6G Networks:
Challenges and Research Directions

Richard Li

Chief Scientist and SVP, Network Technologies,

Futurewei, USA

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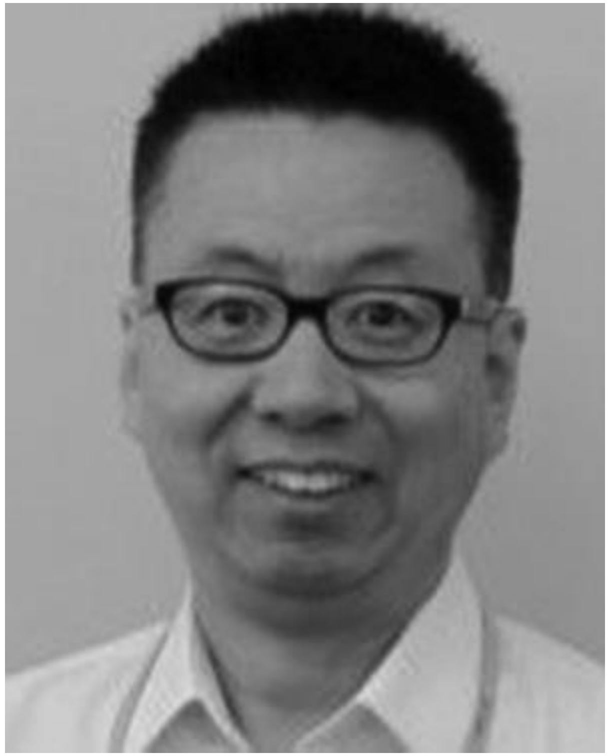
Richard LI

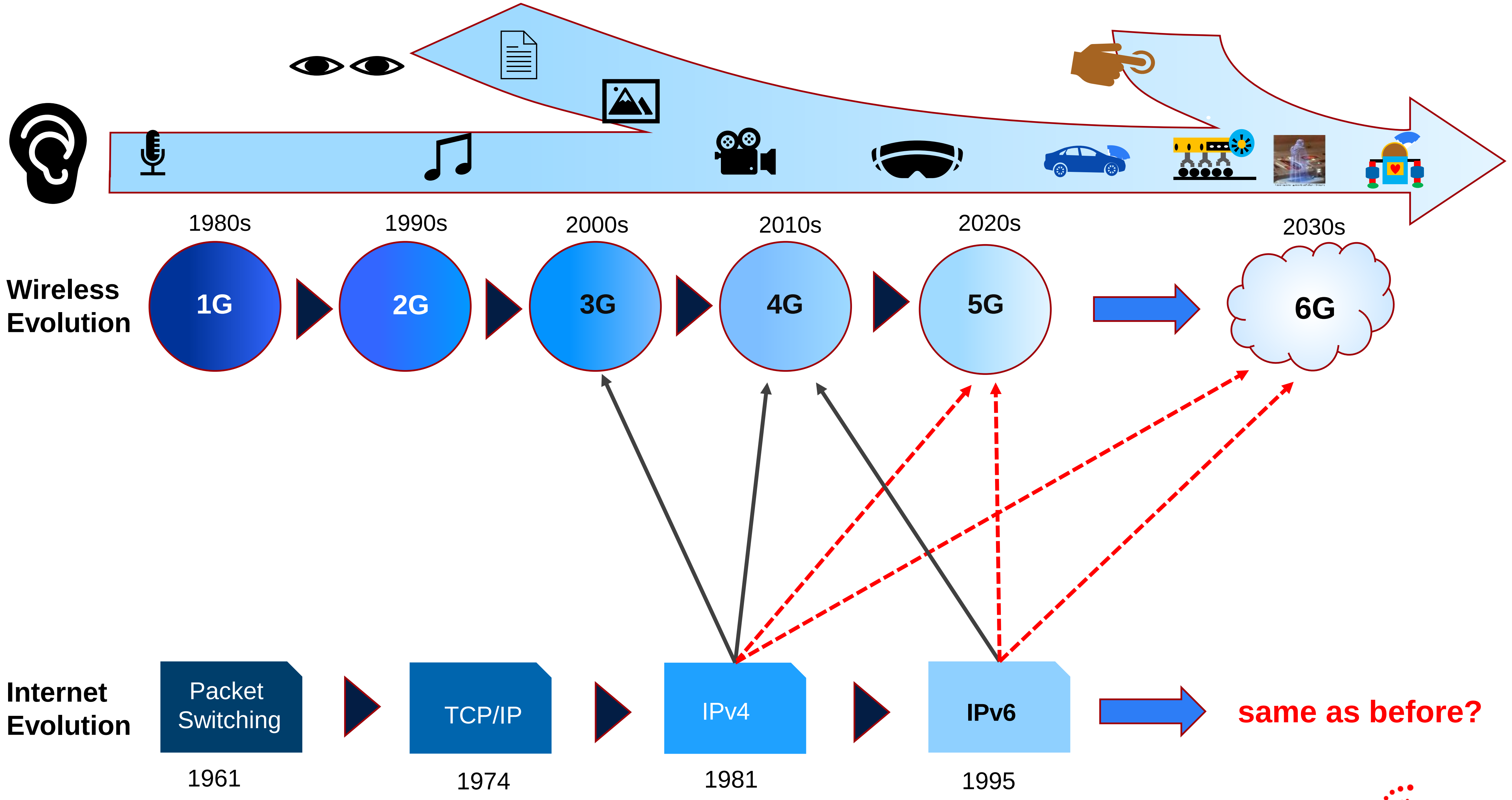


- Chief Scientist, SVP, Head of the Network Technologies Lab, Futurewei, USA (219 – Now)
- Chairman, ITU-T Focus Group on Network 2030, ITU-T, Switzerland (2018 – 2020)
- Vice-Chairman, ETSI ISG NGP (Next-Generation Protocols), ETSI, France (2016 – 2019)
- Chief Architect, SVP, Technical VP, Senior Director, Distinguished Engineer, Huawei R&D USA (2007-2019)
- Fellow of IARIA, 2016 Spring/Summer
- Ph.D. in Mathematics, Instituto Superior Técnico, Universidade de Lisboa, Portugal
- Master and Bachelor in Computer Science and Engineering, Southeast University, China

6G is not yet defined, but …

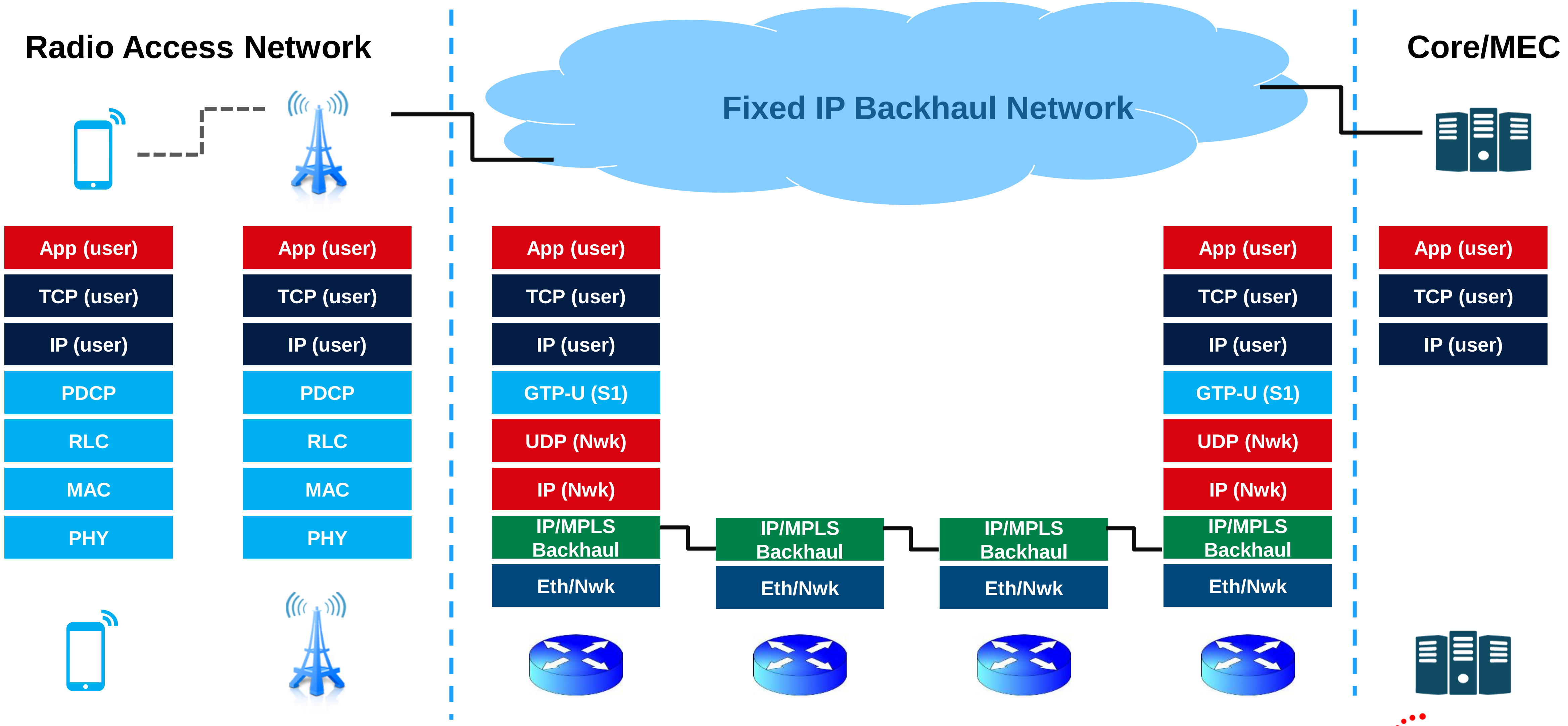
- ❖ Its visions are being set up, and use cases are being identified
  - ITU-T Focus Group on Network 2030
  - Next-G Alliance, USA
  - 6G Flagship, Finland,
  - 5G/6G Innovation Center, University of Surrey, UK
  - Europe Hexa-X
  - China IMT-2030 Promotion Group
  - Many, many others
- ❖ Its enabling technologies are under way
  - Basic Technology: Physics, Material, Biology, Chemistry, Semi-Conductor
  - Radio Technology: TeraHtz, RIS, OAM, IHR
  - Networking Technology: New Architecture, New Communication Methods , New Protocols
    - – Omni-Convergence and Reconvergence
    - – High Precision Communications
    - – Qualitative Communications and/or Semantic Communications
    - – Heterogenous Networks: Heterogenous Access, Heterogenous Control, Heterogenous Networking Resources and Power
- ❖ All that 5G promised but not delivered are expected to be supported by 6G
- ❖ 6G will ultimately rely on enabling technologies: neither over-promised nor under engineered

Will 6G Networks Be the Same as Before?



Source: Richard Li, New IP: Motivations and Technical Considerations, Keynote Speech, UNet 2021- International Symposium on Ubiquitous Networking, May 19-22, 2021

Does this network protocol stack still work for 6G applications? If yes, why? If not, what will we do about it?



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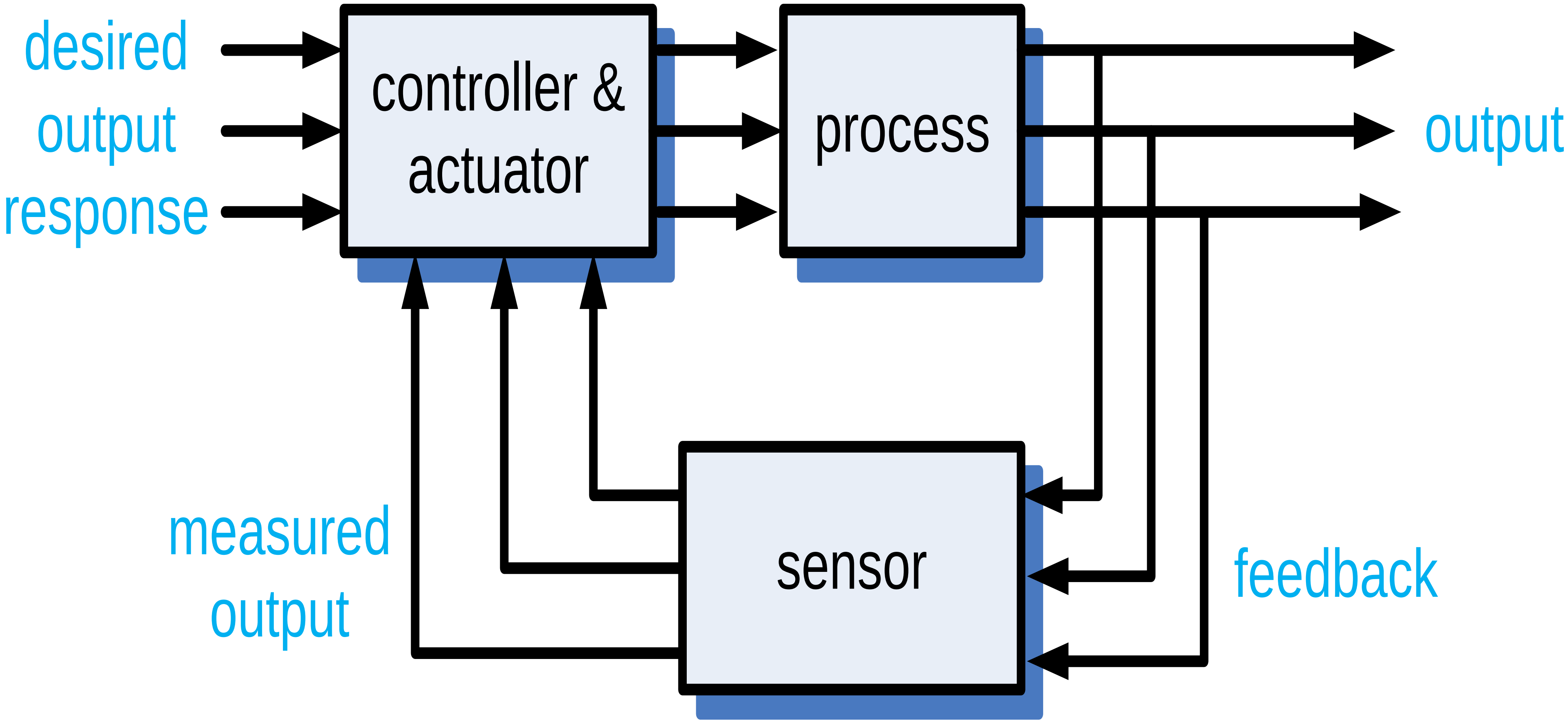
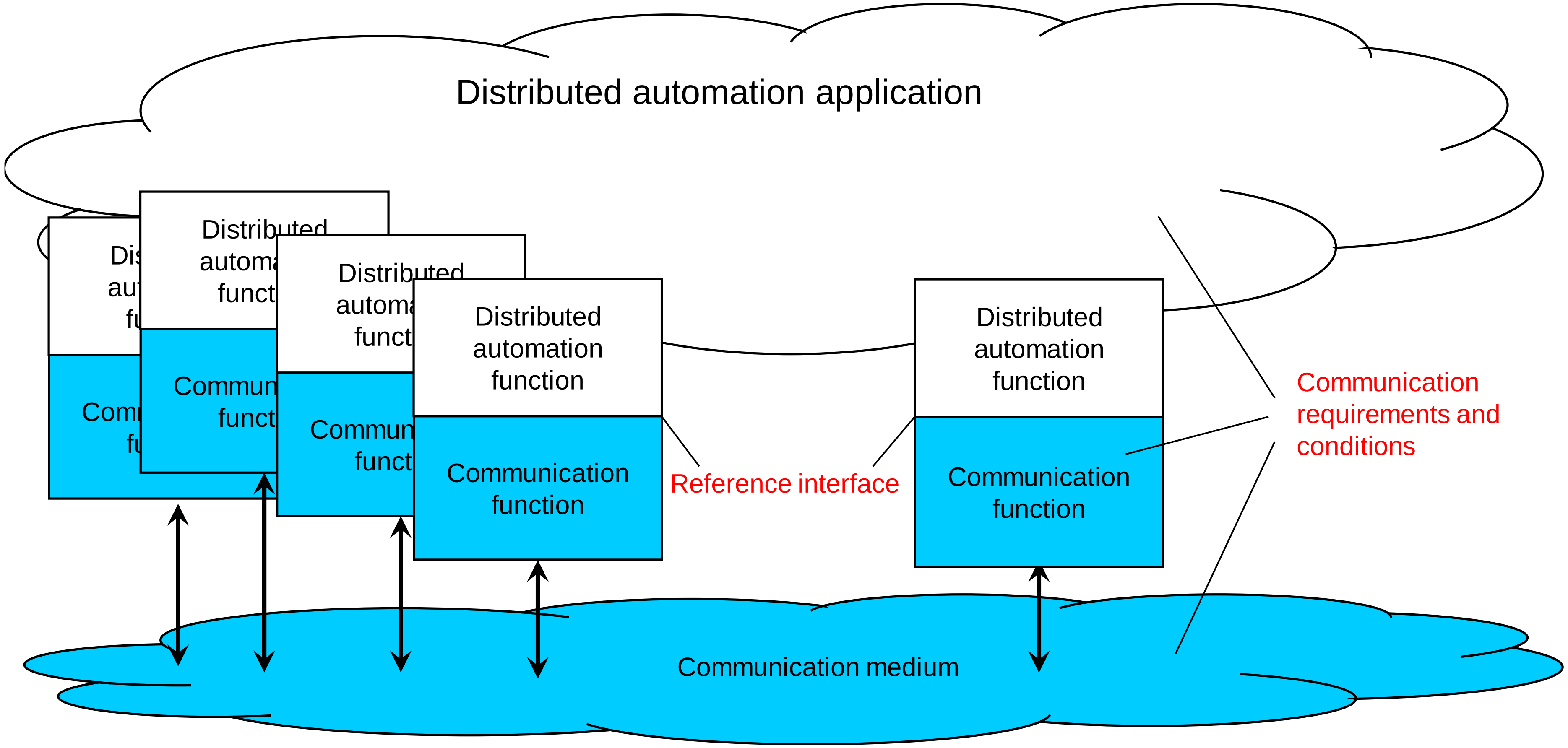
Let’s start with industrial automation and control ….

Closed-Loop Control System for Automation



Richard C. Dorf and Robert H. Bishop, "Modern Control Systems", Pearson, Harlow, 13th Edition, 2017.

Communication Network for Distributed Automation System



Source: 3GPP TR 22.804 V16.2.0 (2018-12)

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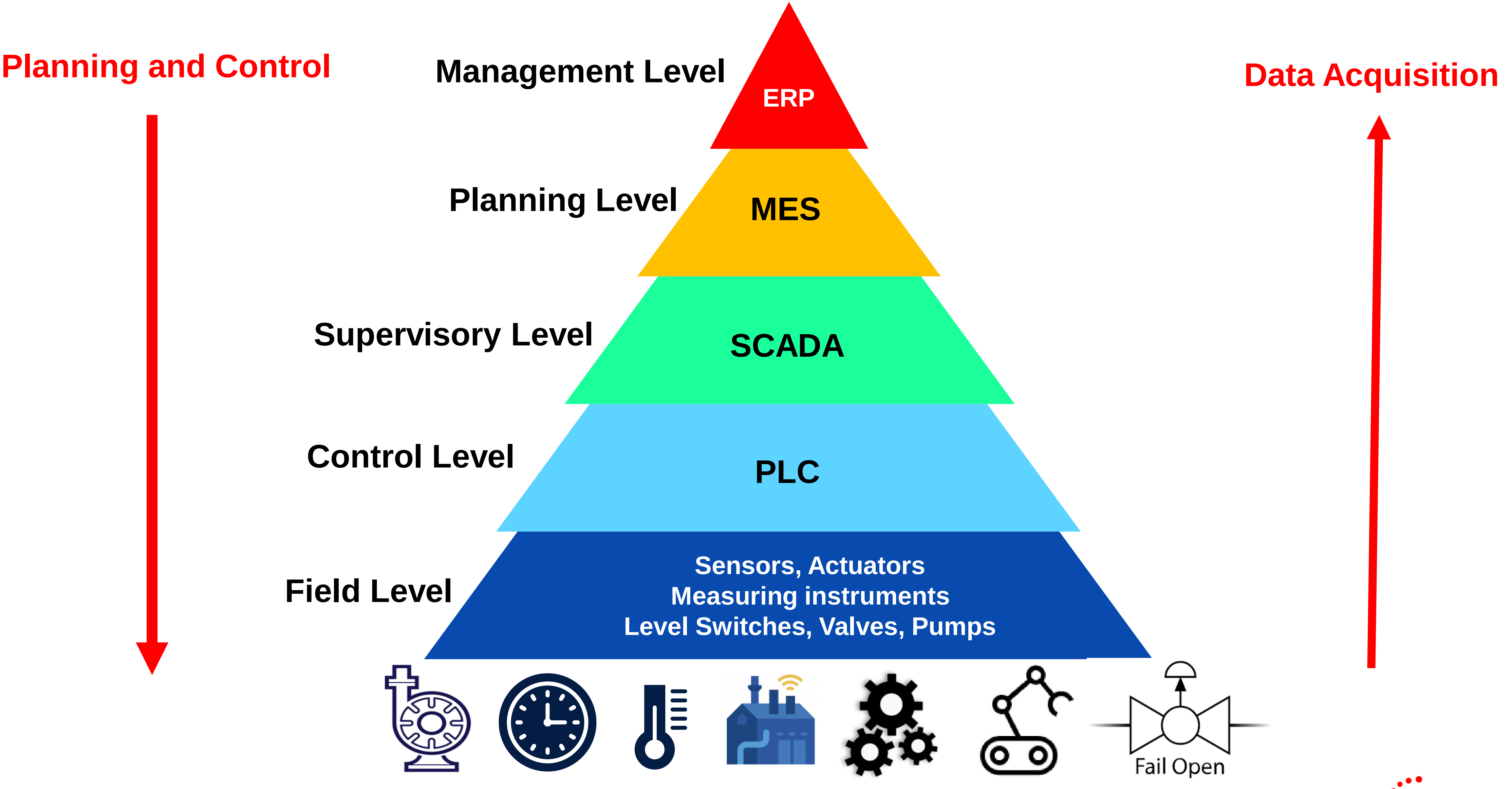
Classical Automation Pyramid



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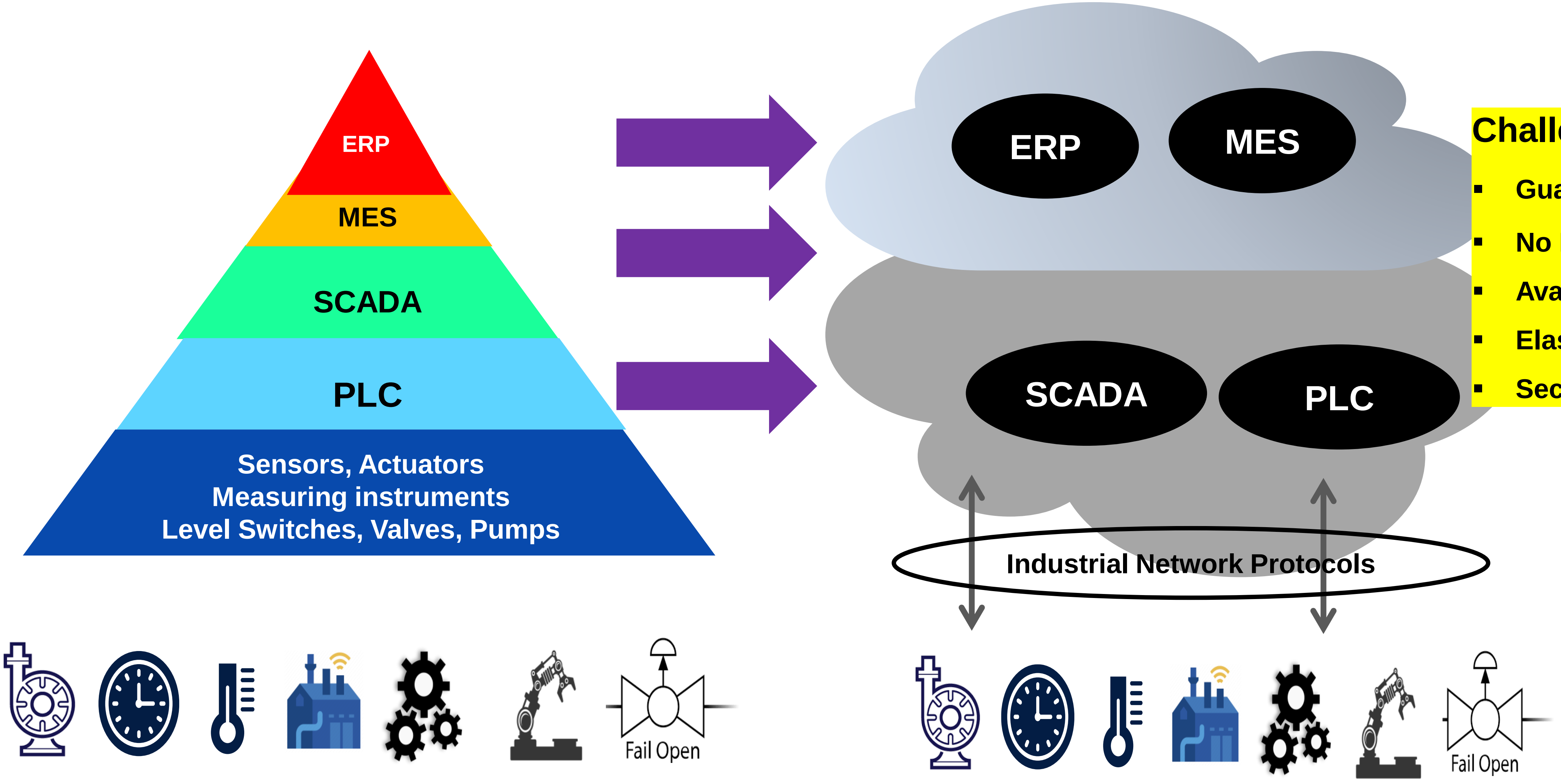
Cloudification of Automation Pyramid

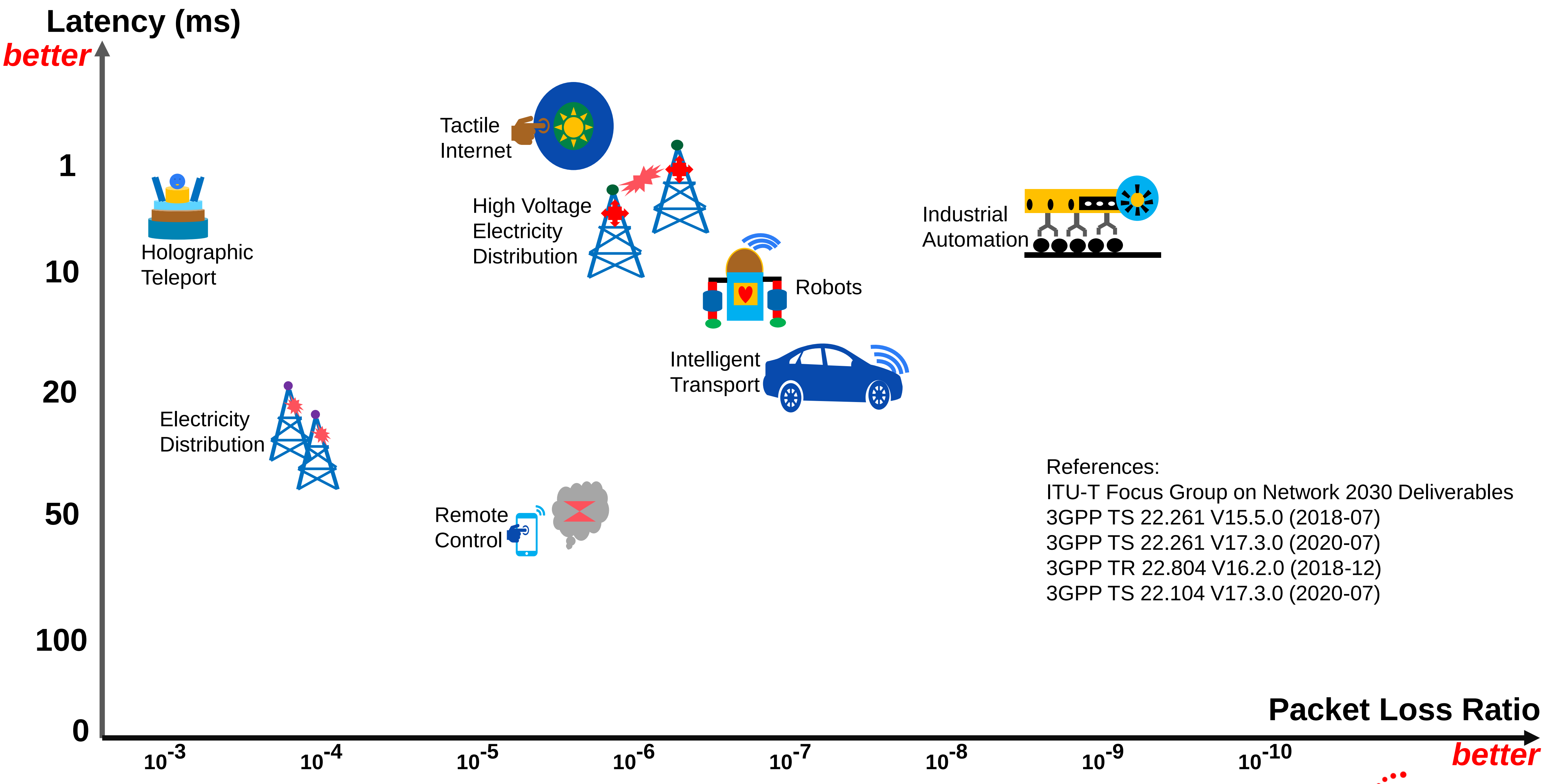


Challenges:

- Guaranteed Latency
- No Packet Loss
- Availability
- Elasticity
- Security

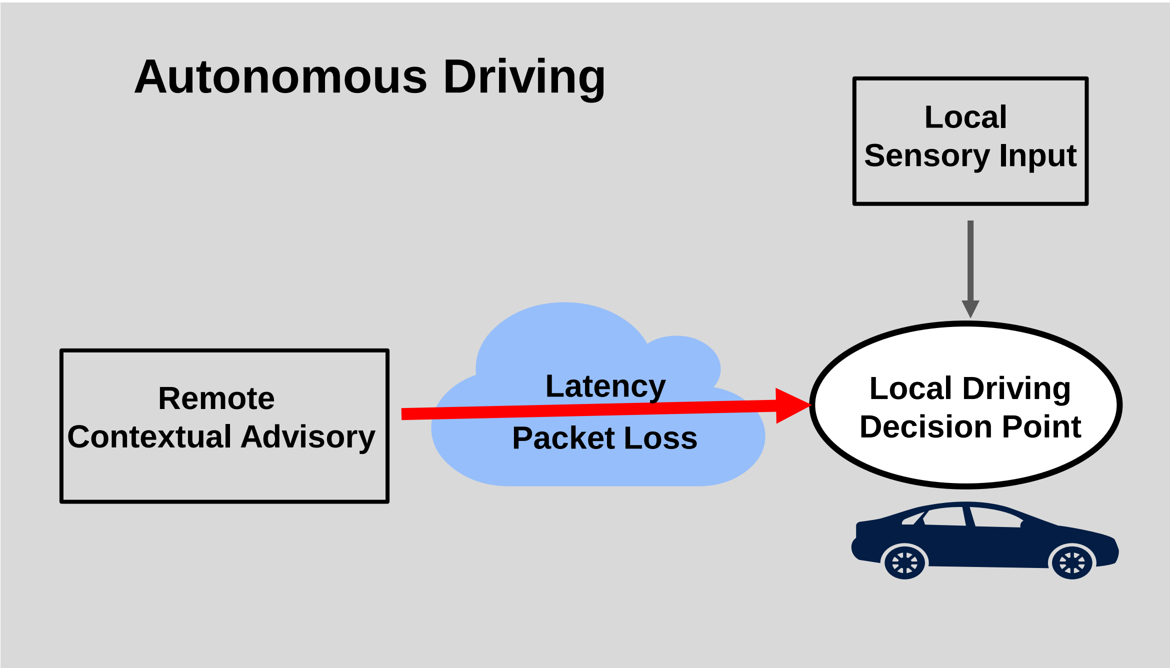
Credit: Heiko Koziolek, Towards the Automation Cloud Architectural Challenges for a Novel Smart Ecosystem, ABB Group

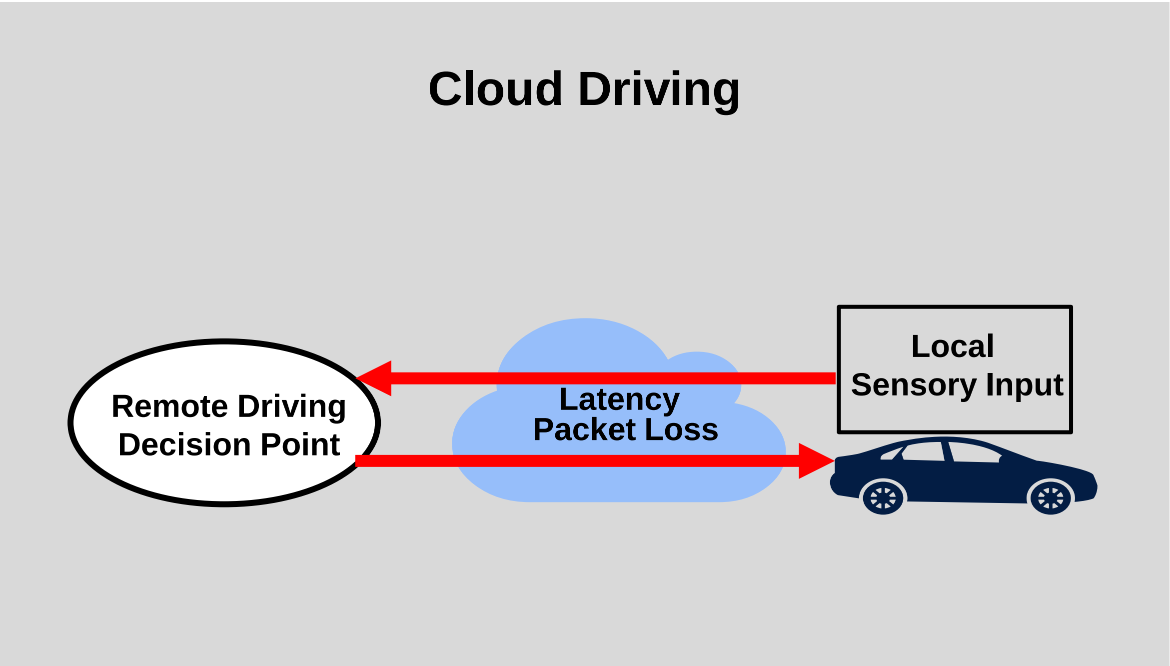
Many 6G use cases require more than connectivity; KPI guarantee is a must!!!



Some 6G applications are mission-critical, and even life-critical

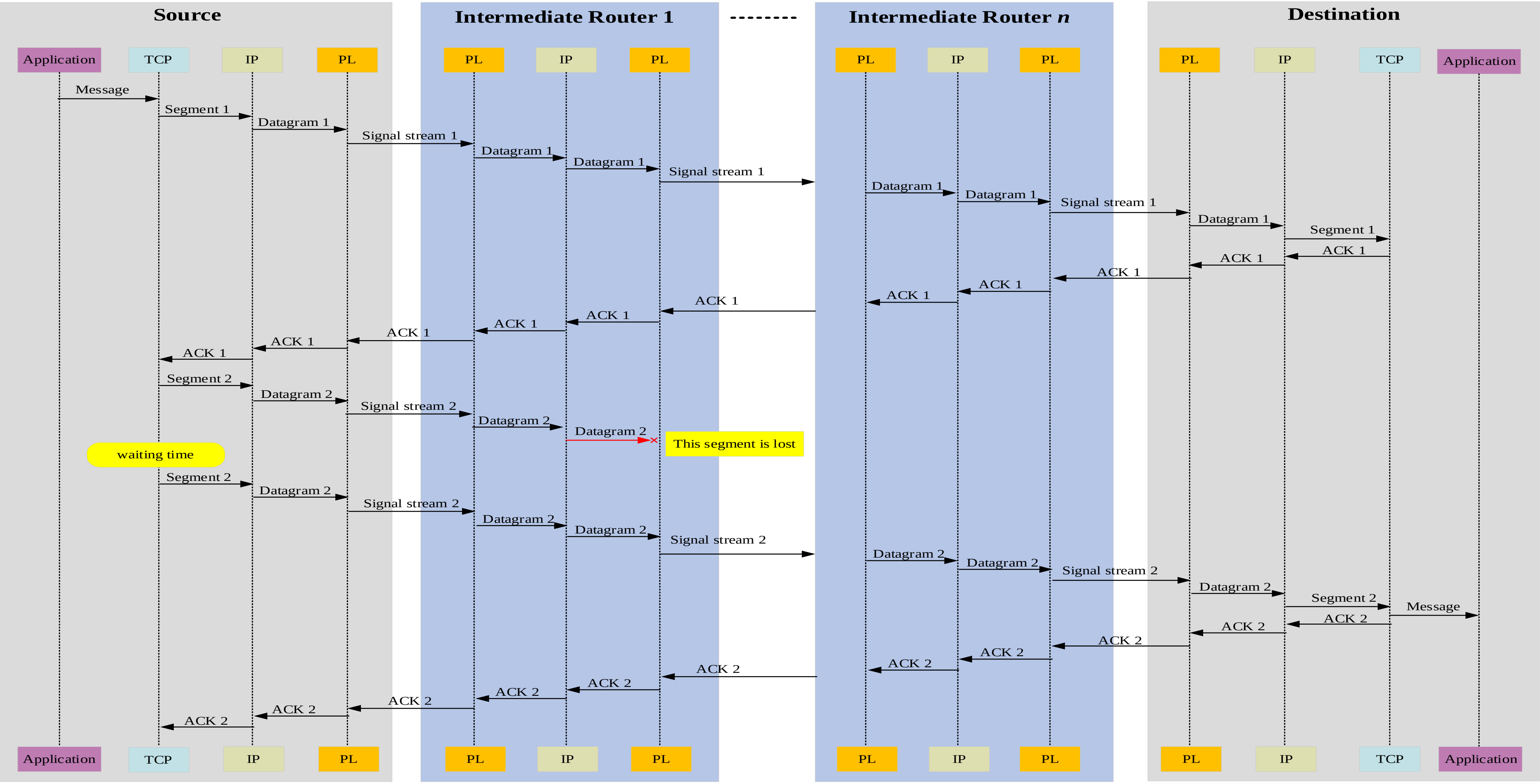
Maximal End-to-End Latency = 30 ms (3GPP TS 22.261 version 15.5.0 Release 15)



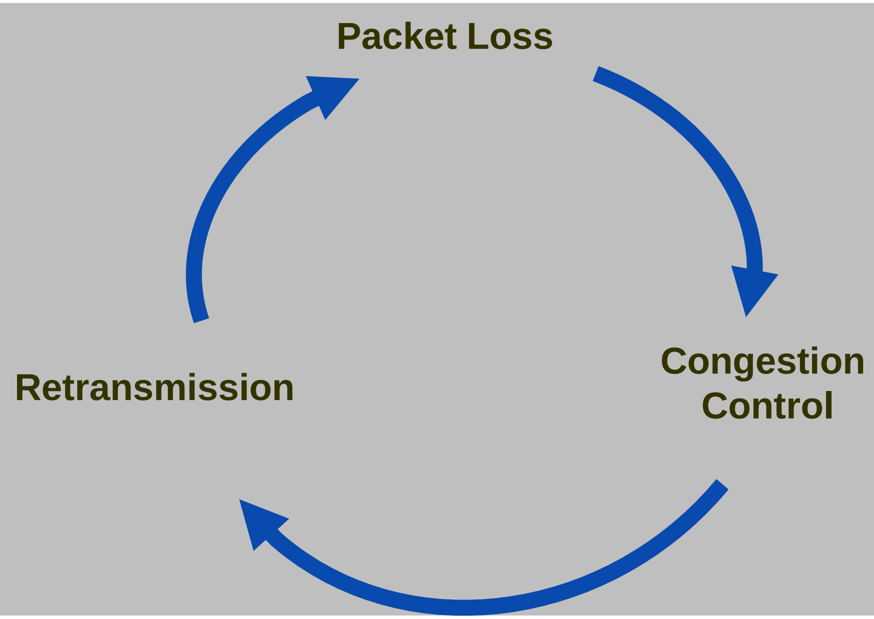


What happens in the existing networks?

A packet can get lost. If it is lost, the sender is responsible for its re-transmission. If the retransmission happens, the latency will triple that of a single successful trip.



Current Network: Packet Delivery KPI is unpredictable



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- **Best Effort**: No guarantee for anything
- **DiffServ**: Per-hop differentiation
- **Traffic Engineering**: Bandwidth Guarantee

Unpredictable KPI over the Internet

- **Unpredictable Latency**
- **Unpredictable Packet Loss Ratio**

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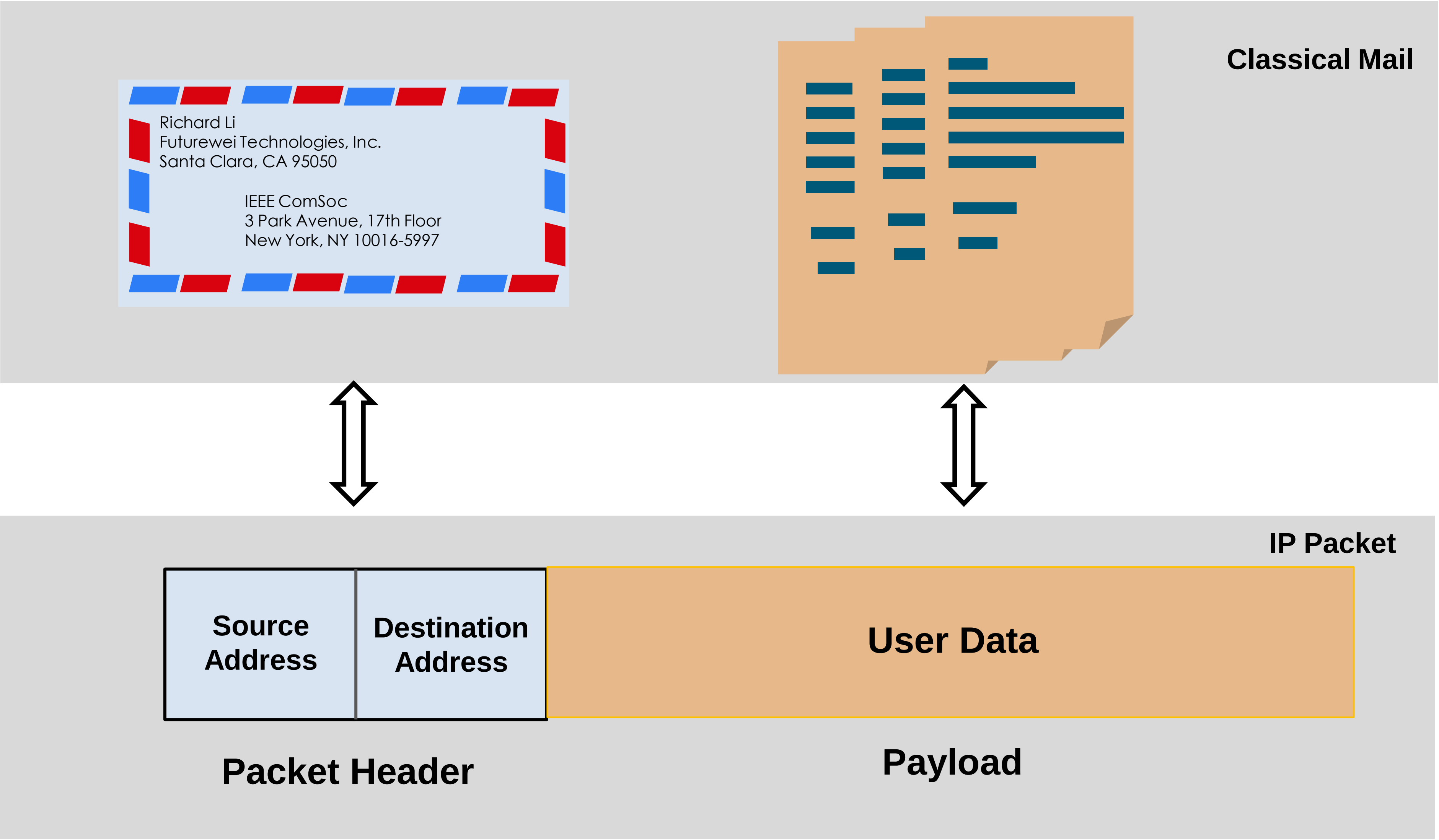
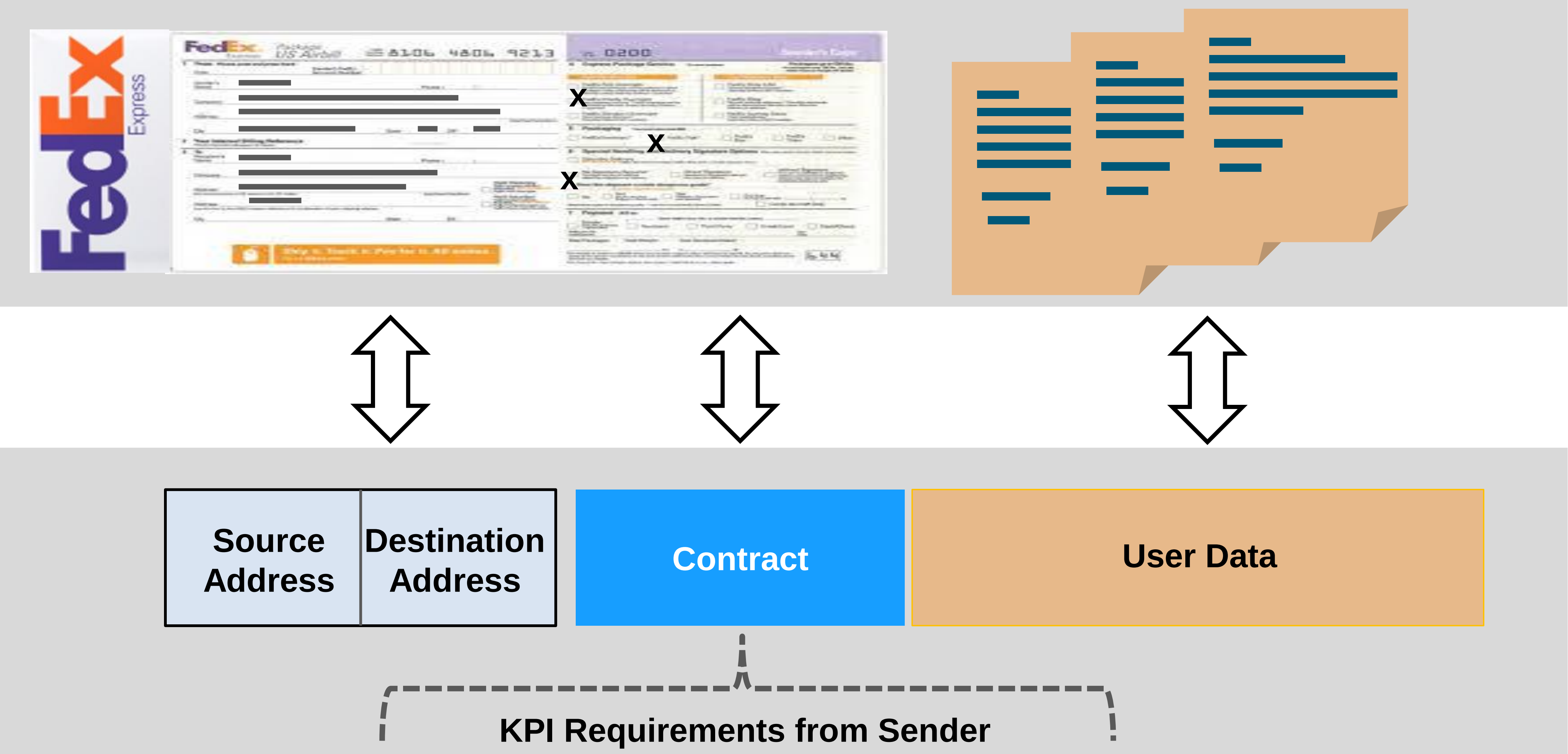
Classical Mail vs. the Existing Protocol



What if We Reimagine a Packet as a FedEx Package?



* FedEx is a trademark of FedEx Corp.

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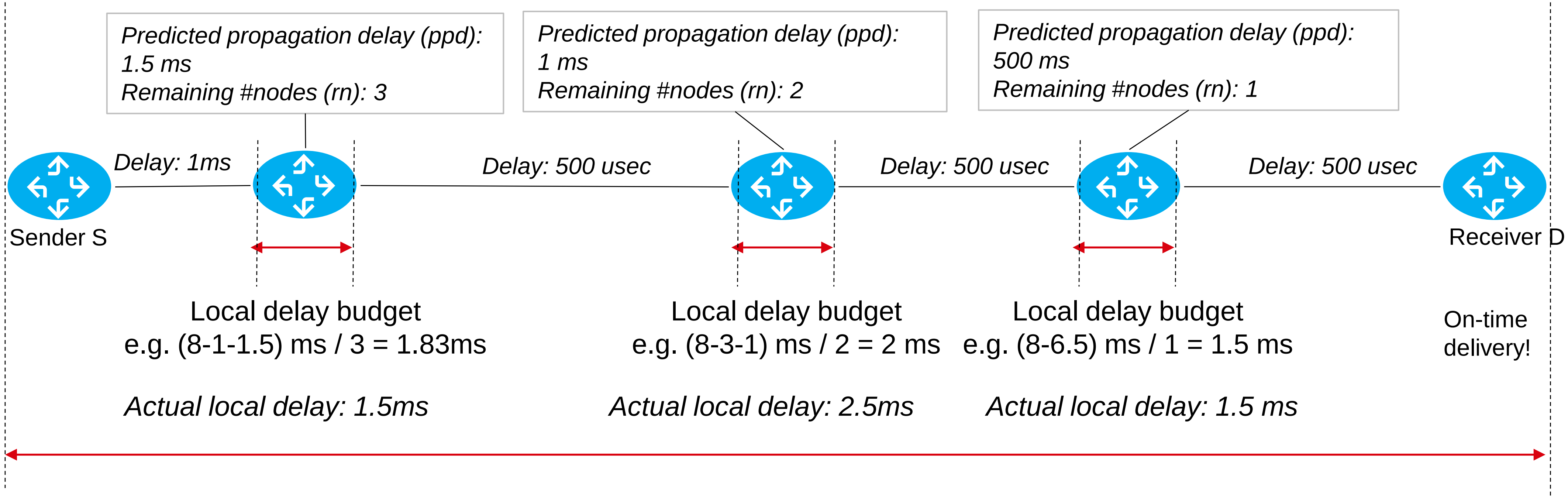
Deterministic and High-Precision KPI Guarantee

New IP Packet

Manifest	Sender S	Receiver D	Contract	User Data
			In-time delay == 8 ms	



Ref: A. Clemm and T. Eckert, High-Precision Latency Forwarding over Packet Programmable Networks, IEEE NOMS 2020, April 2020

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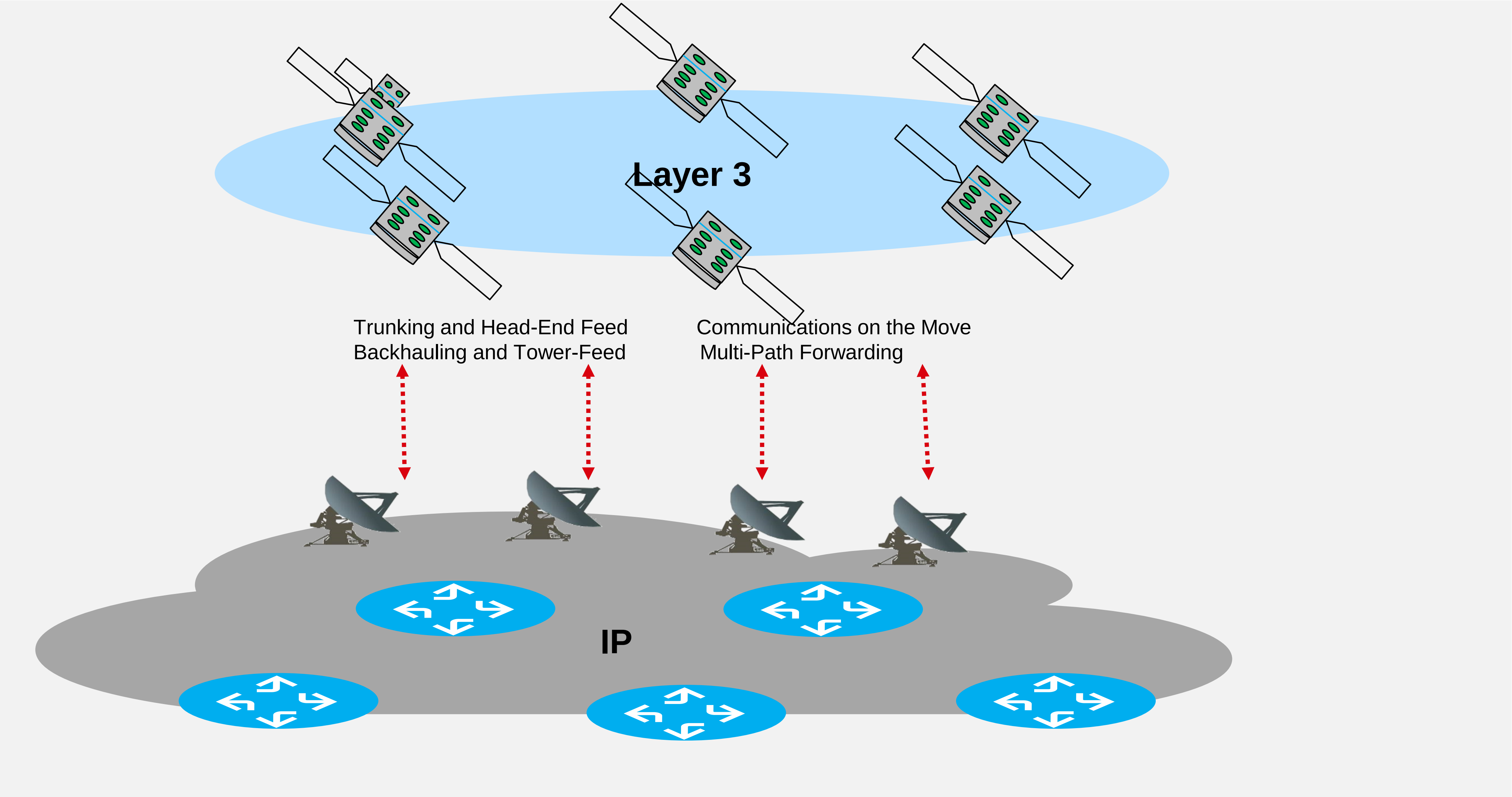
Now let's turn to non-terrestrial networks …

Some 6G use cases require convergence of heterogenous networks



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How do we address and identify a satellite?

- Satellite network
  - Multiple layer
  - Each layer is an interleaved grid network
- Satellite can be identified by:

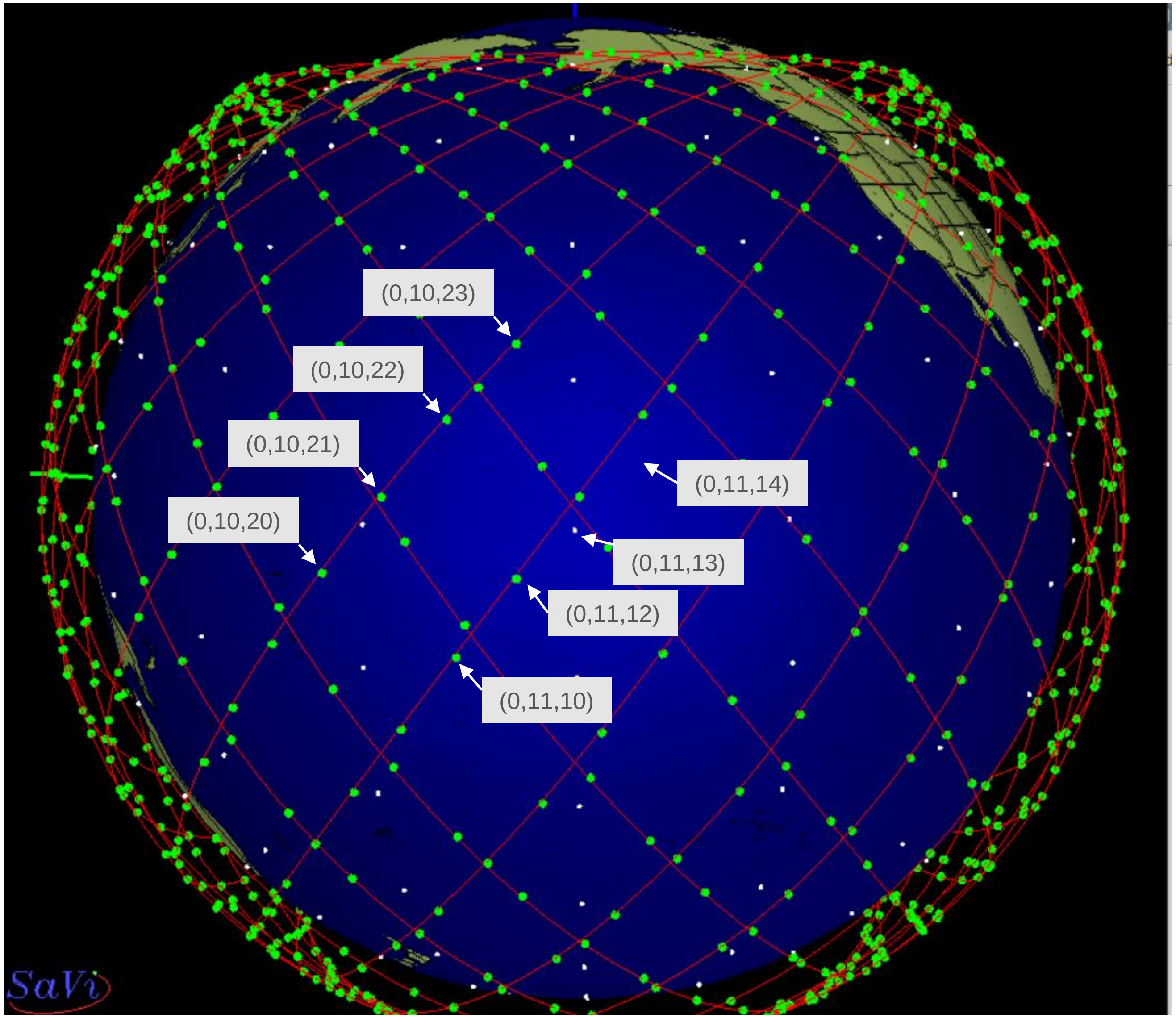
(Owner Code, Shell_index, Orbit_index, Sat_index)

Which layer

Which orbit plane

Which sat in orbit plane

- draft-lhan-satellite-semantic-addressing-01



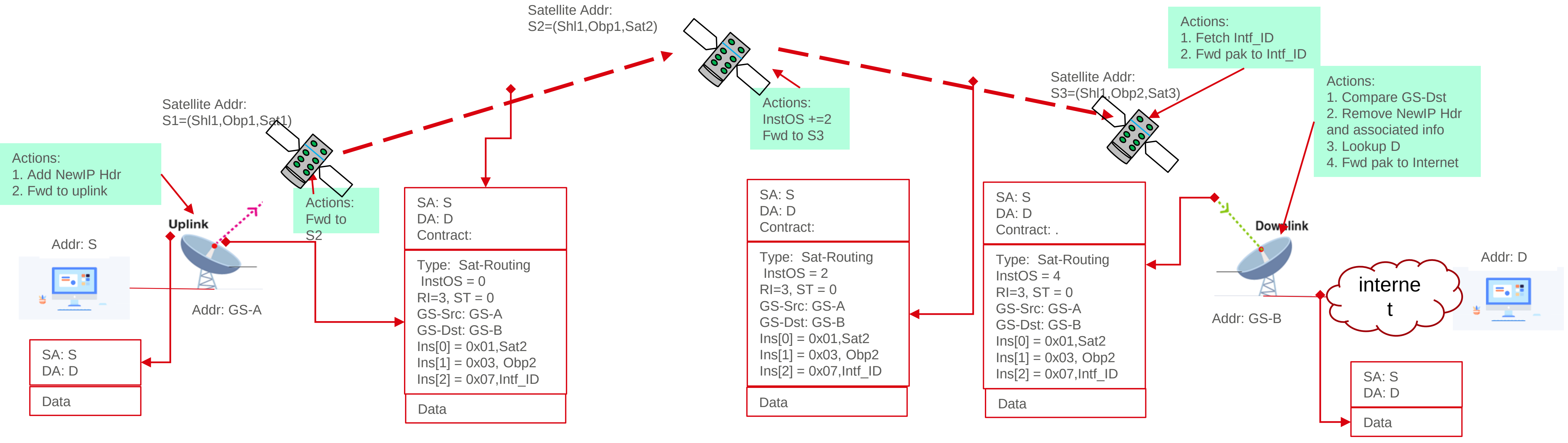
Convergence of Spatial and Terrestrial Networks

Satellite Address Format

Owner Code	Shell Index	Orbit Index	Sat Index

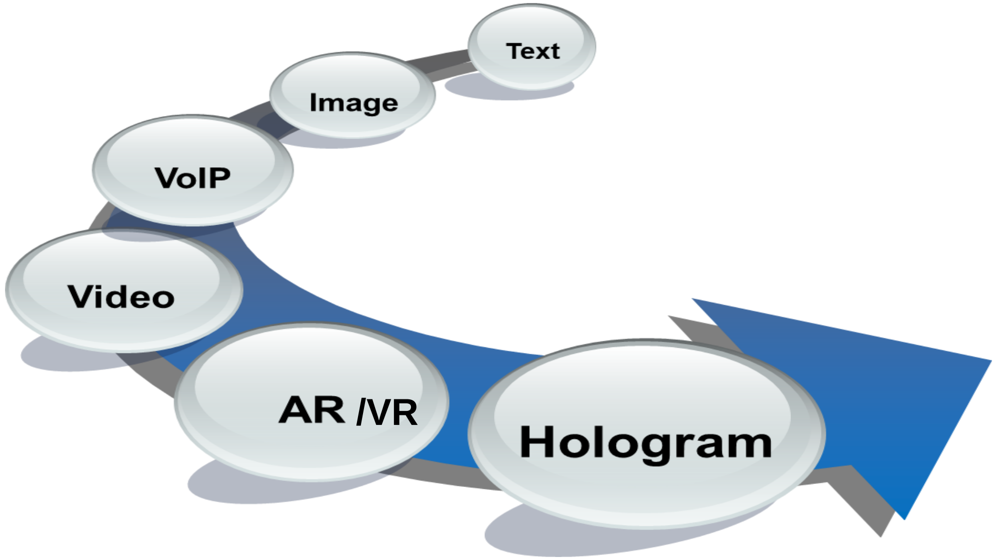
Contract: It uses a new type of routing, called instructive routing, a variant of source routing of the form:

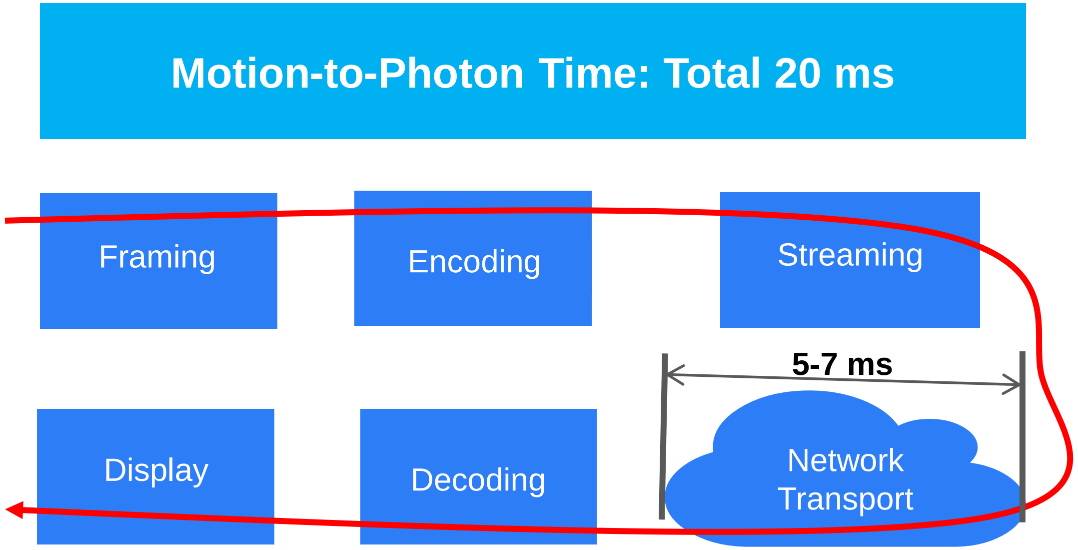
Func Code	Args	Func Code	Args
Instruction 0		Instruction 1	

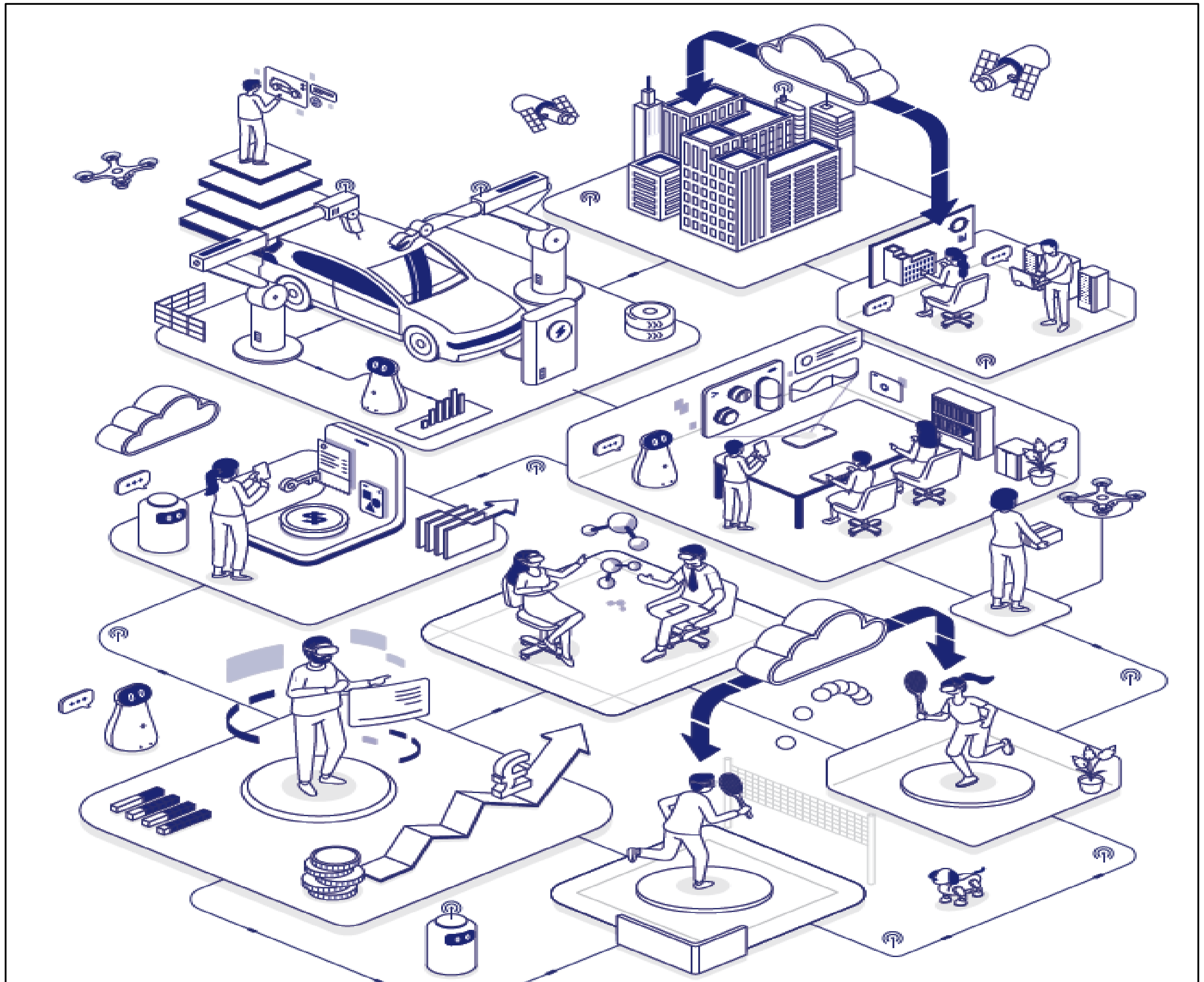


Now let’s talk about Multimedia, AR/VR and Holographic Type Communications …

AR/VR/Holograms are subject to motion-to-photon time







Source: Samsung

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Existing Technology: It’s all about Syntactical information
Quantitative Communications: A *Native Stream* of Bits and Bytes

Sender

Receiver

Packet

Packet

Packet

Corrupted Packet

Syntax

What is received = What is sent

Every bit and byte has the same significance to routers/switches

Good for

- File/Document Transfer
- Banking, Shopping

Overkill for some applications

- Holograms
- Disaster Environment

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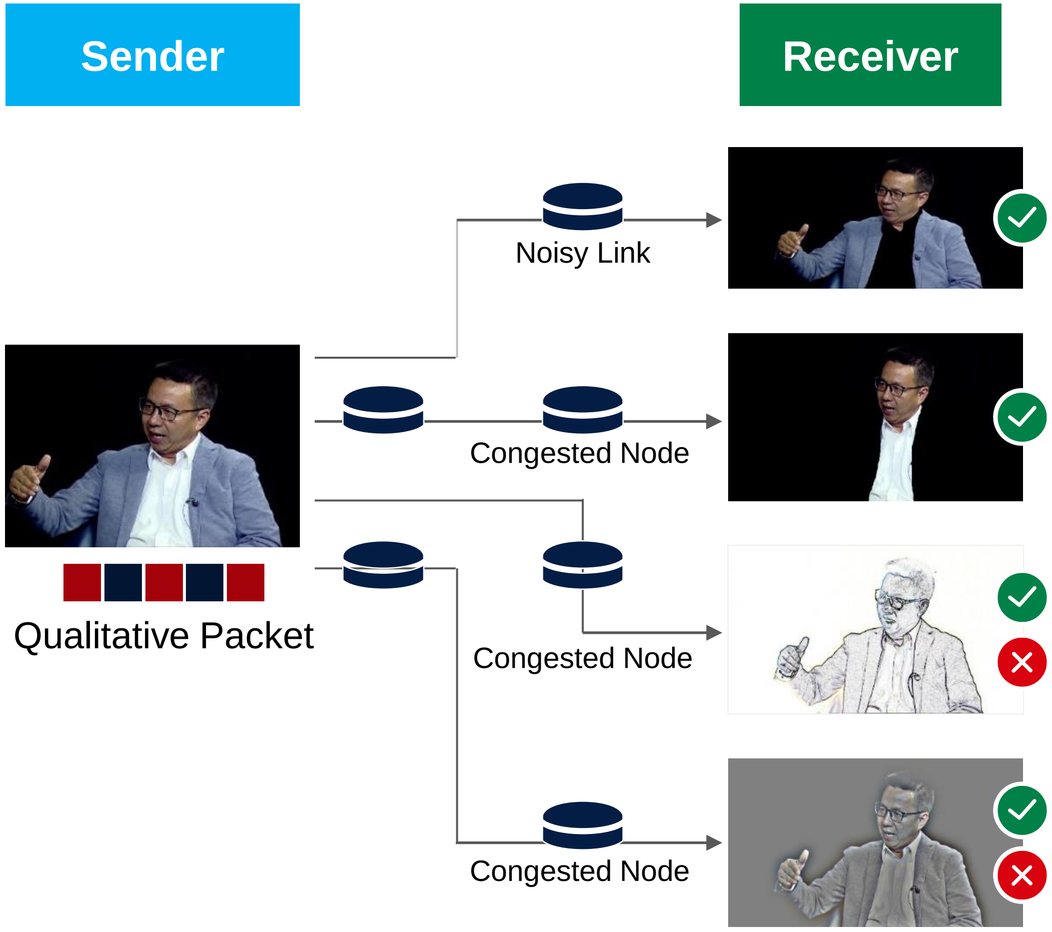
6G networks need Semantic/Qualitative Communications
Qualitative Communications: A *Structure* of Bits and Bytes



Semantics

What is received ═ What is *maximally meant*

In payload, bits and bytes are not equally significant. Instead, they are different in their entropies

Less significant bits and bytes may be dropped

Partial or degraded, yet useful, packets may be repaired and recovered before being rendered

Good for

- Large volume of image-like data
- Holographic type communications
- Media with digital senses
- Disaster Environment

Reference: A Framework for Qualitative Communications using Big Packet Protocol, ACM Sigcomm 2019 NEAT Workshop, Beijing, August 19, 2019. Available at: https://dl.acm.org/citation.cfm?id=3342201

Qualitative Communications: an example for illustration only

User Data Payload: Divided into 10 pages.

Page 1
Page 2
Page 3
Page 4
Page 5
Page 6
Page 7
Page 8
Page 9
Page 10

Contract:

Event: Congested **OR** Radio Unstable
Action: Cut
Meta-Data: Page 1, Page 10, Page 9, Page 2, Page 8

On congested node: after cut

Cut is preferred to drop-and-retransmit

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Qualitative Communications for Remote and Cloud Driving

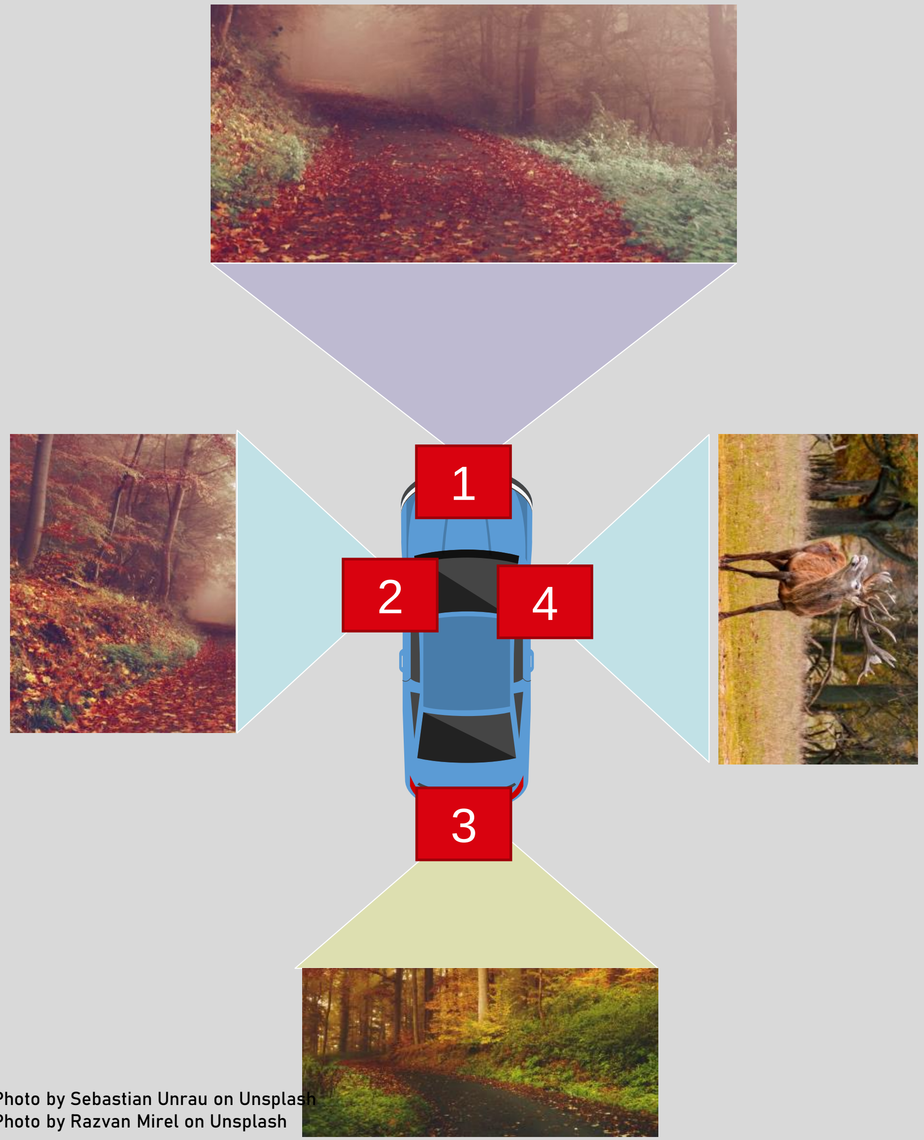
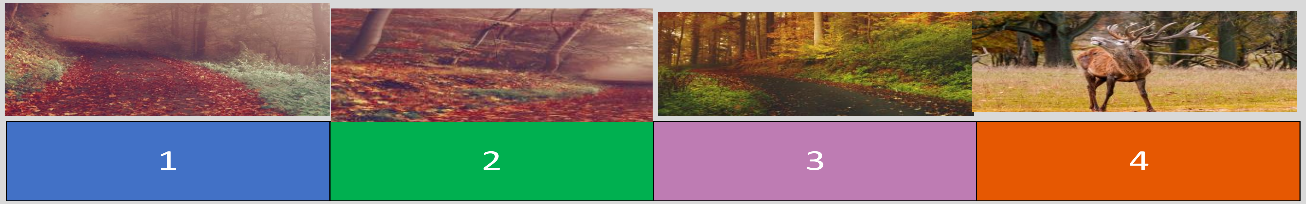


Photo by Sebastian Unrau on Unsplash
Photo by Razvan Mirel on Unsplash

IPv4/IPv6



If a router is congested, the whole packet is dropped

New Approach

Contract — **Payload**

If a router is congested, the less significant chunks are dropped. Camera images, AR/VR, and holograms are usually very large. The packet may still arrive at the destination with the most significant chunks. This is still better than nothing for many applications that do not require an exact copy of information

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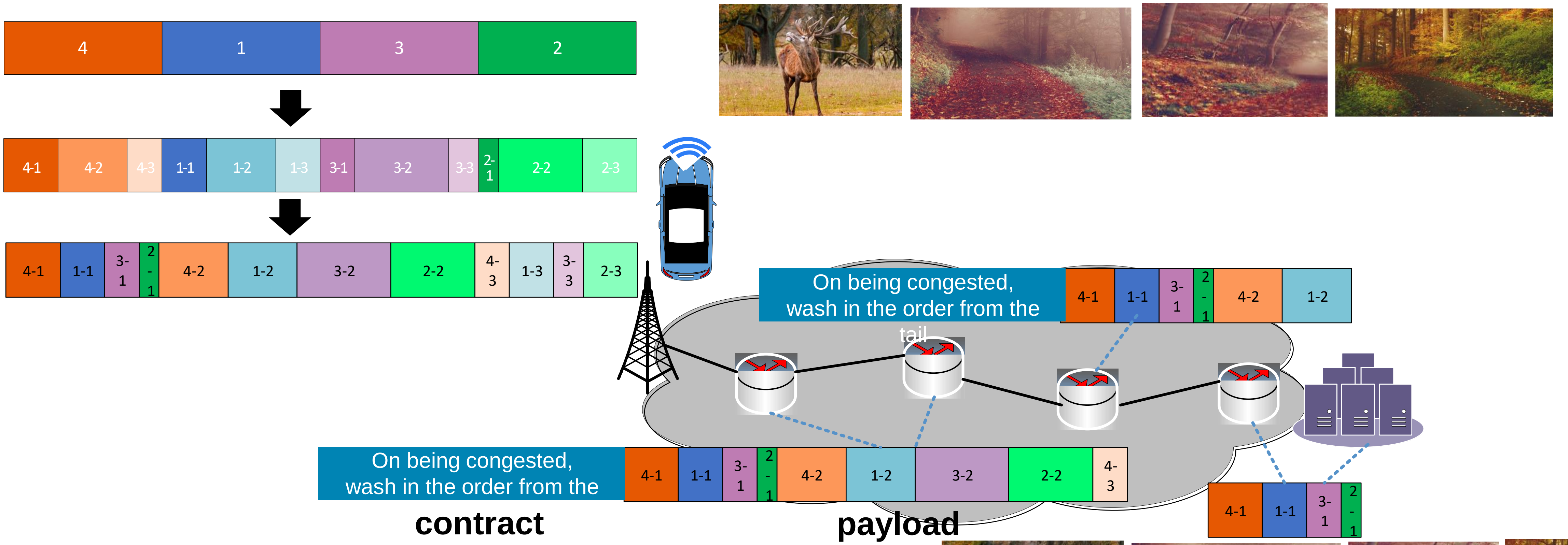
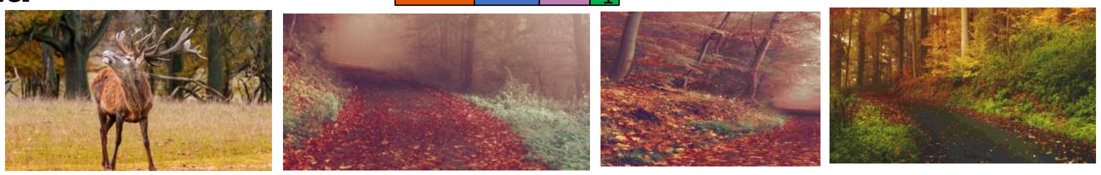
Qualitative Communications with New 6G Networks





Camera 4 Image, 30% Quality Level

Camera 1 Image 20% Quality Level

Camera 2 Image, 7% Quality Level

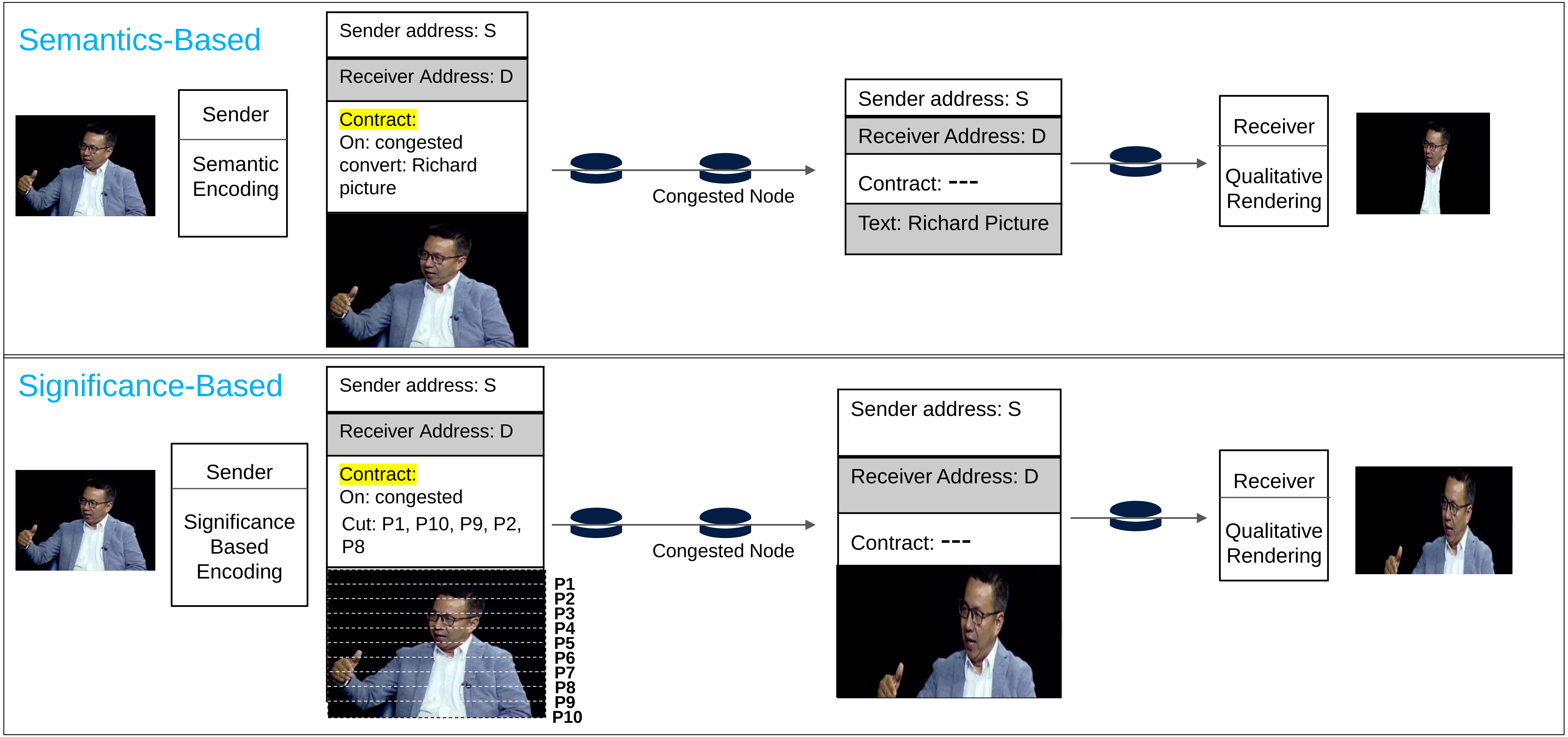
Camera 3 Image, 10% Quality Level

(1)The image is structured into different pages/chunks with different entropy values; (2) The pages with smaller entropy values will be washed away when congestion arises; (3) Even when the network is congested, the packet still arrives at the destination mostly with lower but acceptable quality; (4) No retransmission is required; (5) This is especially useful for Holographic Teleport, Holographic Type Communications, Real-Time Broadband Video Communications, where latency is more important than partial loss of information

Ref:

- A Framework For Qualitative Communications Using Big Packet Protocol, Proc. of ACM Sigcomm Workshop on NEAT 2019, ACM, 2019, pp. 22–28
- Qualitative Communication Via Network Coding and New IP, IEEE HPSR 2020

Qualitative Communications: Semantics-Based and Significance-Based



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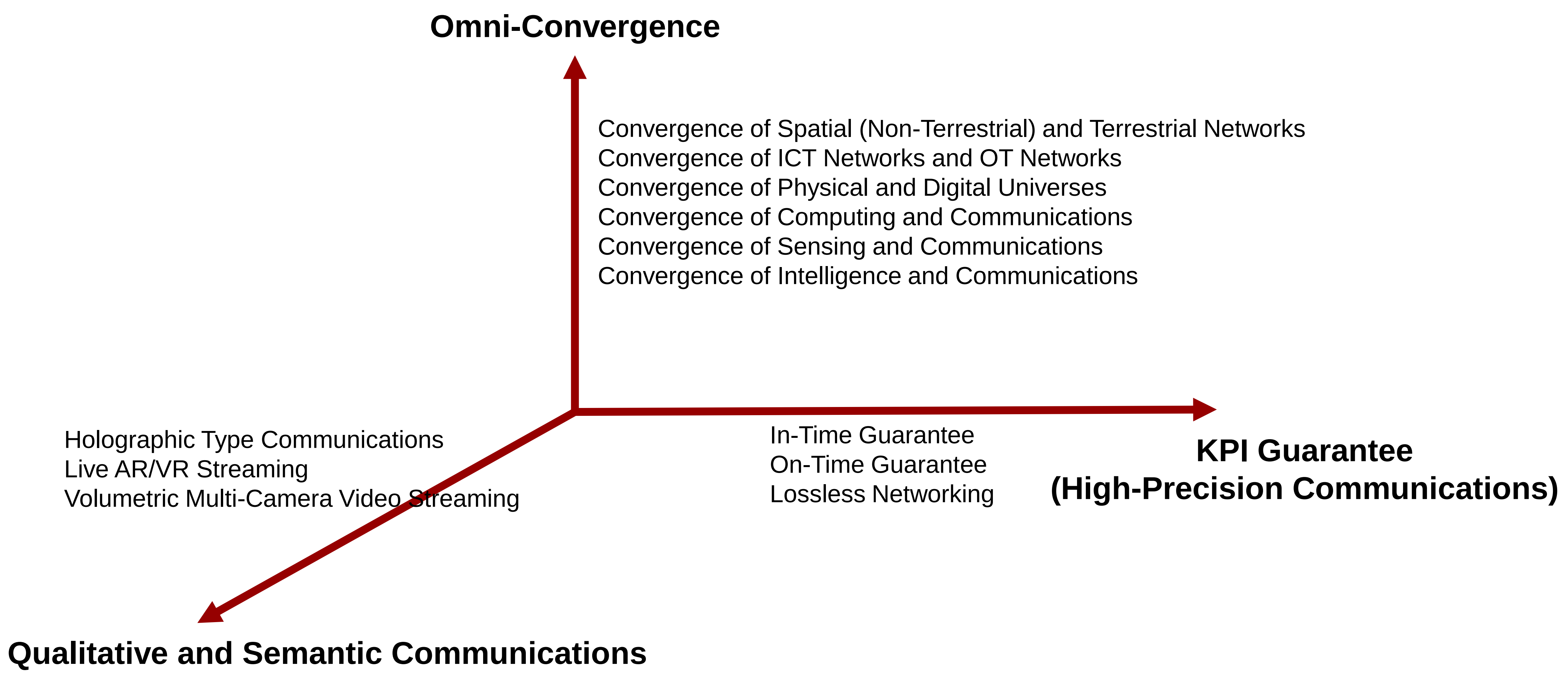
Summary

6G Networks Expected to Support:

Omni-Convergence, KPI Guarantee, and Holographic Transport



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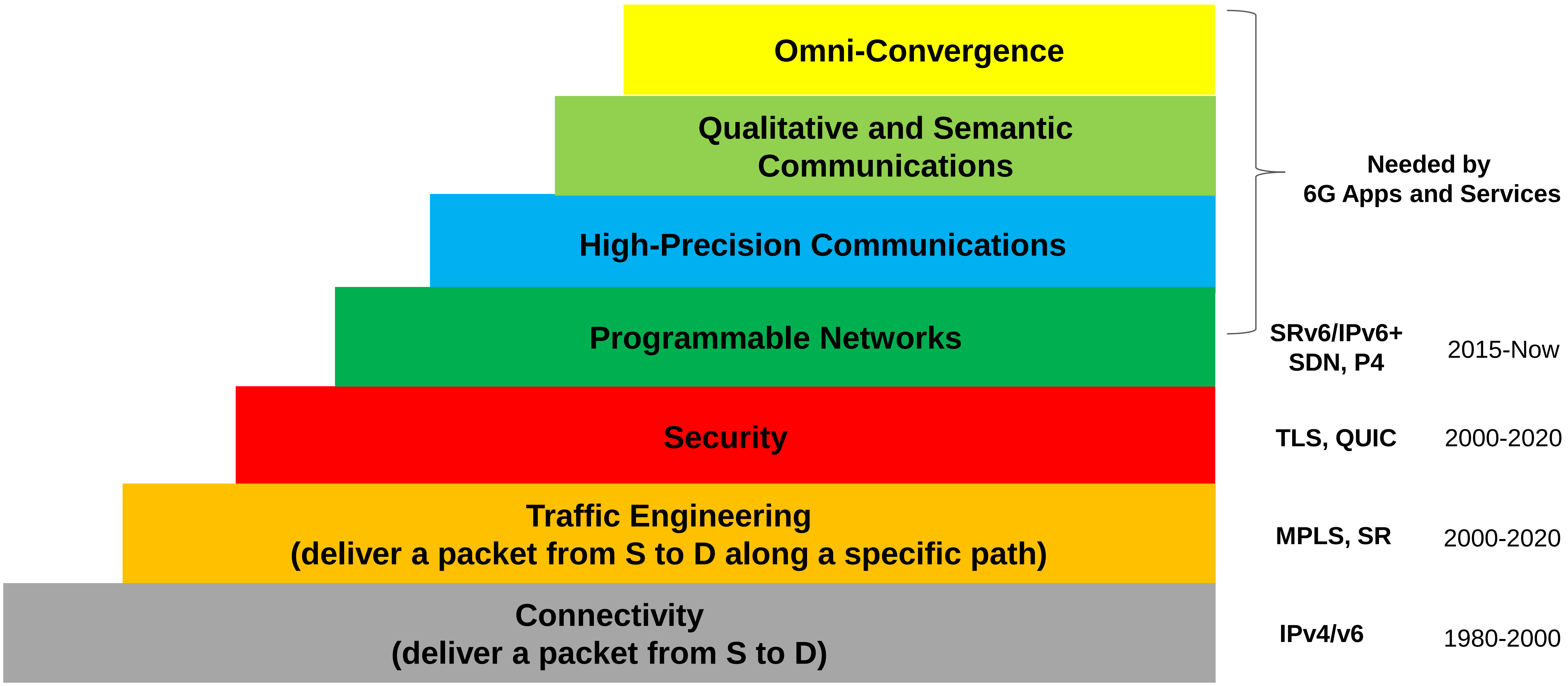
Research Topics Needed for 6G Networks



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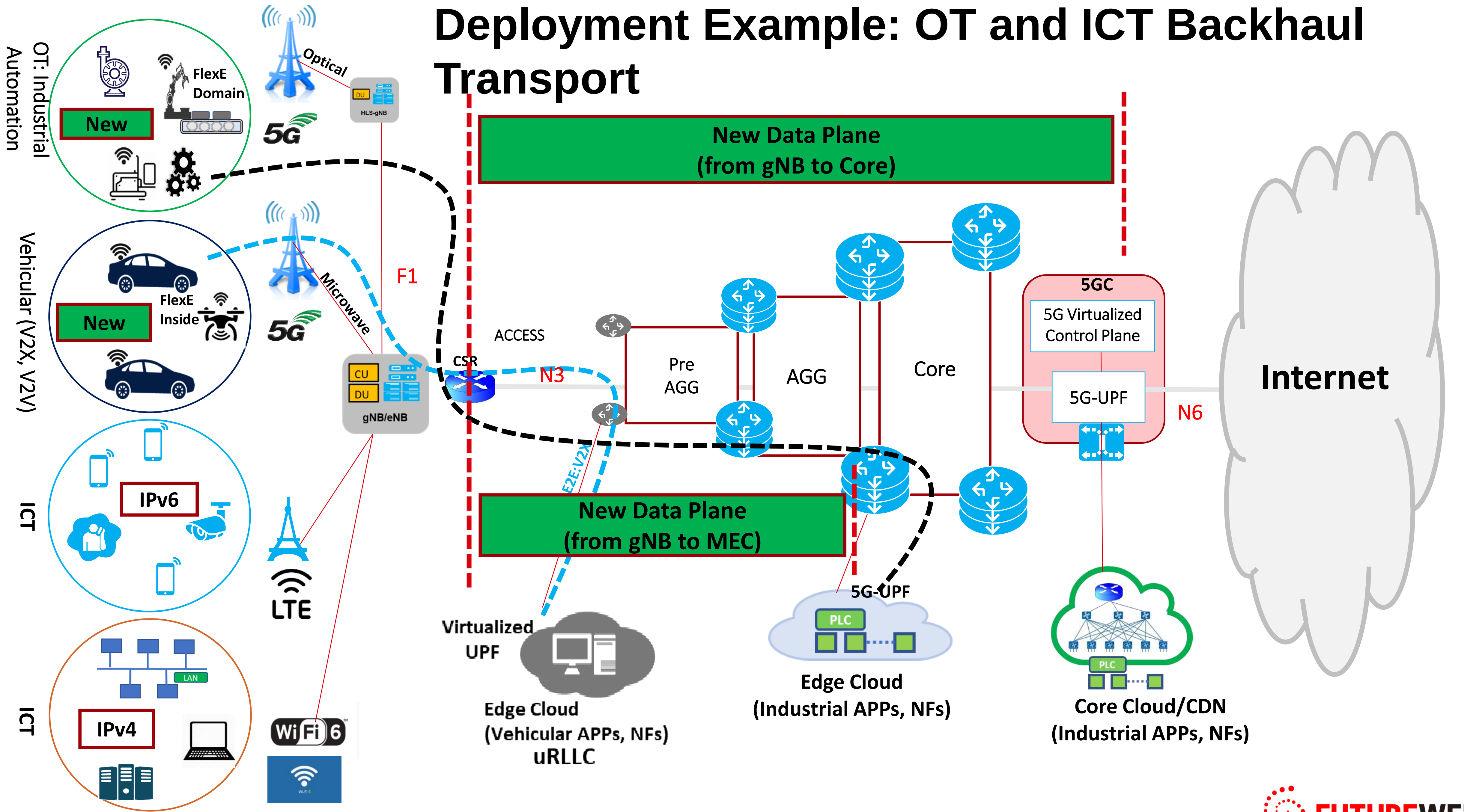
Deployment Example: OT and ICT Backhaul Transport



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Selected Publications and Talks

- **Concepts**
  - A New Way to Evolve the Internet, Keynote Speech at IEEE NetSoft 2018, Montreal, Canada, June 2018
  - What if we reimagine the Internet?, Keynote Speech at IEEE ICII 2018, Bellevue, Washington, USA, Oct 2018
  - New IP: Going beyond the Limits of the Internet, Keynote Speech, IEEE Globecom 2019, Big Island, USA, Dec 9-13, 2019
  - What is New IP about? Industry Keynote Speech, IEEE Infocom 2020, July 6-9, 2020
  - New IP and Market Opportunities, Keynote Speech, IEEE HPSR 2020, May 11-14, 2020
- **Market Drivers and Requirements**
  - Network 2030: A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond, A White Paper of Network 2030, ITU-T, May 2019
  - Towards a New Internet for the Year 2030 and Beyond, ITU IMT-2020/5G Workshop, Geneva, Switzerland, July 2018
  - Network 2030: Market Drivers and Prospects, ITU-T 1st Workshop on Network 2030, New York City, New York, October 2018
  - Next Generation Networks: Requirements and Research Directions, ETSI New Internet Forum, the Hague, the Netherlands, October 2018
- **Framework and Architecture**
  - A New Framework and Protocol for Future Networking, ACM Sigcomm 2018 NEAT Workshop, Budapest, August 20, 2018
  - A Framework for Qualitative Communications using Big Packet Protocol, ACM Sigcomm 2019 NEAT Workshop, Beijing, August 19, 2019
  - New IP: A Data Packet Framework to Evolve the Internet, Invited Paper, IEEE HPSR 2020, May 11-14, 2020
  - Qualitative Communication for Emerging Network Applications with New IP, IEEE MSN 2021, 2021
- **New Technologies or Algorithms**
  - A. Clemm and T. Eckert, High-Precision Latency Forwarding over Packet Programmable Networks, IEEE NOMS 2020, April 2020
  - Preferred Path Routing – A Next-Generation Routing Framework beyond Segment Routing, IEEE Globecom 2018, December 2018
  - Flow-Level QoS Assurance via In-Band Signaling, 27th IEEE WOCC 2018 , 2018
  - Using Big Packet Protocol Framework to Support Low Latency based Large Scale Networks, ICNS 2019, Athens, 2019

Concluding Remarks

- Three challenges for 6G networks: omni-convergence, KPI guarantee and holographic type communications
- Existing networks are not suitable for 6G applications and use cases
- A new data plane protocol is motivated by solving problems as commonly found in:
  - Industrial machine-type communications (Industry 4.0, Industrial Internet, Industrial IoT, Industrial Automation)
  - Emerging applications such as holographic type communications
  - IP Mobile Backhaul Transport for 5G/B5G uRLLC, mMTC, especially when Connecting Industrial Networks
  - Emerging Industry Verticals (driverless vehicles, smart agriculture)
  - ITU-T Network 2030
- The new data packet protocol is an extension and optimization of IP with new functions (capabilities, features), and is being designed to be interoperable with IPv4, IPv6 and many others
- Research and empirical results have been published in ITU, IEEE, and ACM. Some industrial manufacturing-related companies, service providers and network operators have shown their interest for their real problems and applications.

Thank you!