Wireless Time-Bounded Communication: Unde vedis et Quo vadis?

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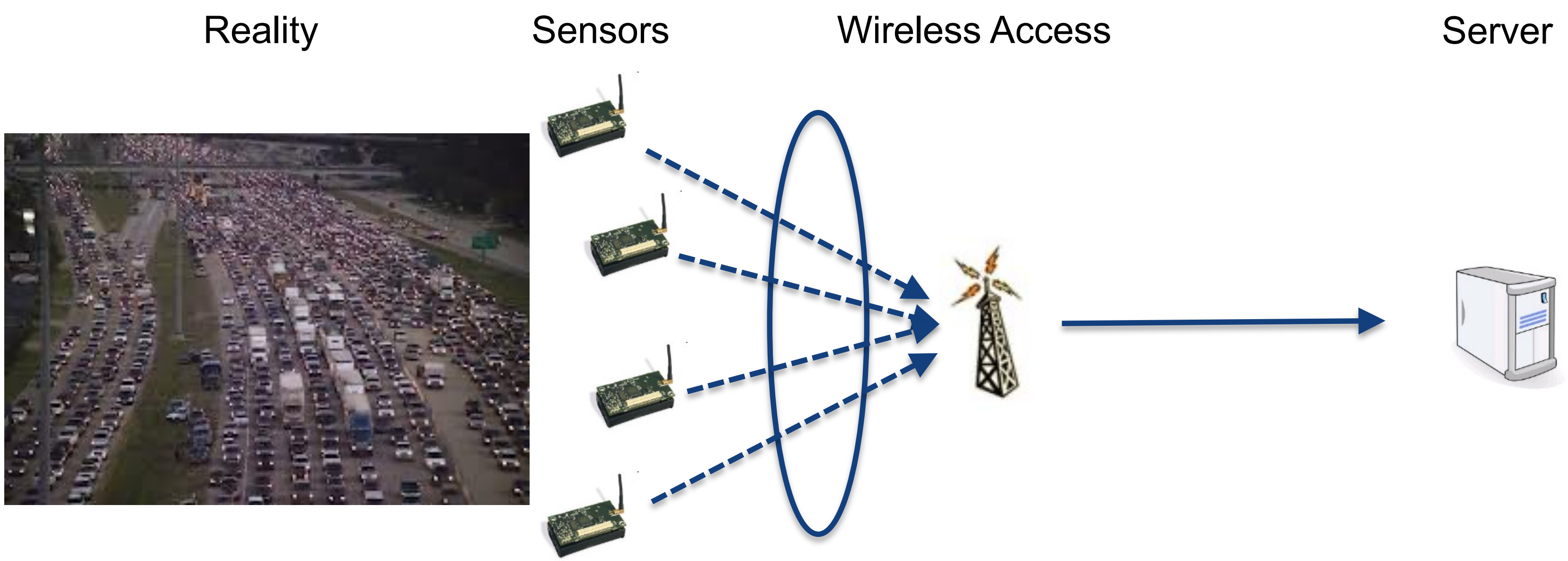
Outline

- Cyber-Physical Networking: How did it start?
- Major developments towards 5G
- The Future: Cyber-Physical Networking in 6G

Cyber-Physical Networking: Origins

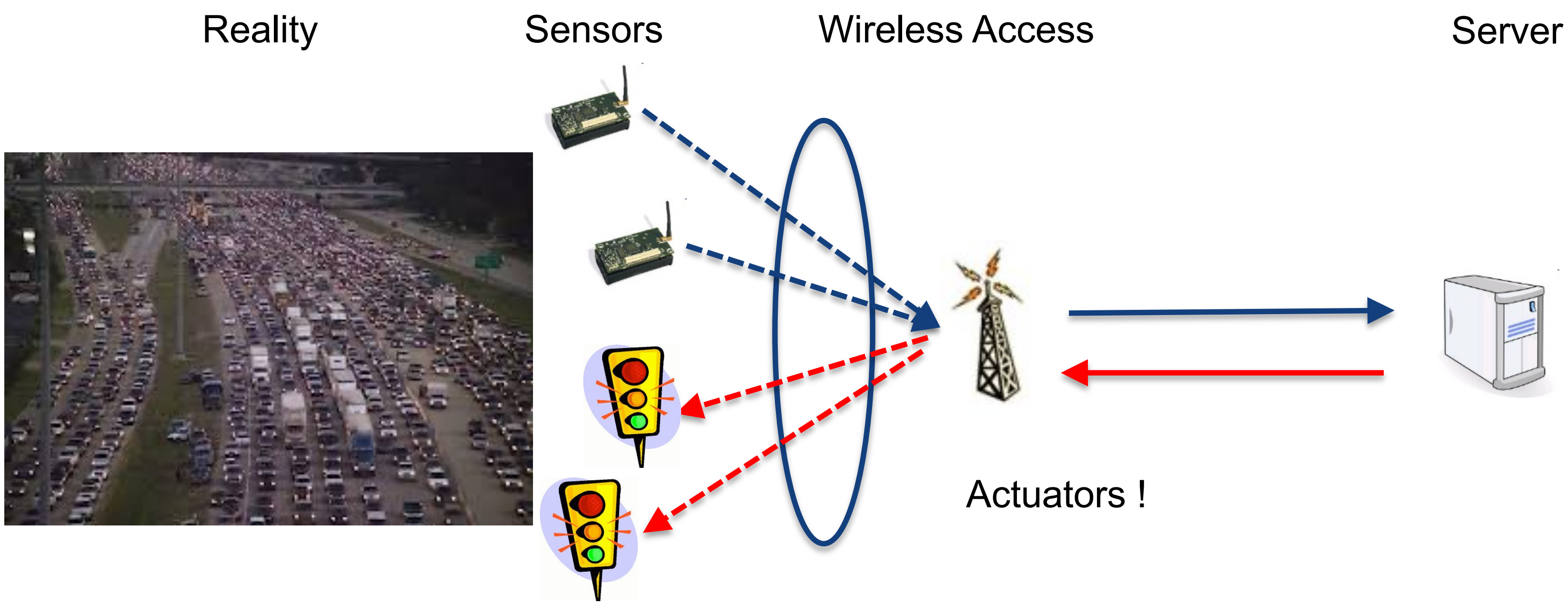


<u>Autonomous</u> monitoring & metering purpose

- End of 90s: First research on "sensor networks"
- Mid 2000: First standards (802.15.4, 6LowPAN)
- ~2010: Picked up by cellular networking industry (M2M business)

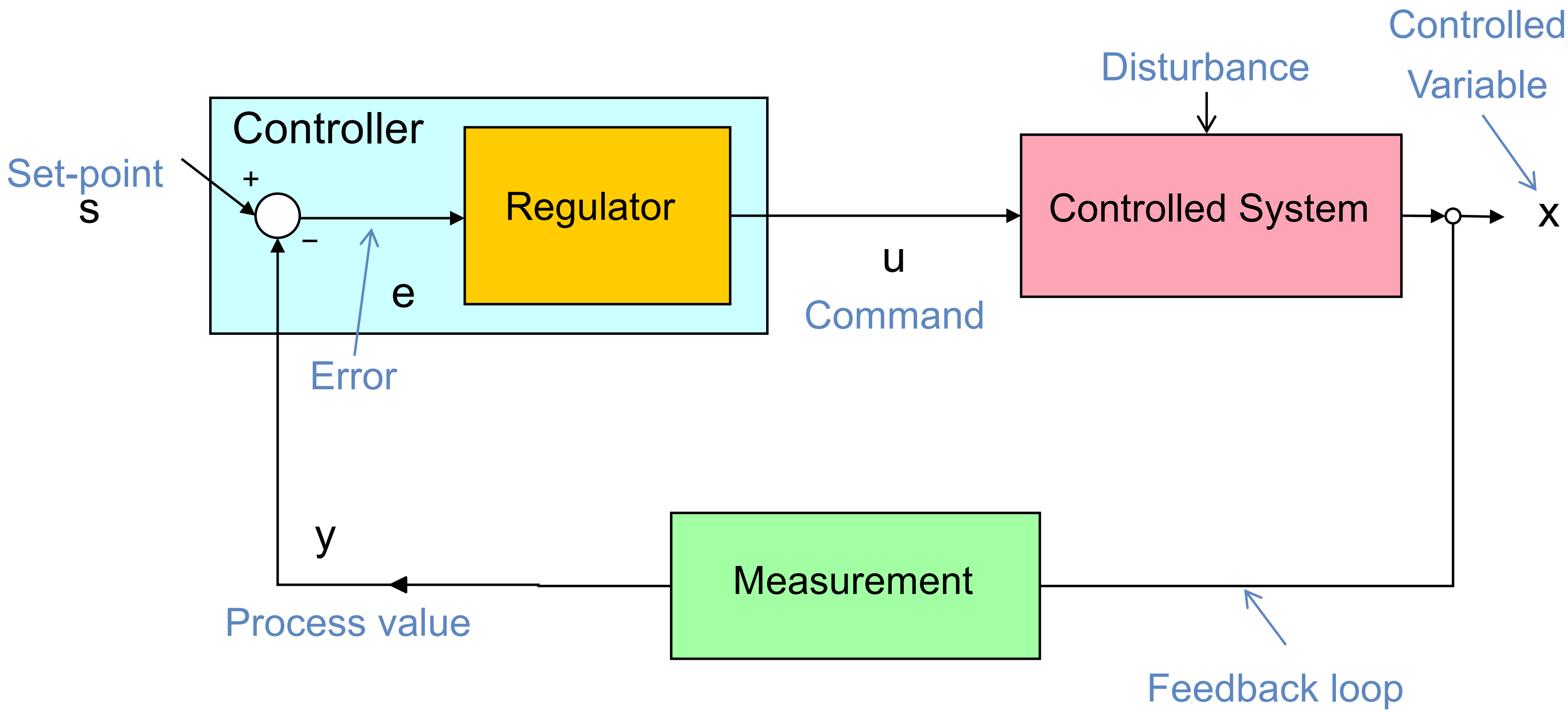
➔ Massive machine-type communications

Critical Cyber-Physical Networking



- Closed-loop control (driven by autonomy trend)
- Dependability becomes the focus
- Some early research around 2000, fell dormant afterwards till 2010

Meanwhile in the Control Community …



Objective of controller: Stability of the system (i.e. minimize the error to zero or bound the error to a small value)

Networked Control System (NCS)

- In practice, sensor, controller and actuator are closed over a shared wireless/wired network.

- Network parameters can influence stability:
  - Network-induced delay
  - Packet drops
  - Multiple packet transmissions
  - Sampling interval

- NCS is a theoretical model to study this impact
- Focus on **network-induced delay** and **packet drops**

Status Quo around 2010

- Large body of research on sensor networks
- Established standards like 802.15.4, work in the IETF, direction generally captured as Internet of Things (IoT)
- Sensor networking community started to move on towards application
- BUT: No significant commercial uptake

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Communication at Finite Blocklength

- Shannon capacity used for principle design of networks

$$C_{\mathrm{IBL}} = \log_2 (1 + \gamma) \;\; [\text{bits / channel use}]$$

- Low latencies ➔ Shannon capacity inappropriate
  - Assumes infinitely long coding words

- Tight finite blocklength approximation:

$$r_{\mathrm{FBL}} \approx C_{\mathrm{IBL}} - \sqrt{\frac{V}{n}} \cdot Q^{-1}(\epsilon) \;\; [\text{bits / channel use}]$$

V : Channel dispersion, n : blocklength, ε : block error rate

Y. Polyanskiy, H. Poor, and S. Verdu, “Channel coding rate in the finite blocklength regime,” IEEE Trans. Inf. Theory, vol. 56, no. 5, pp. 2307– 2359, May 2010.

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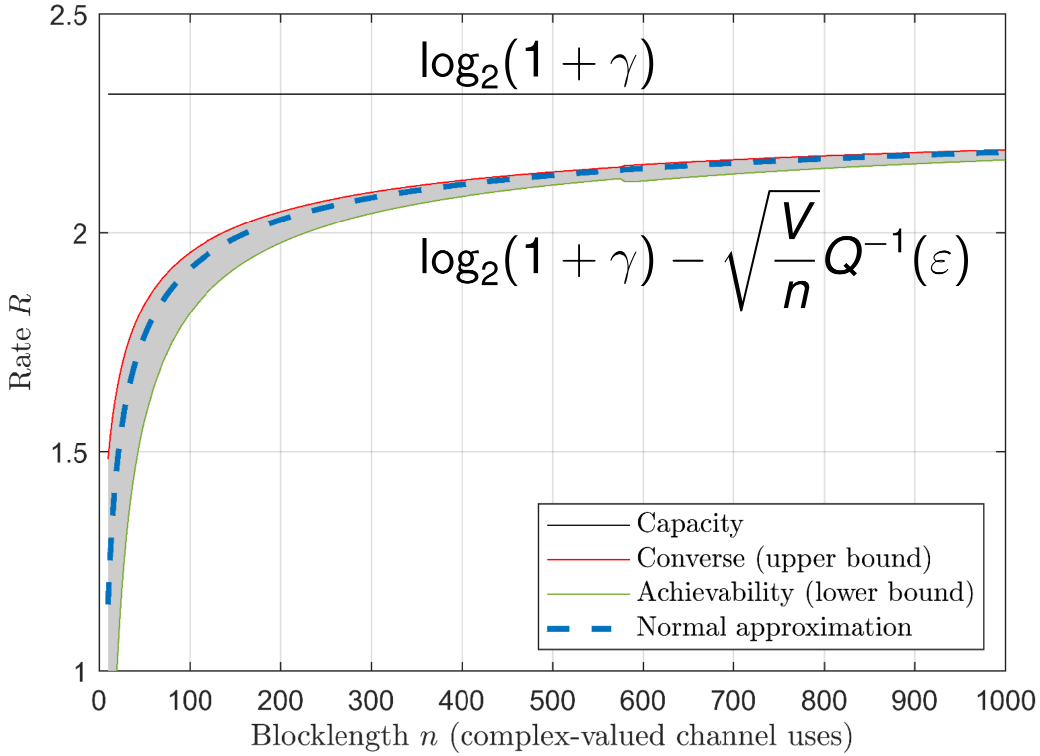
- In other words, the supportable rate is a Gaussian R.V. under finite blocklength, and so

$$\varepsilon \approx \mathrm{Q}\left((C_{IBL} - r_{FBL})\sqrt{\frac{n}{V}} \right)$$

- Technically, for a given channel V (dispersion) must be obtained
- This Gaussian approximation is tight for large ranges of *n* !

Finite Blocklength Rate Model



Age-of-Information

- If a packet i generated at t_i is delivered at t'_i, then

$$\Delta(t) = t - \max\{t_i : t'_i \leq t\}.$$

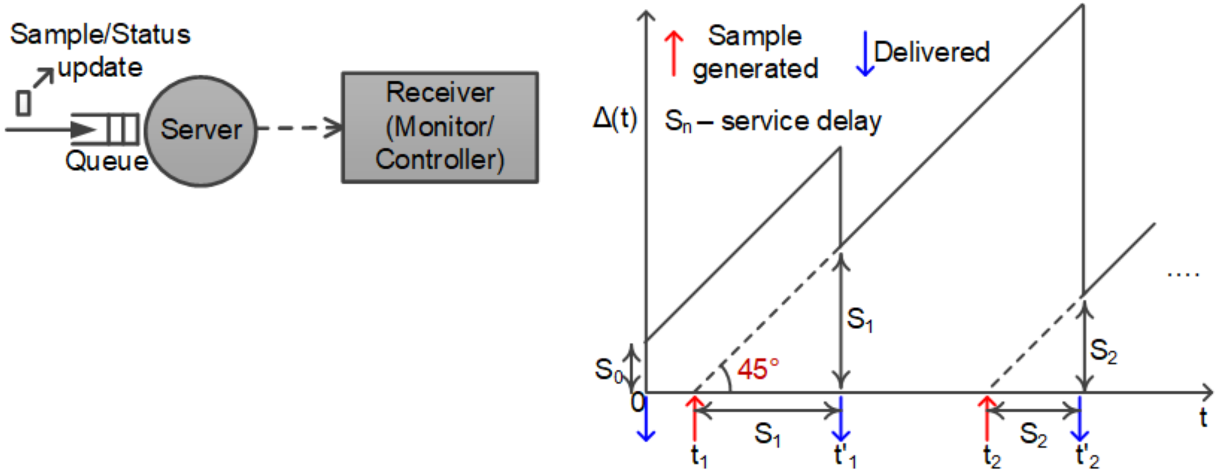
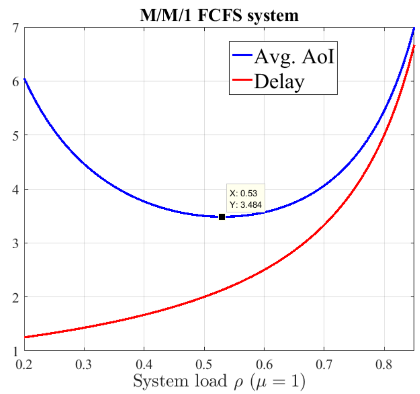


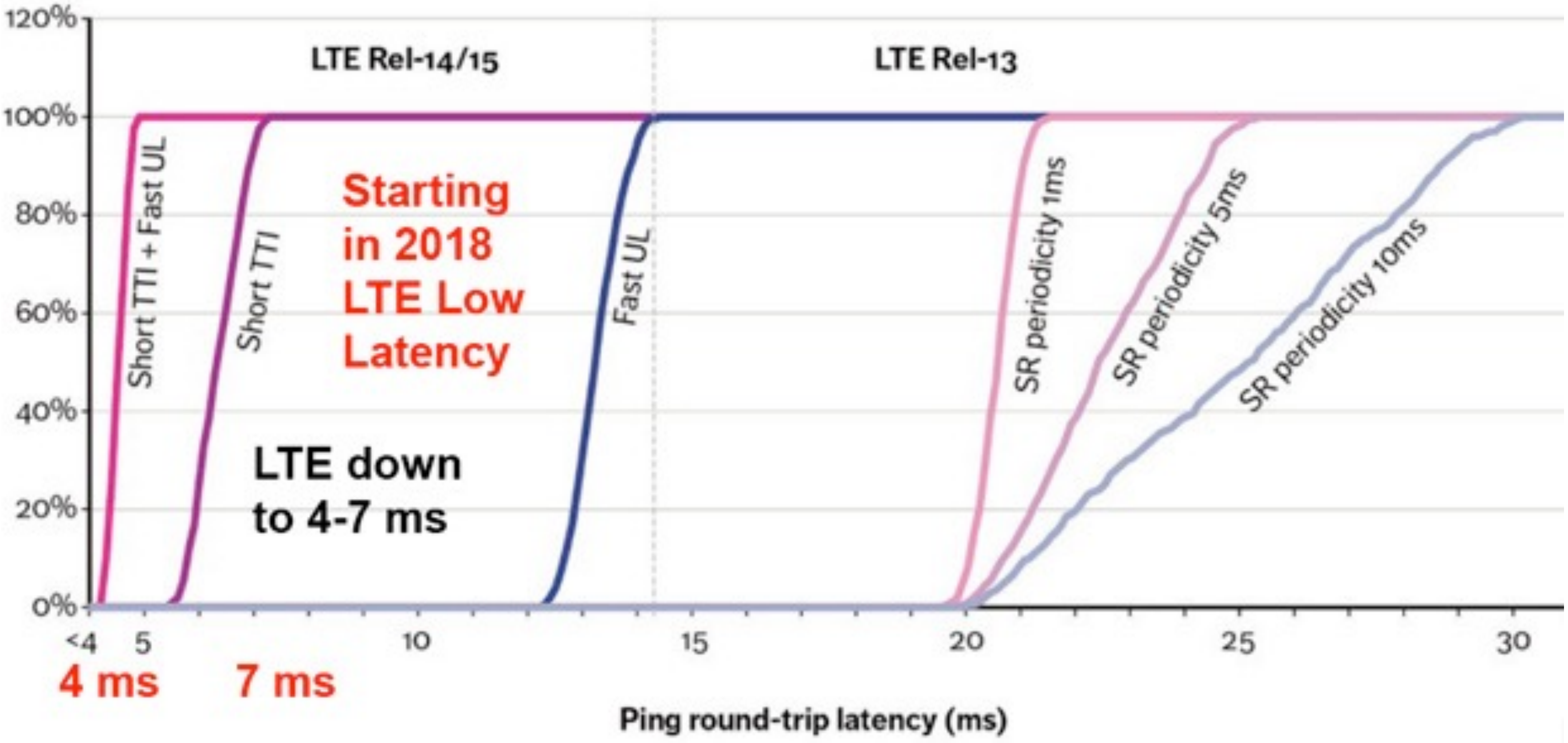
Figure: Sample path of AoI (right) at the receiver.

Age-of-Information



- For small values of ρ, AoI is high because of the large inter-arrival times, while for high values of ρ, AoI is high because of the increased queueing delay.
- While the average AoI is minimized at $\rho = 0.53$, delay is minimum when ρ is close to 0.
- On the other hand, the *throughput*, i.e., the number of packets received per second at the receiver, is maximized when ρ approaches 1.

Pre-URLLC: Latency Characterization



Source: Ericsson Technology Review, 1-2017.

Release 16: URLLC

Realize major KPIs of industrial use cases:

- Gbps bandwidth
- <1ms latency
- 99.999% + reliability
- Referred to as ultra-reliable low latency communications (URLLC)

5G URLLC Key Concepts

- Three main technical areas
  - Low latency through short transmissions (new frame structure, referred to as NR), pipelined processing, and centralized scheduling
  - Reliability through diversity, and predictable interference
  - Availability through multi-connectivity & multi-antenna

URLLC: Optimized Framing & Scheduling

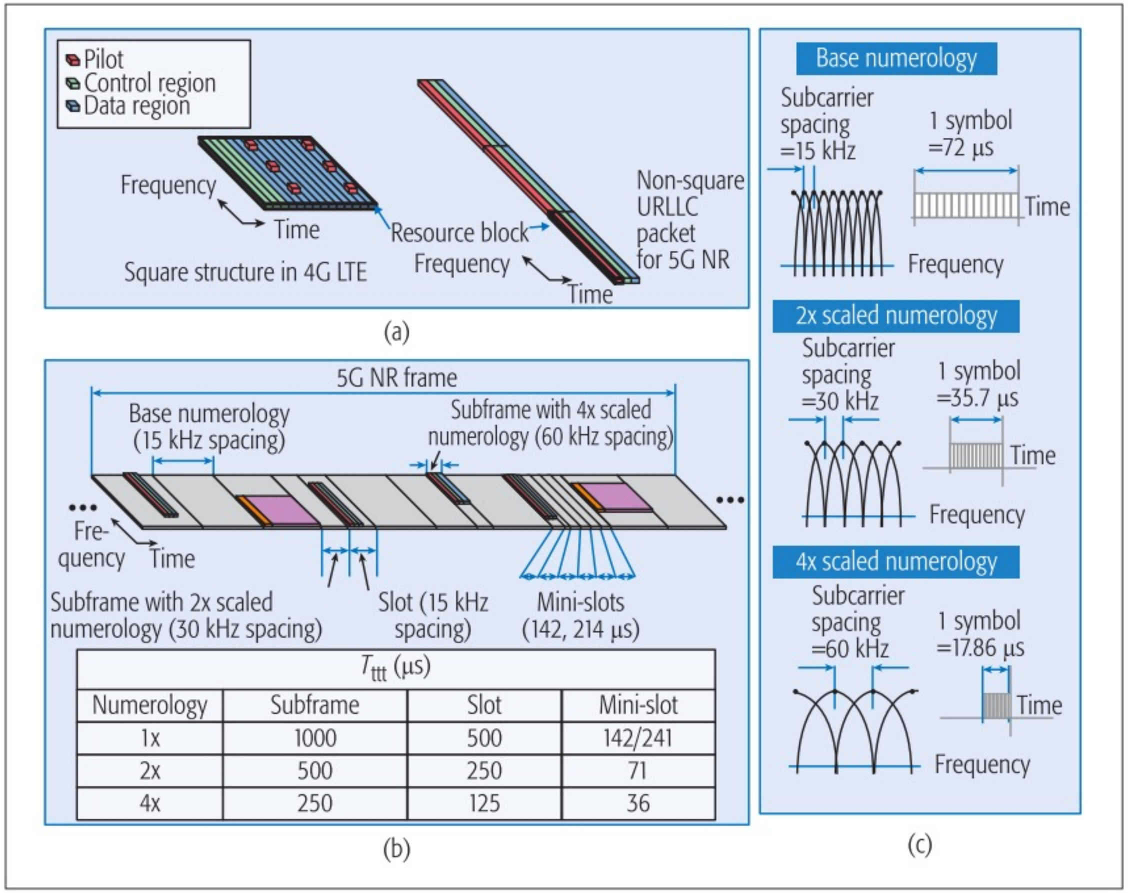
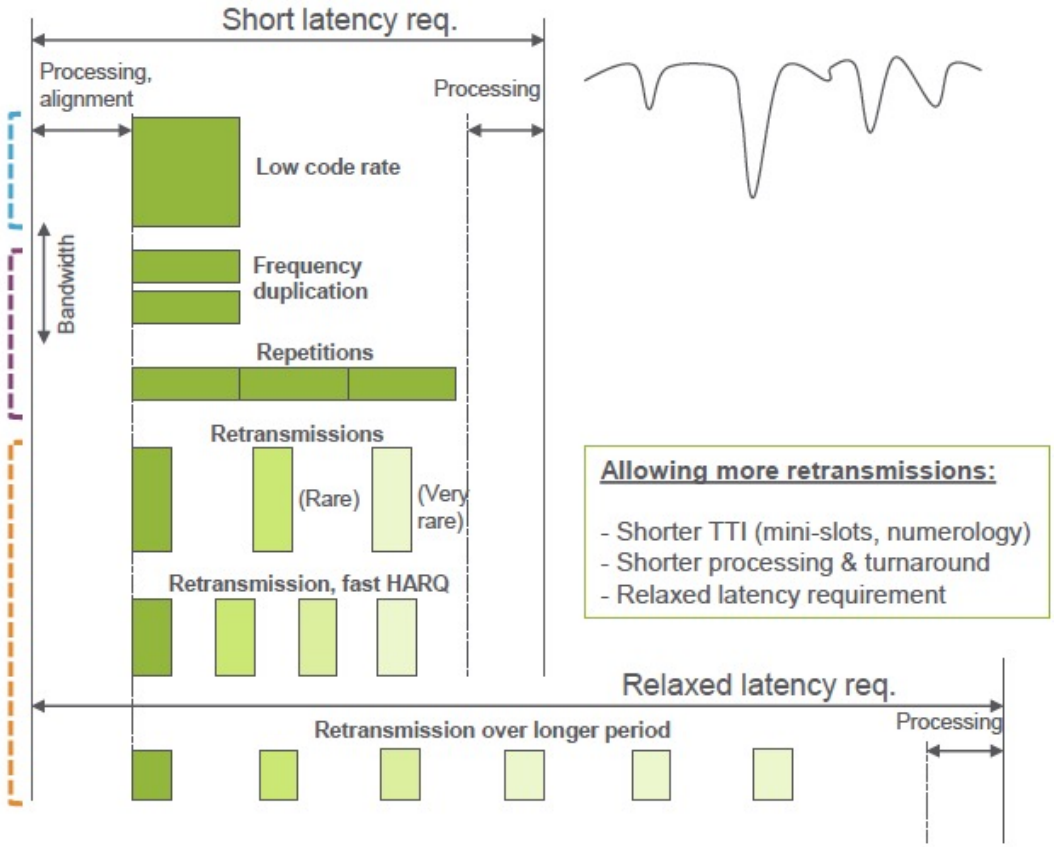


FIGURE 3. Packet and frame structure for URLLC: a) packet structure; b) frame structure; c) supported numerologies for 5G NR.

URLLC Reliability: Coding, Diversity, HARQ



HARQ-ACK feedbacks for DL/UL data frames, UE processing delay:

- Traditionally, the minimum processing delay for LTE is 3 *ms*,
- 5G NR significantly reduces this processing delay to 0.2 – 1 *ms* for DL data and 0.3–0.8 *ms* for UL data.

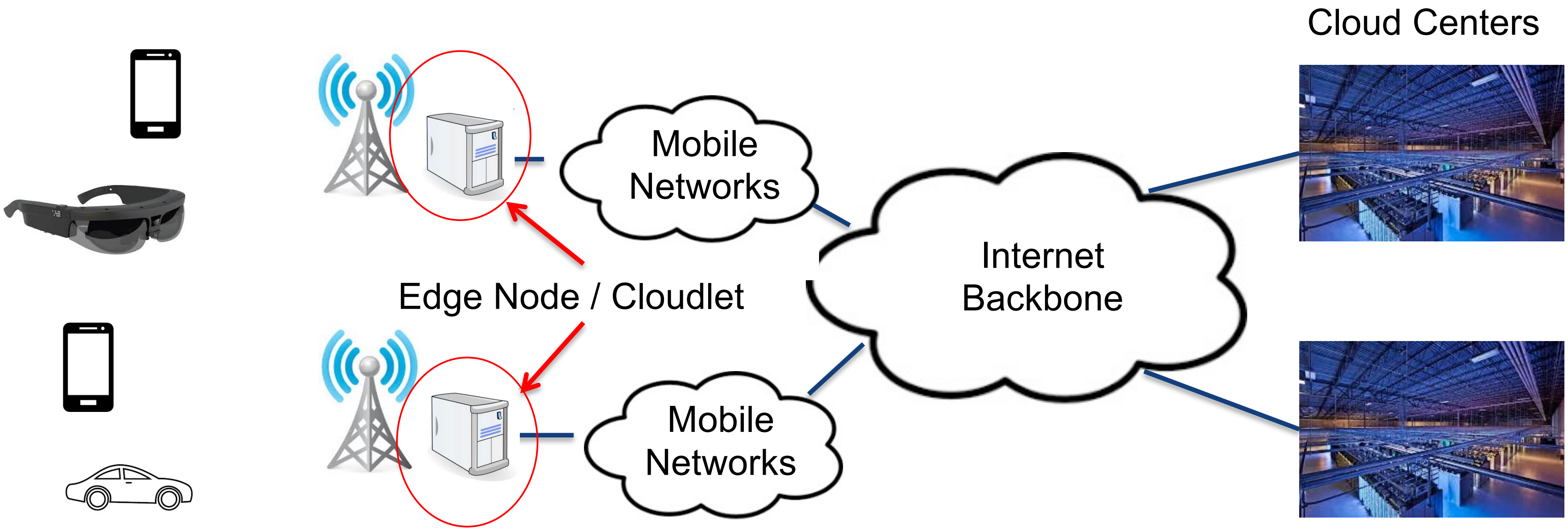
URLLC: Application Fields

- Various application fields according to 3GPP:
  - Rail-bound mass transit
  - Building automation
  - Factory of the future / industrial automation
  - Smart living / smarty city
  - Electric power distribution & power generation

- In addition:
  - Support for autonomous devices (cars, drones, robots)
  - Human-in-the-loop applications (AR / cognitive assistance)

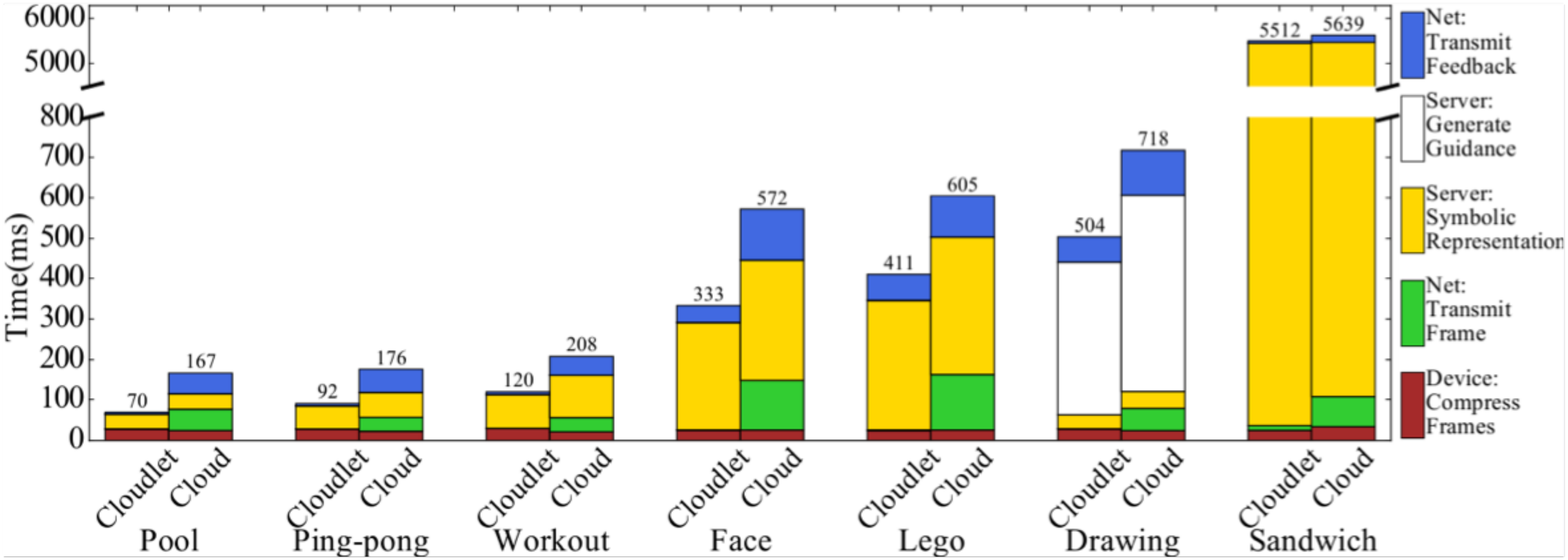
3GPP, TR22.804 v1.0.0, December 2017

The Rise of Edge Computing



Deploy compute closer to the application ends.

Fundamental Driver: Latency



Depending on workload, migrating from cloud to edge computing reduces round-trip latencies by 50 – 100 ms, or more.

Chen et al. “An empirical study of latency in an emerging class of edge computing applications for wearable cognitive assistance,” *IEEE SEC* 2017.

https://publications.computer.org/computer-magazine/2017/01/17/wearable-cognitive-assistance-pingpong-assistant/

Status Quo around 2020

- Explosion of the ‘low latency’ area
  - Fundamentally, much better understood through scientific breakthroughs
  - Substantial technology development through various standards and industrial alliances
- Significant commercial uptake of IoT (several wide-area low power standards like LTE-M, SigFox etc.) -> Driven by cloud computing!

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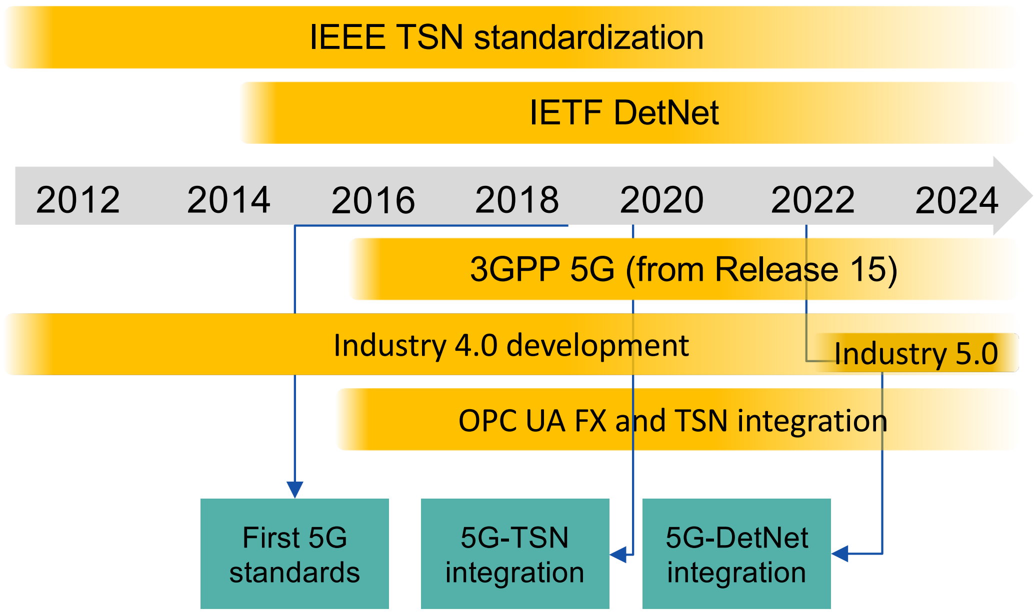
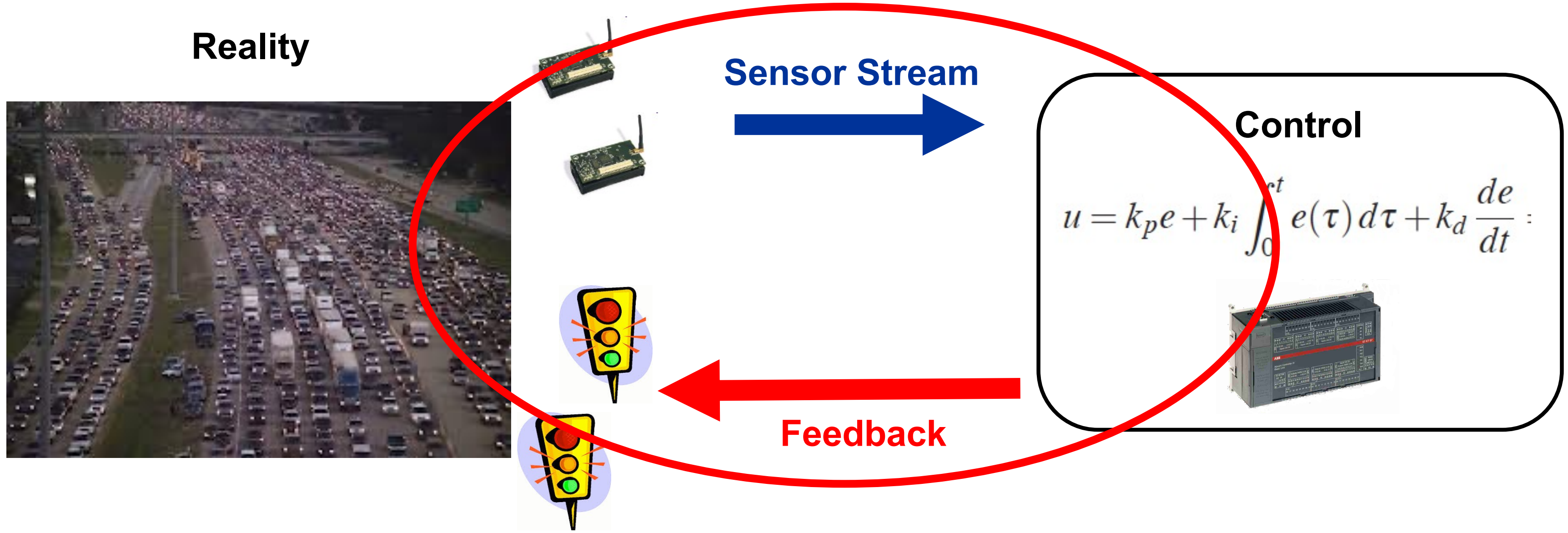
Status Quo in Cyber-Physical Networking



Technology Islands: TSN, DetNet, 5G, OPC UA, MEC

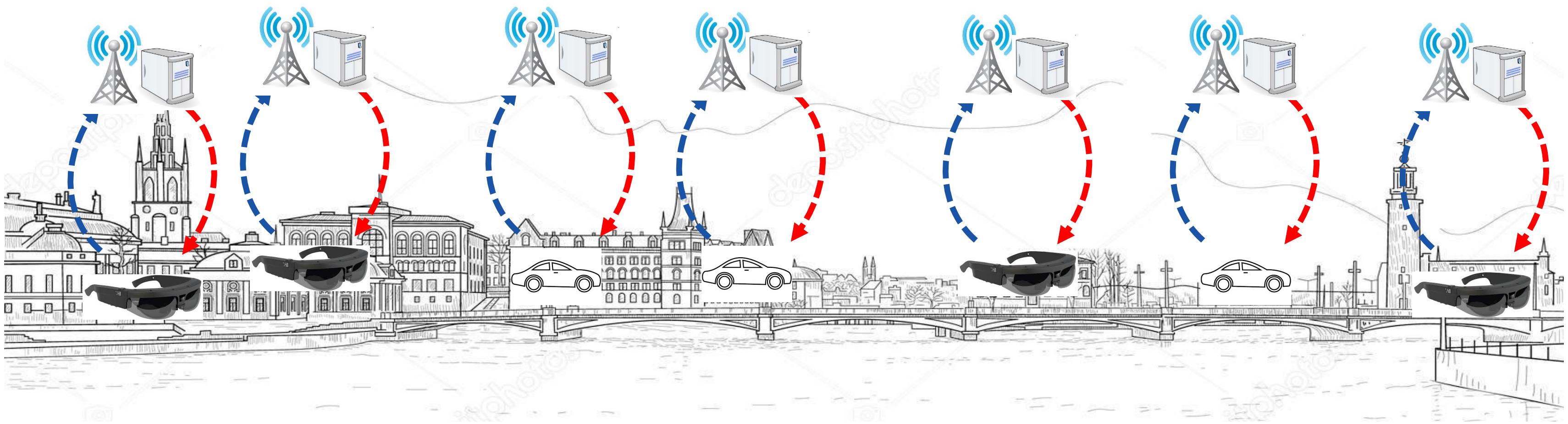
- Independently evolving, limited interworking
- Slow commercial uptake, some success in niche domains
- Conceptually: Eliminate uncertainty as much as possible!

Cyber-Physical Networking (CPN)



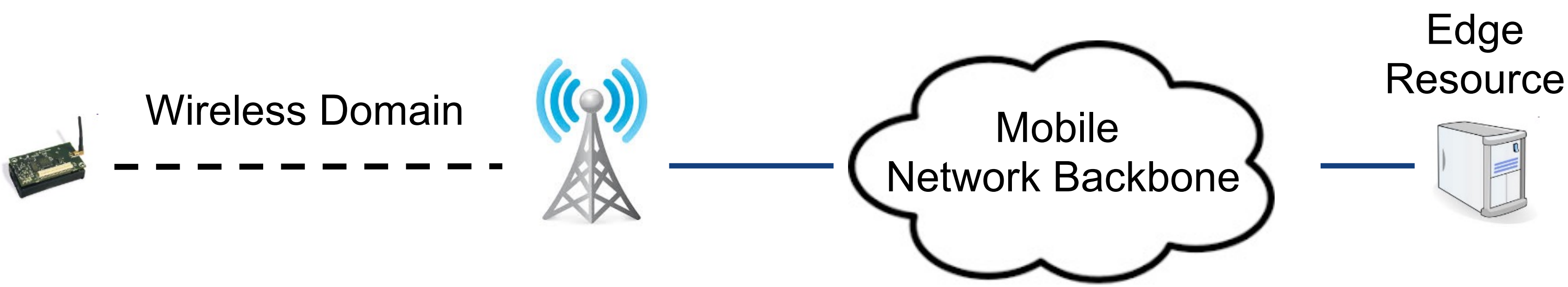
Compute and Communications for CPS = CPN!
Domains: Automation, Robotics, AR, VR, Exoscelotons etc.

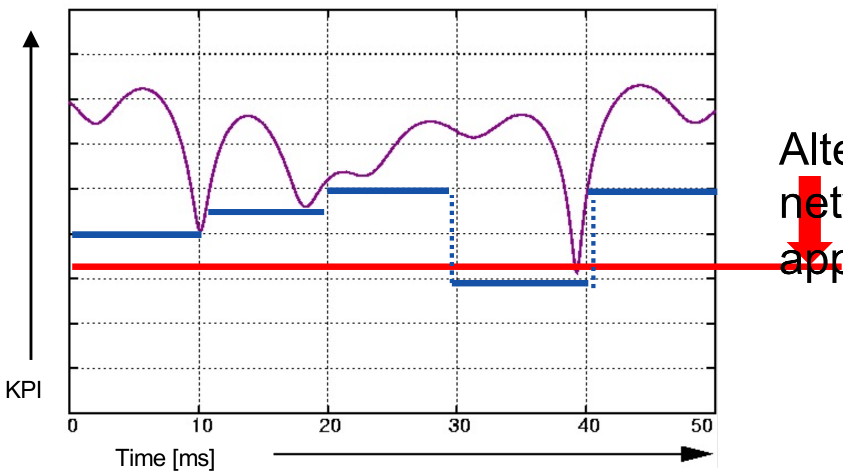
Towards a Cyber-Physical Continuum



- Ubiquitous provisioning of CPS through mobile networks
- Last decade: Pull towards compute, latency & reliability

Towards Predictability and Adaptation

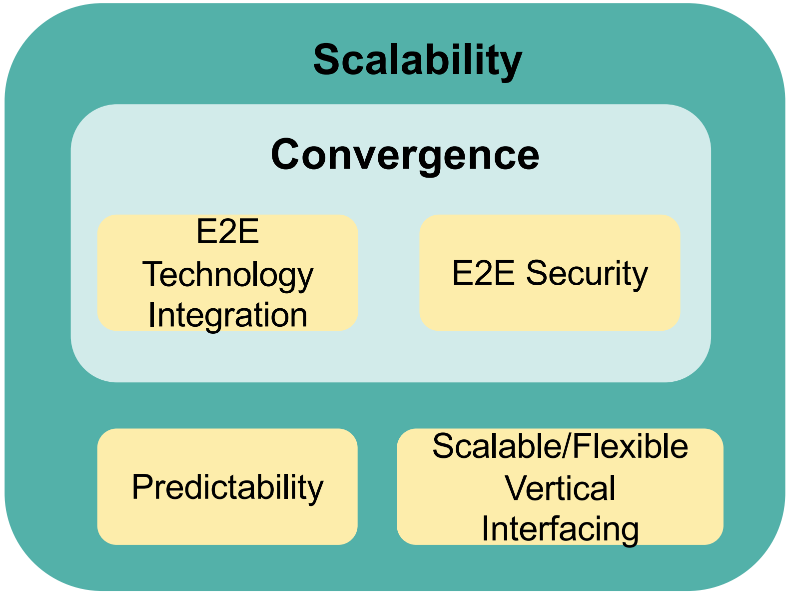




Alternative Approach: Predict network KPI and harmonize with application at run-time.

Current Approach: Static requirements from applications, translated into large footprint in the infrastructure

Key Goals of 6G Cyber-Physical Networking



- *Convergence* among different technologies and infrastructures to enable CPS applications
- *Scalability* of communication and compute infrastructure to support CPS applications

Sharma et al. “Towards Deterministic Communications in 6G Networks: State of the Art, Open Challenges and the Way Forward”, *arXiv preprint arXiv:2304.01299*

DETERMINISTIC6G

Industrial application players bringing 6G visionary use cases

Key industrial players in 6G research and development

Key university and research institutes at the forefront for 6G fundamental research

Leadership: Ericsson GmbH & KTH Stockholm

Jan 2023 – Jun 2025 (30 months)

€ 5.8 M€

https://deterministic6g.eu/