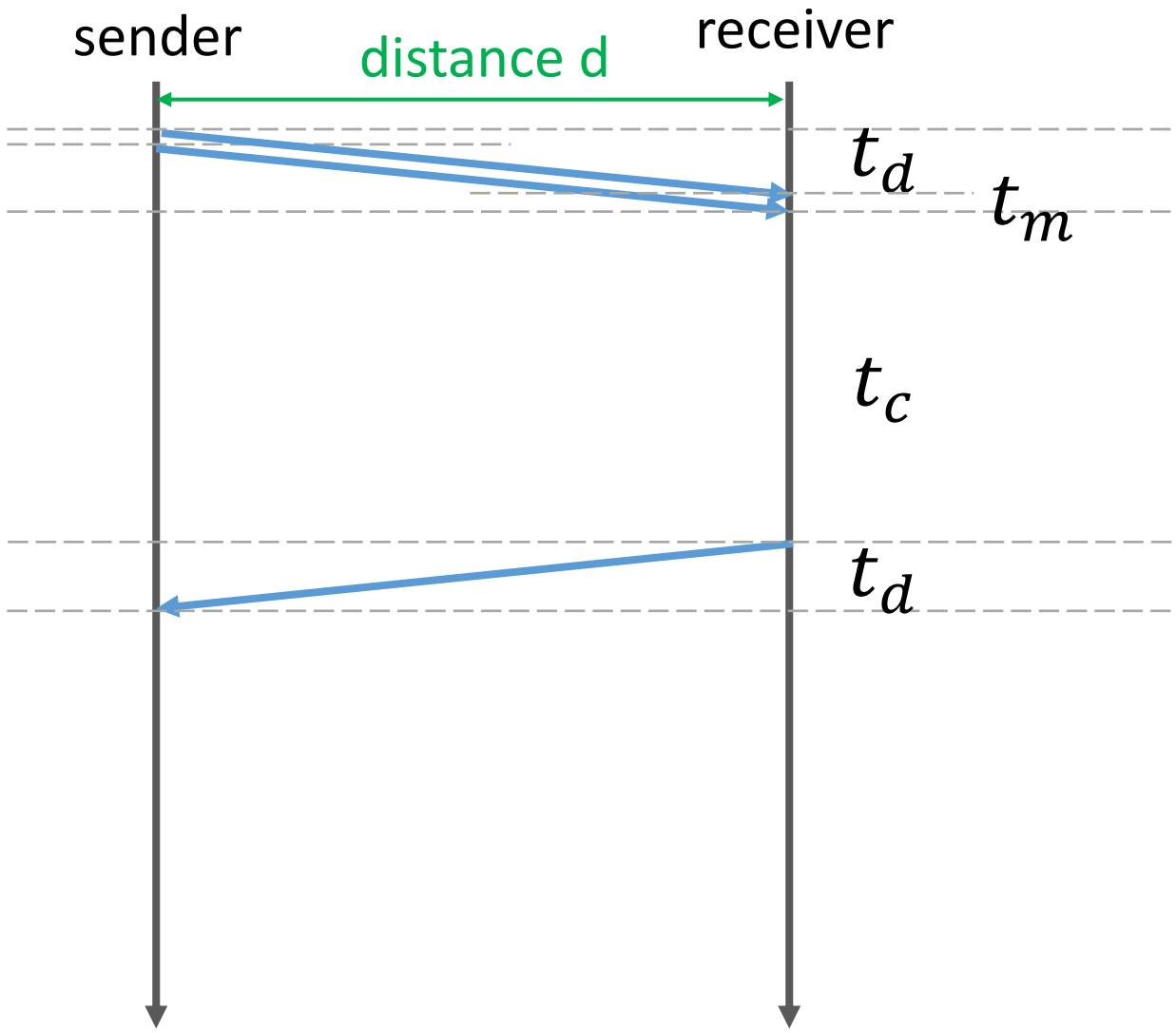
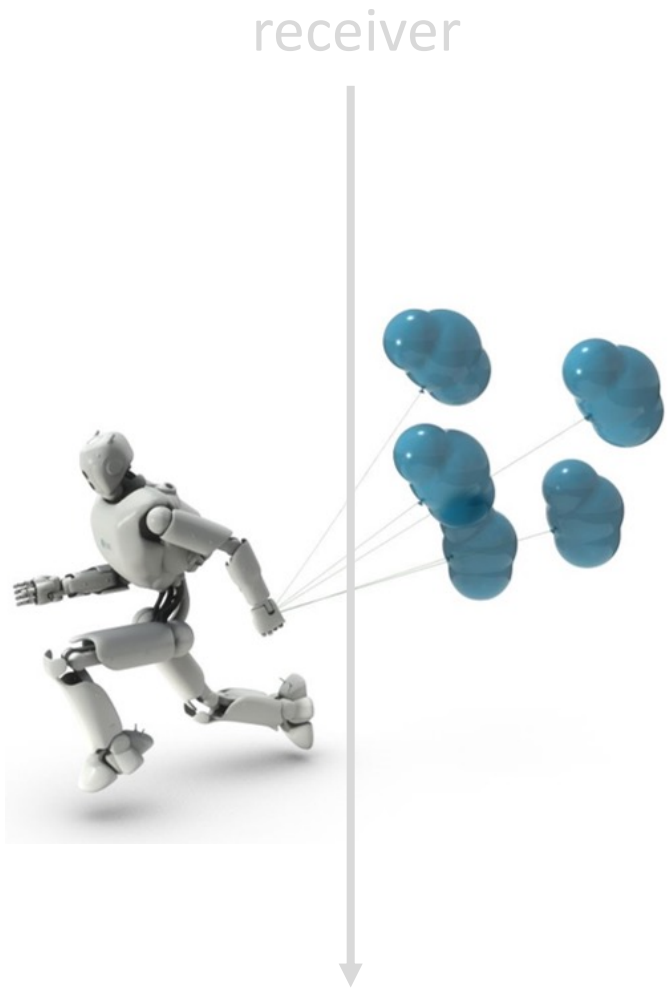
Latency definition: Advantage of the mobile edge





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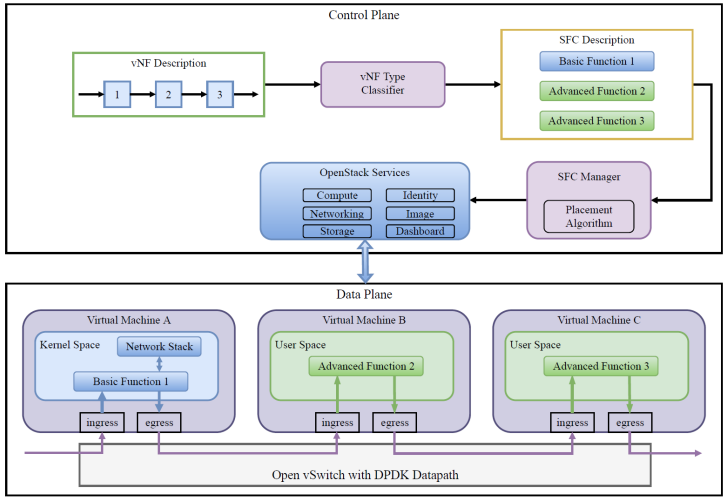
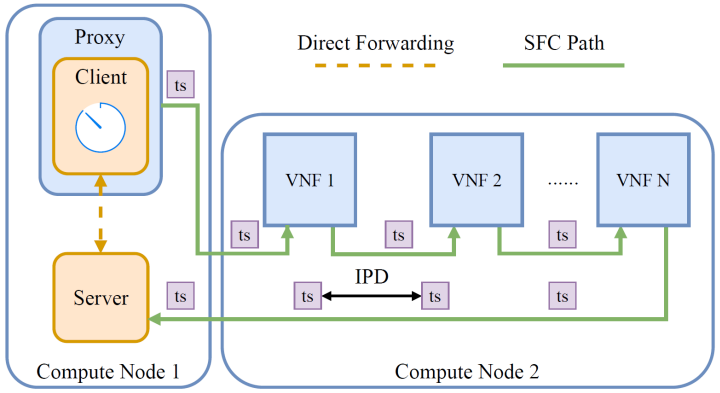
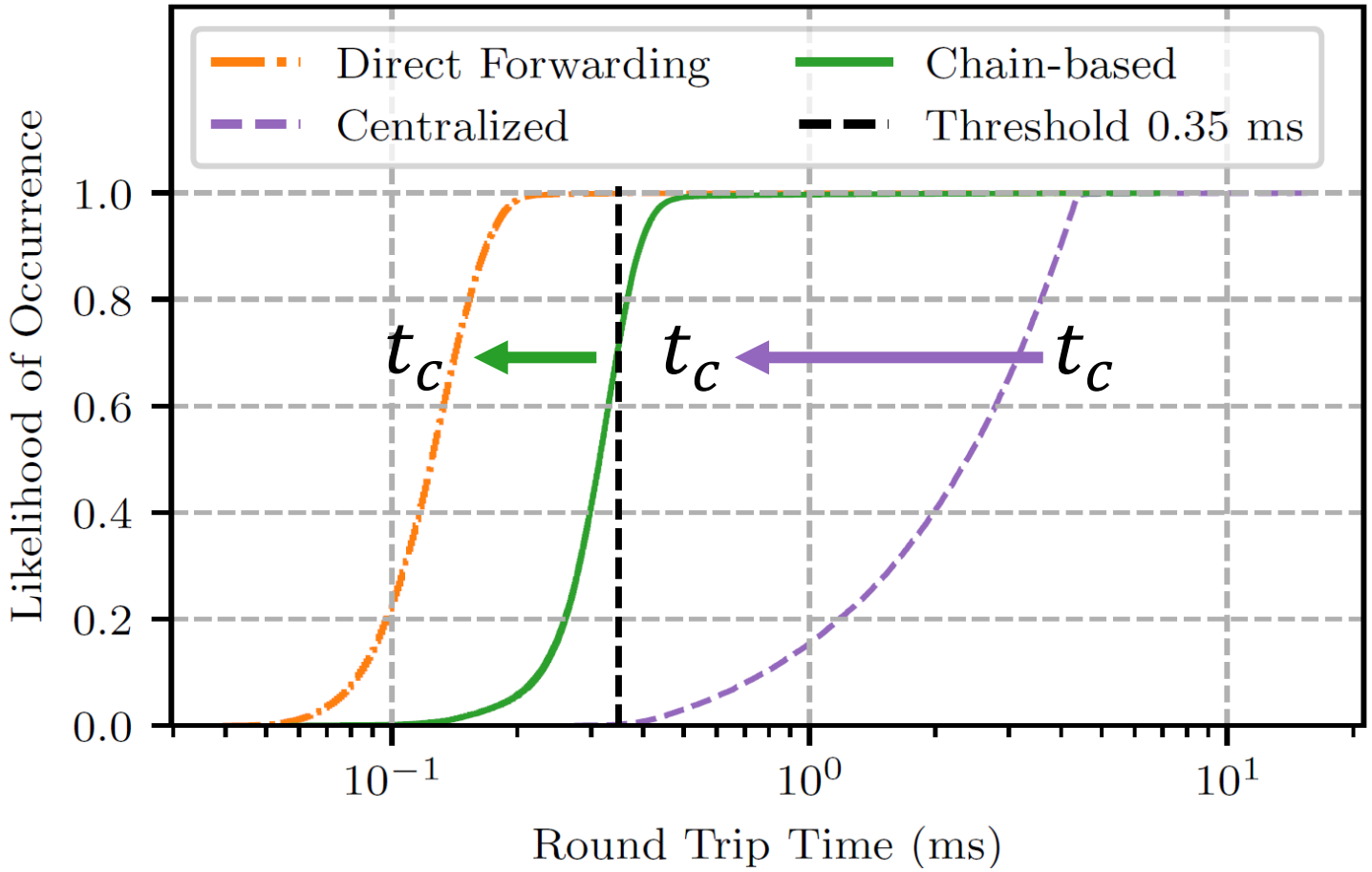
Latency definition: Softwarization will add to the latency







Zuo Xiang; Frank Gabriel; Elena Urbano; Giang T. Nguyen; Martin Reisslein; Frank H. P. Fitzek, **Reducing Latency in Virtual Machines Enabling Tactile Internet for Human Machine Co-working Journal Article** IEEE Journal on Selected Areas in Communications, 37 (5), pp. 1098-1116, 2019, ISSN: 0733-8716.

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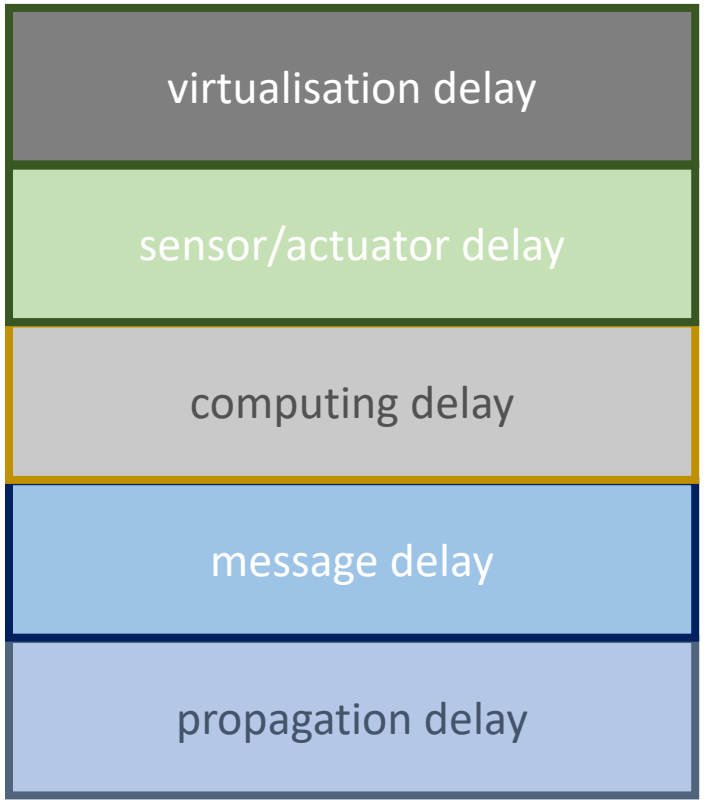
How to reduce the latency?



Patrick Seeling; Frank H. P. Fitzek
Anticipatory Networking: Negative Latency for Ubiquitous Computing
2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC) (CCNC 2021), Las Vegas, USA, 2021.

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How to reduce the latency?

- Prediction of human behavior to create negative latency
- Current approach is sensor based

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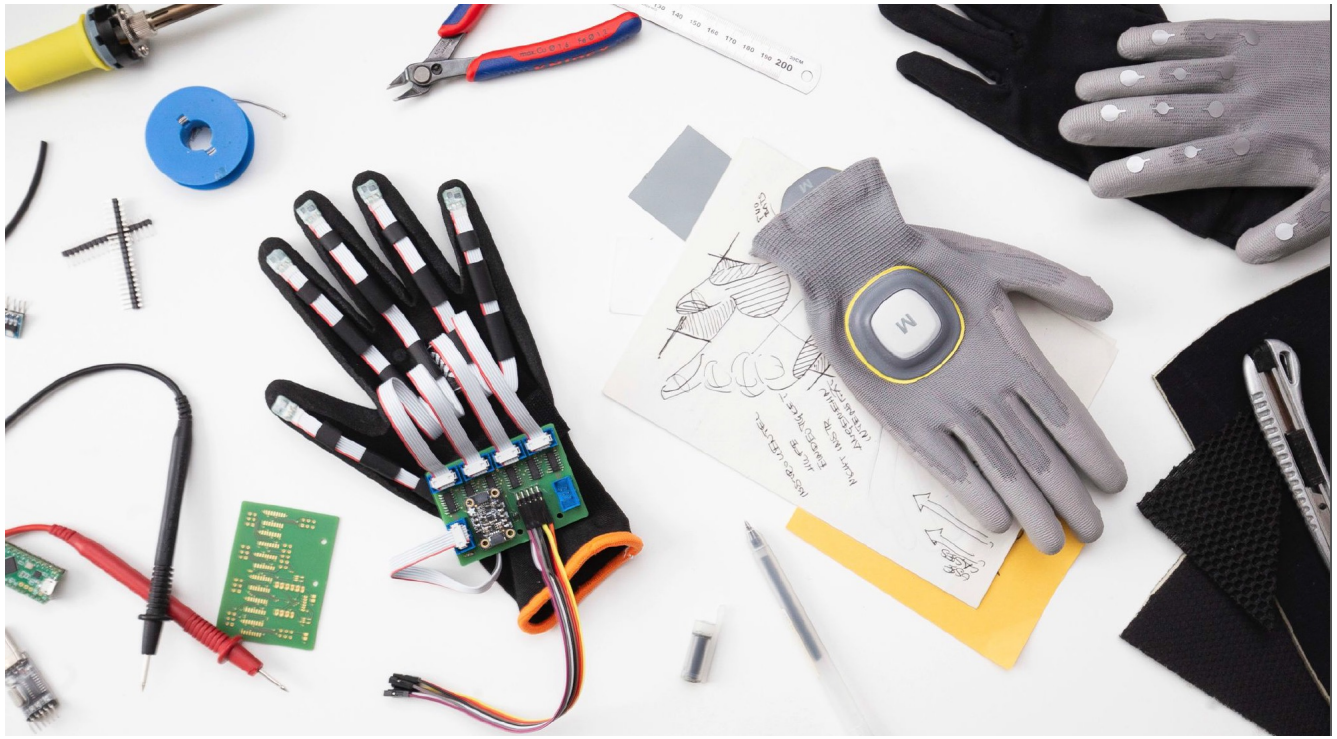
Mimetik



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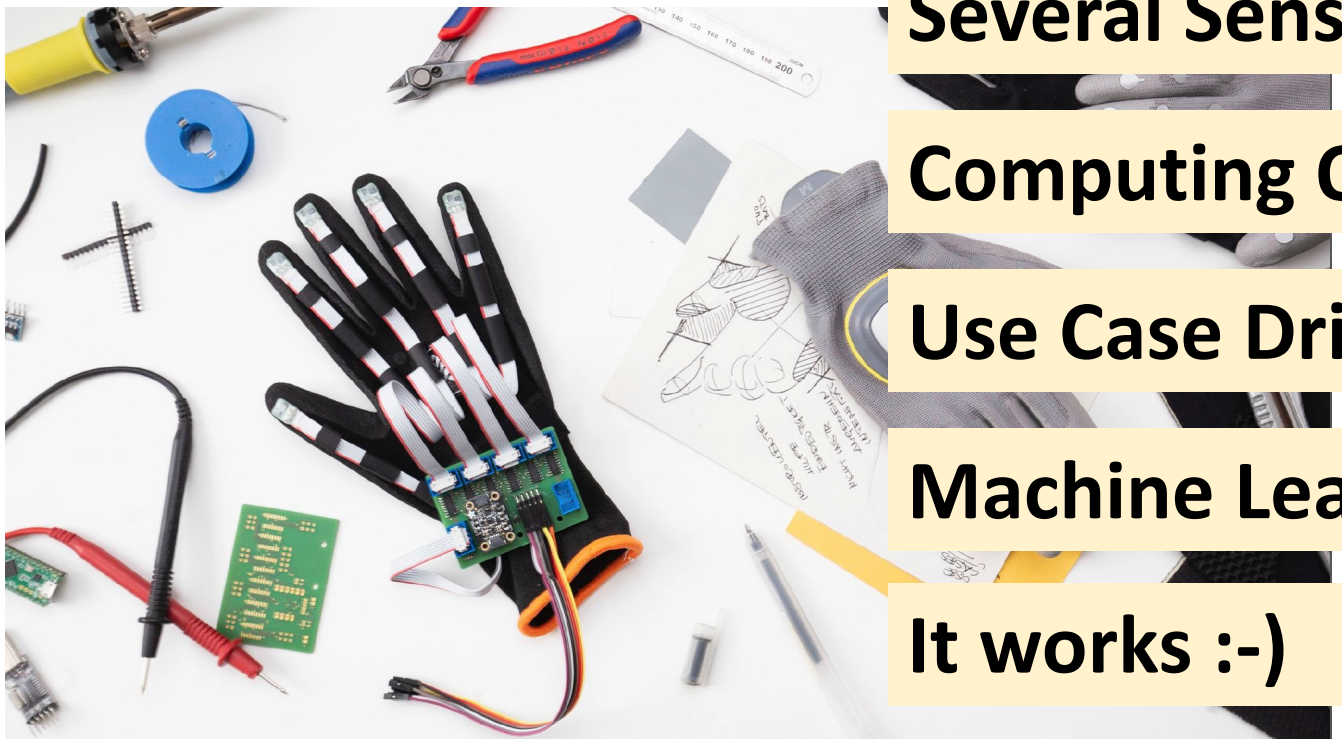

Several Sensors

Computing Onboard

Use Case Driven

Machine Learning

It works :-)

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How to reduce the latency?

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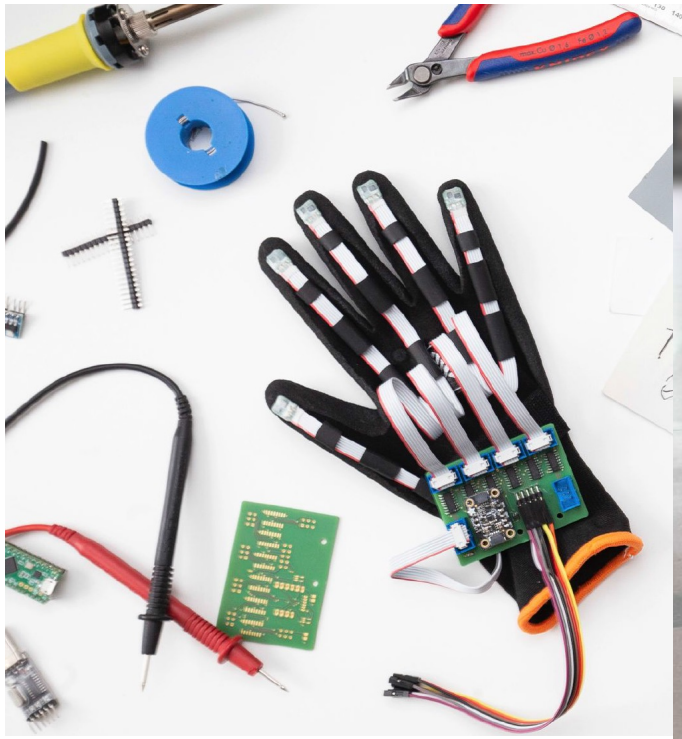
Mimetik



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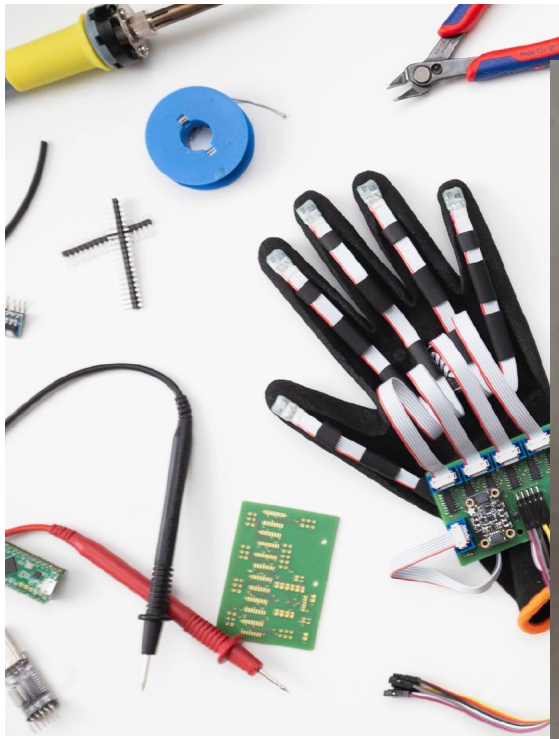

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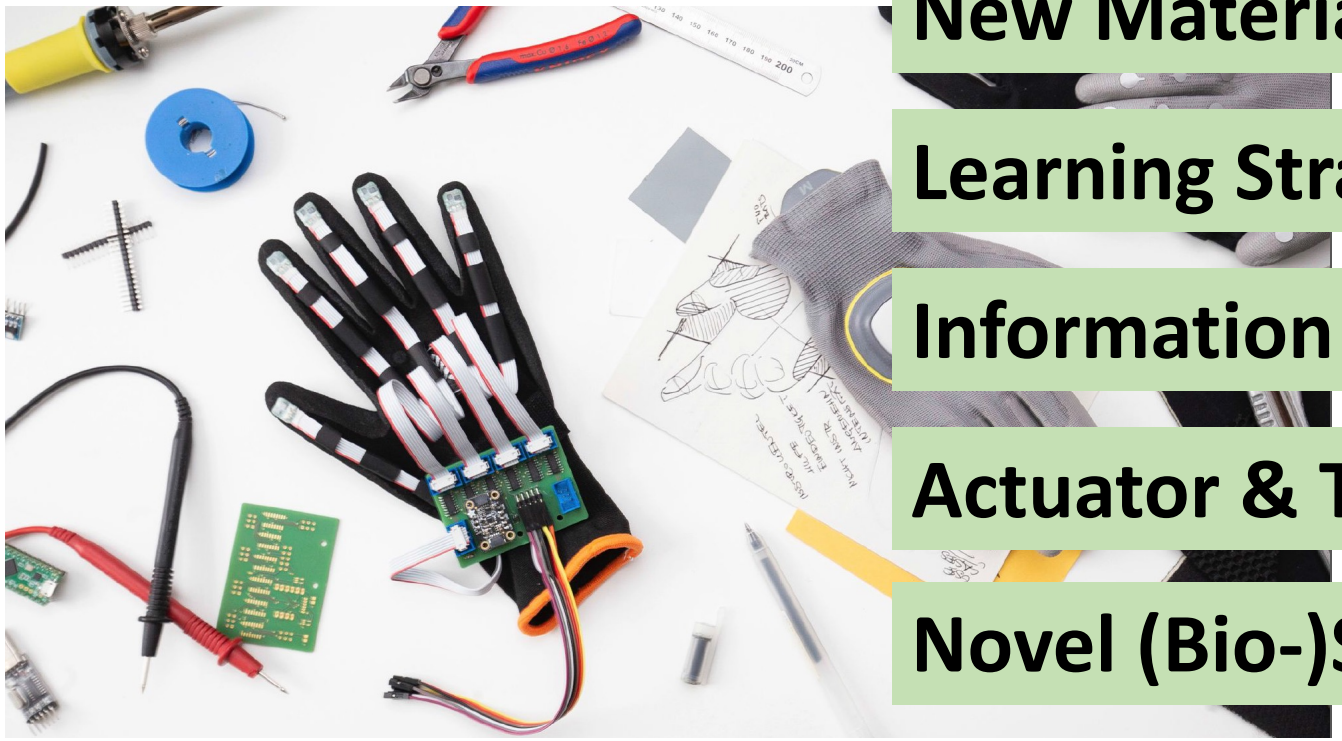

New Materials

Learning Strategies

Information Theory

Actuator & Touch

Novel (Bio-)Sensors

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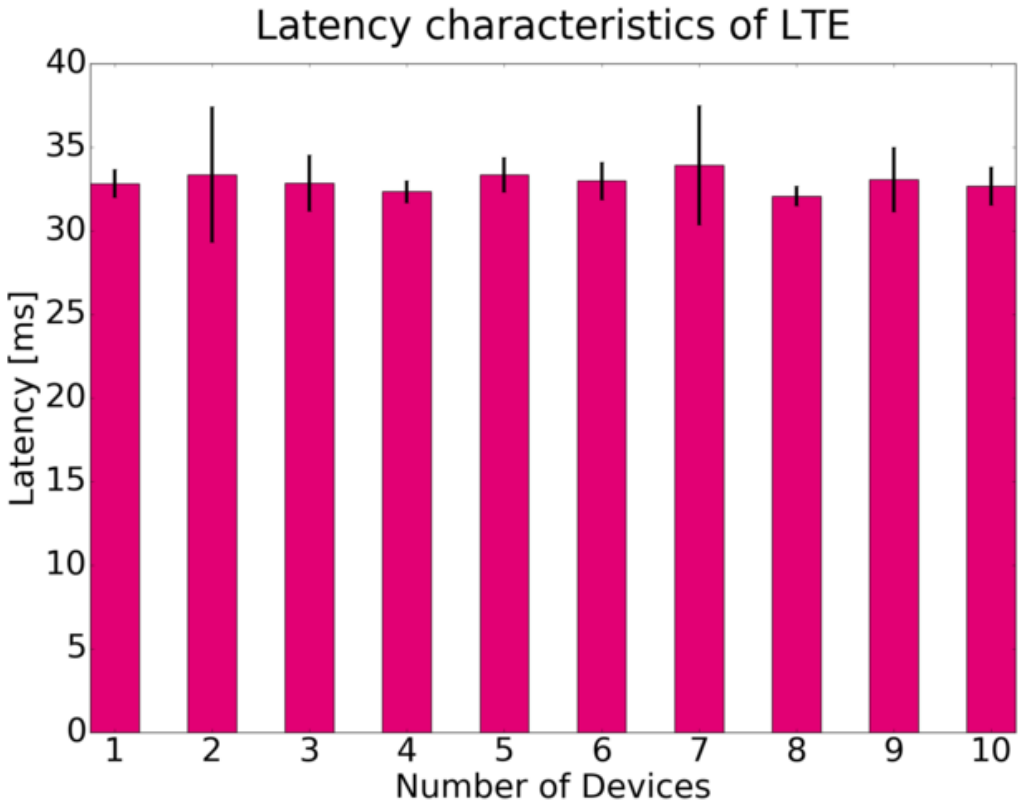
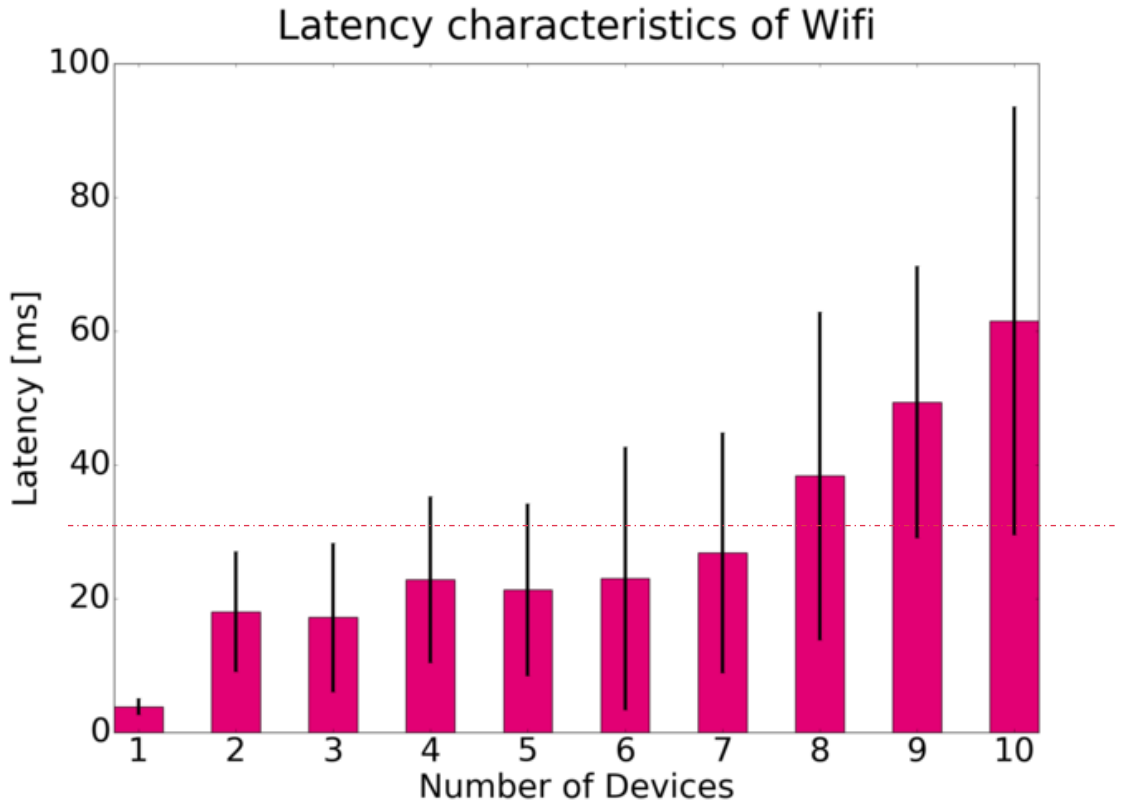
SoA Latency Values





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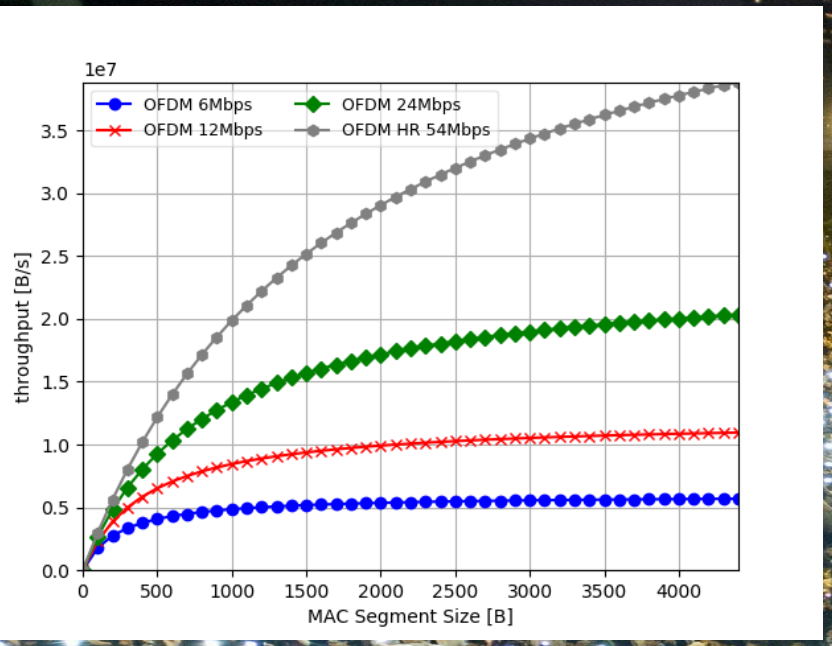
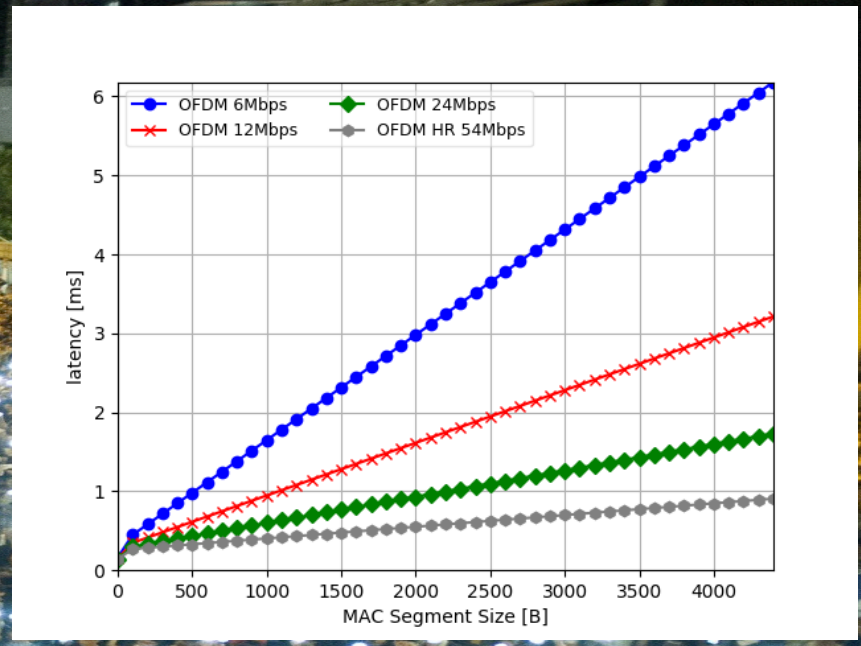
5G atom definition





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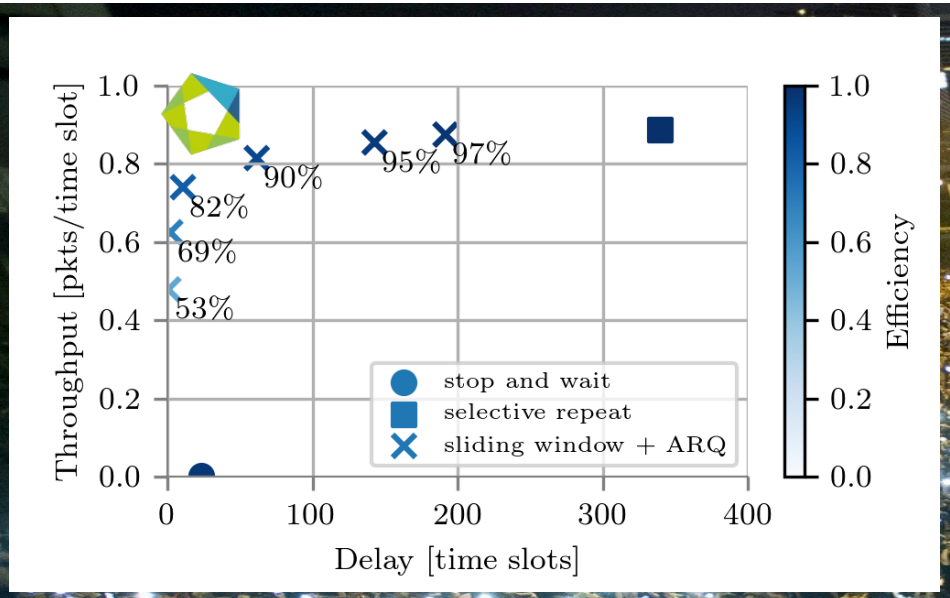

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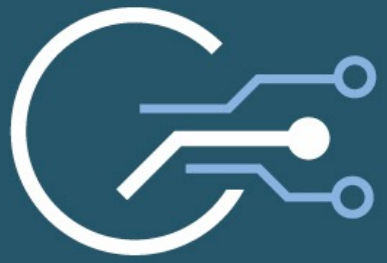

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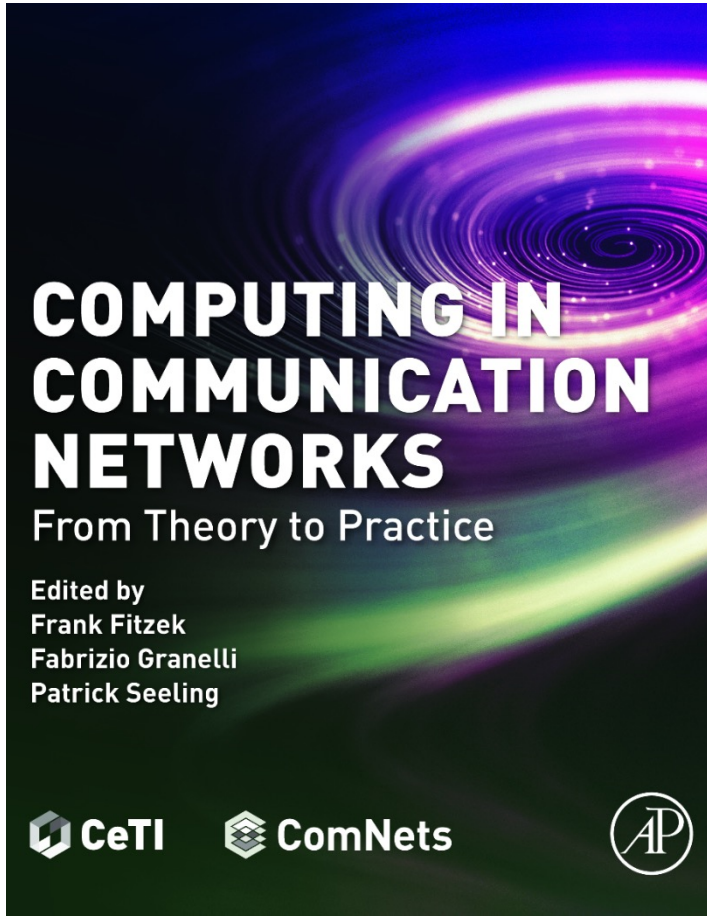
5G Concepts

Computing in Communication Networks



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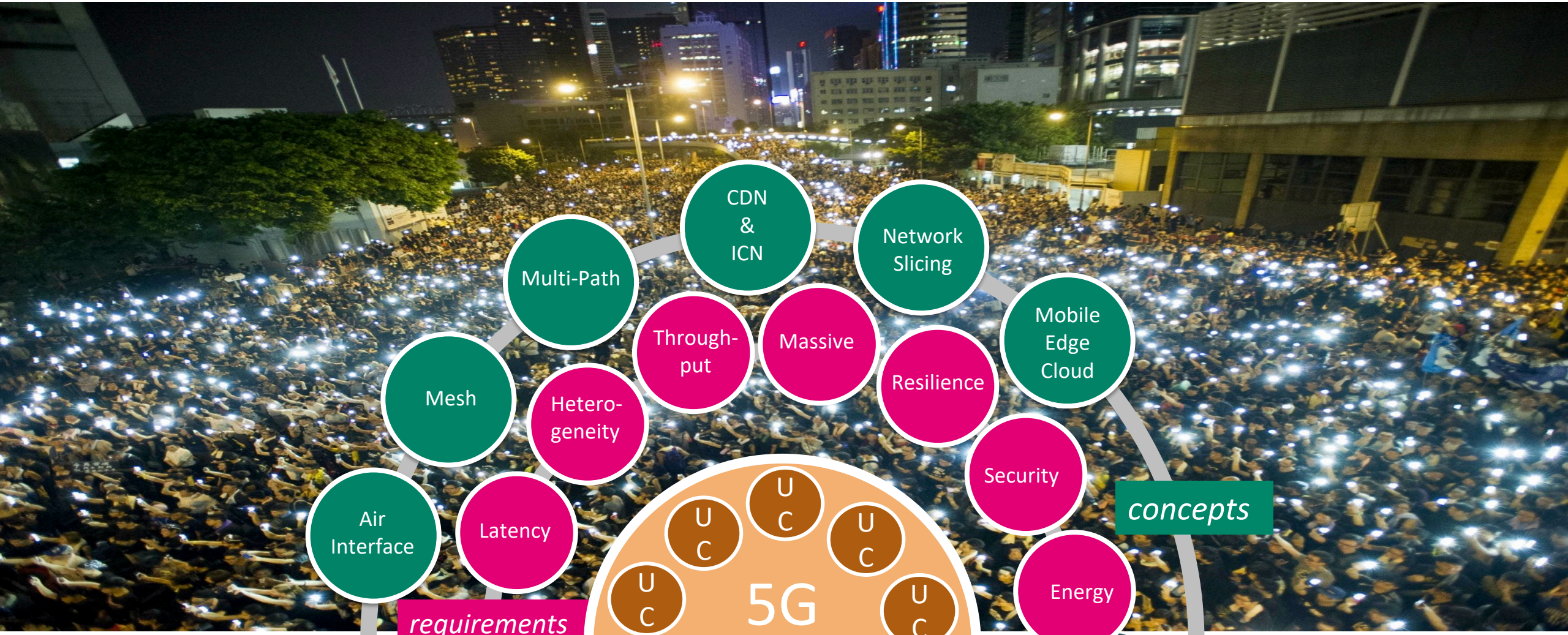

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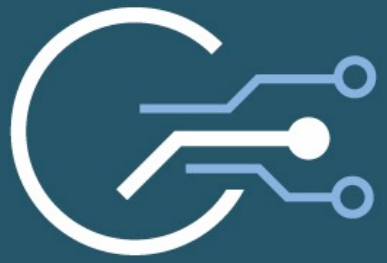

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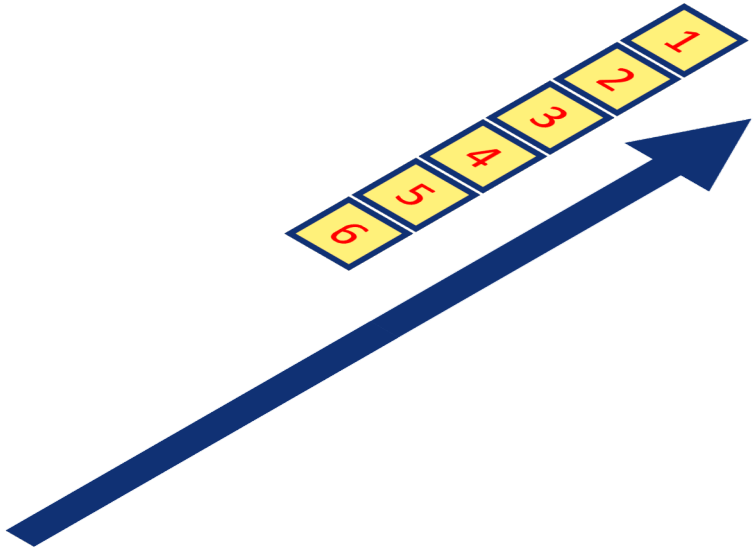
5G Concepts: Multi-Path

Multi-Path Explanation



Single Path

Throughput

Resilience

Security

Latency

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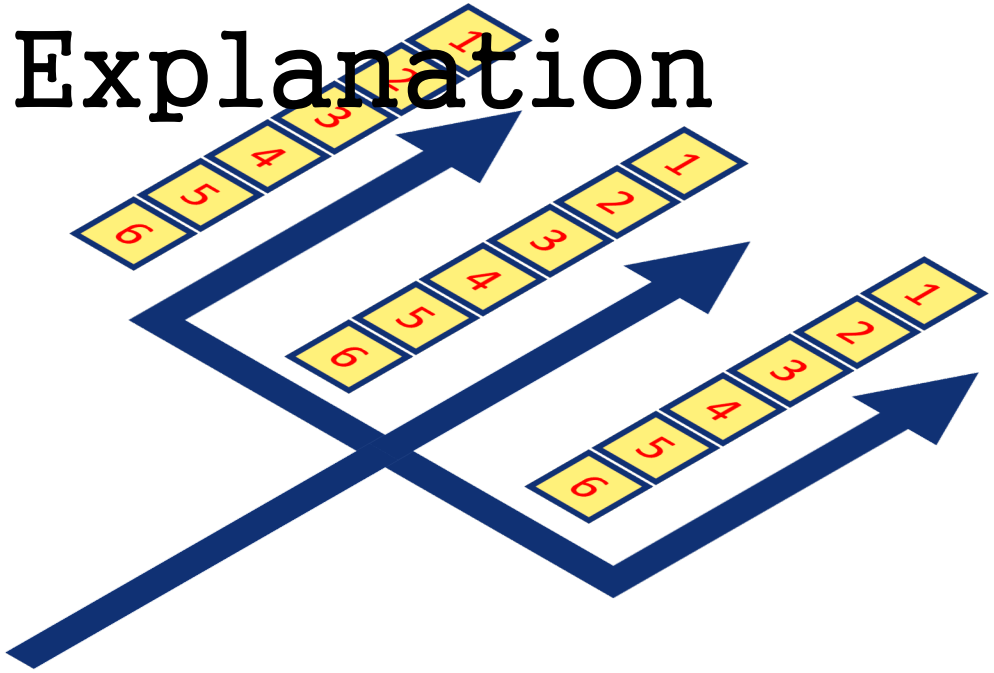
Multi-Path Explanation



Multi-Path

Replication

Throughput

Resilience

Security

Latency

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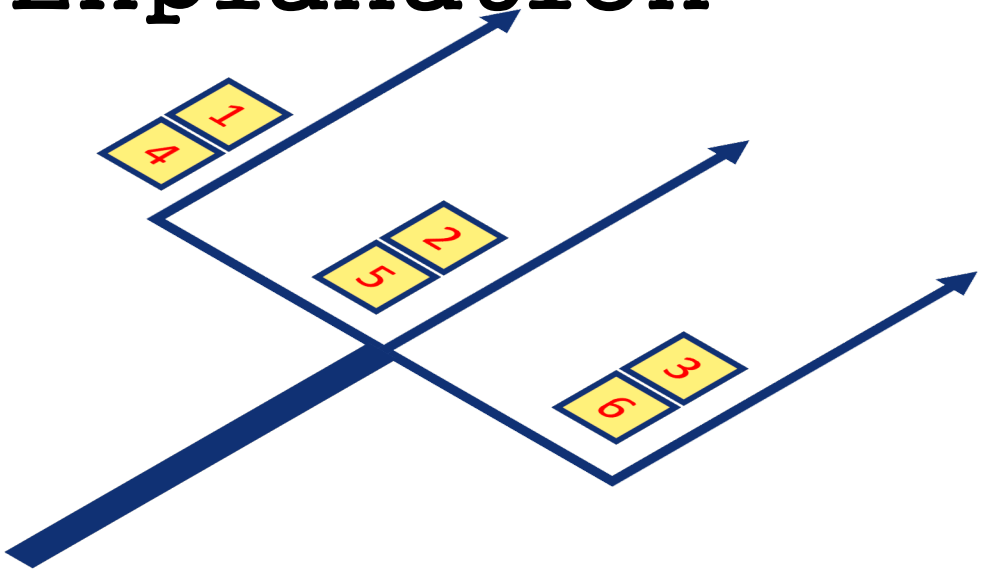
Multi-Path Explanation



Multi-Path

Splitting

Throughput

Resilience

Security

Latency

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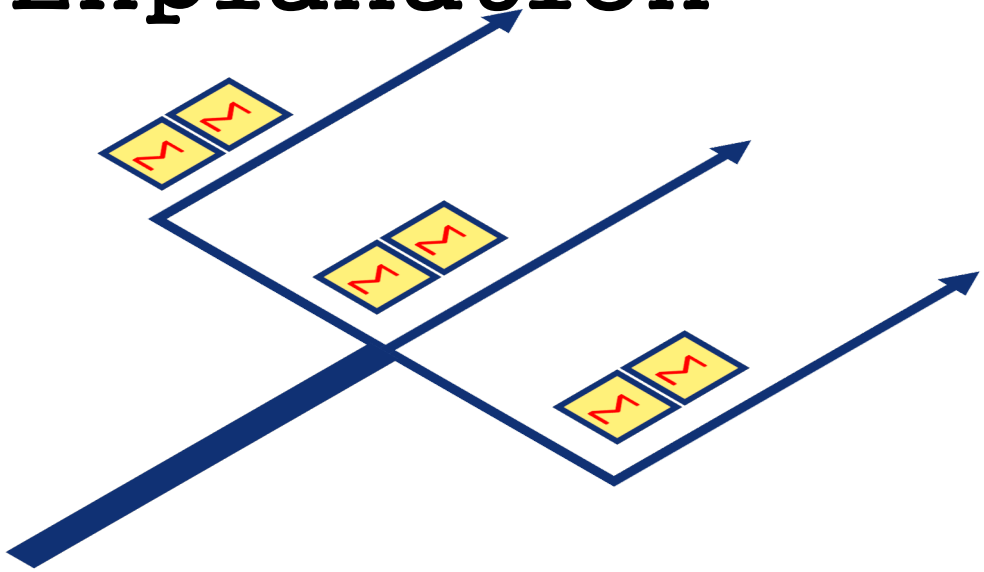
Multi-Path Explanation



Multi-Path

Coding

Throughput

Resilience

Security

Latency

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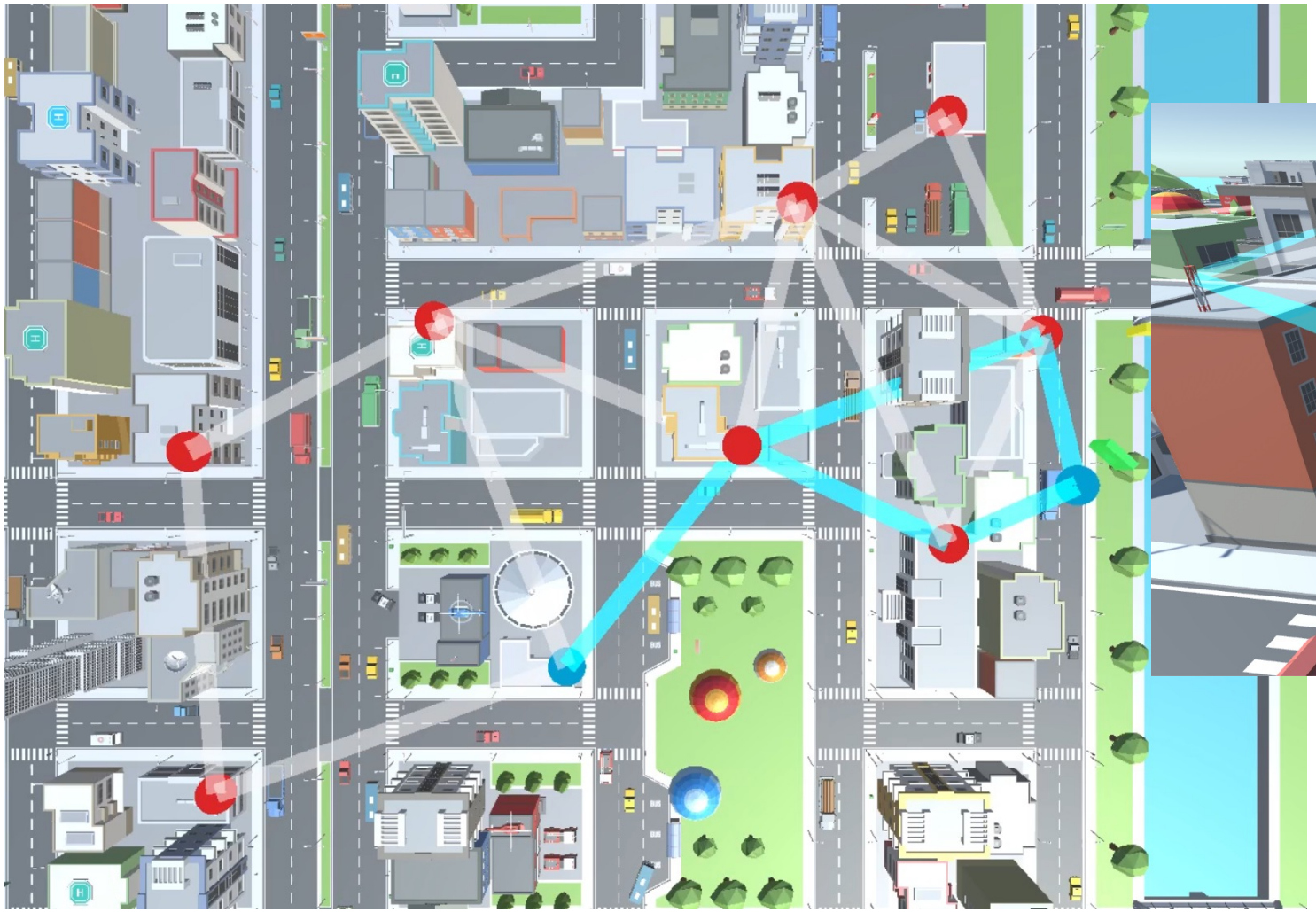
The 5G Atom concepts: Meshmerize (multi-path) vs. B.A.T.M.A.N. (single-path) demonstrator



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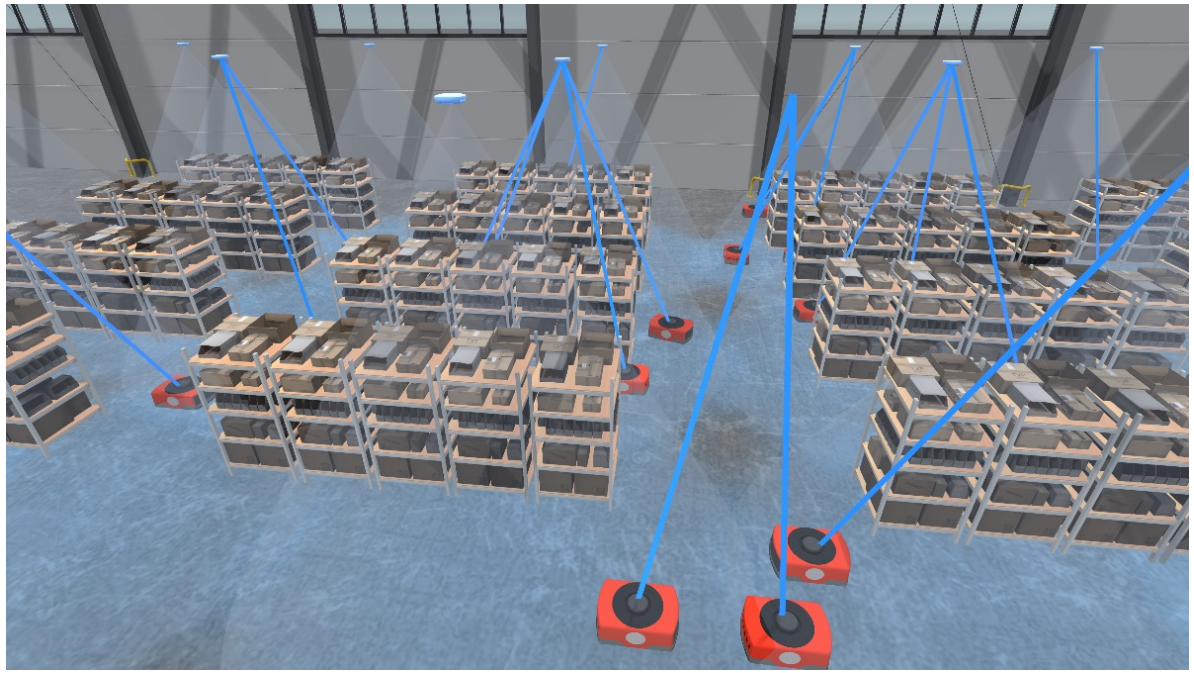
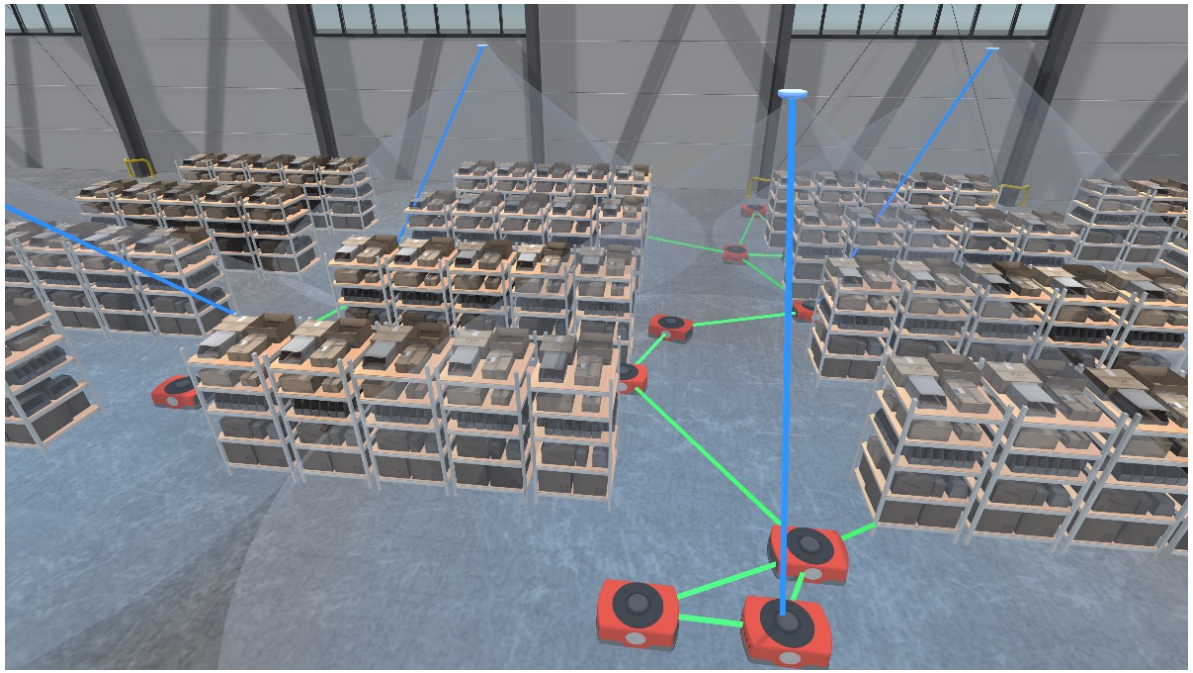
The 5G atom concepts: Combination of multi-path and mesh communication system in an Industry 4.0 environment





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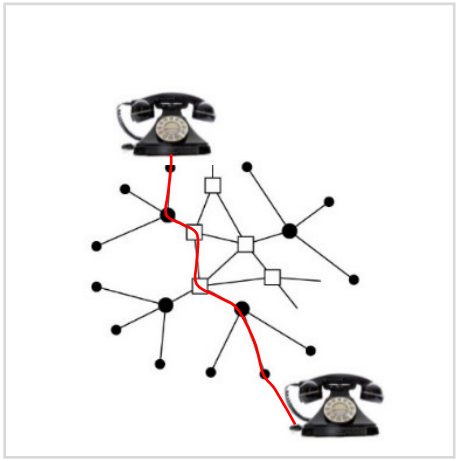
Communication Networks

***Circuit* Switched Networks**



Voice

Places

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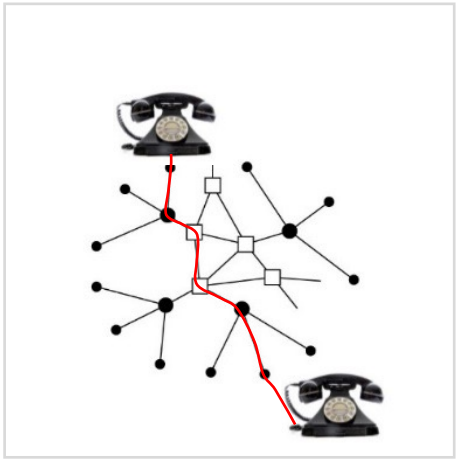
Communication Networks

***Circuit* Switched Networks**



Voice

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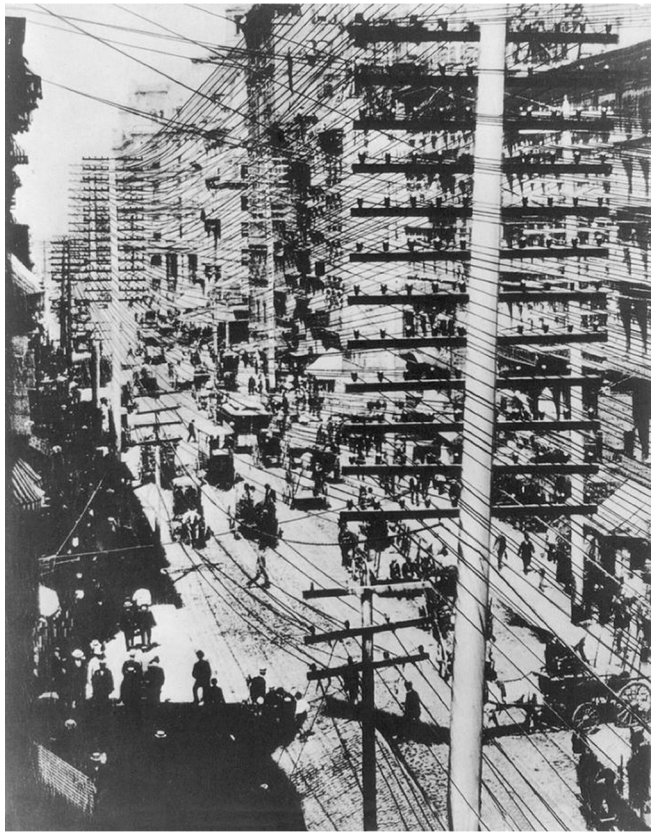

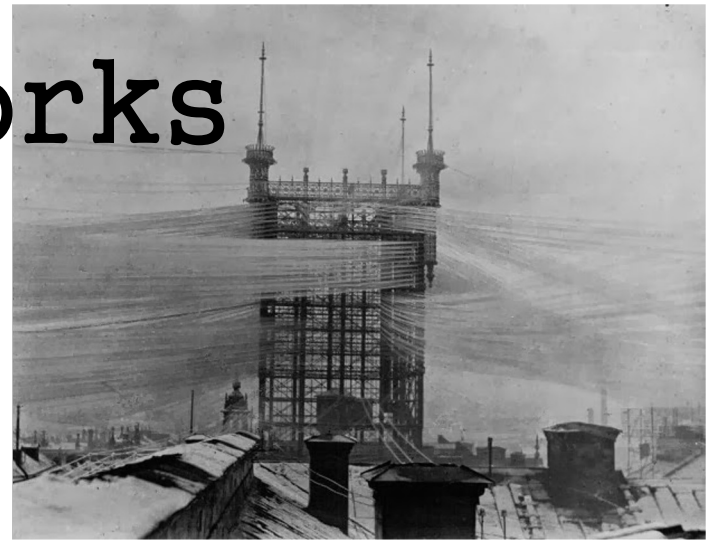

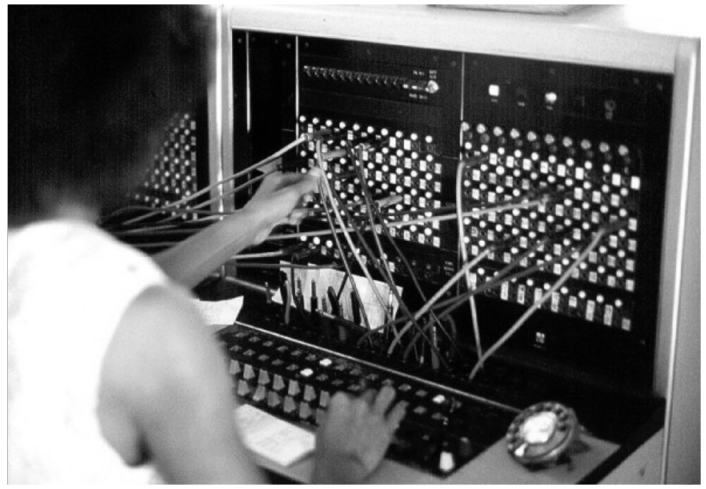

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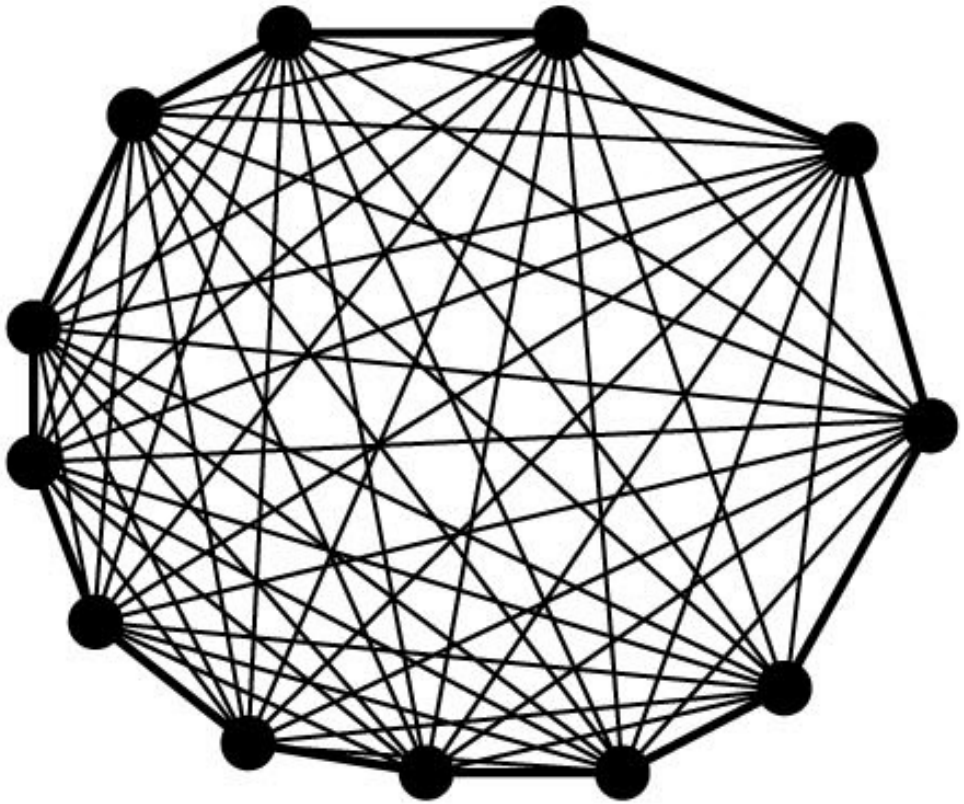
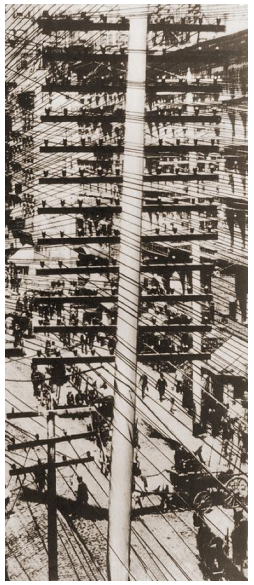
The Telephone System





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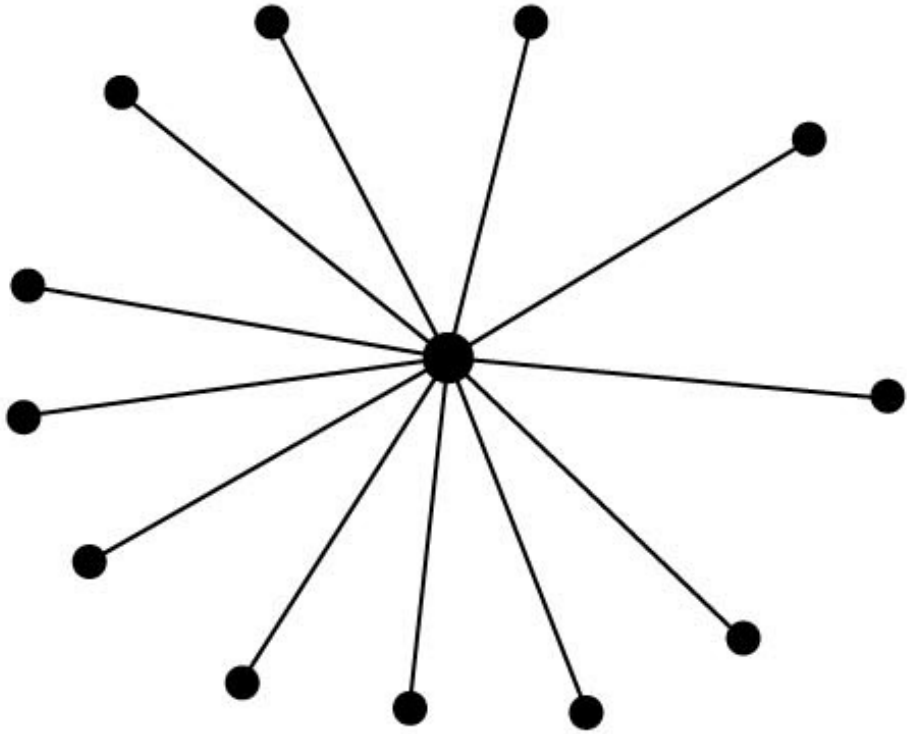
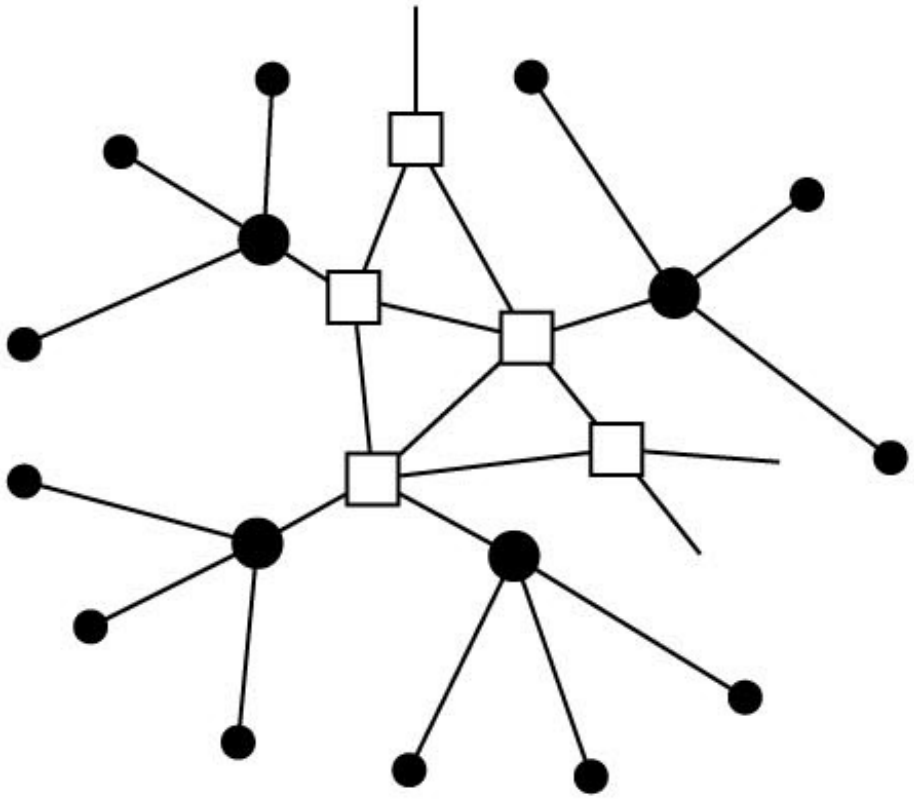
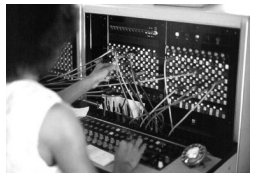
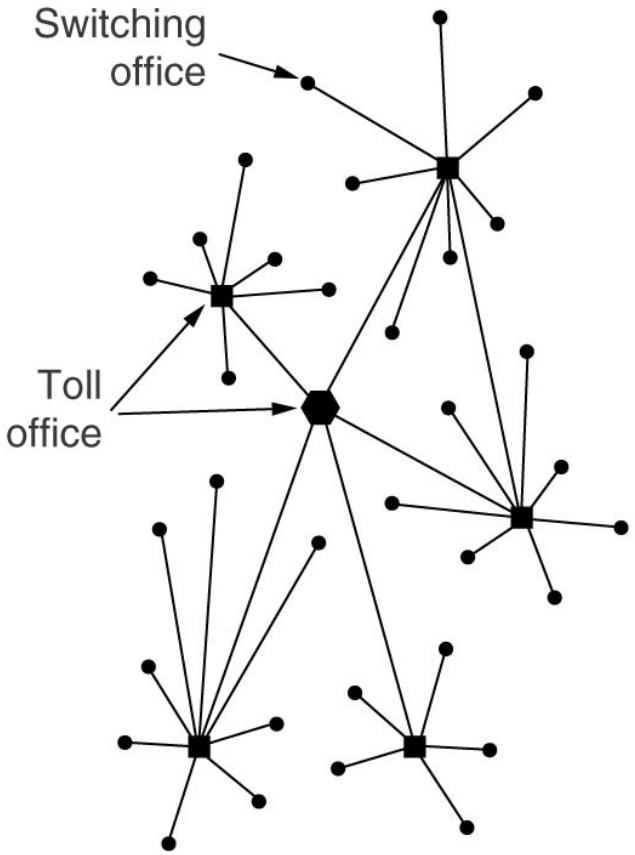


The Telephone System

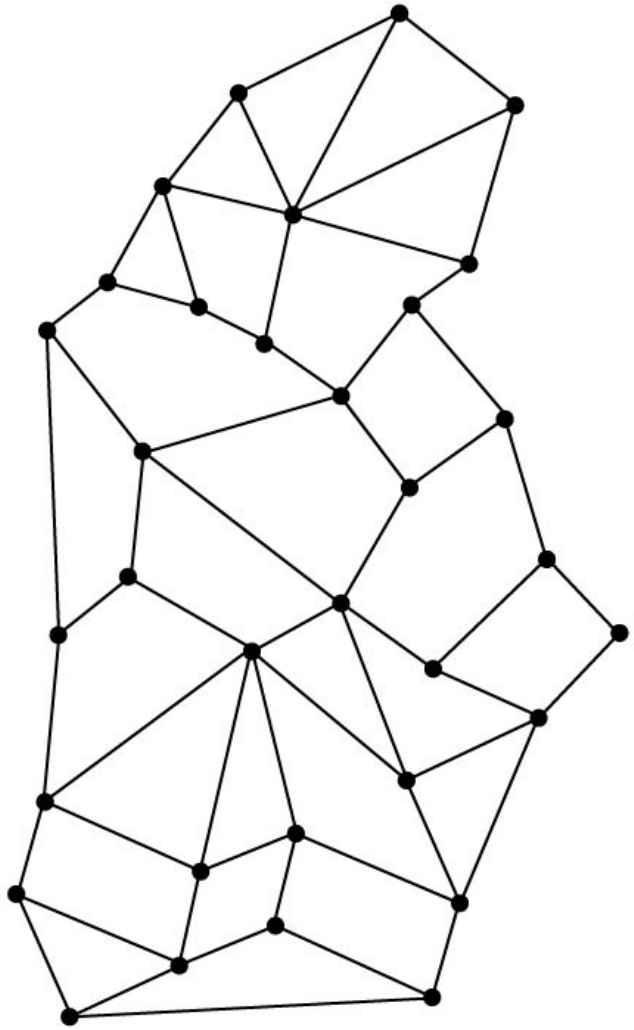




The Internet



Circuit switched to packet switched



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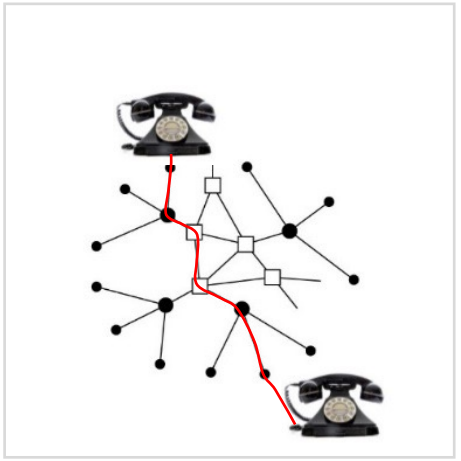
Communication Networks

***Circuit* Switched Networks**



Voice

Places

Revolution

***Packet* Switched Networks**

Data

Voice

People

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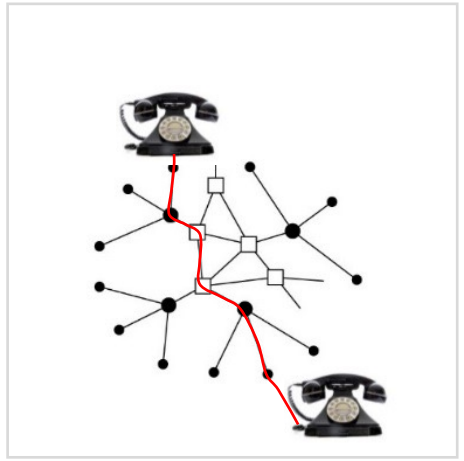
Communication Networks

***Circuit* Switched Networks**



Voice

Places

Revolution

***Packet* Switched Networks**

Data

Voice

People

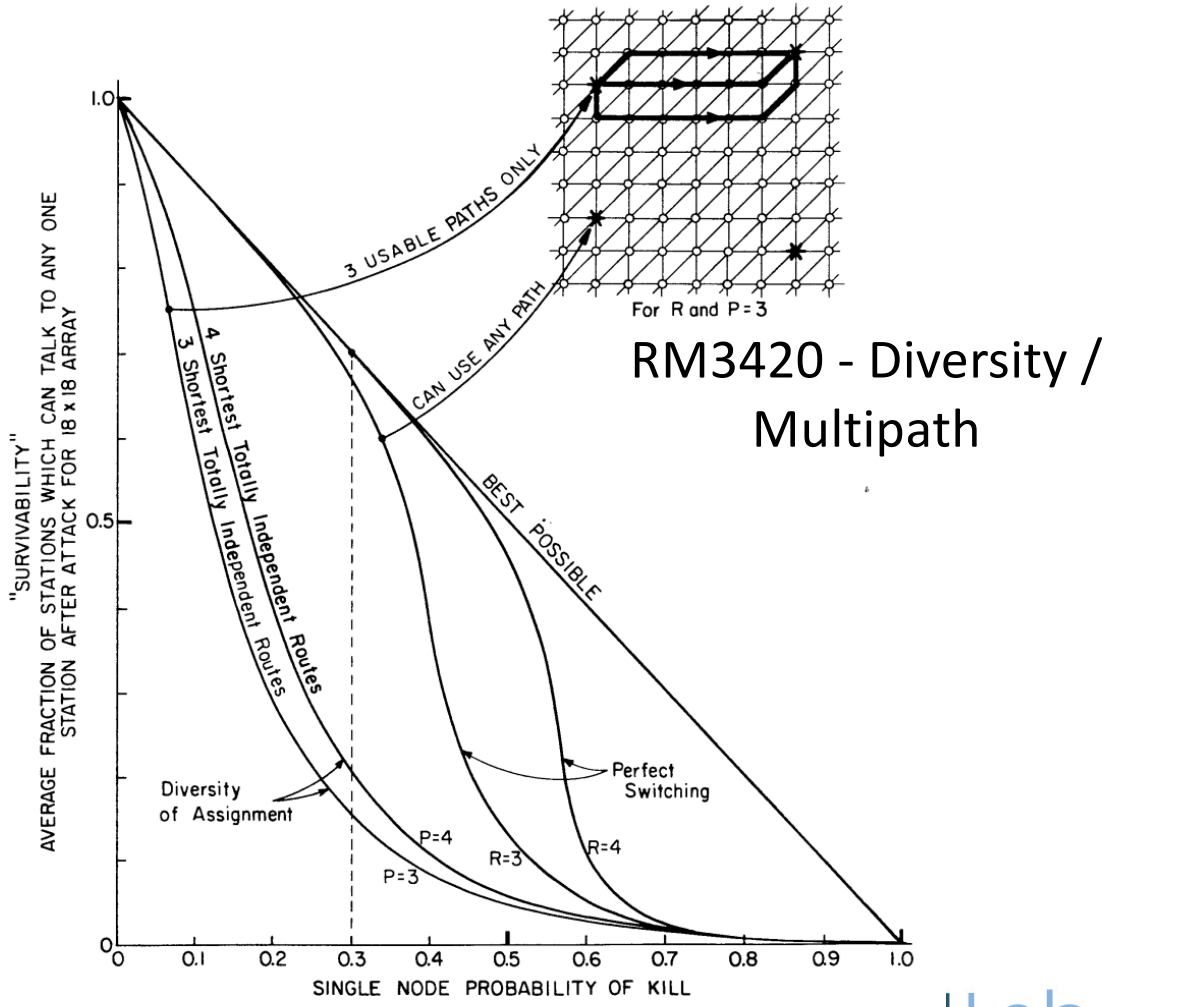


FIG. 8 — Diversity of Assignment vs. Perfect Switching in a Distributed Network.

RM3420 - Diversity / Multipath

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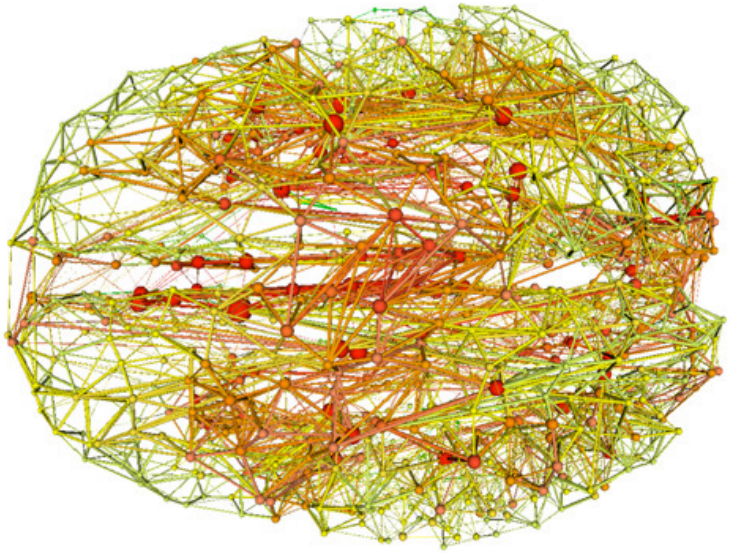
Single Path vs. Multi Path

- Comparison with the **brain**
- Our brain uses multiple paths
- Reliability (Pain)



- Comparison with **ants**
- Food retrieval strategies

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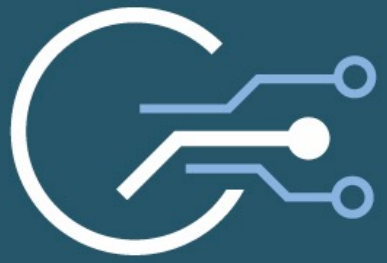

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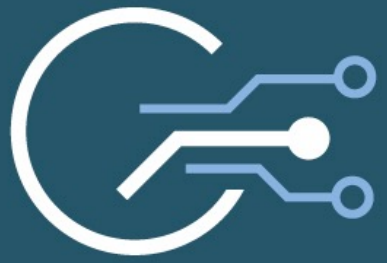
5G Concepts: Mesh



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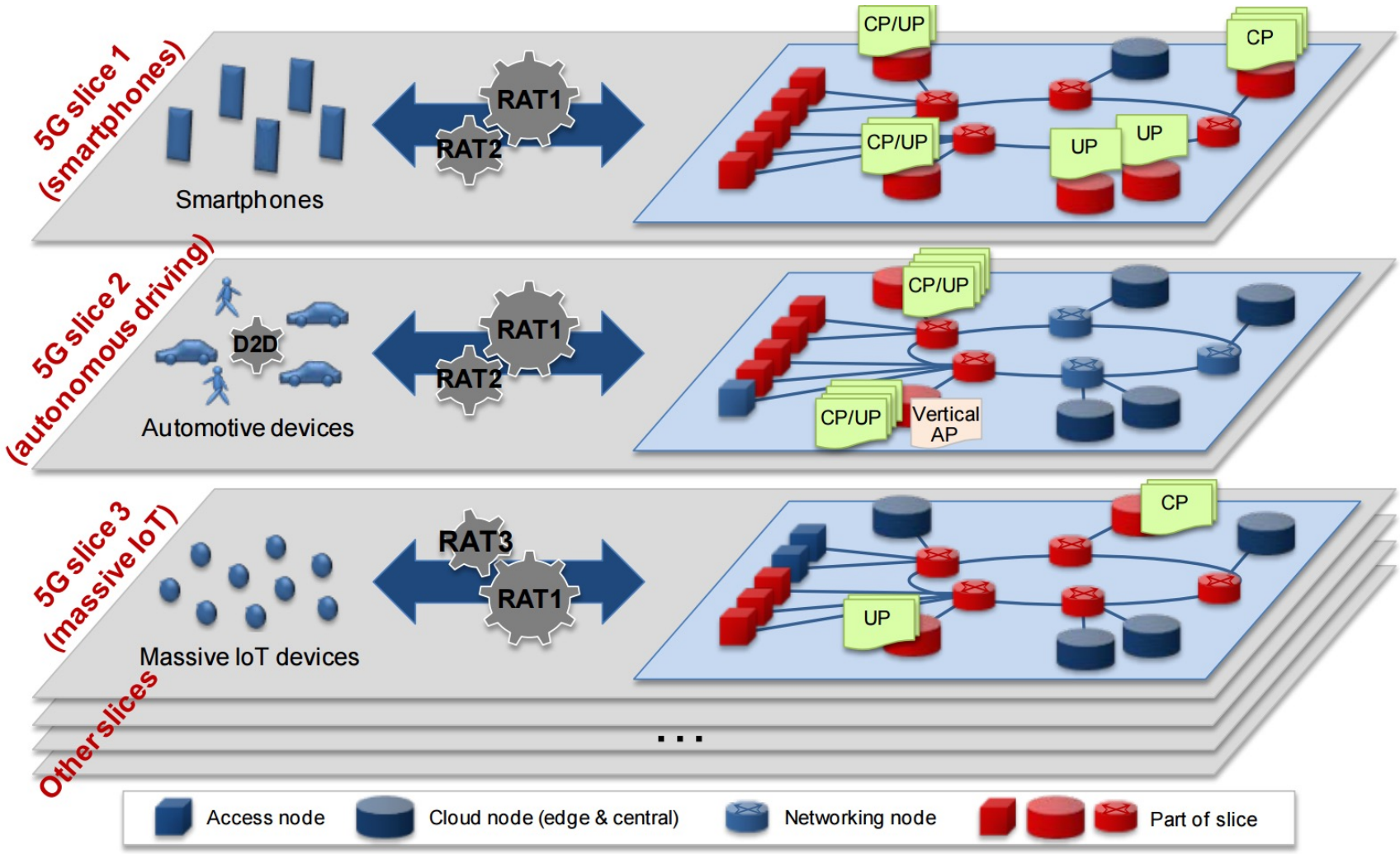
5G Concepts: Network Slicing

Network Slicing



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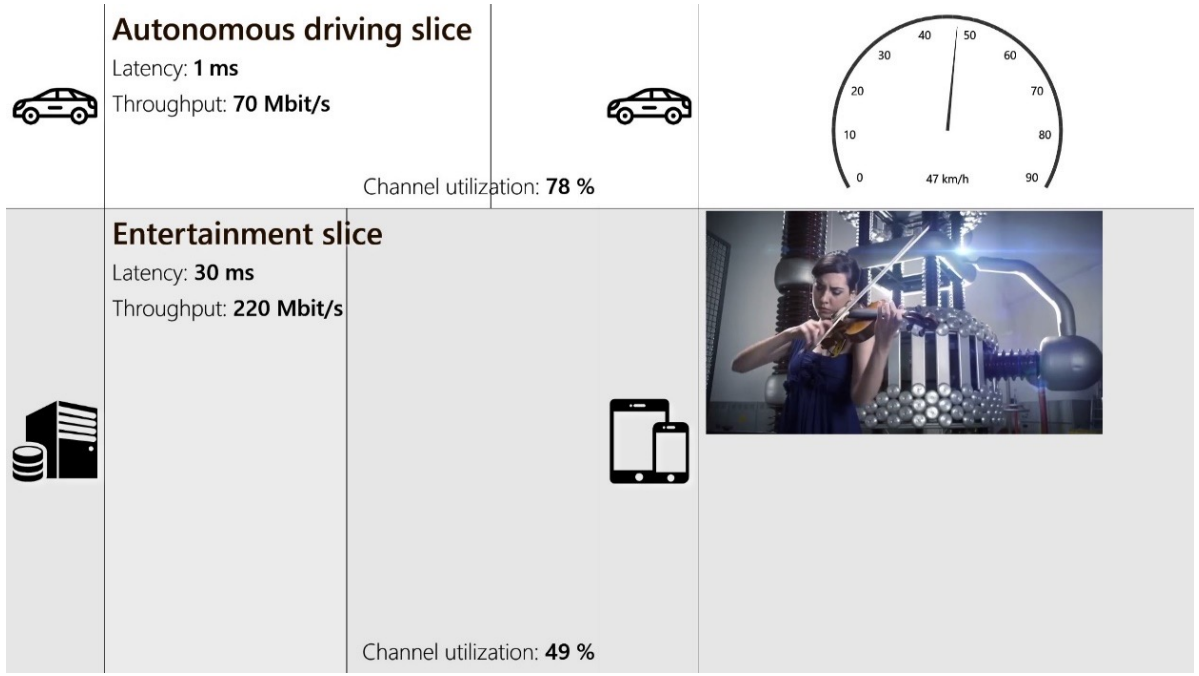
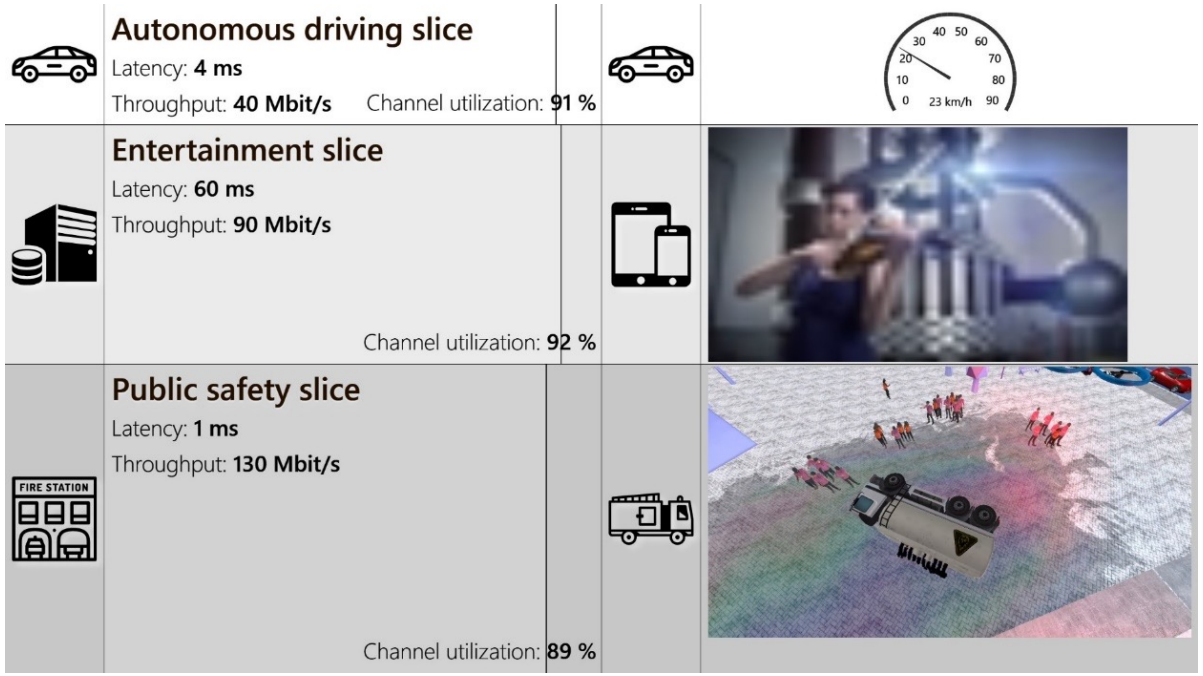
The 5G atom concepts: Network slicing





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Barcelona Network slicing demo

Made by ComNets
Deutsche Telekom Chair of Communication Networks

In association with 5G Lab GERMANY

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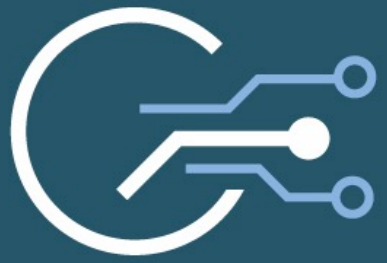

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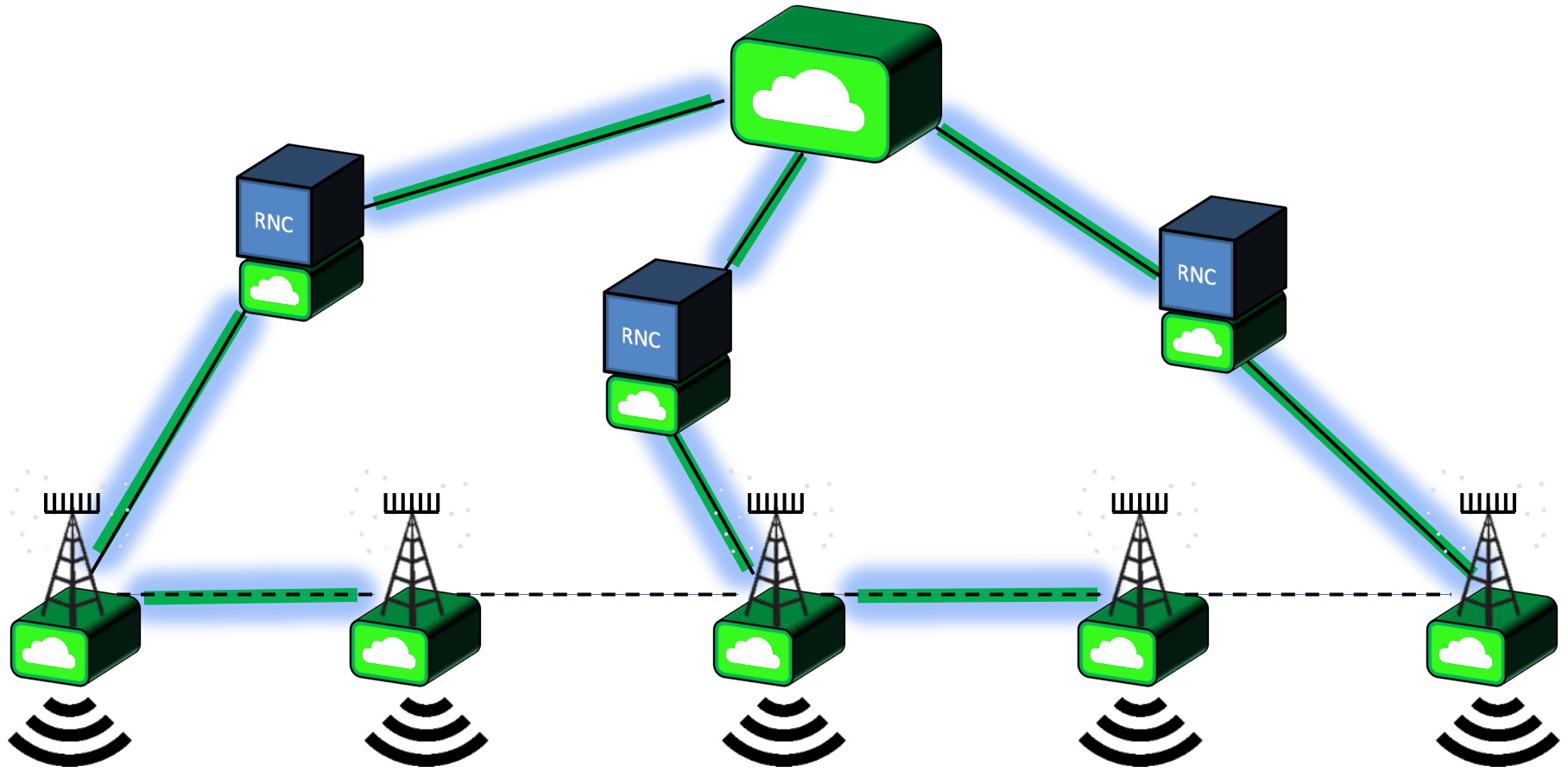
5G Concepts: Mobile Edge Cloud

Mobile Edge Cloud



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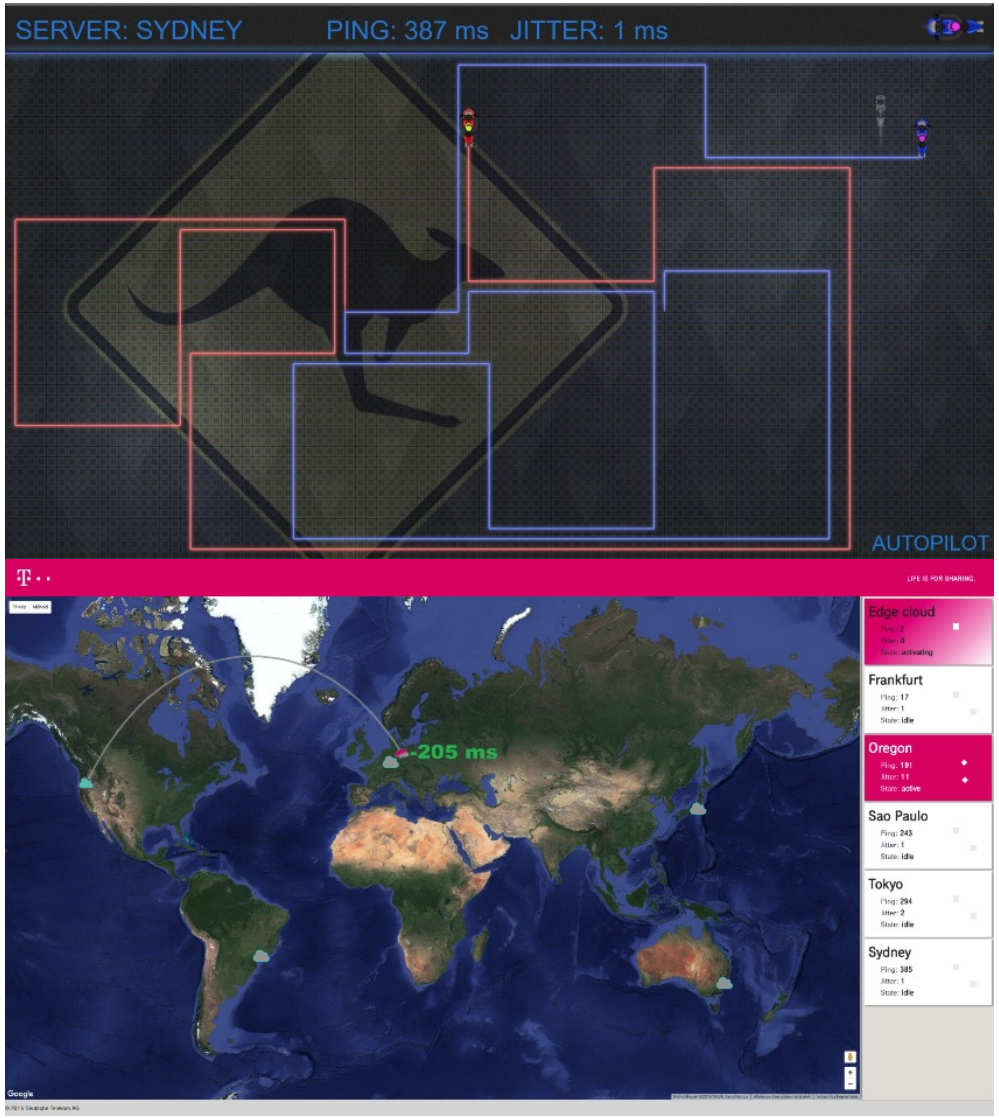
Mobile Edge Cloud Demo

- Browser based multiplayer game
- Game servers:
  - Run in the cloud, as a service
  - Latency to the cloud affects the game play (classic gamer's ping problem)
- Game can be migrated LIVE between the different cloud servers.
- Thus game always can run on the closest edge cloud server.



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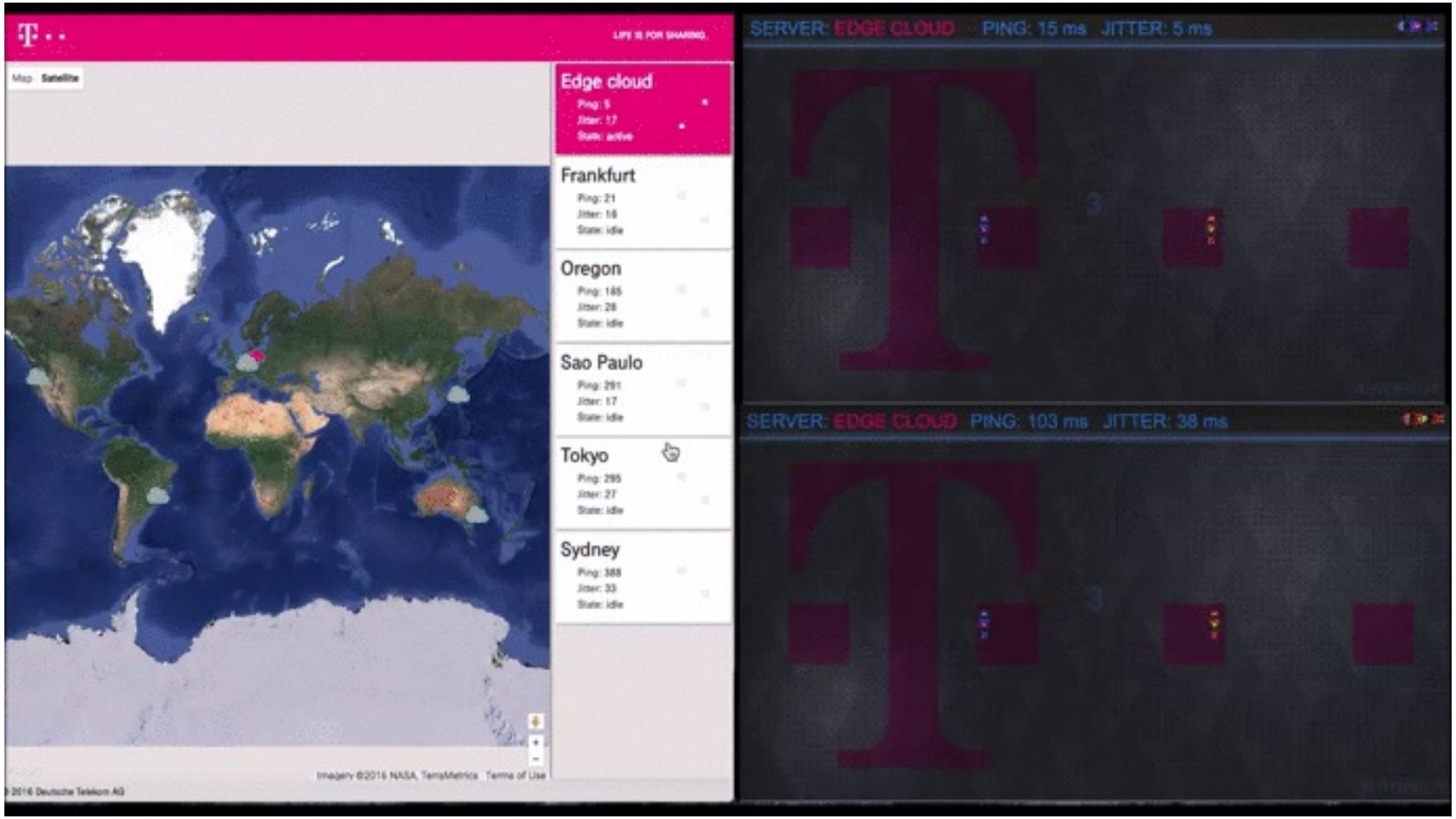
Mobile Edge Cloud Demo

- Five cloud servers: Oregon (US), Frankfurt, Sao Paulo, Tokyo, Sydney
- One edge cloud
- Soft handover – Zero downtime.
- ‘Ghost’ bots to show latency effect
- Display latency, Jitter to each server.



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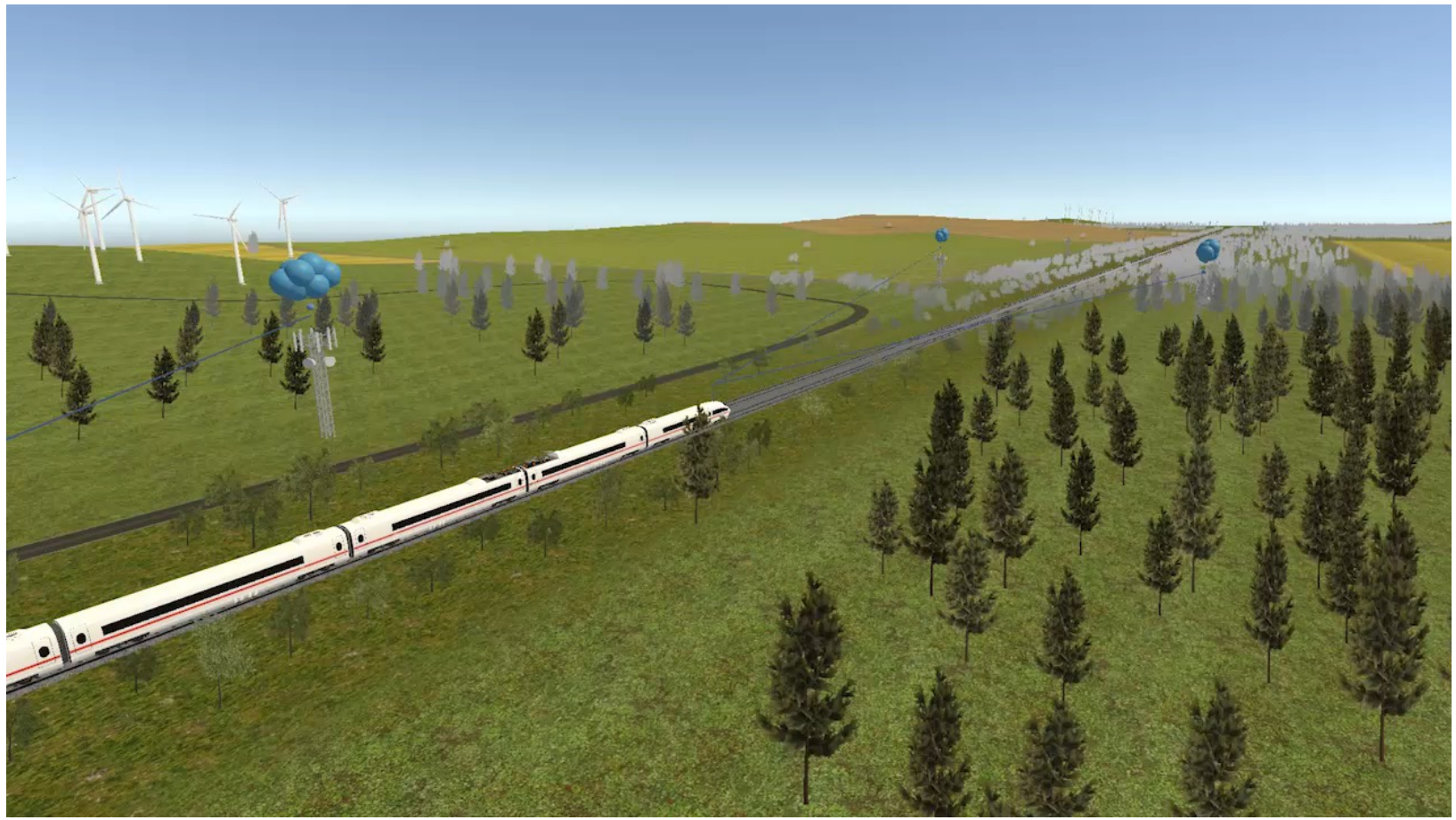
JITTER: 3.11 MS
LATENCY: 82 MS

TECHNISCHE UNIVERSITÄT DRESDEN

BMW MEC demo

Made by ComNets
Deutsche Telekom Chair
of Communication Networks

In association with 5G Lab GERMANY



Nature: Sea Squirts / Ascidiacea

- Why do animals have brains and plants do not?
- Interesting is the case of ascideiacea
- Mobility to find the perfect spot
- Brain needs to find the place and to coordinate muscles
- After the perfect spot is found, the ascideiacea will stay there forever
- First thing after “moving in” , ascideiacea eats its own brain
- Therefore, mobility needs brains in nature, and network need computing to support mobile agile network functions

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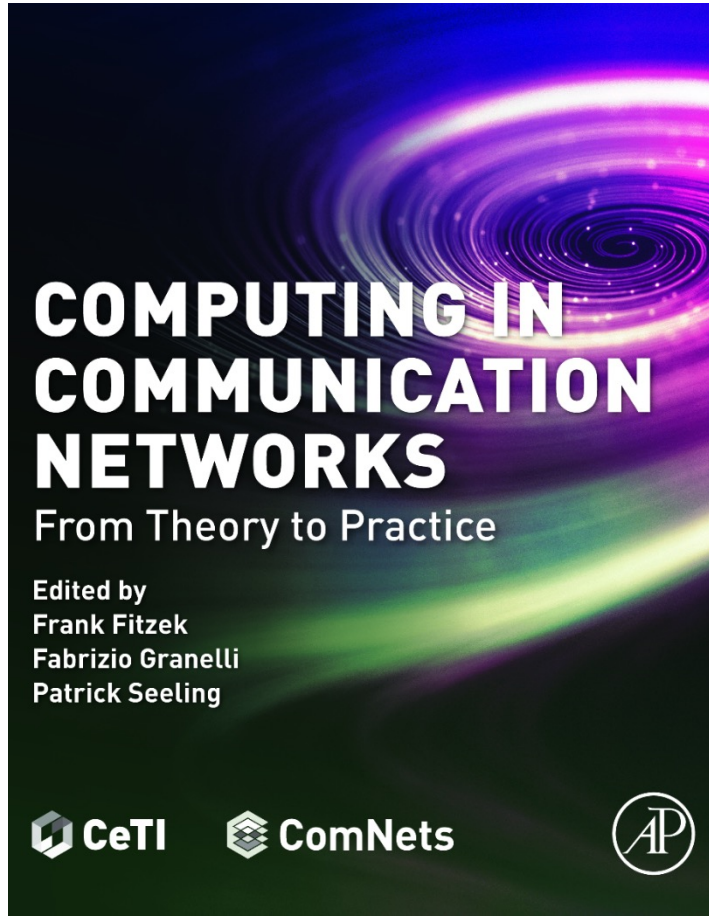
5G technologies
the software belt

Computing in Communication Networks



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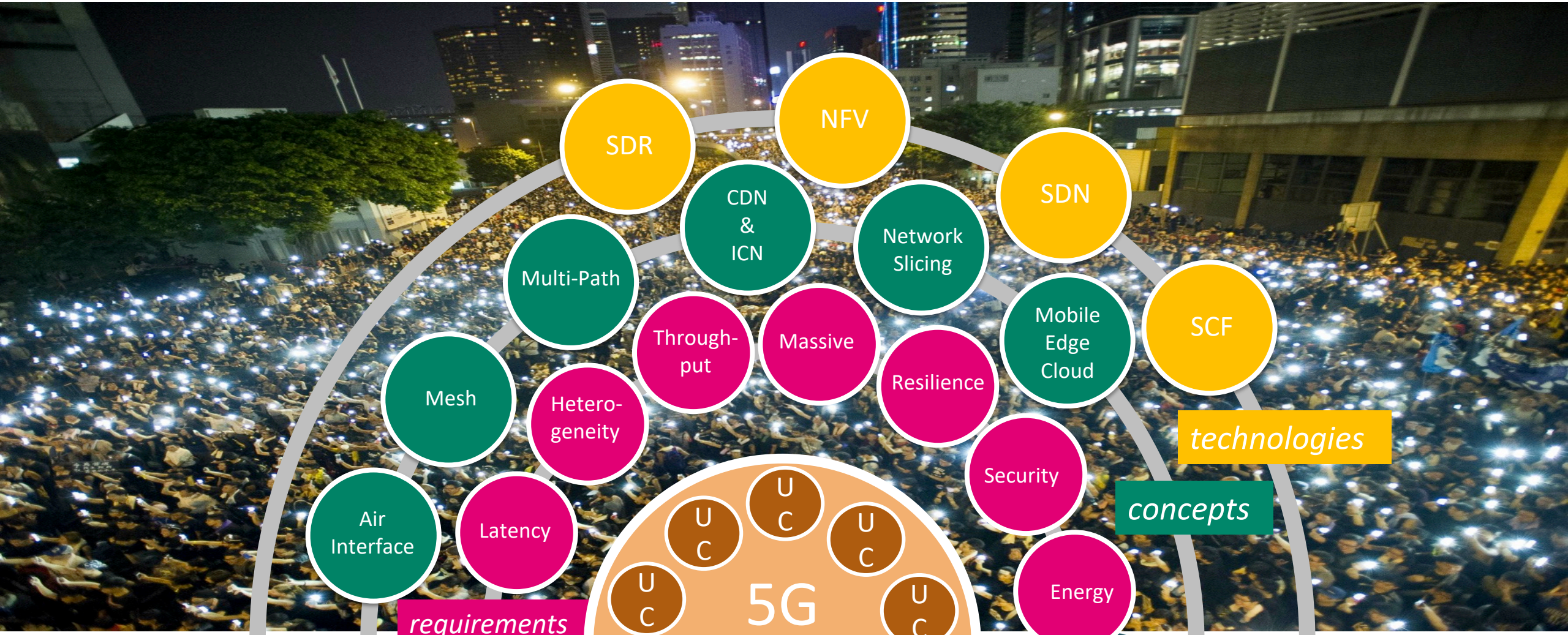
5G atom definition



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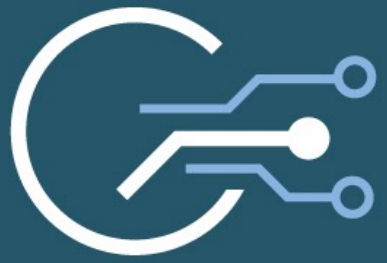

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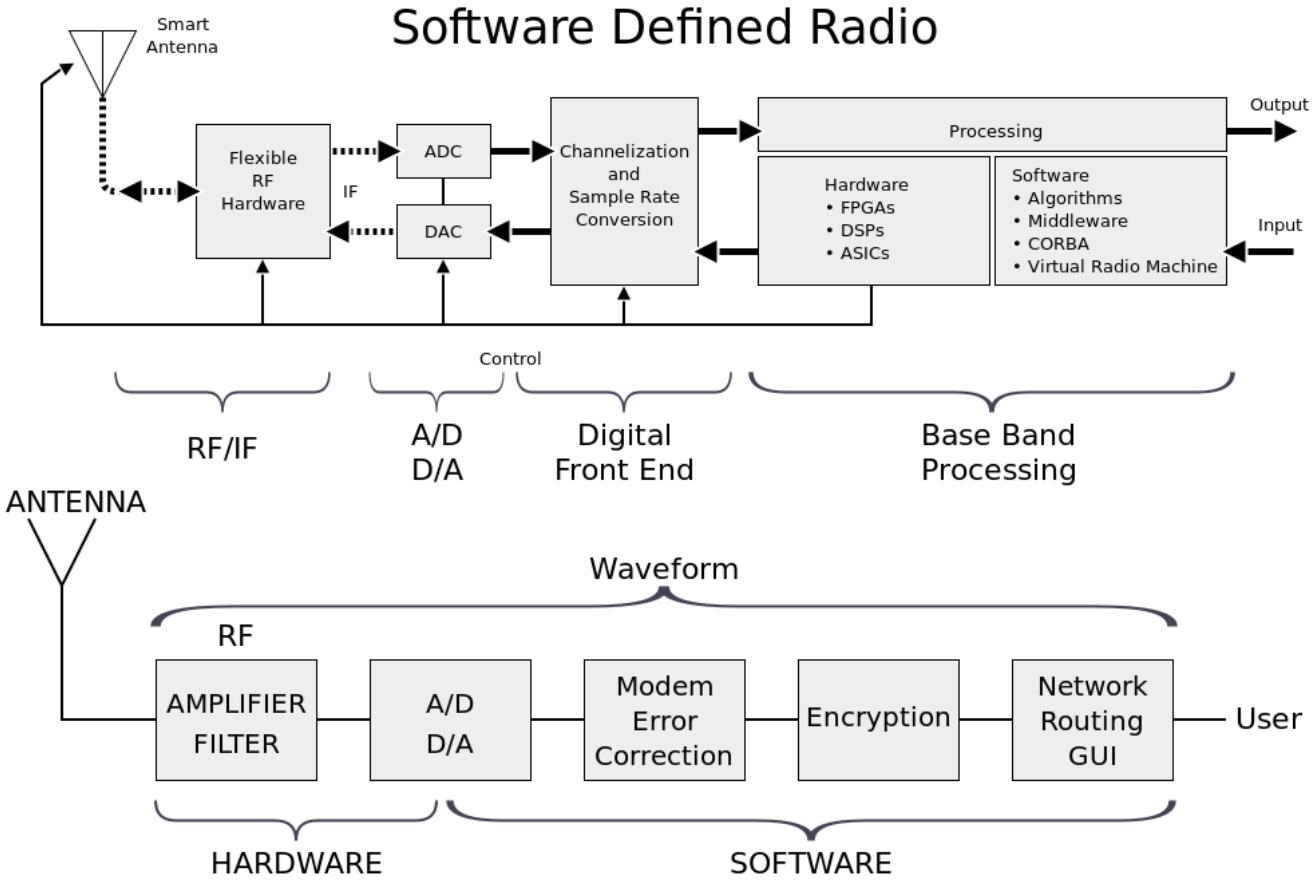
Software Defined Radio

Software Defined Radio

- Different concepts
  - Reuse of hardware components
  - Flexible control of components
- Softwareization of the air interface
- End to End paradigm



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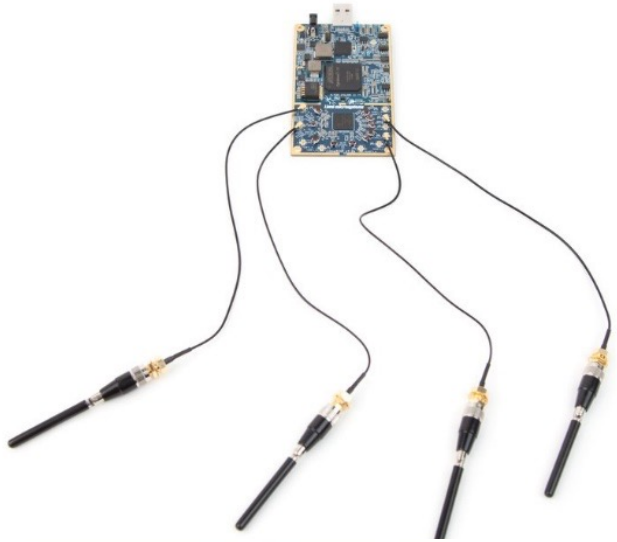
Software Defined Radio



- GNUradio
- New kid on the block LimeSDR
- Interesting
  - Low latency
  - Network coding at the edge
  - Analog network coding
  - Multi connectivity

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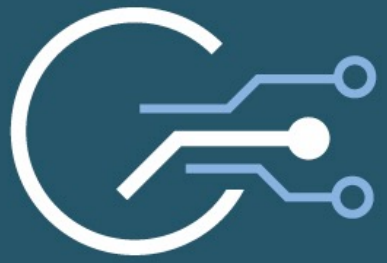

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Software Defined Networks & Network Function Virtualization

Motivation for SDN and NFV

- SDN was motivated by the relation of ***computation*** and ***communication***, which led to new principles for ***software*** and ***networking***.

communication

computation

computation and ***communication***

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Motivation for SDN and NFV

- SDN was motivated by the relation of ***computation*** and ***communication***, which led to new principles for ***software*** and ***networking***.
- NFV was motivated by the flexibility, timely deployment and financial gains of ***cloud and OTT providers***, which was not available to ***network operators.***
- SDN and NFV are often intertwined

SDN & NFV

- **Software Defined Networks**
- *SDN advocates to replace distributed static network protocols with centralized flexible software applications.*

- Enables fast experiments with new ideas
- Fast deployment of software compared to long lasting standardization processes
- Optimization due to centralized control as a function of time
- New functionality can be deployed in nearly no time relocated, and upgradet depending on the needs.

- **Network Function Virtualization**
- *NFV advocates to use generic hardware running software solution compared specialized hardware.*

- Hardware becomes cheaper (COTS)
- Relocation of functionality to optimize network performance such as latency, capacity, etc.

- New functionality can be deployed in nearly no time relocated, and upgradet depending on the needs.

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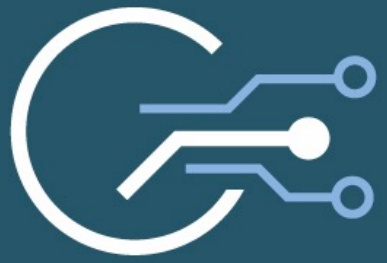

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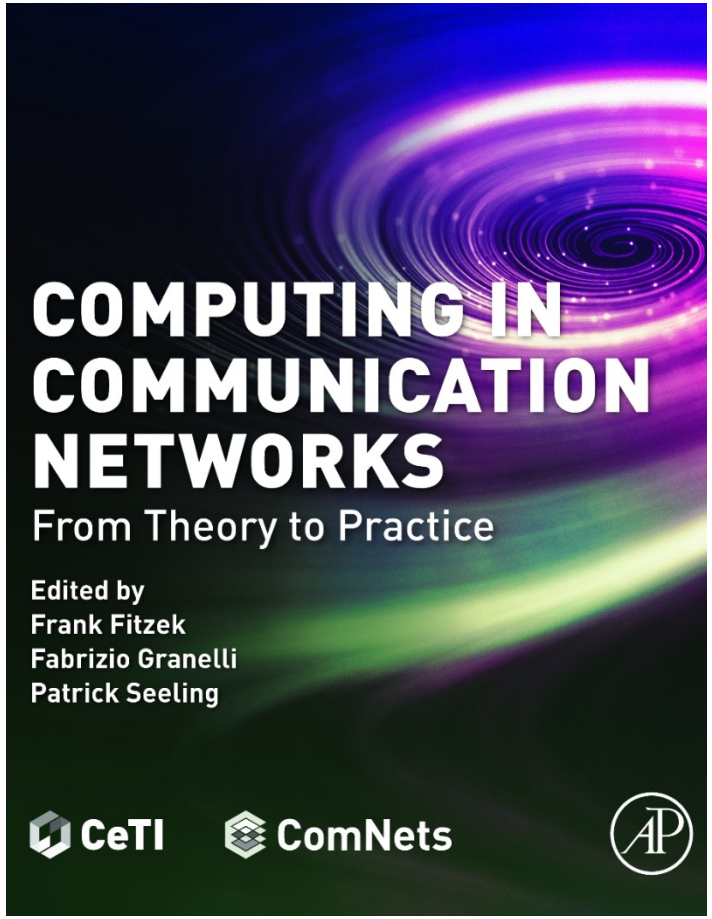
5G novelty

Computing in Communication Networks



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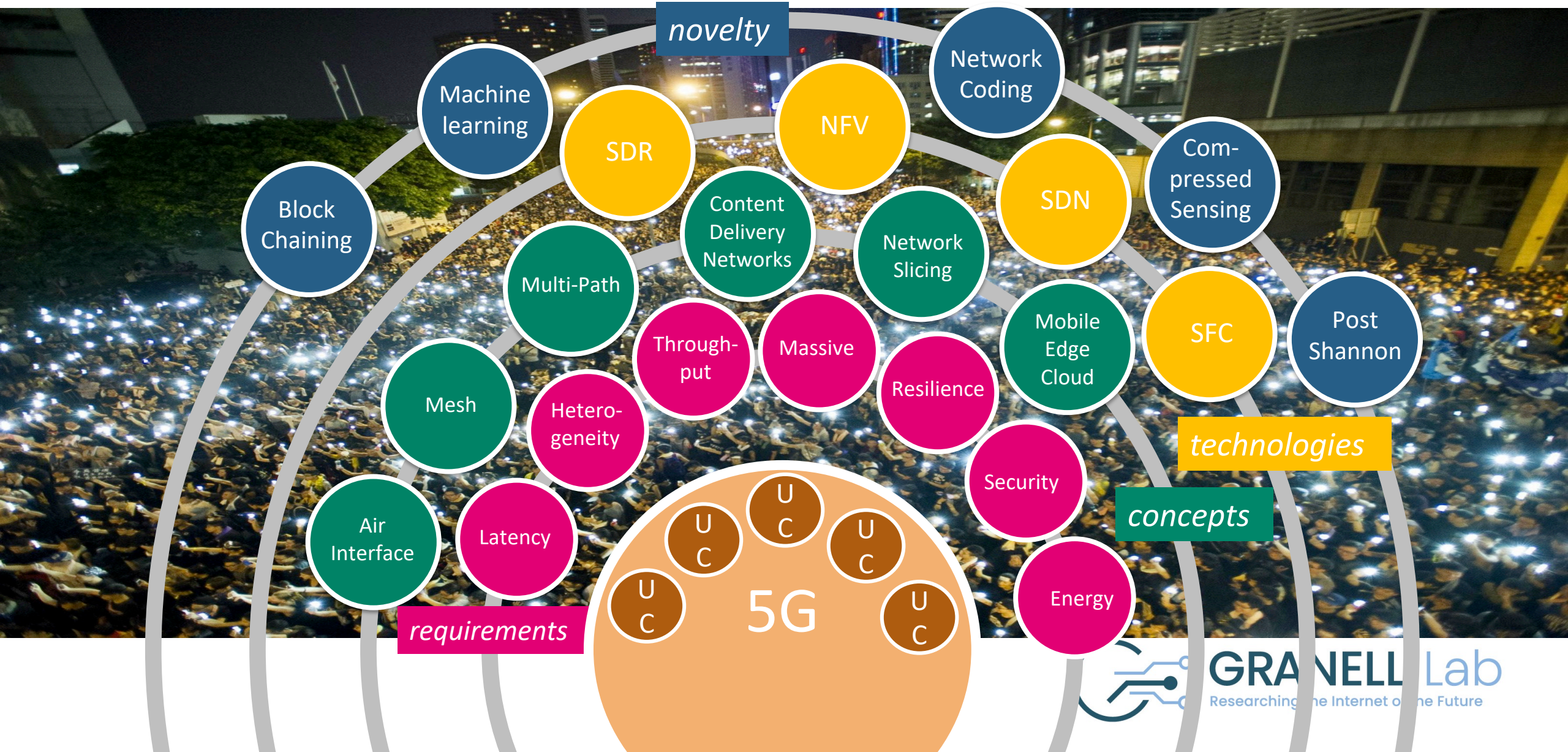
5G atom definition



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5G Network Coding

- https://www.youtube.com/playlist?list=PLtngEjKSkXc04VBKxJR-ZNFKhyxW2Uny2

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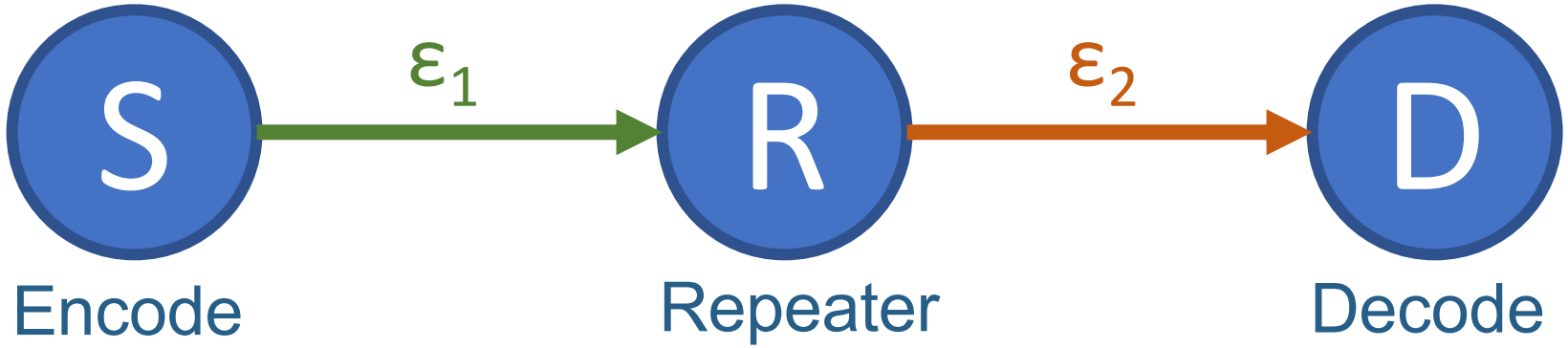
Network Coding



Reed Solomon
LDPC
LT
Raptor

$(1-\varepsilon_1)(1-\varepsilon_2)$

Store and Forward

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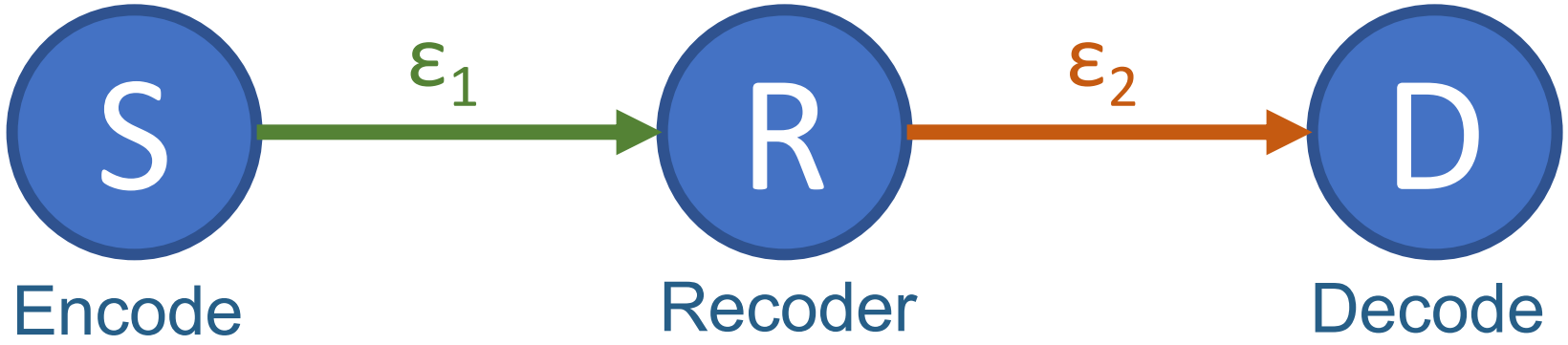
Network Coding



Reed Solomon
LDPC
LT
Raptor

$(1-\varepsilon_1)(1-\varepsilon_2)$

Store and Forward

Network Coding

$\min\{(1-\varepsilon_1);(1-\varepsilon_2)\}$

Compute and Forward

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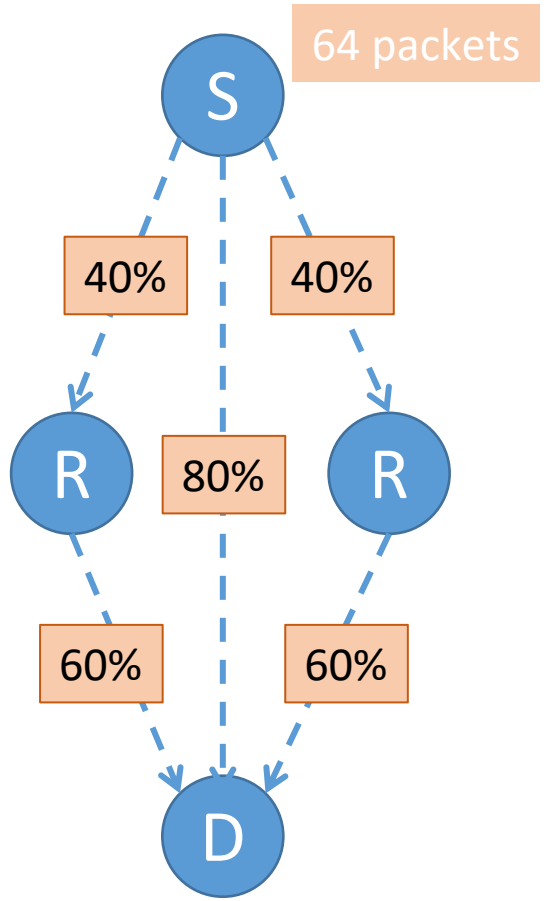
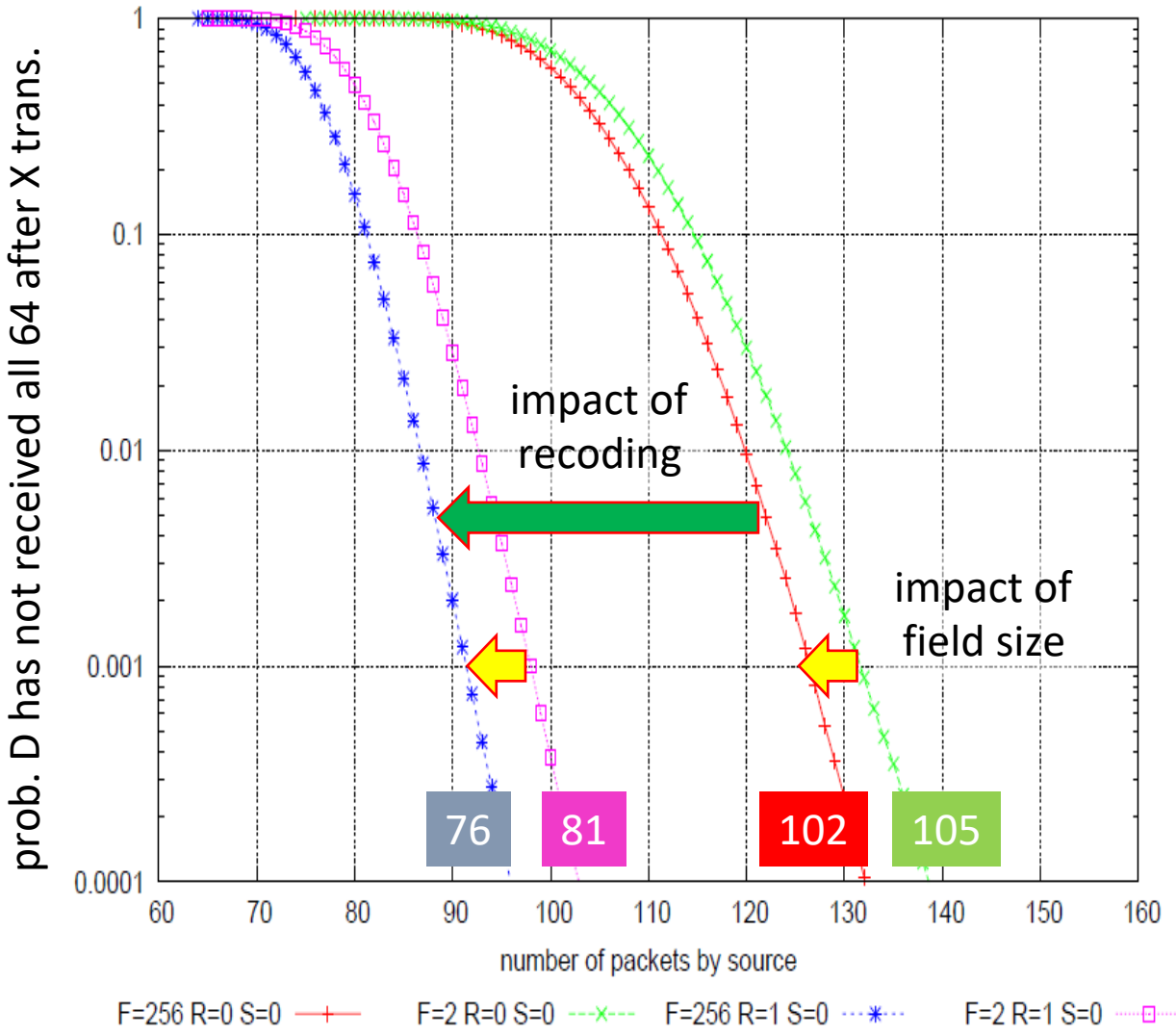
Impact of Recoding



No need for signalling!



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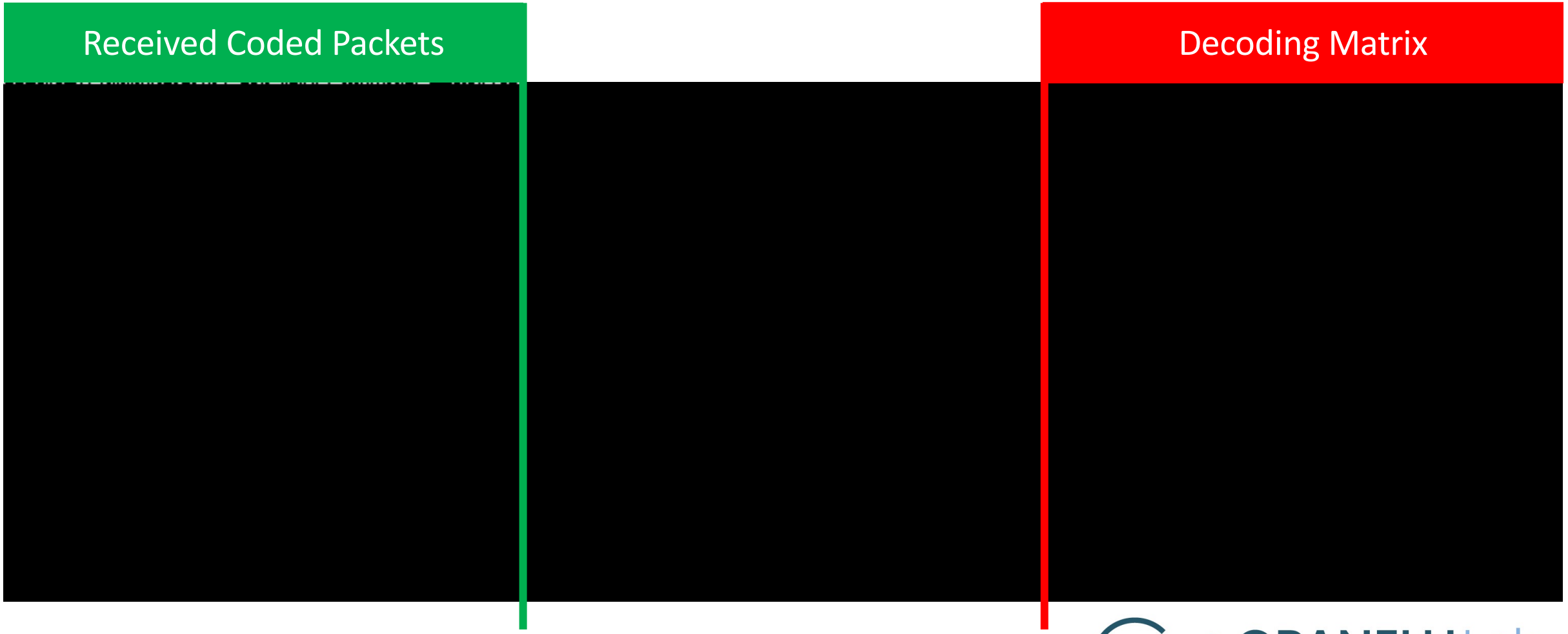
Motivation – Pure Network Coding in GF2



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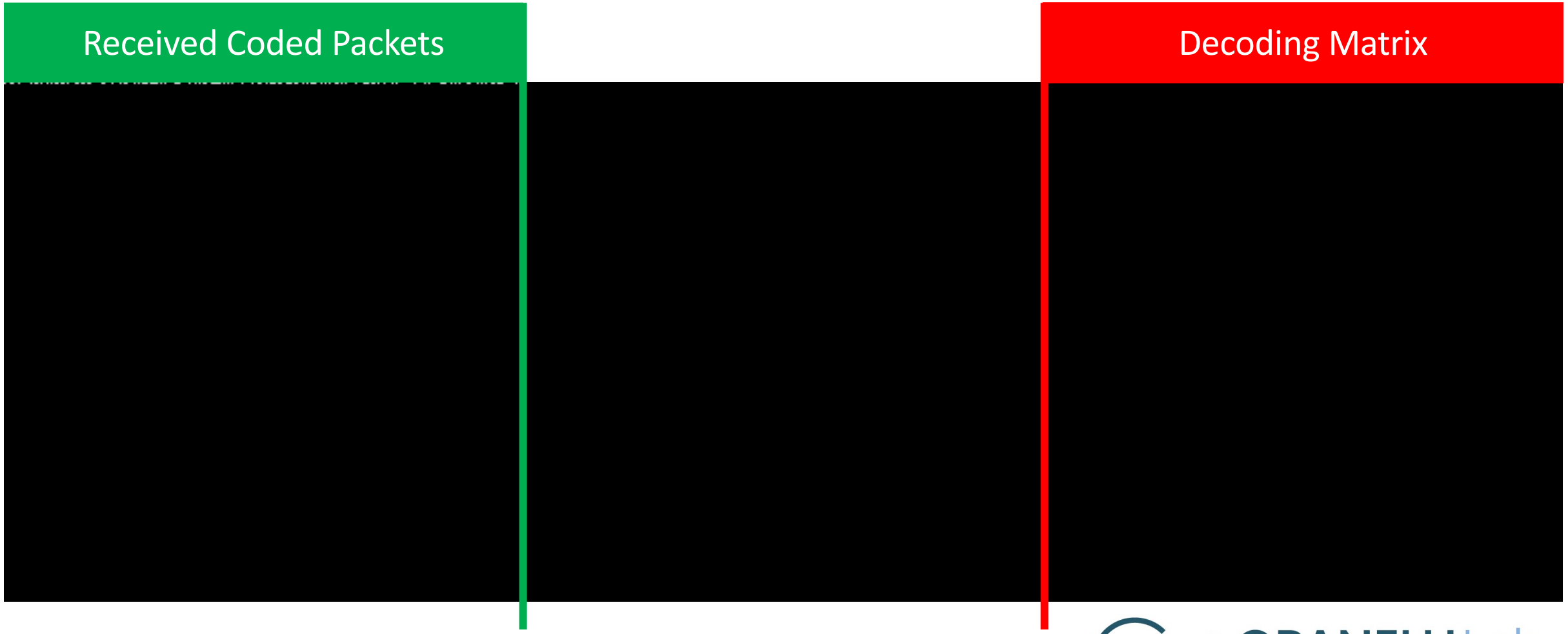
Motivation – Network Coding in GF2 with Sorting



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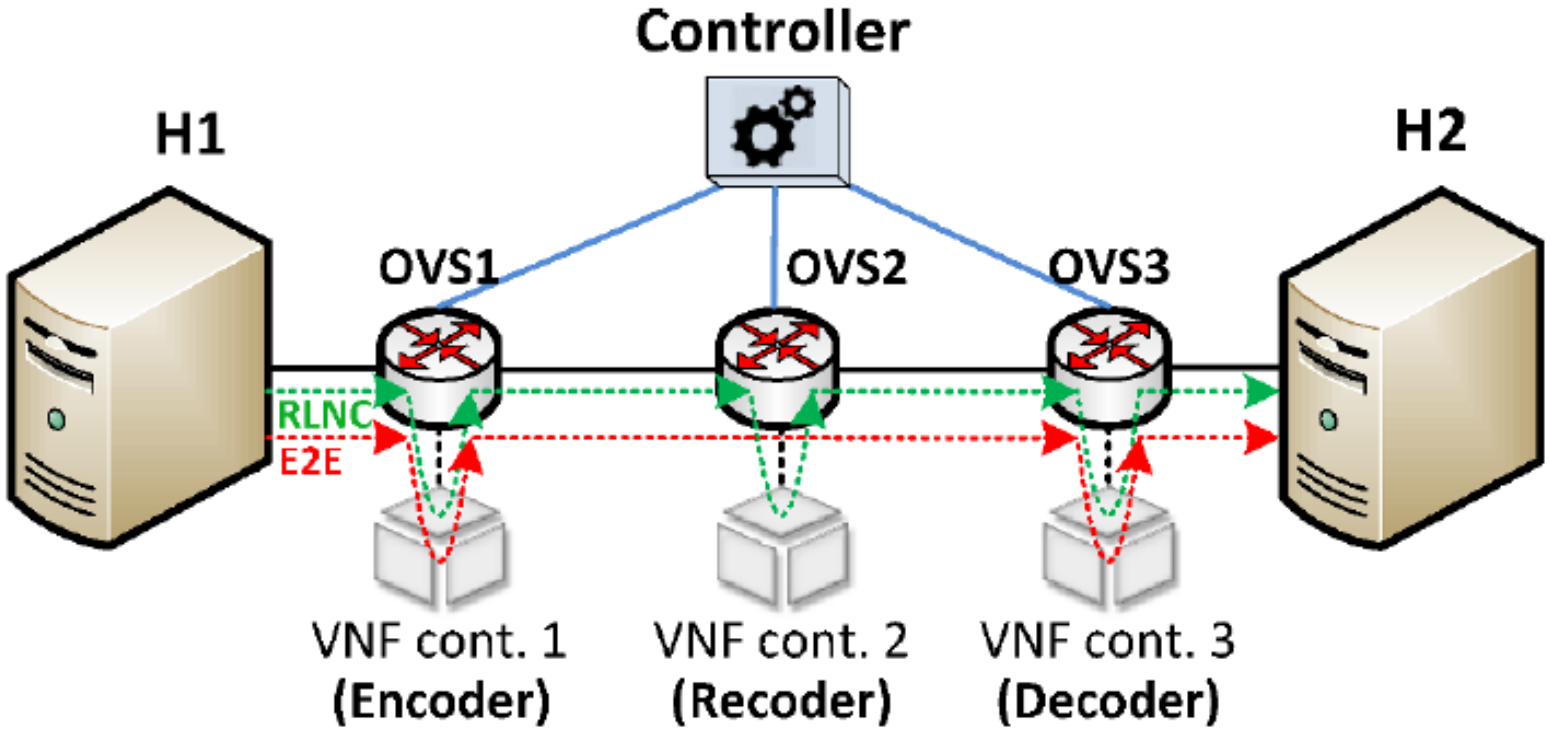
SDN testbed & Network Coding

- Example with ESCAPE prototyping environment



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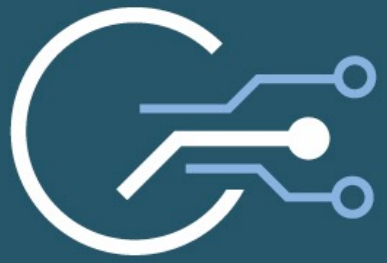

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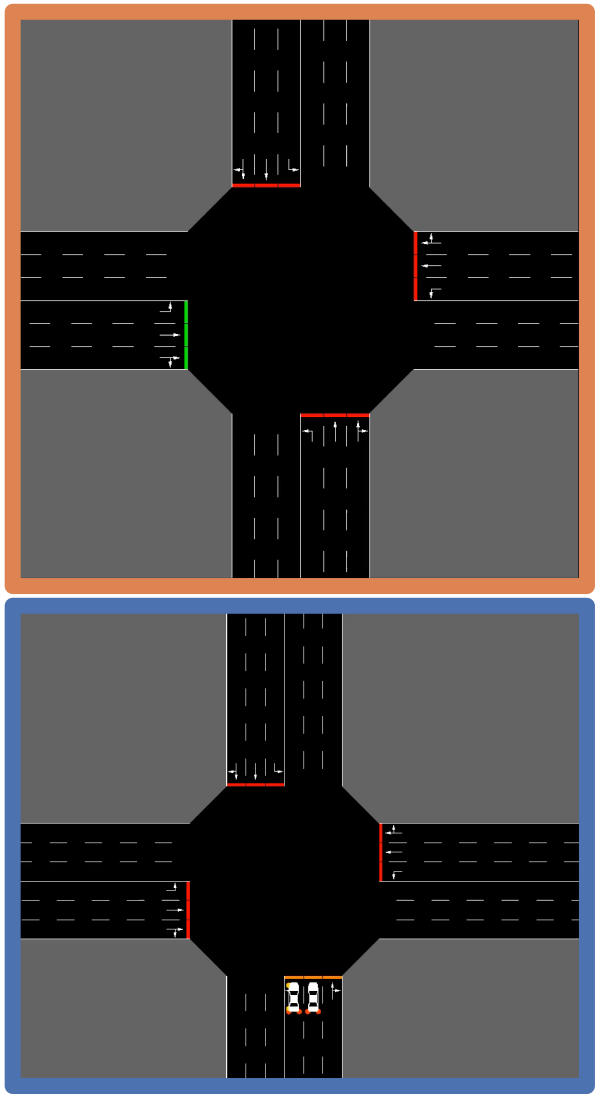
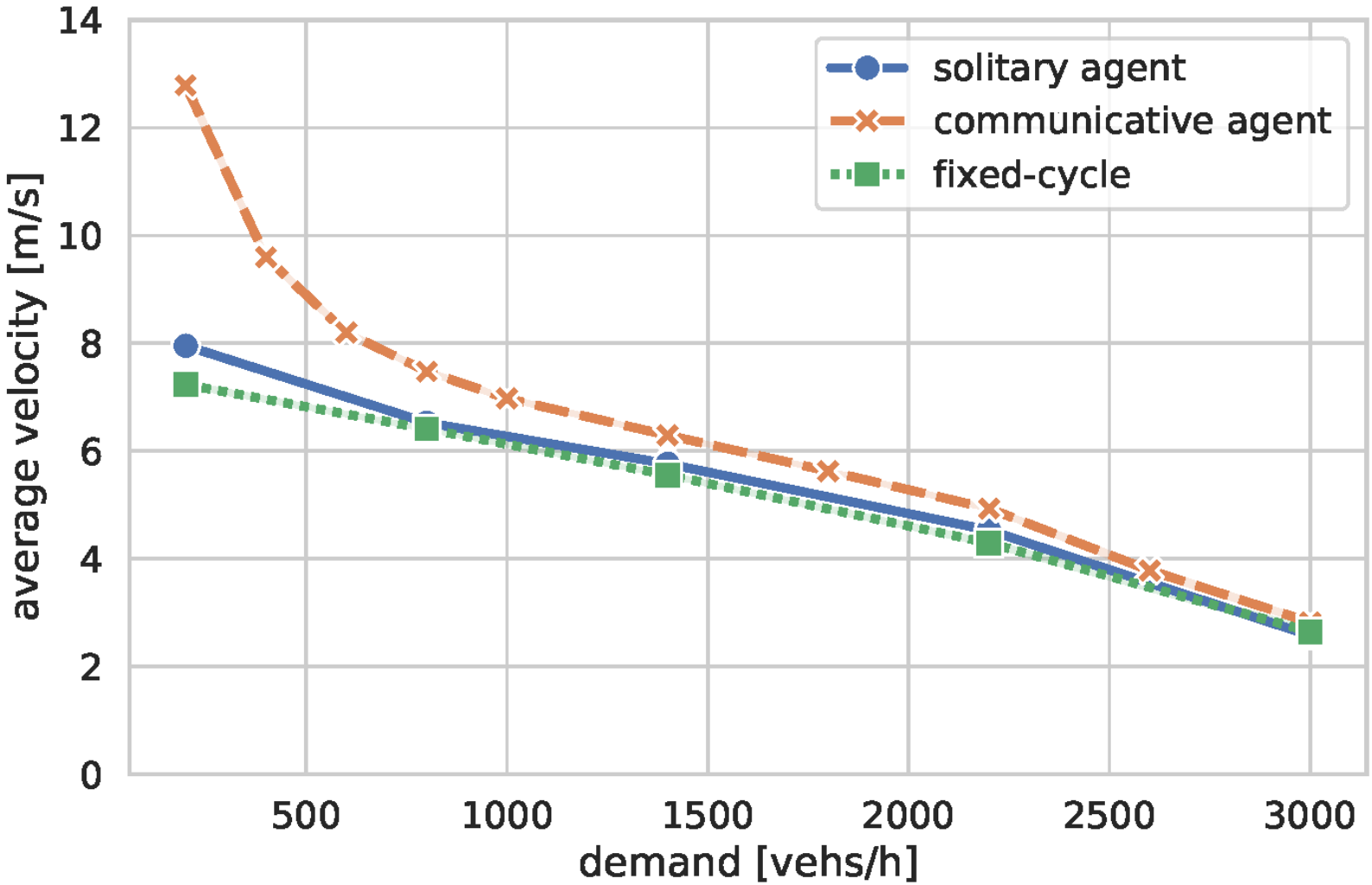
AI ?
(just machine learning)

Communication and AI





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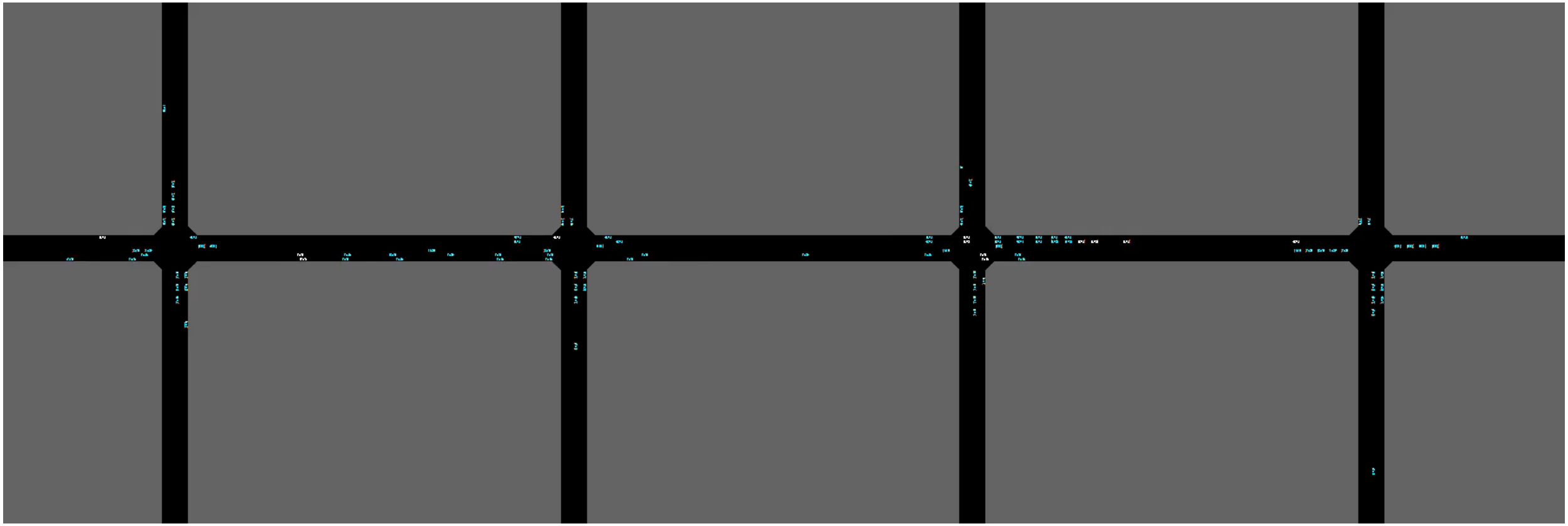
AI: Learned Multi-Intersection Management



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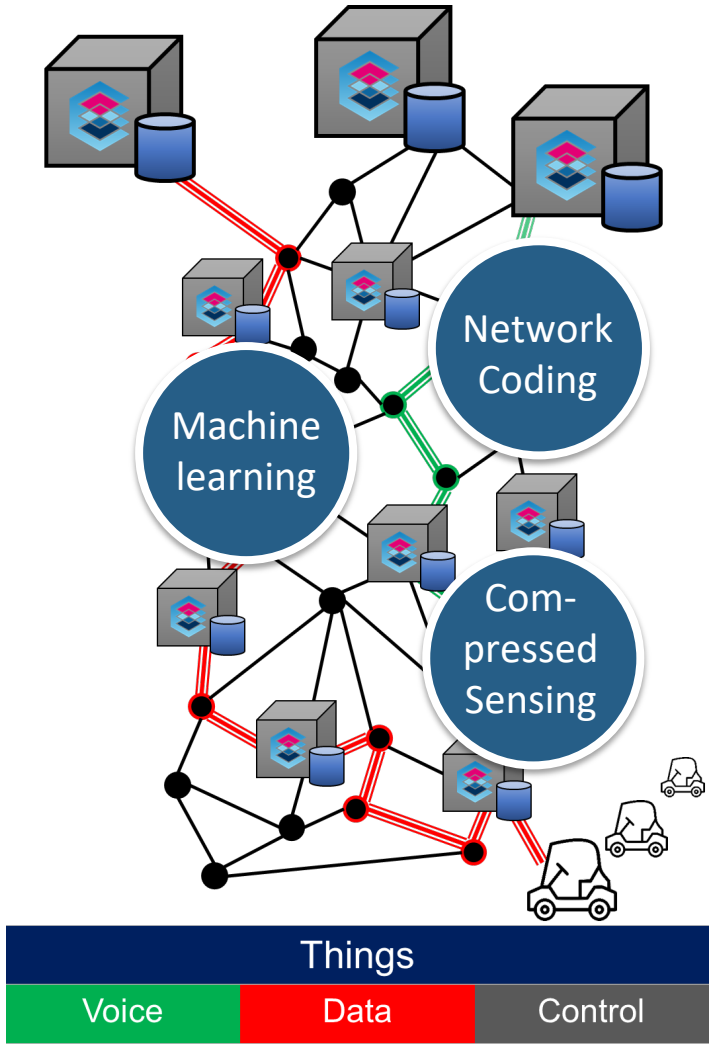
Remember the Need of Computing in Communication Networks

- It really happens in the network!



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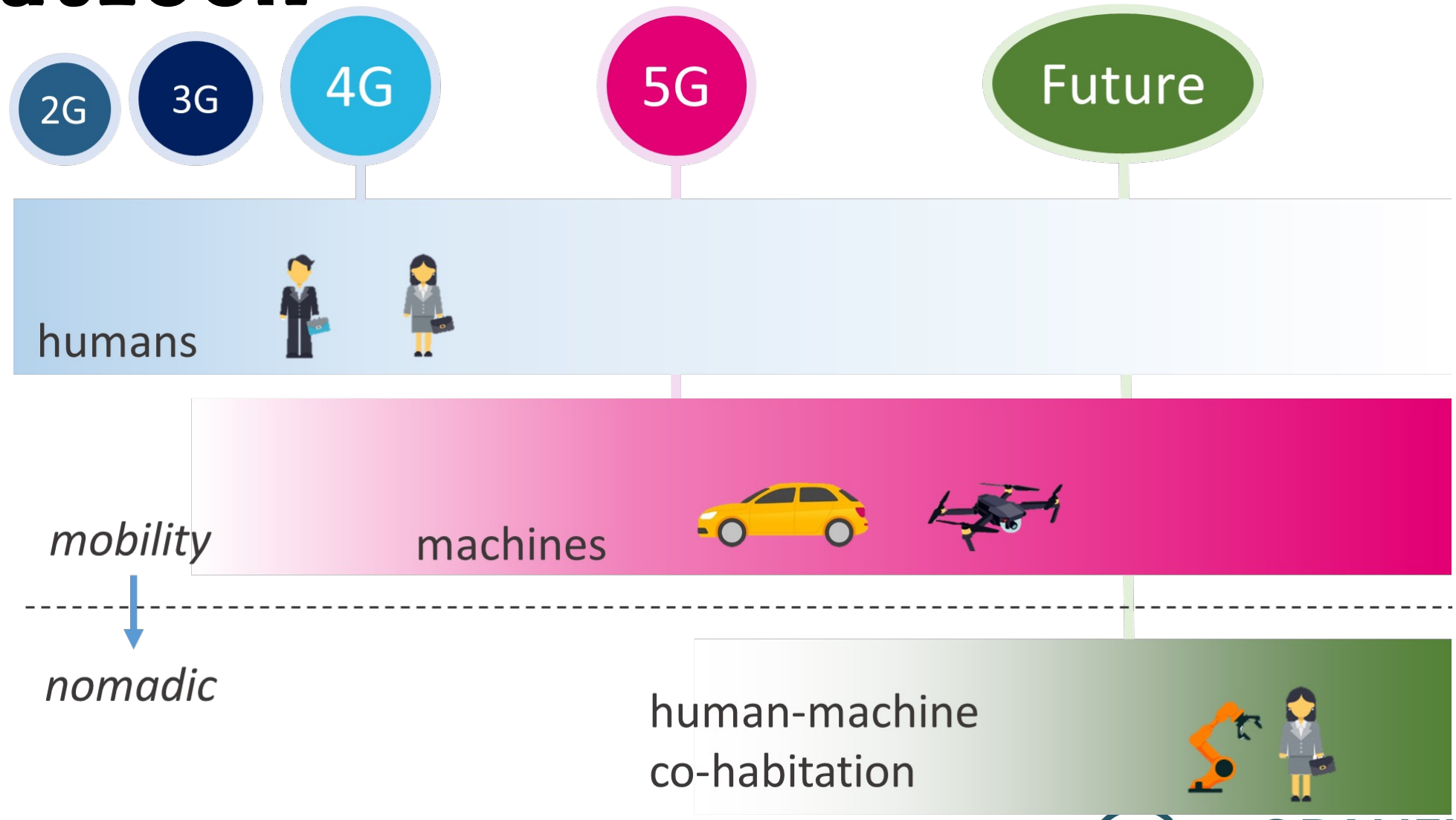
Future of Communication Networks

Outlook



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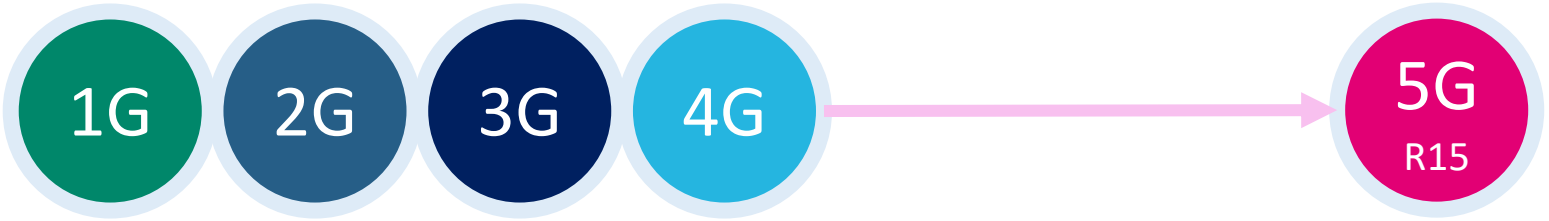
Outlook



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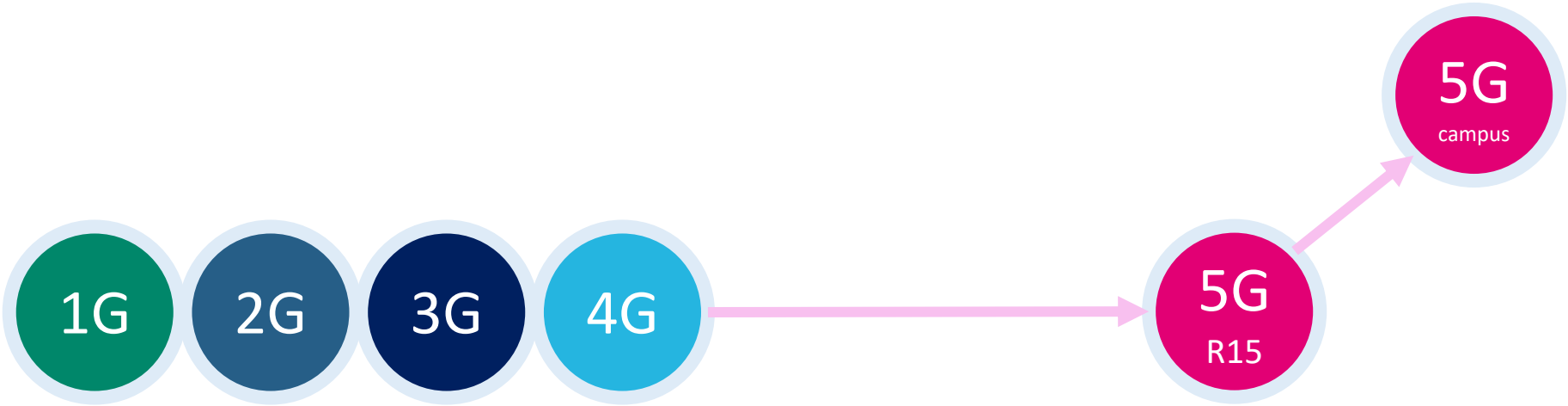
Outlook



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5G Campus (BMBF)

TECHNISCHE UNIVERSITÄT DRESDEN

DE CIX

SAP

Deutsche Funkturm

Telemotive
a company of Magna

wandelbots

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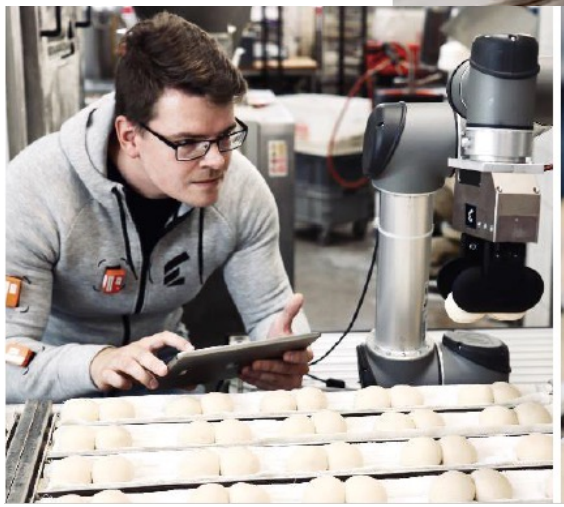
5G Campus (BMBF)

wandelbots



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5G Campus (BMBF)

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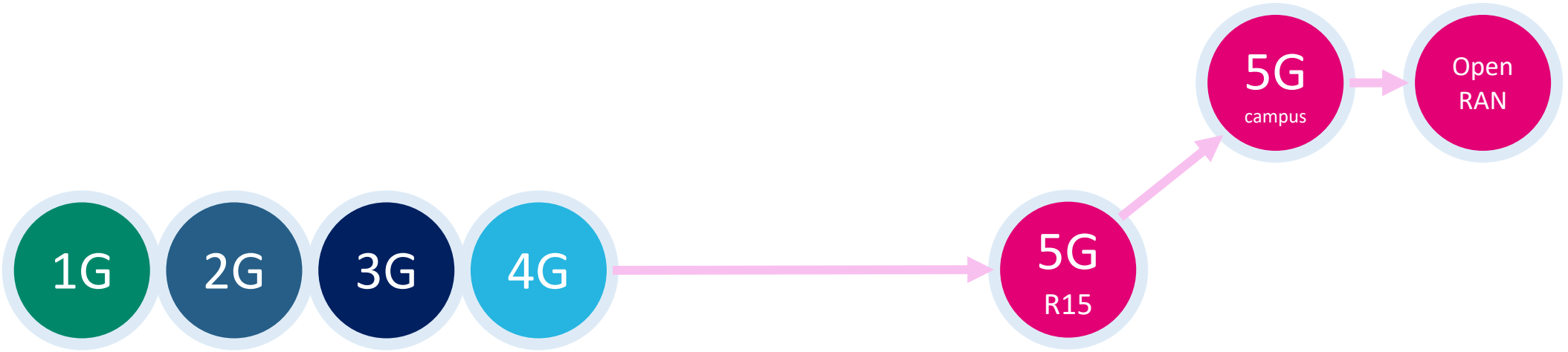
Outlook



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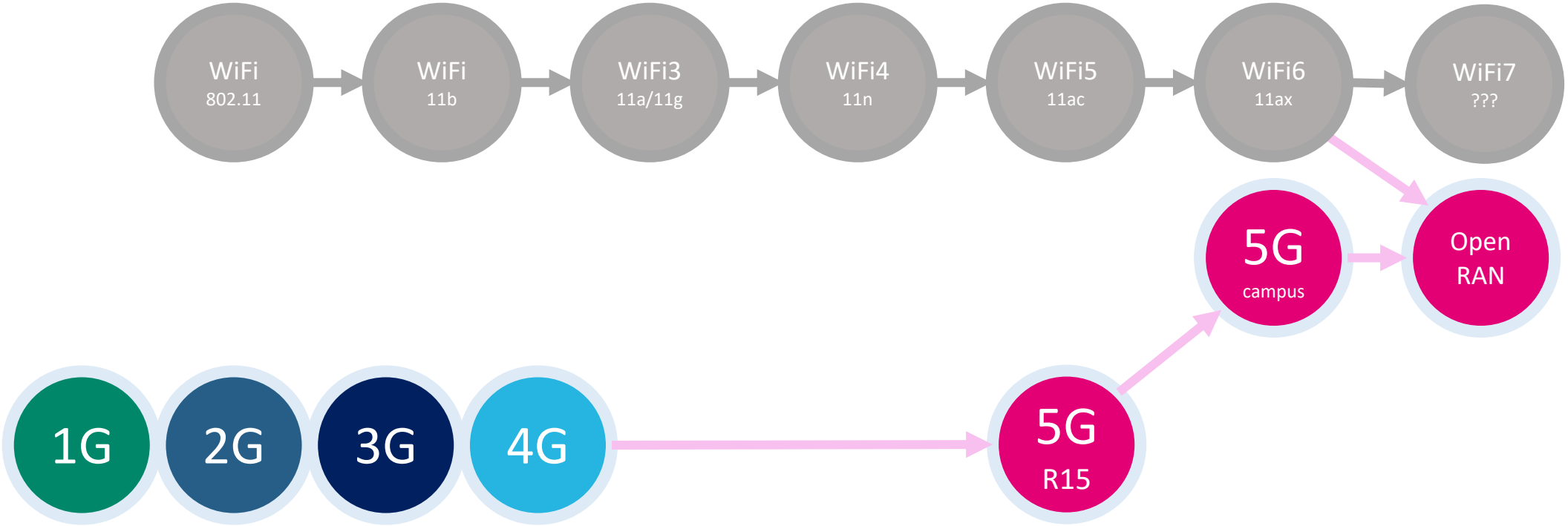
Outlook



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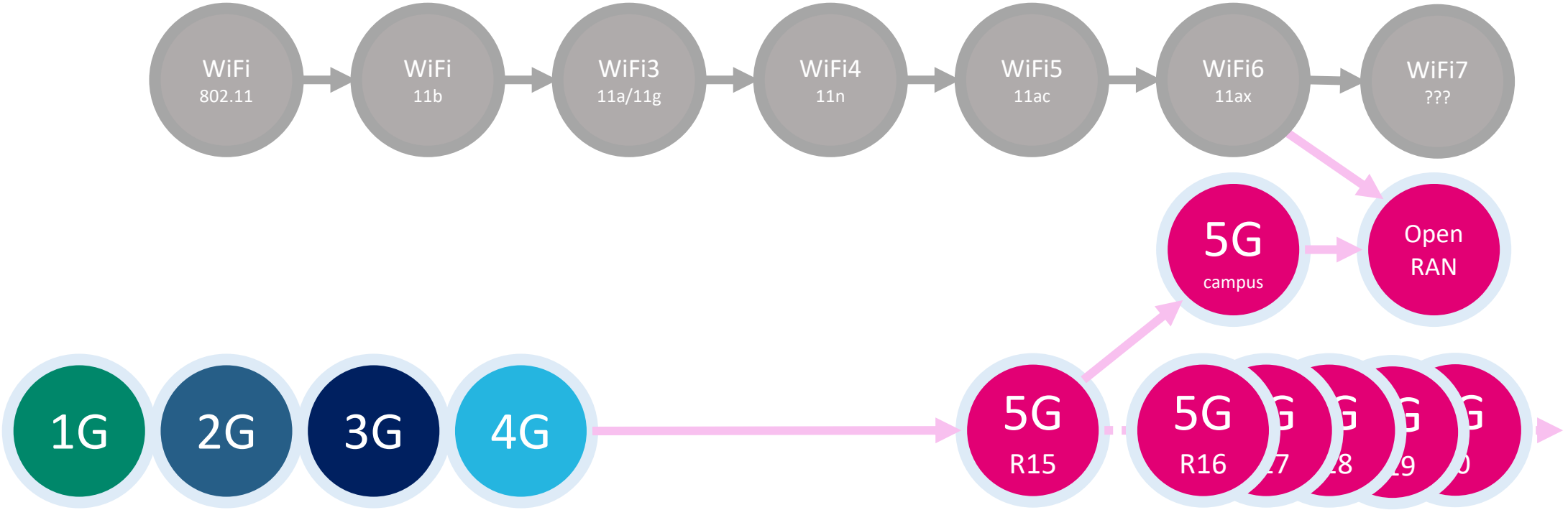
Outlook



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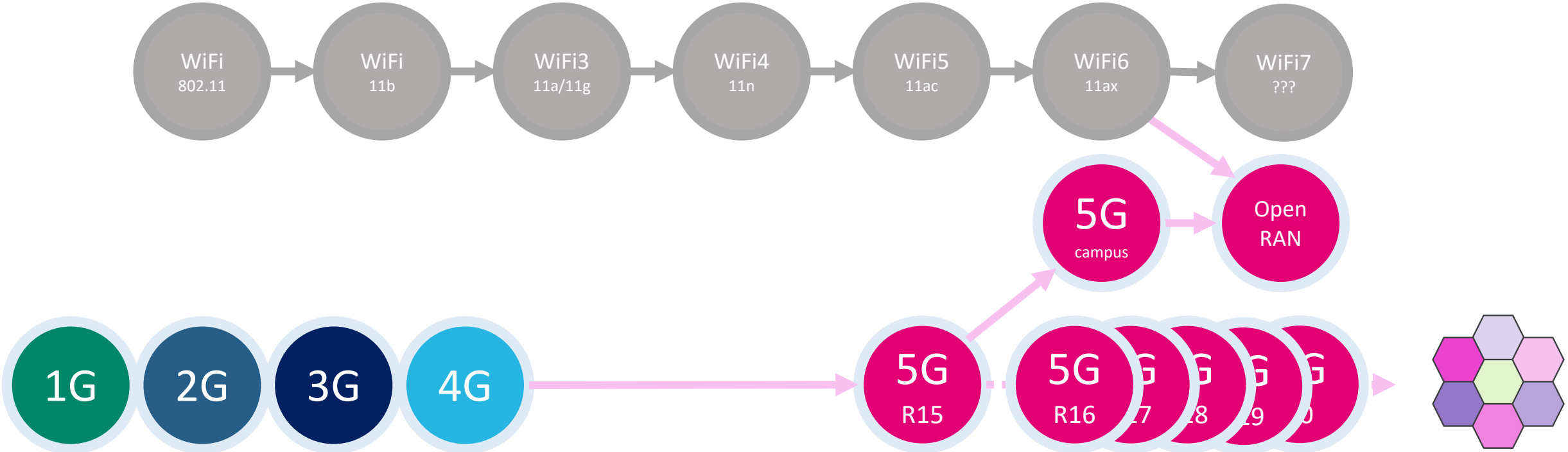

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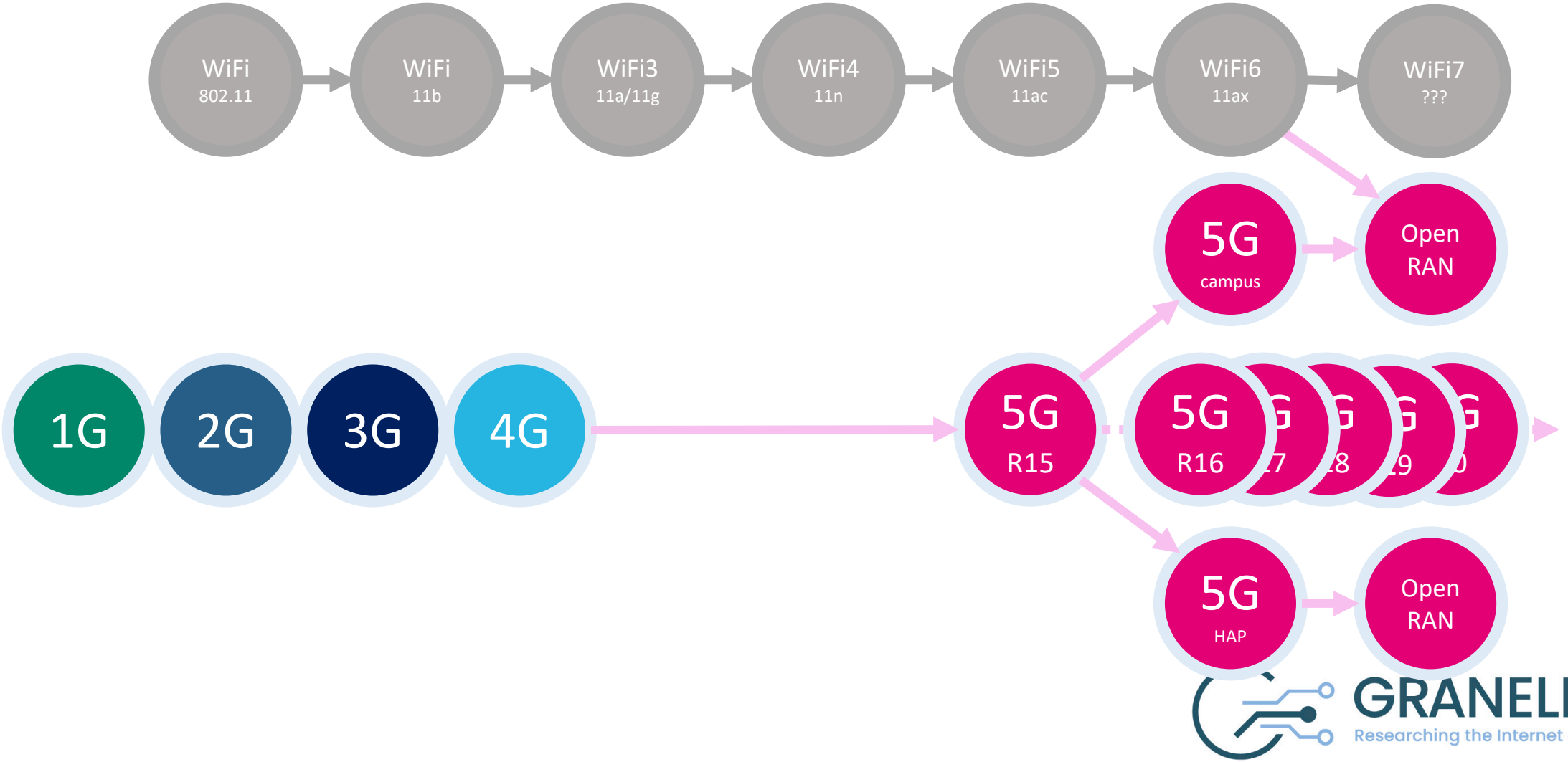

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High Altitude Platforms

1G 2G 3G 4G → 5G R15 → 5G HAP → Open RAN

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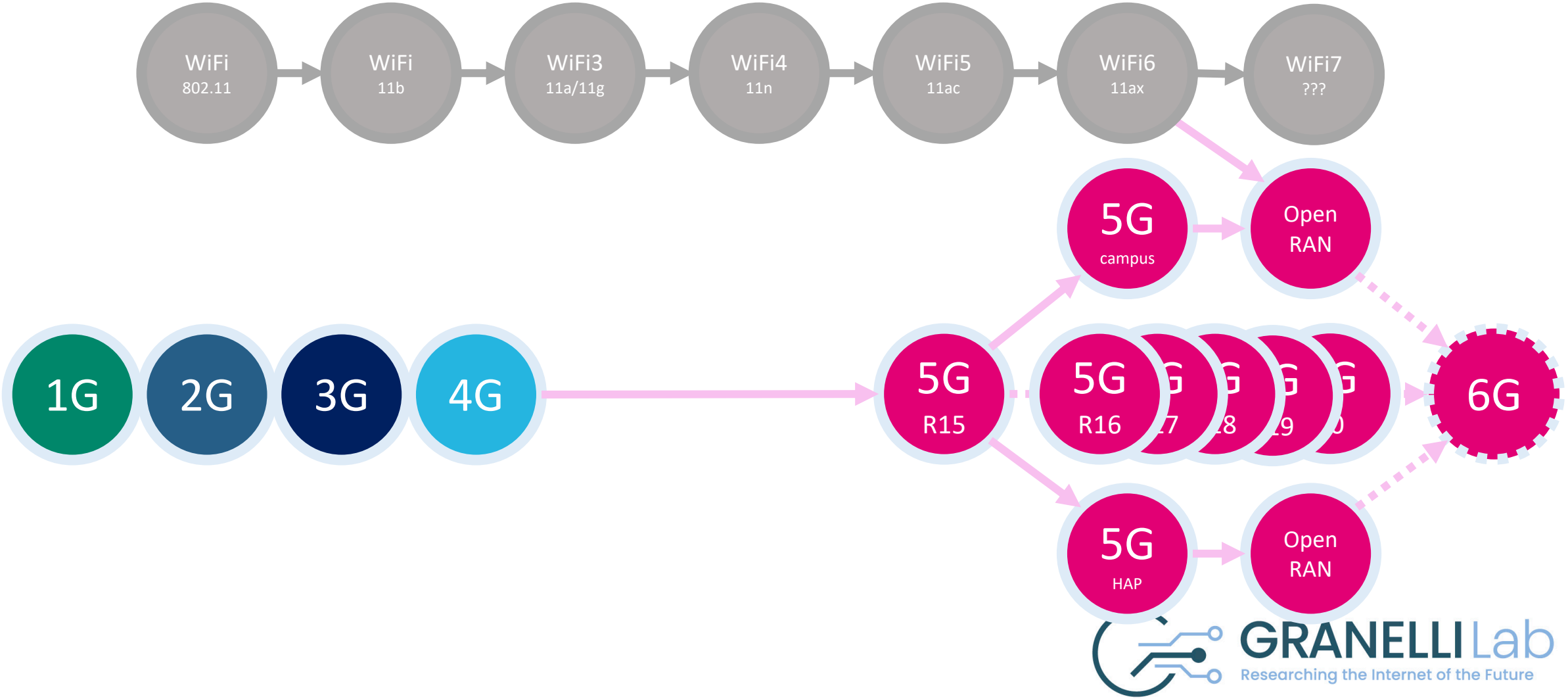
WiFi
802.11
WiFi
11b
WiFi3
11a/11g
WiFi4
11n
WiFi5
11ac
WiFi6
11ax
WiFi7
???
5G
campus
Open
RAN
1G
2G
3G
4G
5G
R15
5G
R16
6G
5G
HAP
Open
RAN
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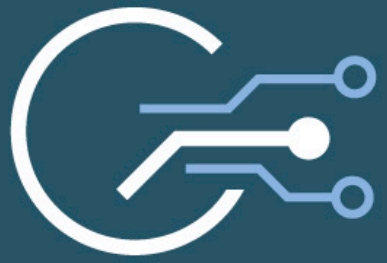

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Networking II

On the need for Computing in Communication Networks

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