DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

SIGNET
signet.dei.unipd.it

Modern Sensing, Communication, and Learning technologies for advanced "smart" services

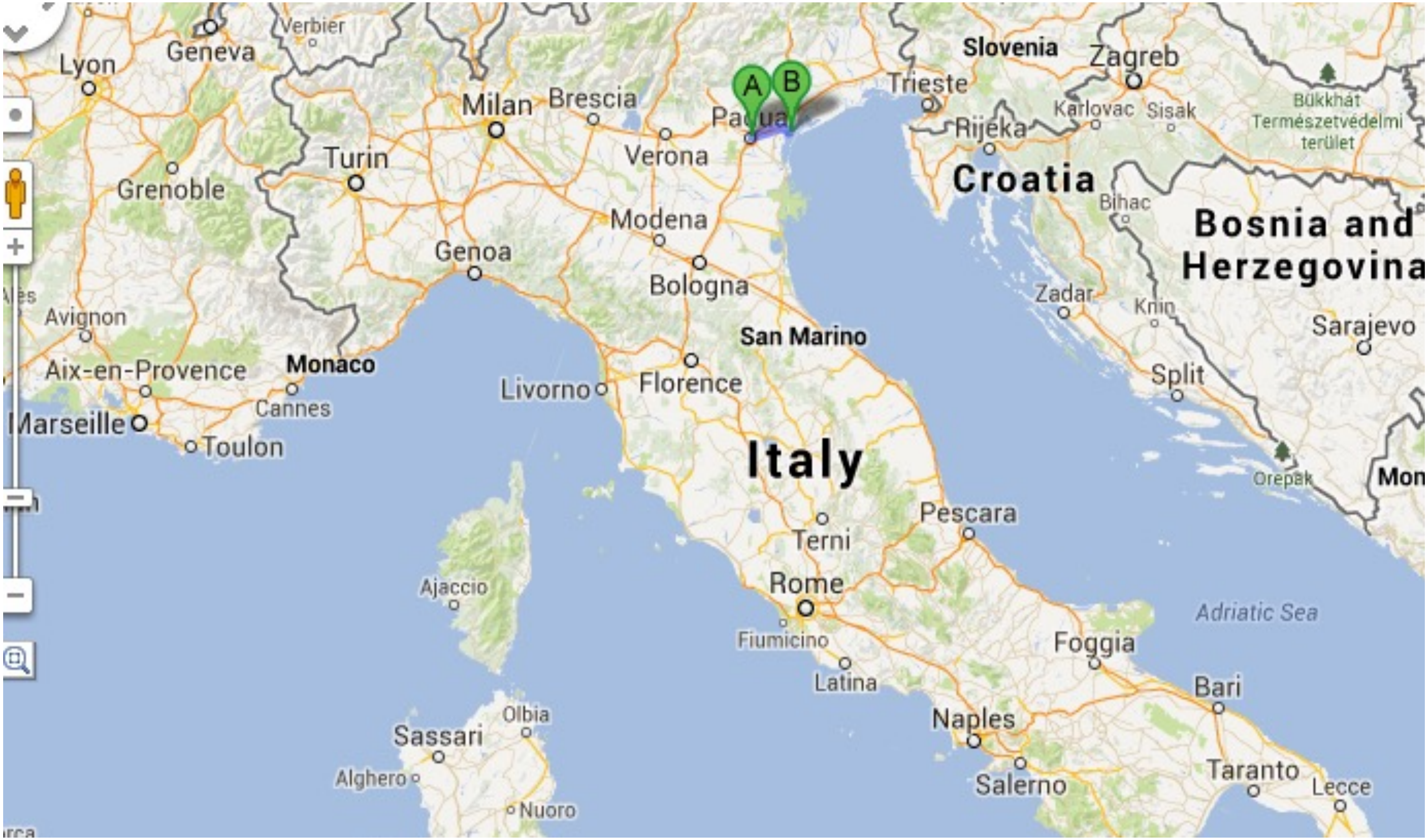
Stavanger AI Lab

Prof. Andrea Zanella
andrea.zanella@unipd.it

Dr. Federico Mason
federico.mason@unipd.it

Friday 26 November 2021

Padova (aka Padua)



SIGNET

1222 · 2022
800
ANNI

MCCXXII

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

FACTS & FIGURES

UNIPD @ a glance

UNIVERSITY OF PADUA

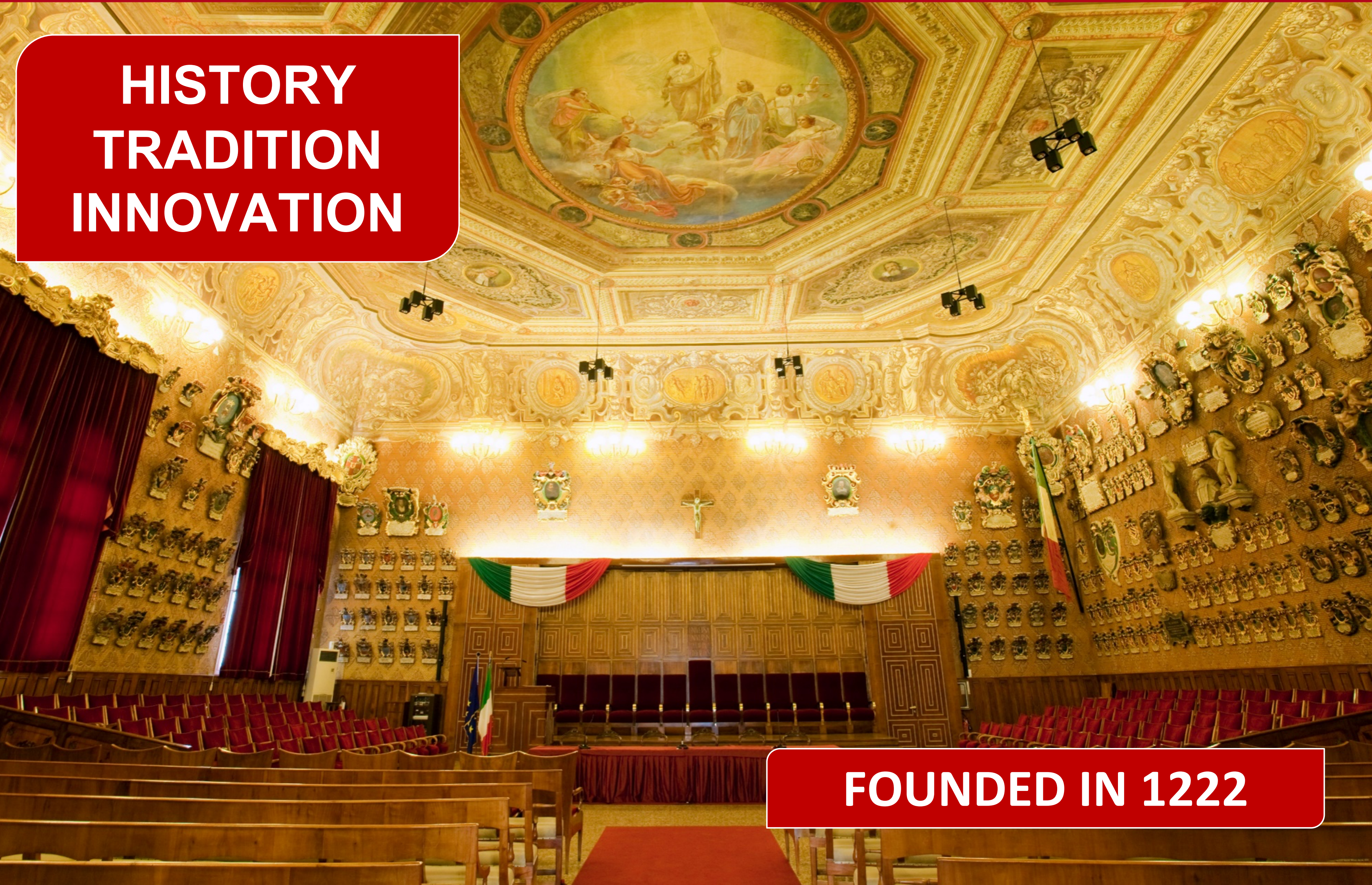
- ITALIAN WORLD-CLASS UNIVERSITY
- TOP 250 UNIVERSITY IN THE WORLD
- RESEARCH-INTENSIVE
- MULTIDISCIPLINARY AND INTERDISCIPLINARY
- BEST UNIVERSITY IN ITALY FOR TEACHING AND RESEARCH QUALITY

Facts & Figures

60,000	Students
3,000	International students
2,300	Academic Staff
2,300	Technical & Admin Staff

32 Departments
8 Schools
1 University Hospital
1 Veterinary Hospital
1 Institute for Advanced Study
10 Halls of Residence
17 University Canteens

8 centuries of academic excellence



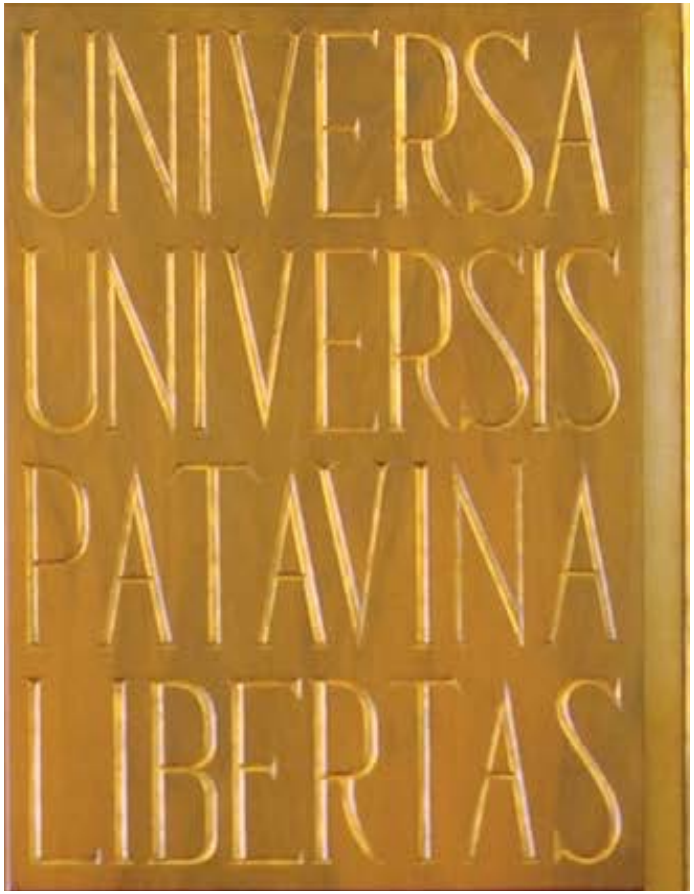
HISTORY
TRADITION
INNOVATION

FOUNDED IN 1222

8 centuries of academic excellence

Elena Lucrezia Cornaro Piscopia

1st woman to graduate, in 1678

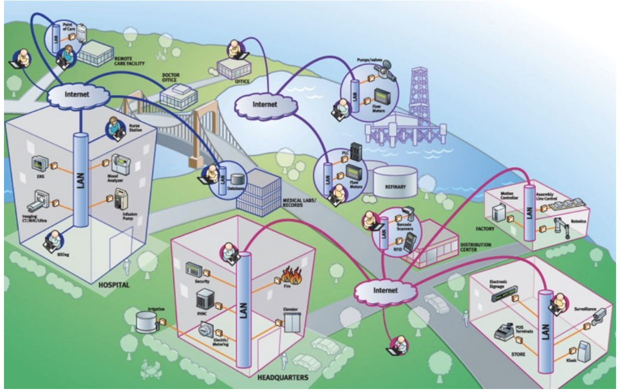


THE UNIVER-CITY

SIGNET people

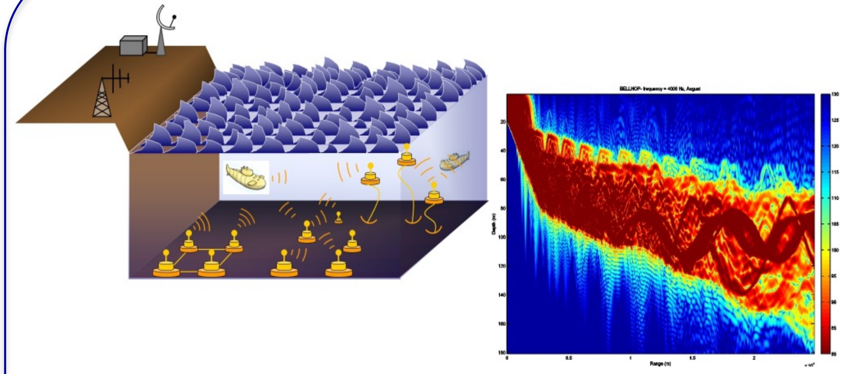
http://signet.dei.unipd.it

Main research areas…

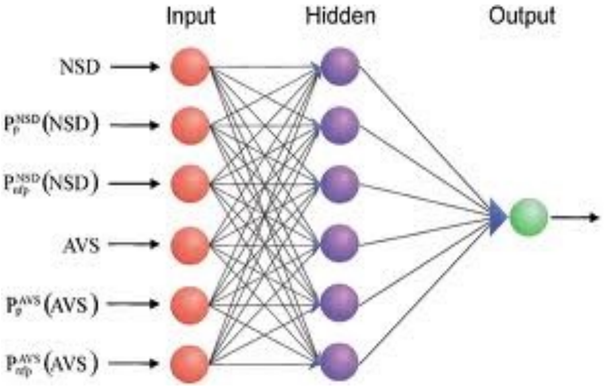


Next generation mobile & IoT

Energy harvesting

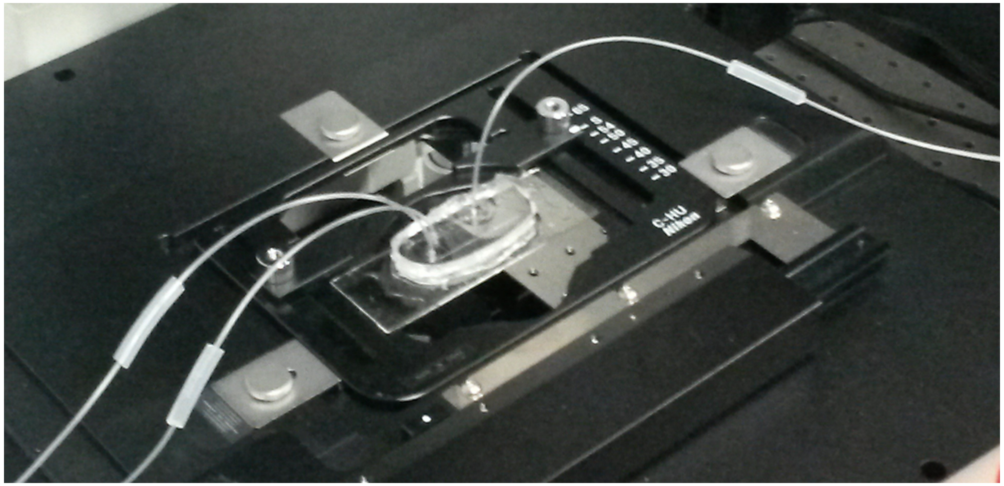


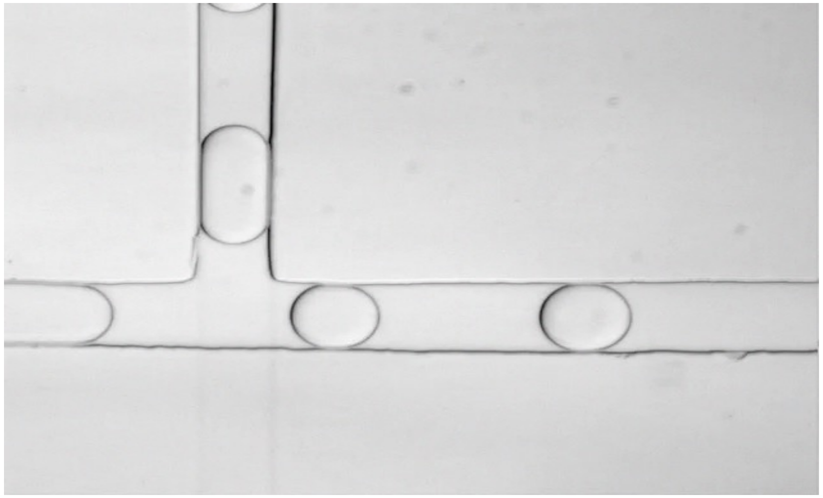
Underwater communications

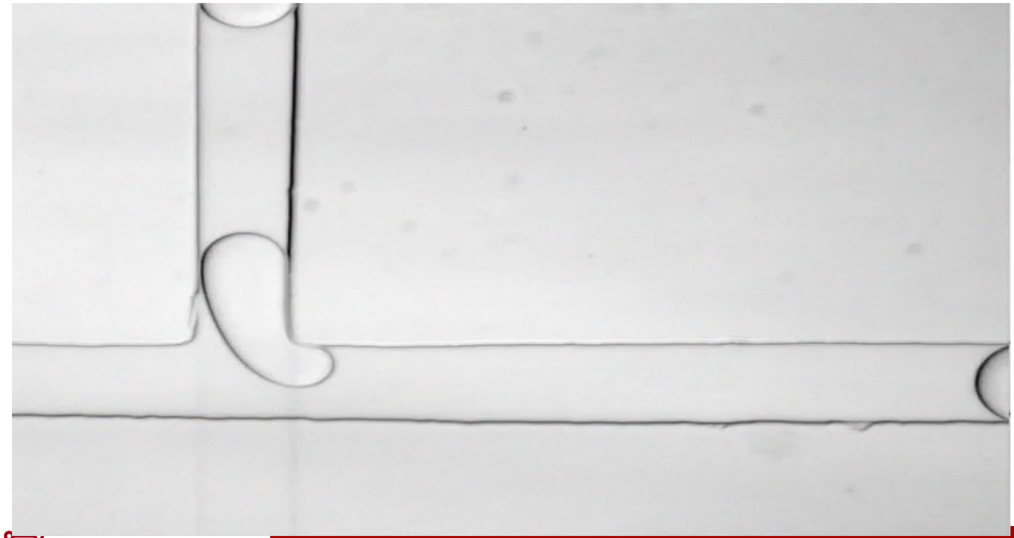


Cognitive Networks

Plus more exotic stuff…







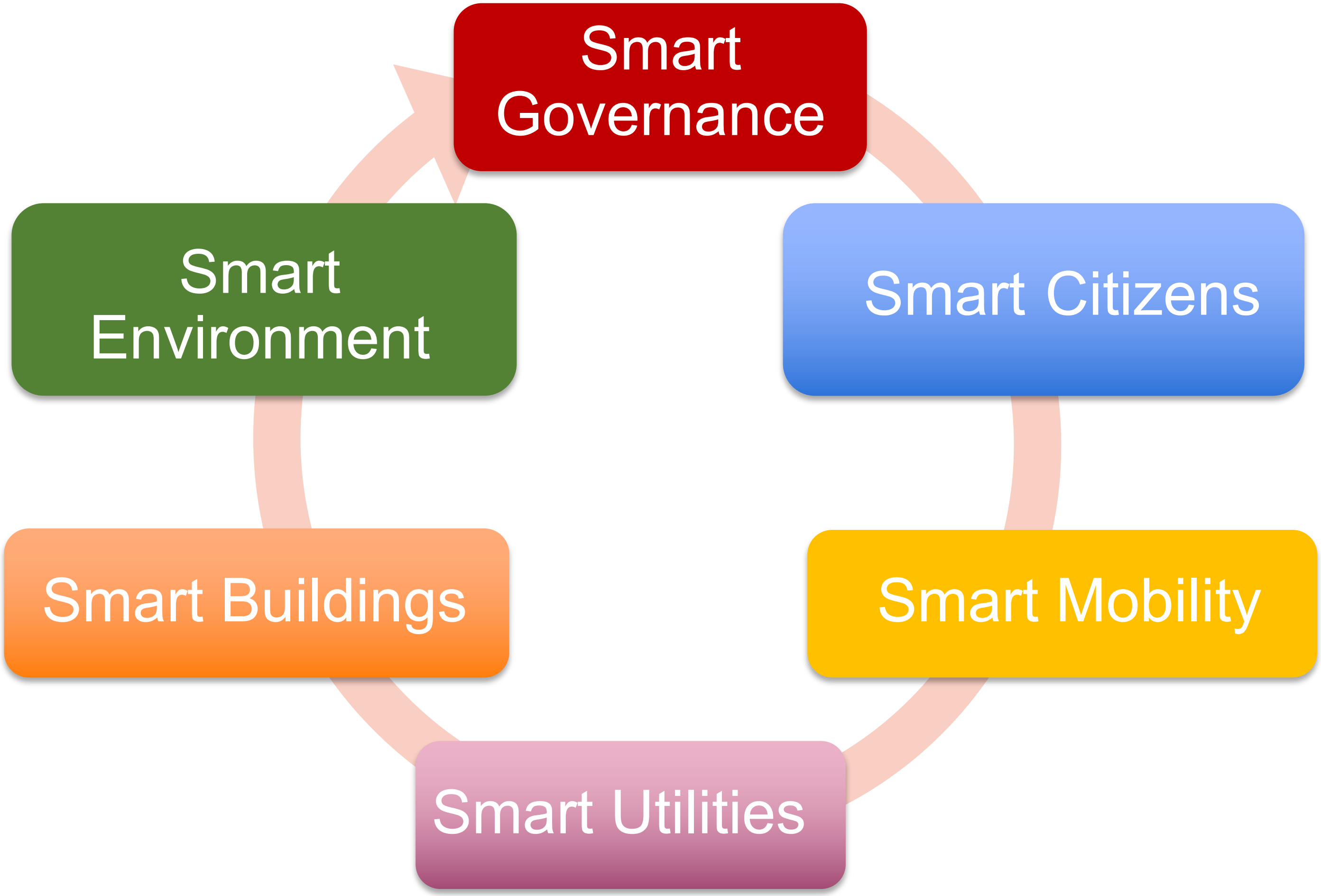
Outline

- Motivations
- The S^3 approach: Smart Sensing and Sending
  - Modelling, tuning and using LoraWAN
  - Delay-constrained Transport Protocols
- Scalable and Dynamic Network slicing
- Conclusions

Outline

- Motivations
- The S^3 approach: Smart Sensing and Sending
  - Modelling, tuning and using LoraWAN
  - Delay-constrained Transport Protocols
- Scalable and Dynamic Network slicing
- Conclusions

The 6 pillars of city smartness



Smart Governance

Smart Citizens

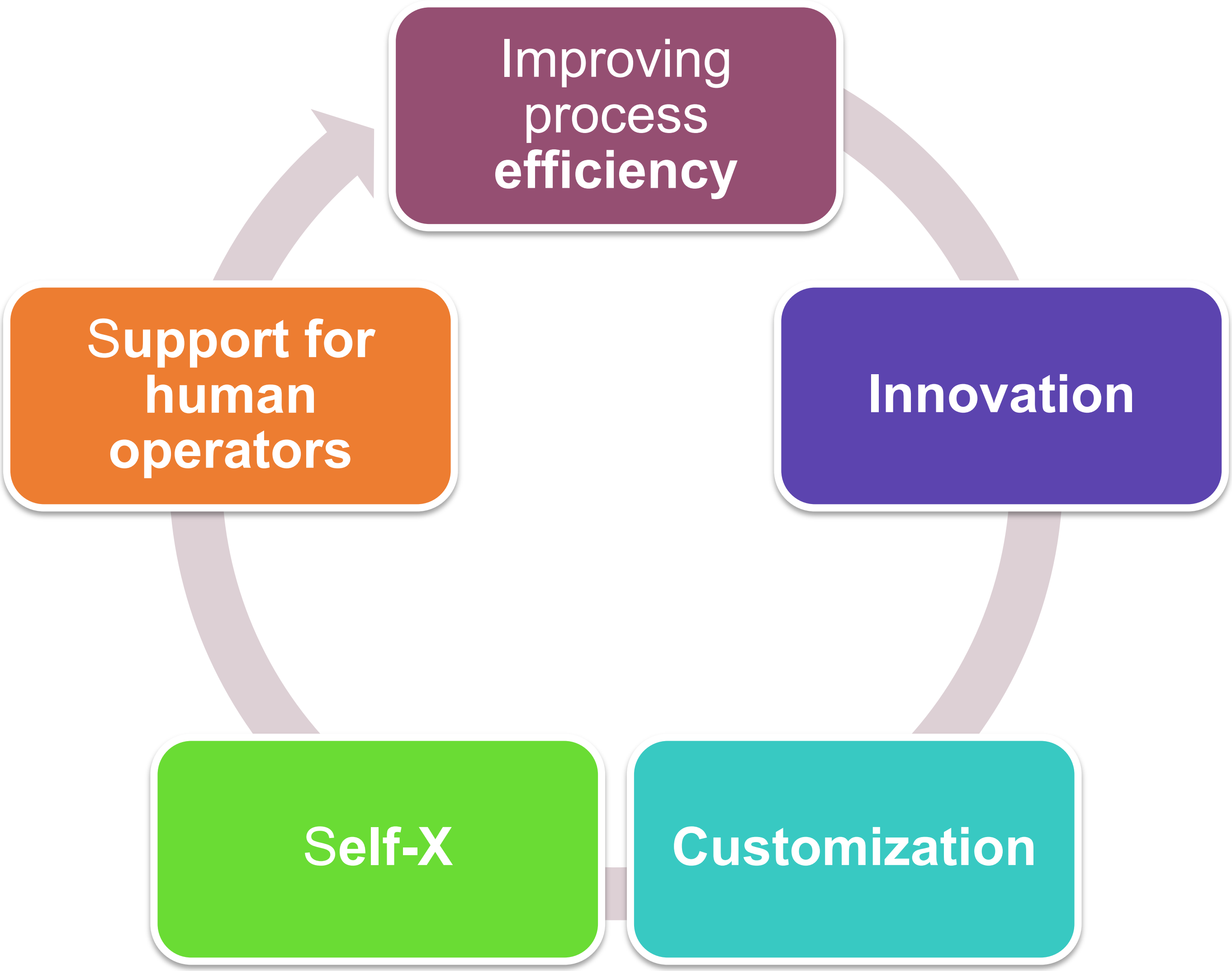
Smart Mobility

Smart Utilities

Smart Buildings

Smart Environment

Smartness in Industry (4.0)



Improving process **efficiency**

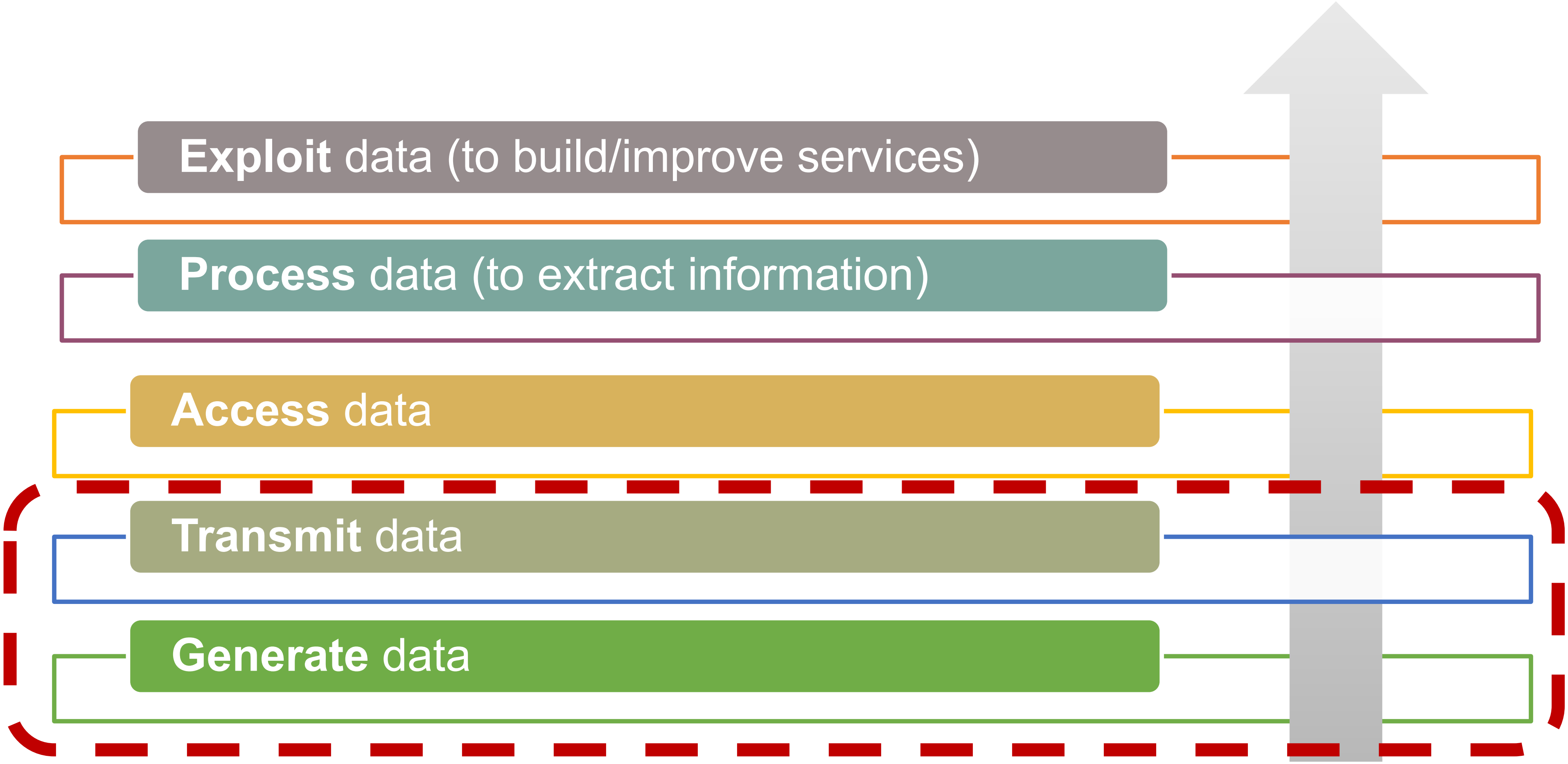
Innovation

Customization

Self-X

Support for human operators

Building smartness



Exploit data (to build/improve services)

Process data (to extract information)

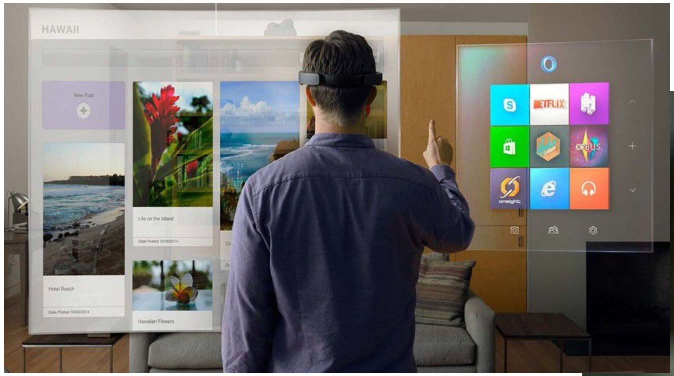
Access data

Transmit data

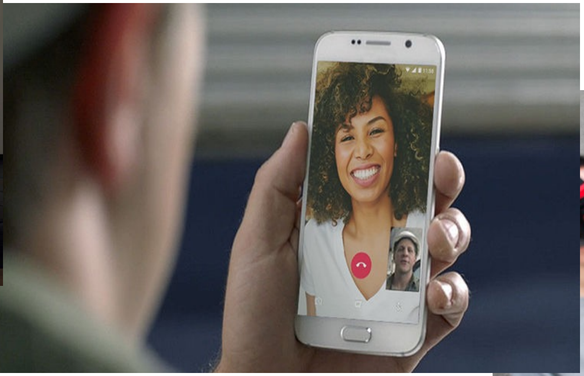
Generate data

New markets

Augmented Reality



Mobile video chat



Drones and AUVs

Interactive, high throughput applications need latency **guarantees**

Summing up

- New markets and applications set very specific (and stringent) quality-of-service requirements to the communication plane

- Transmission services must be
  - Efficient
  - Adaptable
  - Customizable

Summing up

- **Proper configuration** of off-the-shelf technologies can make the difference!

- **New protocols and intelligent resource allocation schemes** are needed for more challenging scenarios

Outline

- Motivations
- The S^3 approach: Smart Sensing and Sending
  - Modelling, tuning and using LoraWAN
  - Delay-constrained Transport Protocols
- Scalable and Dynamic Network slicing
- Conclusions

Rationale

- Electrical engineers work hard to design **power efficient hardware for wireless nodes …**
  - Bluetooth Low energy, ZigBee, LoRa, SigFox, …

…however…

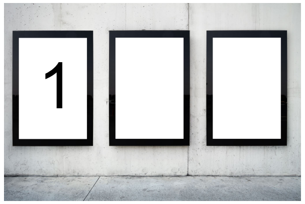
- ill-designed protocols (or wrong parameters configurations) **can spoil the effort**!

The S^3 approach

- Provide mathematical/numerical models for the system components
    - digital twins?
- Understand and model the rate/distortion characteristics of the source
    - Learning framework for context awareness
- **Jointly optimize “sensing” and “sending”**
    - Source-coding and scheduling

You choose!

- Example 1: energy-efficient environmental monitoring



- Example 2:
  - Modeling and configuring LoRaWAN
  - LORAWAN for DRONE TRACKING

- Example 3: Delay-constrained Transport Protocols

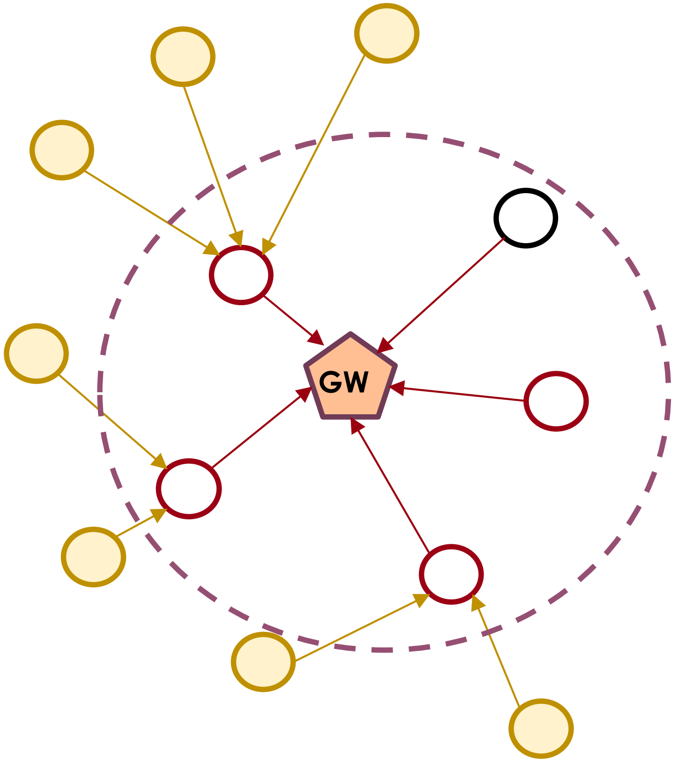
- Jump dire[illegible] Conclusions

S^3: Smart Sensing & Sending

- Example 1: energy-efficient environmental monitoring

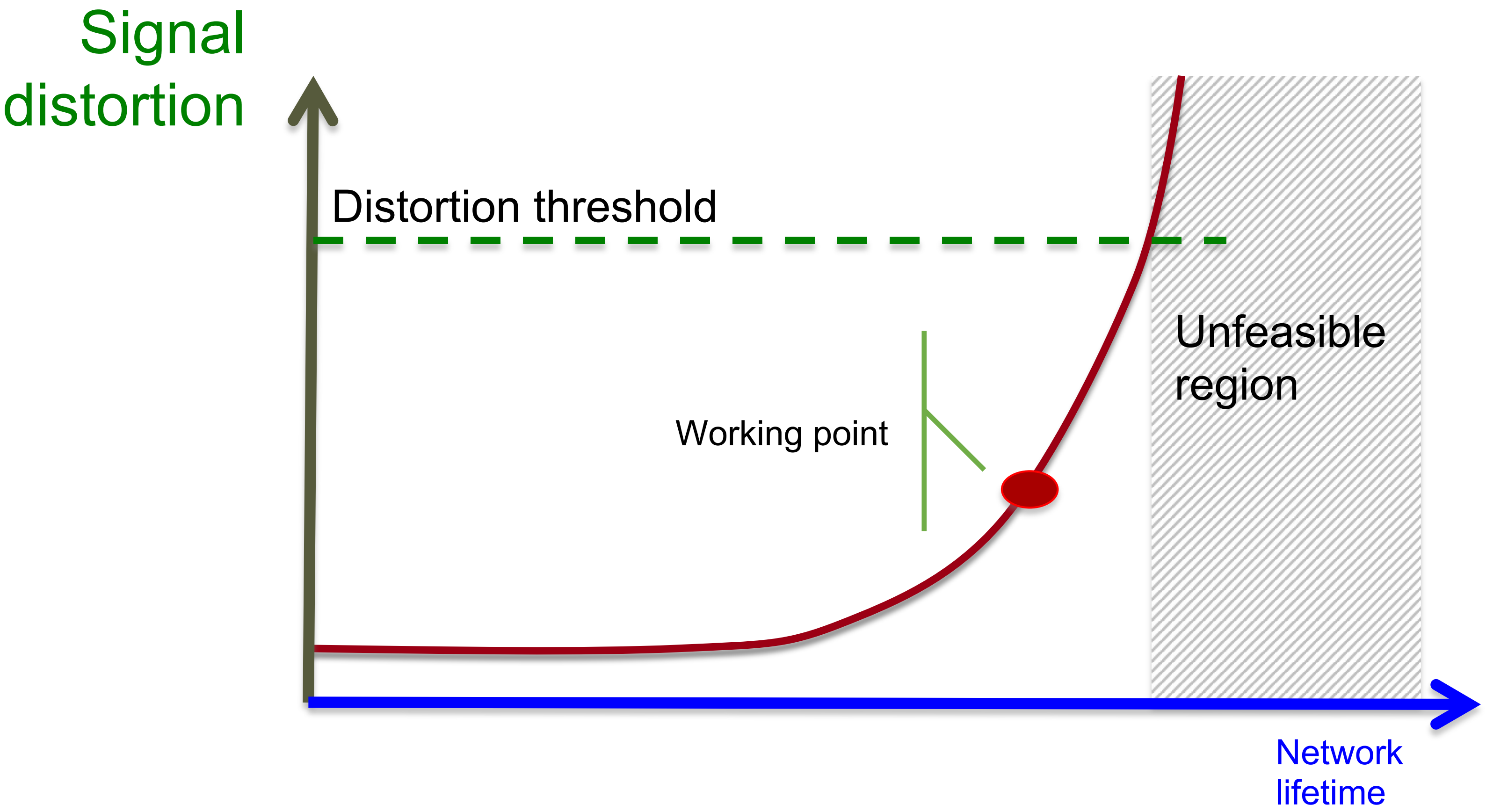
Target scenario

- **Signals suitable for (lossy) compression**
  - Rate-distortion tradeoff
- **Many battery powered peripheral devices**
  - Battery powered → need for energy saving
    - data compression (fewer bits to transmit)
    - intelligent management of the available energy (channel-adaptive modulation schemes)
  - Large number → need for intelligent channel access
    - dynamic allocation of resources
- **One (more powerful) collector (GW)**
  - Can performing complex operations
    - Find optimal access policies and distribute to peripheral nodes



Our Goal

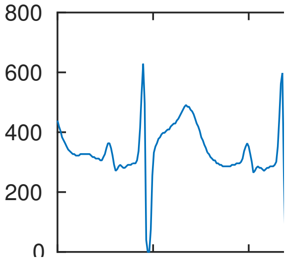
Multi-objective MAC layer optimization



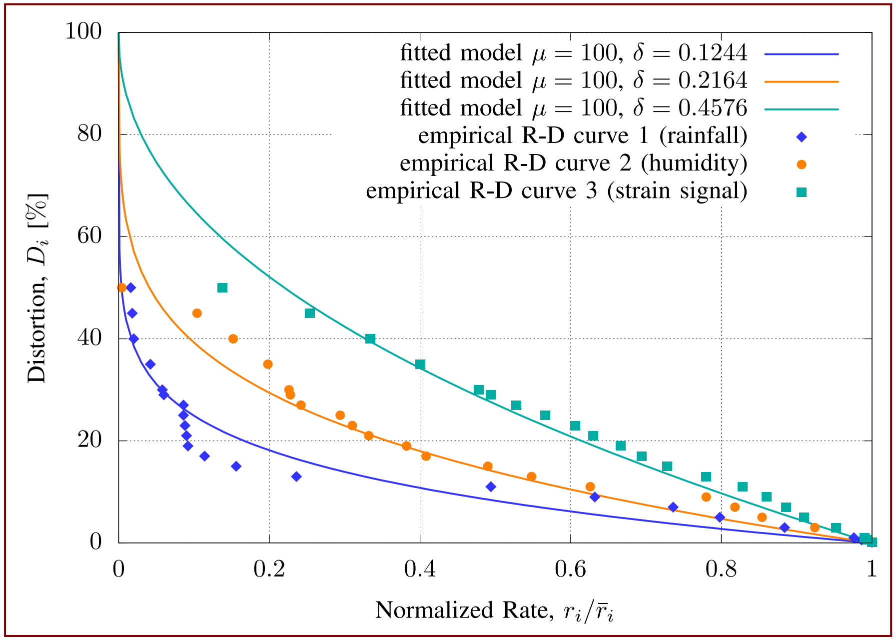
Approach

Rate-distortion characterization

Signals



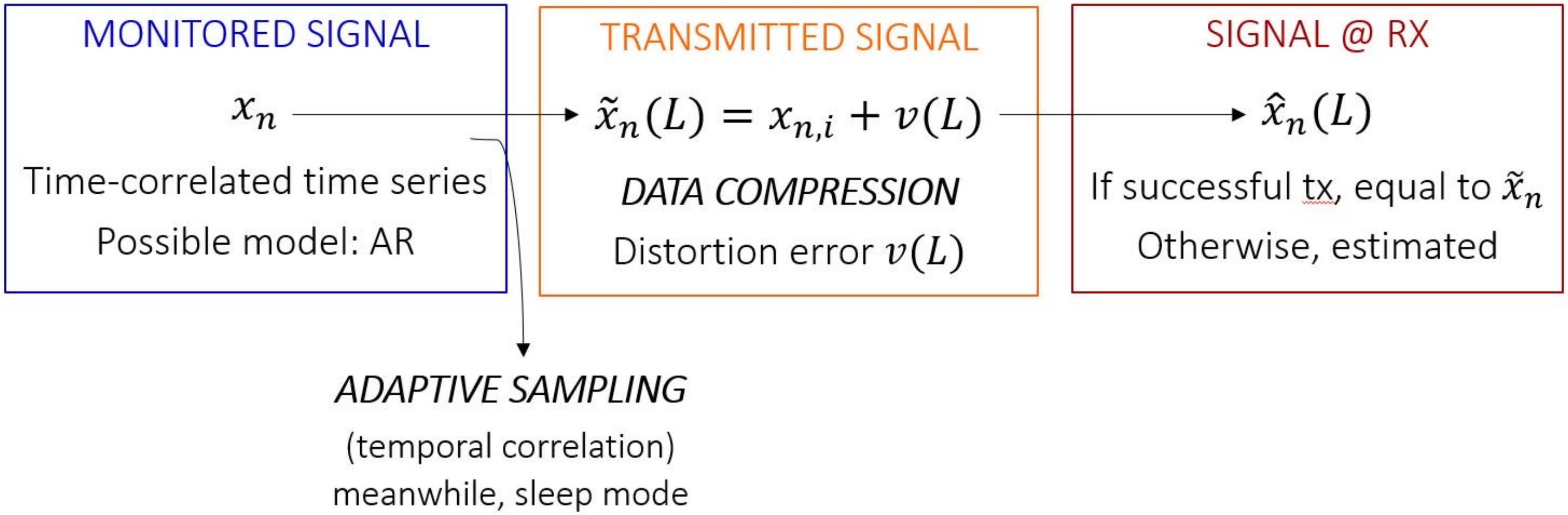
Features extraction



MAC protocols

Our approach

ICC, 20-24 May 2018, Kansas City (MO)



MONITORED SIGNAL

x_n

Time-correlated time series

Possible model: AR

TRANSMITTED SIGNAL

$\tilde{x}_n(L) = x_{n,i} + v(L)$

DATA COMPRESSION

Distortion error $v(L)$

SIGNAL @ RX

$\hat{x}_n(L)$

If successful tx, equal to $\tilde{x}_n$

Otherwise, estimated

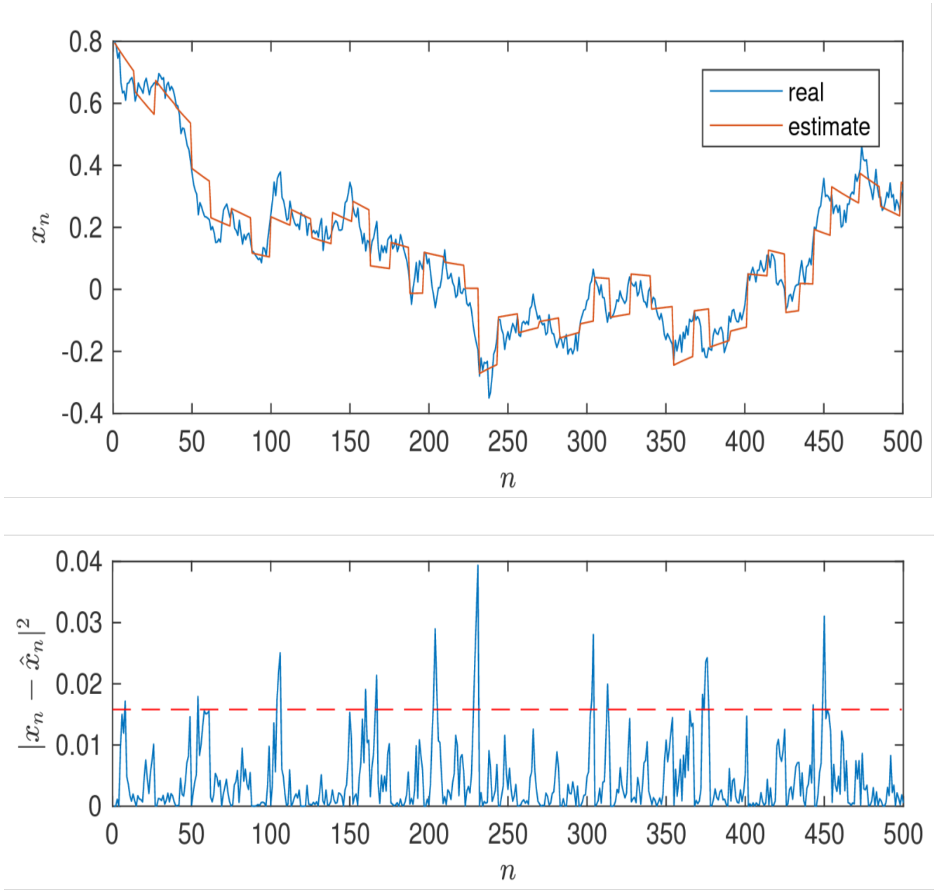
ADAPTIVE SAMPLING

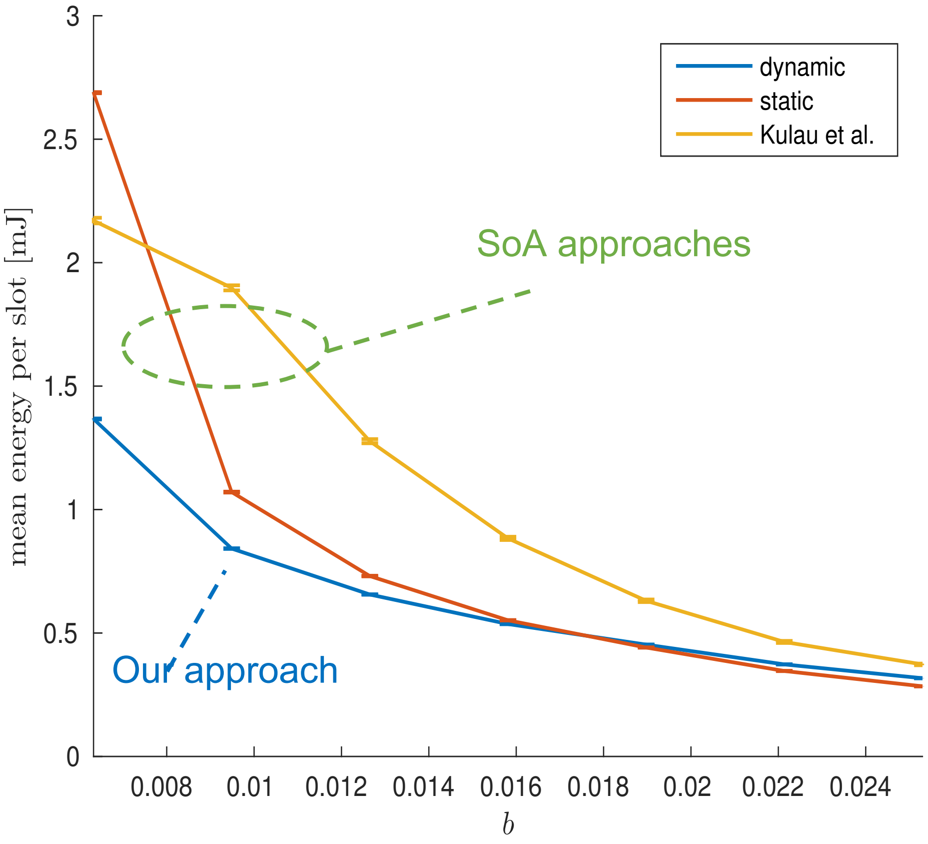
(temporal correlation)

meanwhile, sleep mode

- Reconstruction accuracy: $|\, x_n - \hat{x}_n(L)|^2$
- **Outage probability:** $P(|x_n - \hat{x}_n(L)|^2 > b)$
    - Increases with lag *n* from last data received (correlation fades over time)
    - Increases with compression degree (smaller *L*)
- **Goal**: find balance between sleeping period, transmit power, and packet size that guarantees outage probability is lower than a threshold p_{th}

Example of results




SoA approaches

Our approach

---

[1] U. Kulau, J. van Balen, S. Schildt, F. Büsching, and L. Wolf, "Dynamic sample rate adaptation for long-term IoT sensing applications," *in Proc. 3rd IEEE World Forum on Internet of Things*, Dec. 2016

S^3: Smart Sensing & Sending

- Example 2: modeling and configuring LoRaWAN

Credits to: Martina Capuzzo, Davide Magrin

The LPWAN arena

WEIGHTLESS™

NB-IoT

INGENU

LoRa™ Alliance

Wide Area Networks for IoT

waviot

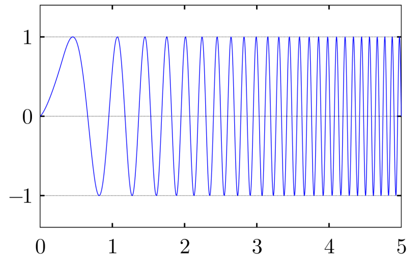
SIGFOX

One network A billion dreams

M. Centenaro, L. Vangelista, A. Zanella, M. Zorzi, ``**Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart City Scenarios**" *IEEE Wireless Communications*, Volume: 23, Issue: 5, October 2016

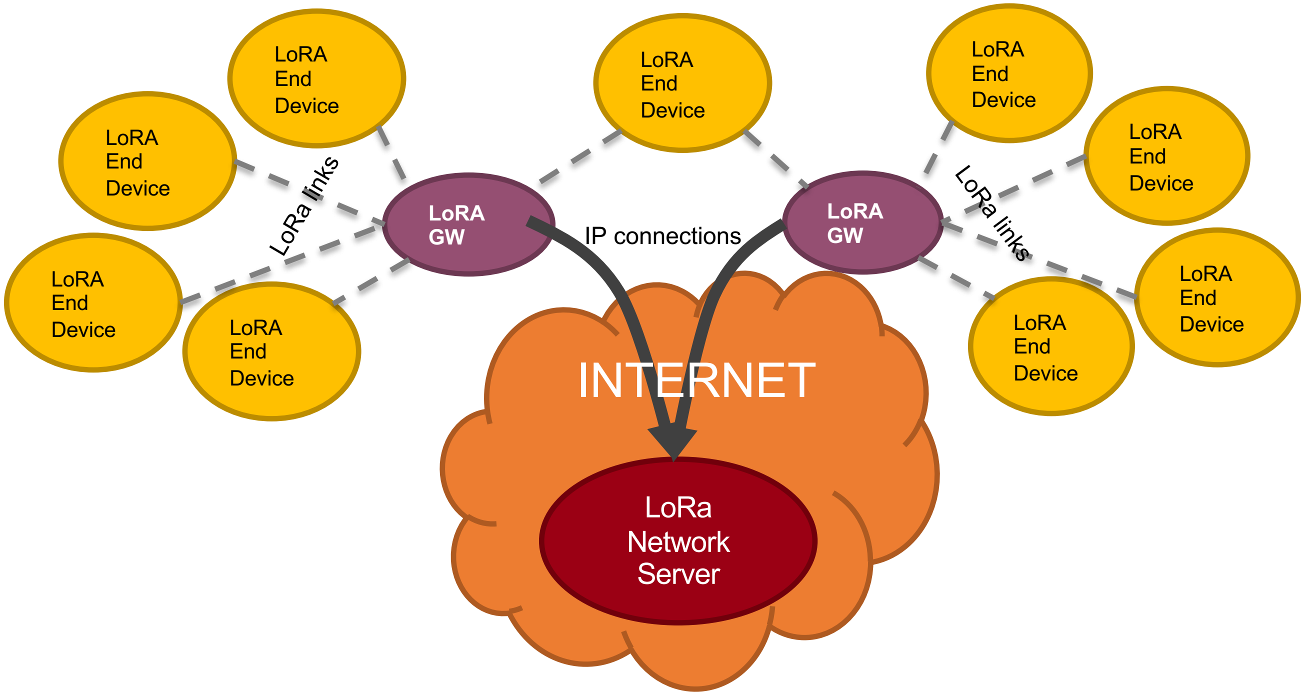
LoRa features

- **LoRa**: Chirp Spread Spectrum (CSS) modulation patented by Semtech
  - ISM 800 MHz
  - Up to **6** different **spreading factors** (SF) number from 7 (highest speed) to 12 (longest range)



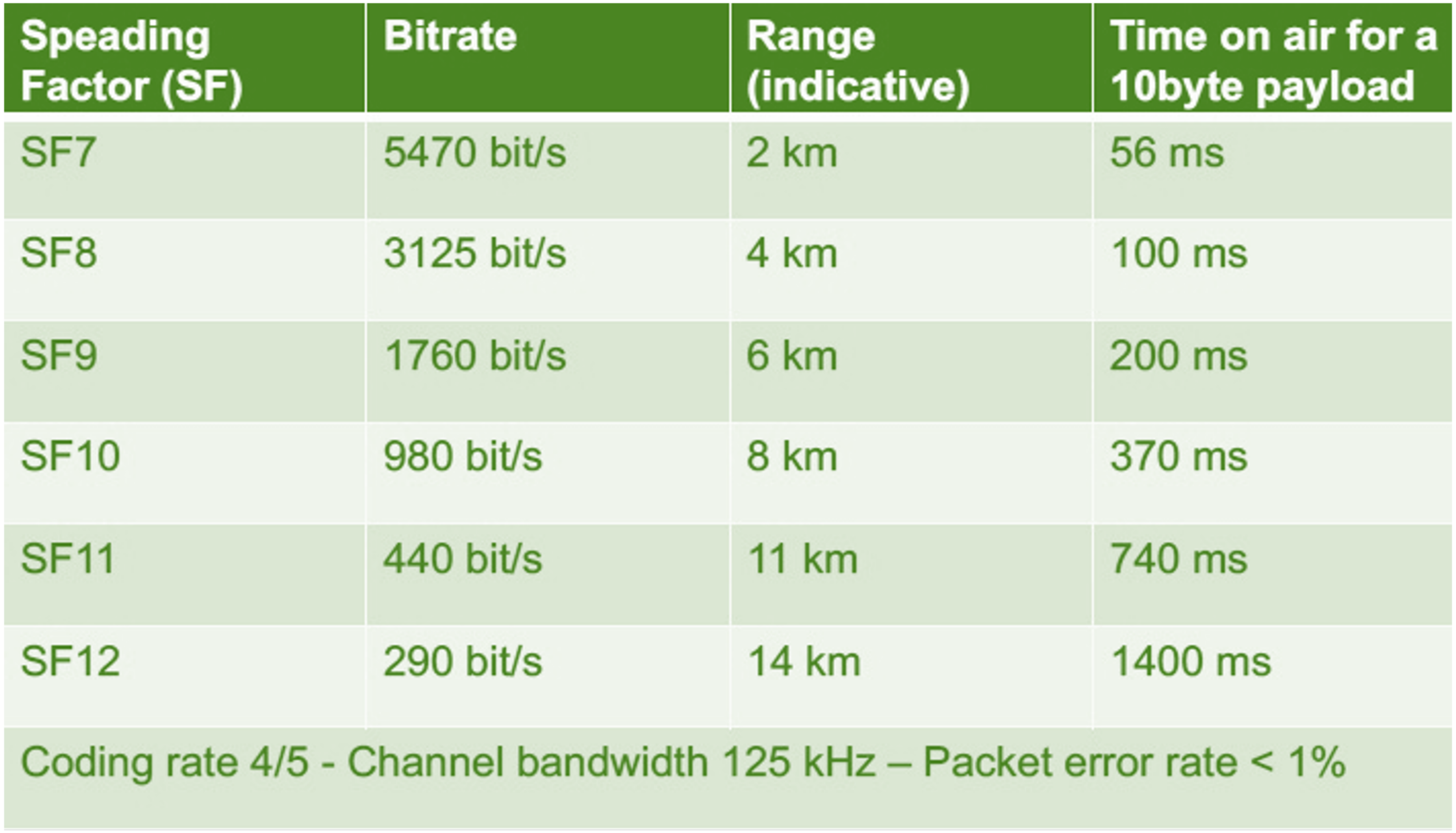
- **LoRaWAN**: open network specifications
- Star topology
  - Network Server
  - Gateways
  - End Devices

LoRaWAN architecture



- ✓ Long coverage
- ✓ Low energy consumption
- ✓ Low bitrates
- ✓ Massive number of nodes
- ✓ Uncoordinated access
- ✓ Multiple GWs

LoRa bitrate & packet duration



Speading Factor (SF)	Bitrate	Range (indicative)	Time on air for a 10byte payload
SF7	5470 bit/s	2 km	56 ms
SF8	3125 bit/s	4 km	100 ms
SF9	1760 bit/s	6 km	200 ms
SF10	980 bit/s	8 km	370 ms
SF11	440 bit/s	11 km	740 ms
SF12	290 bit/s	14 km	1400 ms
Coding rate 4/5 - Channel bandwidth 125 kHz – Packet error rate < 1%			

Credits for the image to Prof. L. Vangelista

Channelization

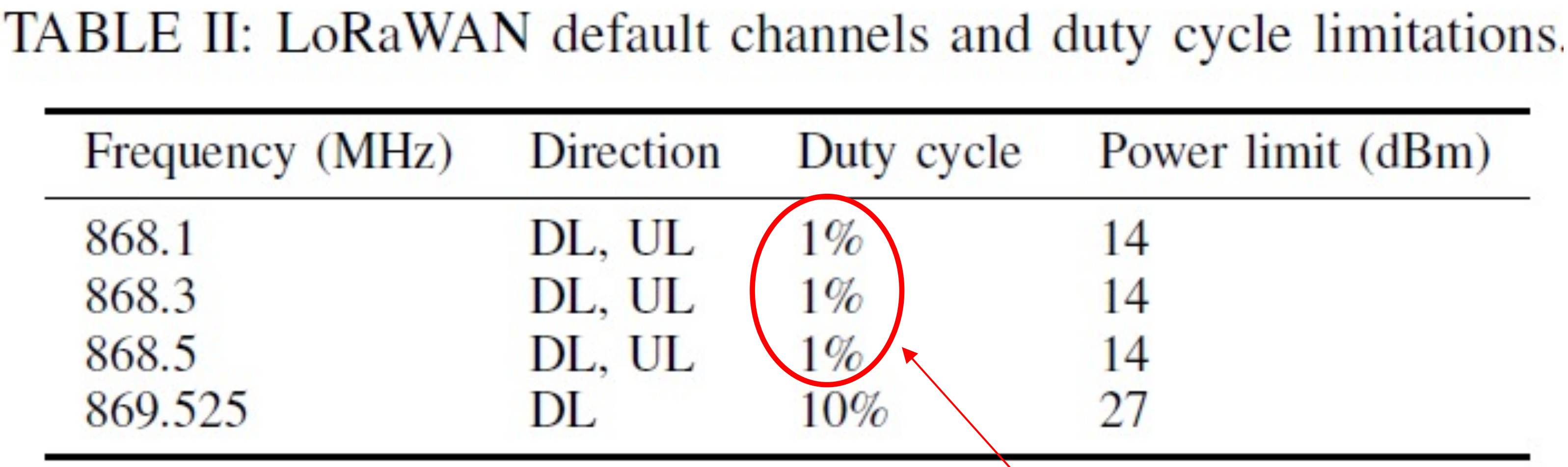


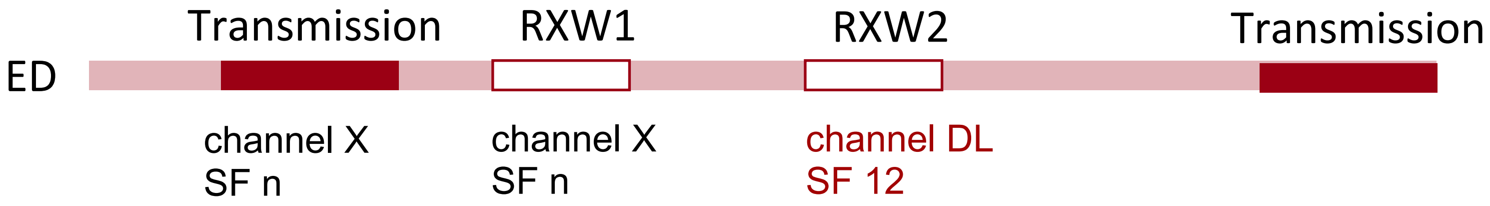
TABLE II: LoRaWAN default channels and duty cycle limitations.

Frequency (MHz)	Direction	Duty cycle	Power limit (dBm)
868.1	DL, UL	1%	14
868.3	DL, UL	1%	14
868.5	DL, UL	1%	14
869.525	DL	10%	27

Shared by all 3 subchannels

ED classes

- Class A (all): receive only after transmission



Transmission RXW1 RXW2 Transmission

ED

channel X
SF n

channel X
SF n

channel DL
SF 12

- Class C (continuous): receive anytime

Transmission RXW Transmission

ED

channel DL
SF 12

Gateway features

- Commercial Gateways feature k parallel receive paths
  - Receive paths are assigned to the different UL channels
  - Each receive path can lock on an UL transmission on the assigned channel
  - Can receive up to k signals in parallel
- **Subject to DC limitations as any other device!**

LORAWAN: Summing Up

- Simple topology & MAC (ALOHA)
- A few tunable parameters
    - Uplink transmission Spreading Factor (SF)
    - ACK-request
    - Number of repetitions (for unconfirmed traffic)
    - Number of retransmissions (for confirmed traffic)
    - Receive Window Channel Association*
    - Duty cycle limitations*
    - Downlink transmission Spreading Factor
    - Transmission preemption at the Gateway*
    - Adaptive Data Rate (ADR) algorithm
- What's the best configuration?

*These settings are not actually permitted by the standard… but possible in our model/simulator!

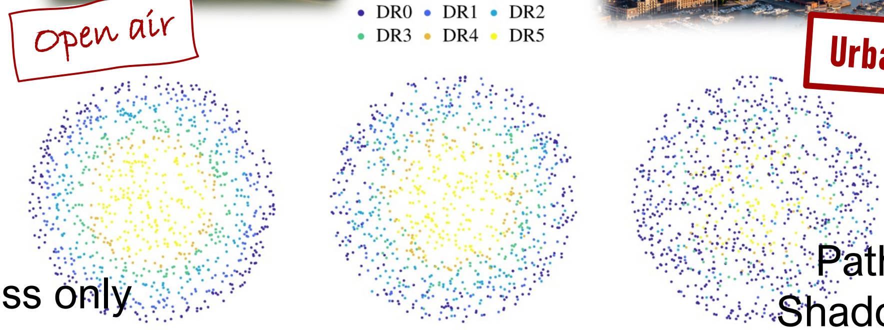
LoRaWAN performance analysis

- Traditional IoT
  - ns-3 simulations [J3]
  - Analytical model [C6, J6]

- Non-traditional IoT
  - Industrial IoT [J5]
  - Drone tracking [C5, J2]

Open air

Urban



Path loss only

Path loss
Shadowing
Buildings

NETWORK SIMULATOR

ns3::lorawan::LorawanMac

Class representing the LoRaWAN MA

`#include "lorawan-mac.h"`

▸ Inheritance diagram for ns3::loraw

▸ Collaboration diagram for ns3::lor

LoRaWAN References

[J2] F. Mason, M. Capuzzo, D. Magrin, F. Chiriotti, “Remote tracking of UAV swarms via 3D mobility models and LoRaWAN communications”, in *IEEE Transactions on Wireless Communications*, (*under revision: Major - Major*).

[J3] D. Magrin, M. Capuzzo and A. Zanella, "A Thorough Study of LoRaWAN Performance Under Different Parameter Settings" in *IEEE Internet of Things Journal, vol. 7, no. 1, pp. 116-127, Jan. 2020.*

[J5] D. Magrin, M. Capuzzo, A. Zanella and M. Zorzi, “Performance Analysis of LoRaWAN in Industrial Scenarios” in *IEEE Transactions on Industrial Informatics*, 2020.

[J6] D. Magrin, M. Capuzzo, A. Zanella and M. Zorzi, “A Configurable Mathematical Model for Single-Gateway LoRaWAN Performance Analysis”, in *IEEE Transactions on Wireless Communications*, (*under revision: Major - Major*).

[C5] F. Mason, F. Chiariotti, M. Capuzzo, D. Magrin, A. Zanella and M. Zorzi, “Combining LoRaWAN and a new 3D motion model for remote UAV tracking”, in *IEEE International Conference on Computer Communications (InfoCom)*, 6-9 July 2020, Virtual Conference.

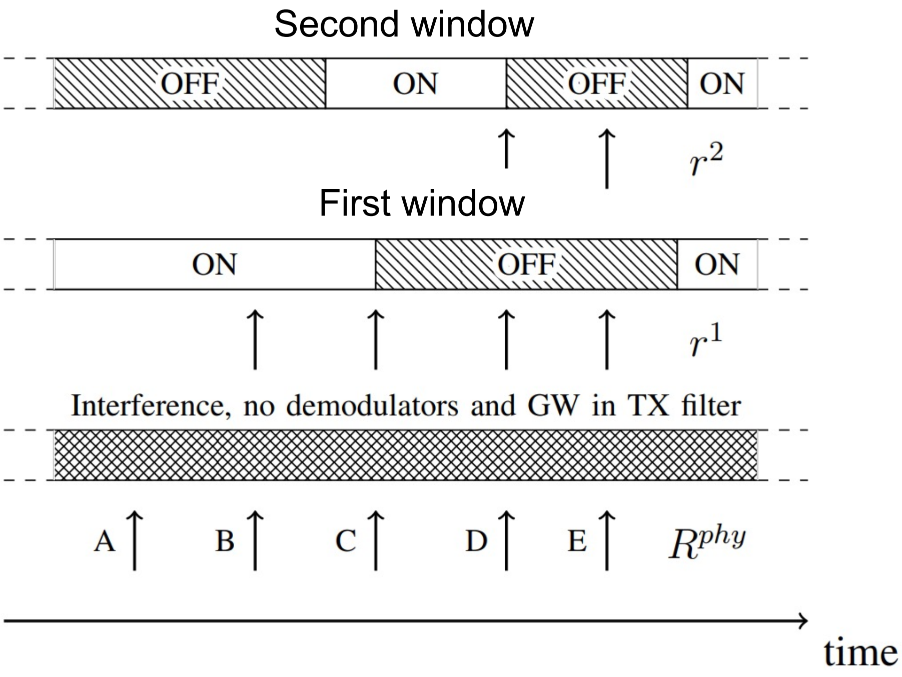
[C6] M. Capuzzo, D. Magrin and A. Zanella, "Mathematical Modeling of LoRaWAN Performance with Bi-directional Traffic," 2018 IEEE Global Communications Conference (Globecom), Abu Dhabi. DOI: 10.1109/GLOCOM.2018.8647351

LoRaWAN modeling

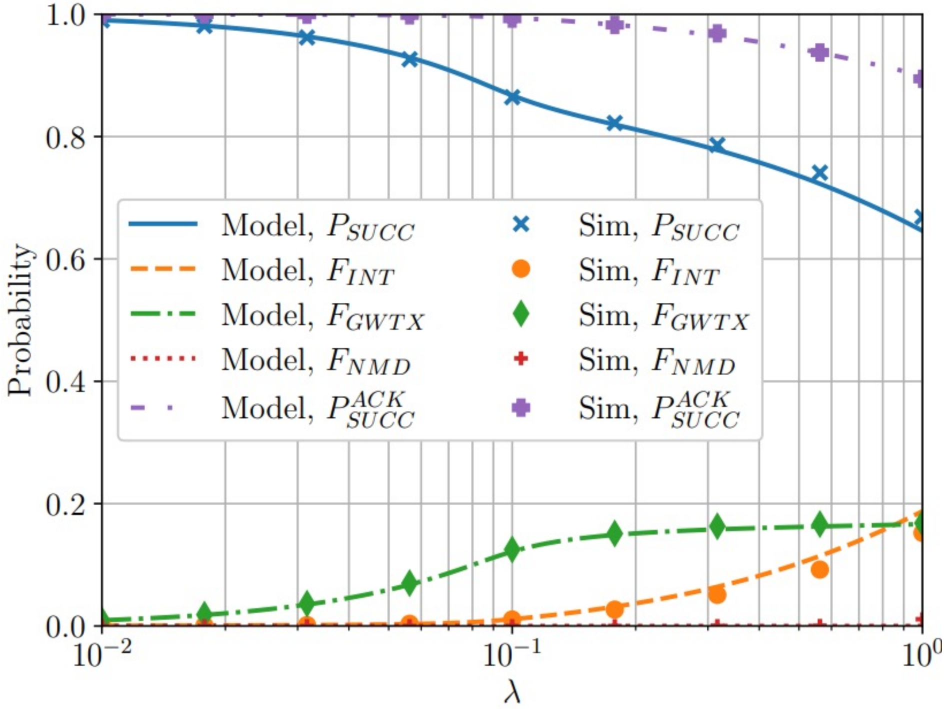
Analytical model [C6, J6]

- EDs randomly and uniformly distributed around the GW, all in range
- Packets generated following a Poisson process with aggregate rate λ [pck/s]
- Perfect orthogonality between SFs
- Capture probability for packets with same SF
- Uncorrelated re-transmissions
- Availability of sub-bands for ACK transmission modeled with two alternating renewal processes

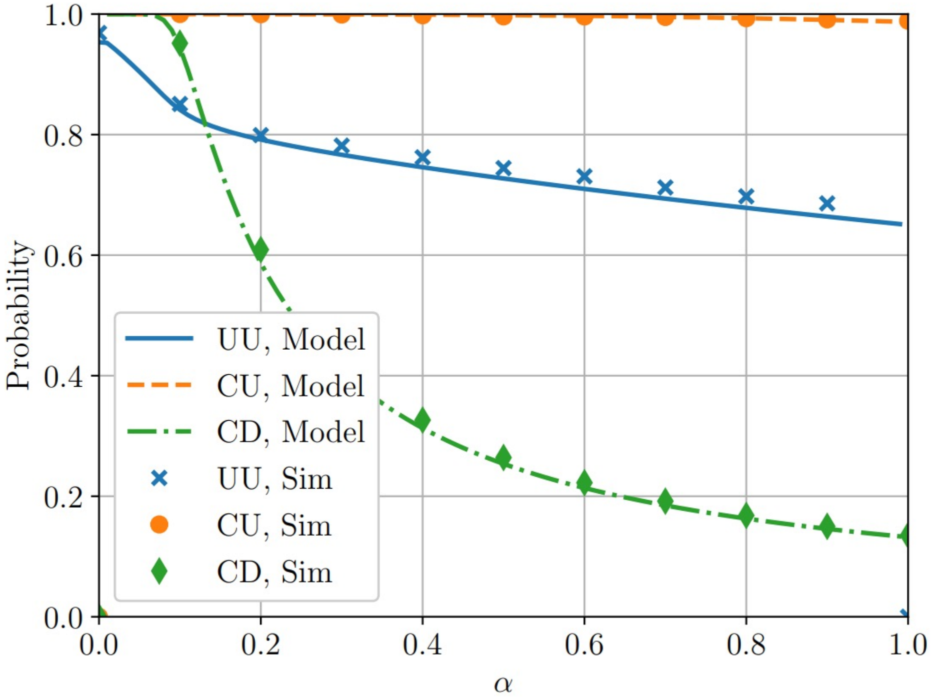
Model's packet filtering structure



LoRaWAN model validation



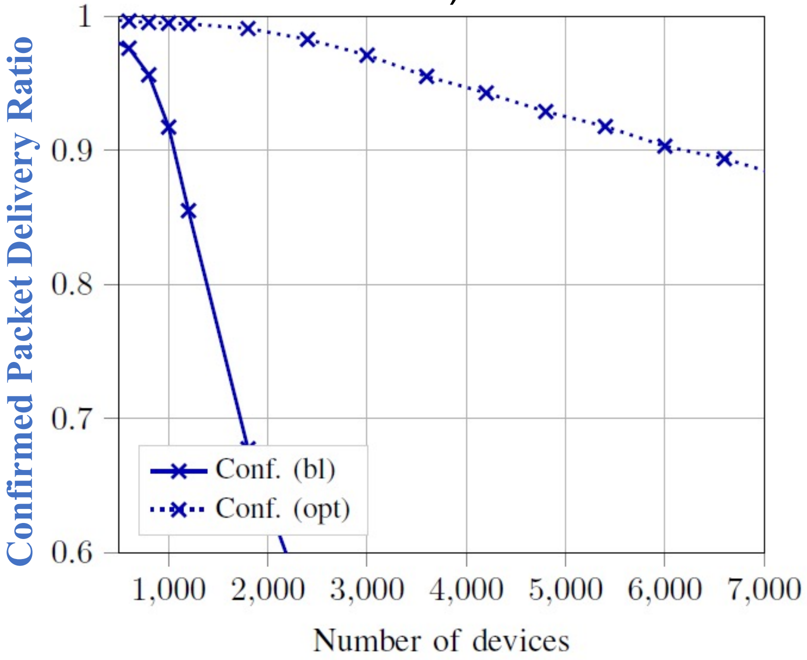
PHY-level performance with only confirmed traffic



Performance when varying the fraction of confirmed traffic (λ=1 pck/s)

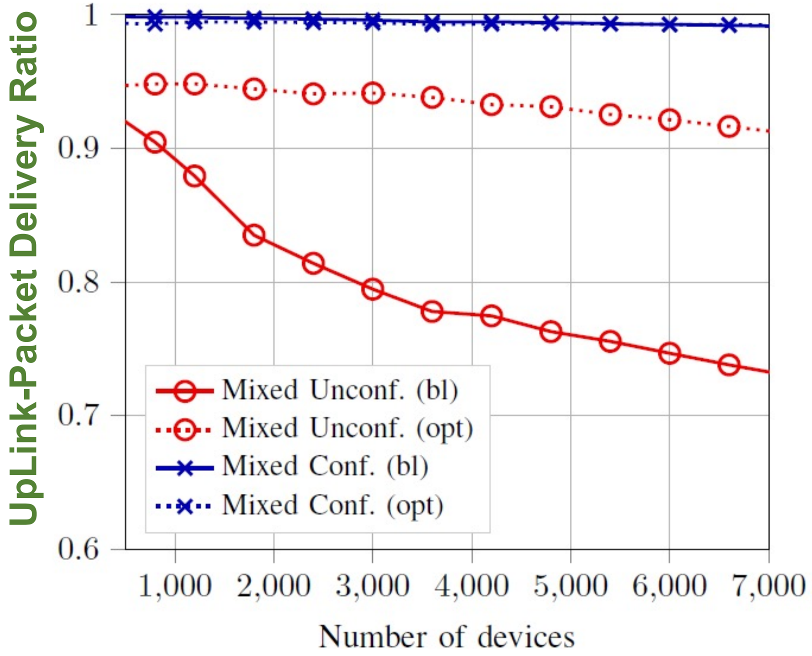
LoRaWAN performance analysis

- Realistic scenario, **confirmed traffic only** (delivered& confirmed)



Optimal configuration for CPSR	value
Re-transmissions (*m*)	8
Sub-band swapping	Yes
DL data rate	same as UL

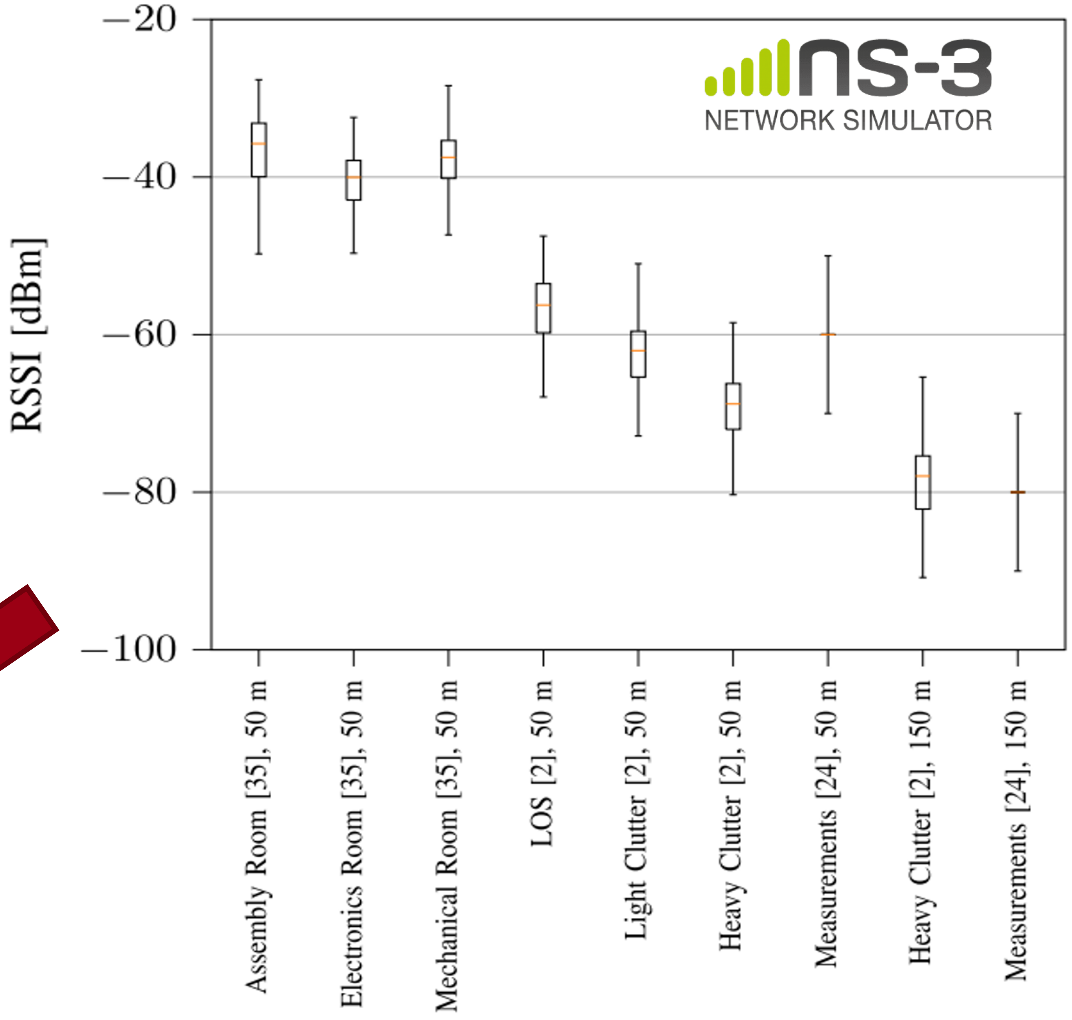
- Realistic scenario, **mixed** traffic (delivered)



Optimal configuration for UL-PDR	value
Re-transmissions (*m*)	4
Sub-band swapping	Yes
DL data rate	same as UL
Priority to RX at the Gateway	

LoRaWAN in Industrial scenarios

- Propagation model for industrial environments
- Industrial plant of 200x200 m^2
- 300 nodes
- Application period ∈ {30 s, ~3,5 d}
- Confirmed traffic, m = 1
- SF7 (fastest)

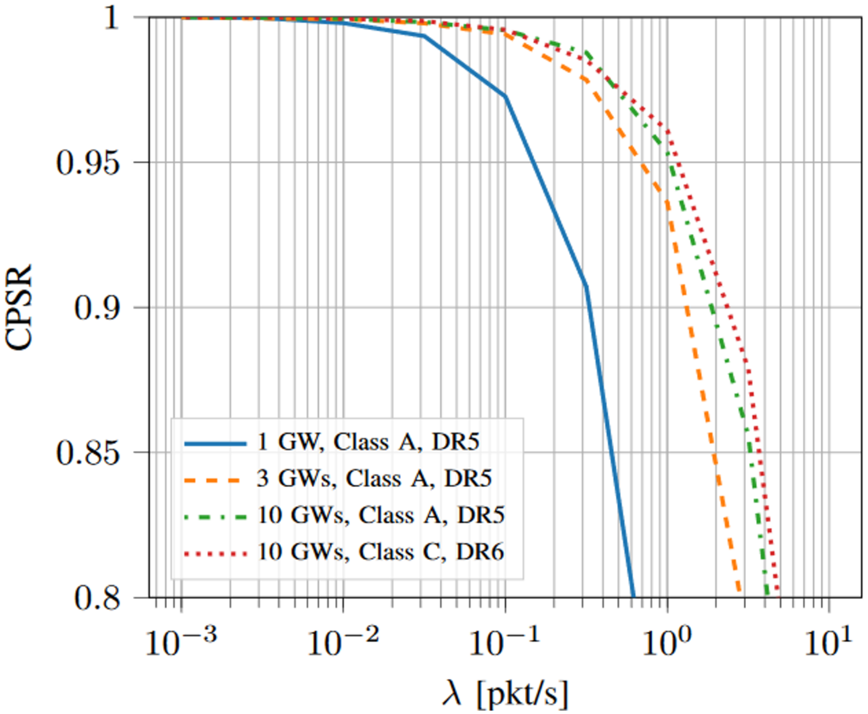


Nakagami-m distribution for small scale effects (reflections)

Shot noise from the literature (conservatively simulated as 3dB sensitivity reduction at receiver)

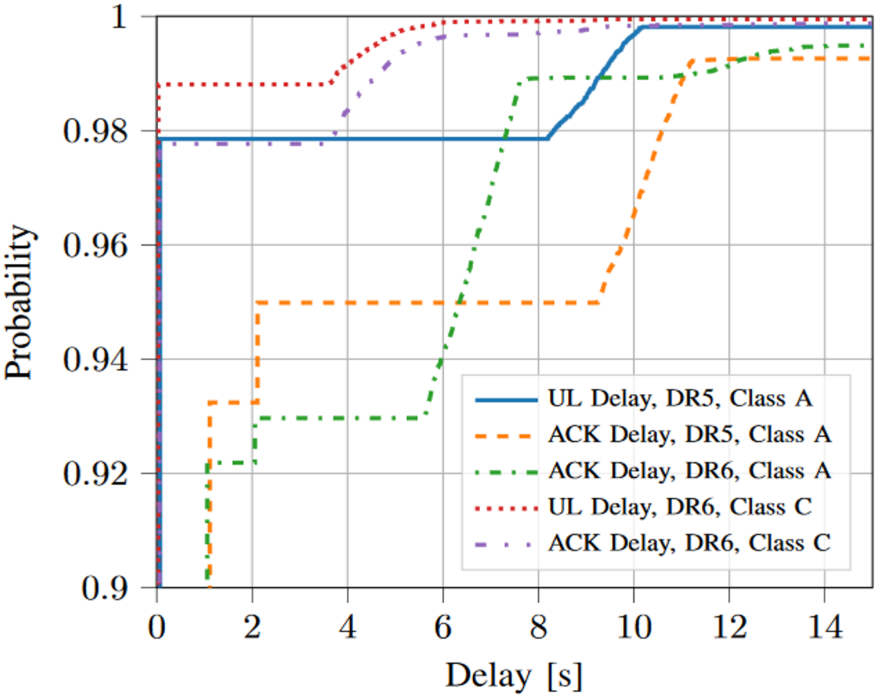
LoRaWAN performance analysis

- Reliability



Effect of different deployments on the CPSR for *m*=1.

- Delay



CDF of UL and ACK delays for a 10-GWs network with *m*=4 and λ=1 for different solutions.
(CPSR > 99%)

CPSR = Confirmed Packet Success Ratio

LORAWAN for DRONE TRACKING

Credits to: Federico Chiariotti, Federico Mason, Martina Capuzzo

Motivation

- In last years Unmanned Aerial Vehicles (UAVs) have been implemented in many different scenarios

A **fundamental requirement** is to monitor the position of the deployed drones

Scenario

In a **distributed scenario**, drones behave independently and transmit state information to a control station

Long-range communication with minimal energy-cost

Tracking tool to estimate drones' trajectories

Objectives

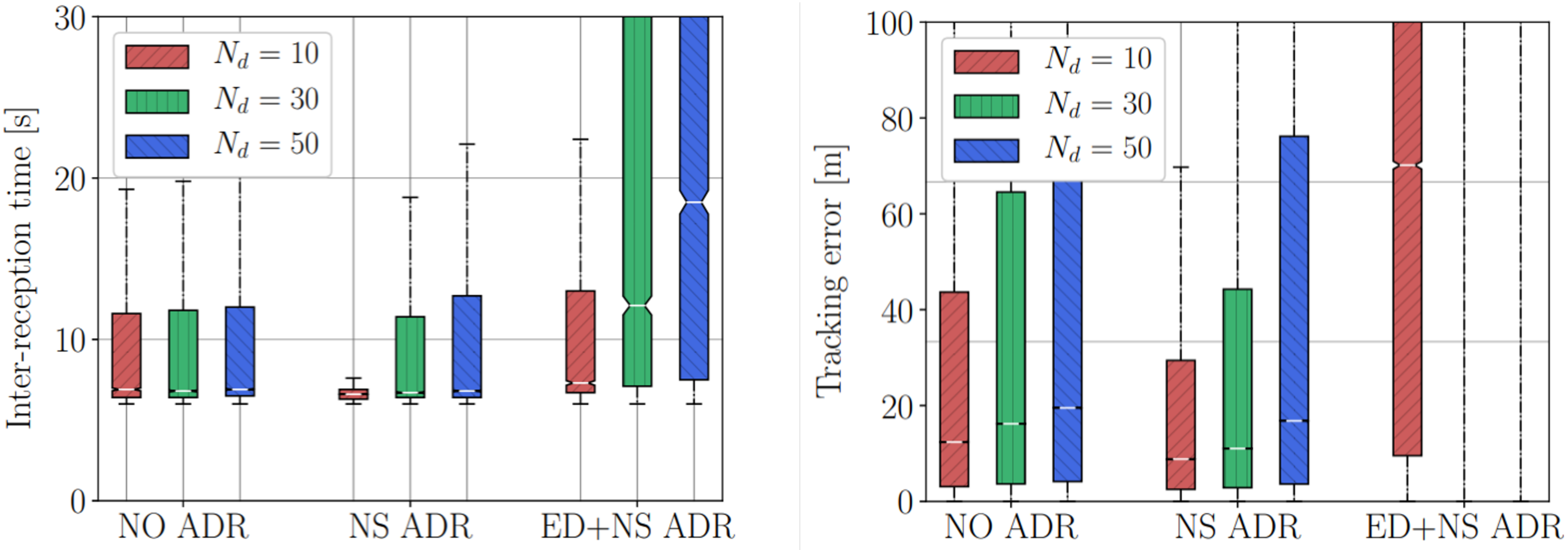
- We design a system where a control station remotely tracks a drone moving in a 3D environment
- The **LoRaWAN** technology is used as communication protocol
- The **Unscented Kalman Filter (UKF)** is used as tracking algorithm
- We need to build **NEW MODELS**

  to represent the drone motion

Tracking Setup

- The UKF is a Bayesian algorithm used to model non-linear motion
- Each drone uses on-board UKF to estimate its current position
- The last position estimate is sent to the control station via LoRa
- The control station uses a predictive UKF to evolve the received position over time

Impact of communication settings



Performance when using different ADR settings with Nd drones flying within a radius of 3000 m from the control station

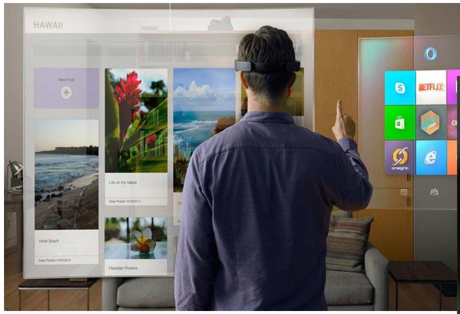
S^3: Smart Sensing & Sending

- Example 3: Delay-constrained Transport Protocols

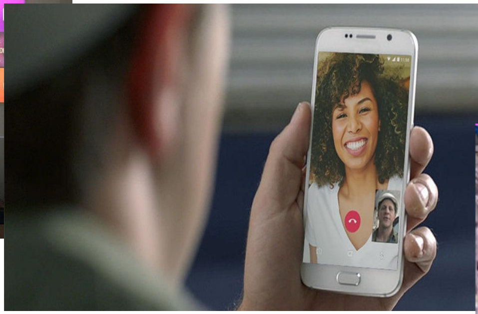
Credits to: Federico Chiariotti, Stepan Kucera

Future interactive apps

Augmented Reality



Mobile video chat



Tele-control

Drones and AUVs

Interactive, high throughput applications need latency guarantees

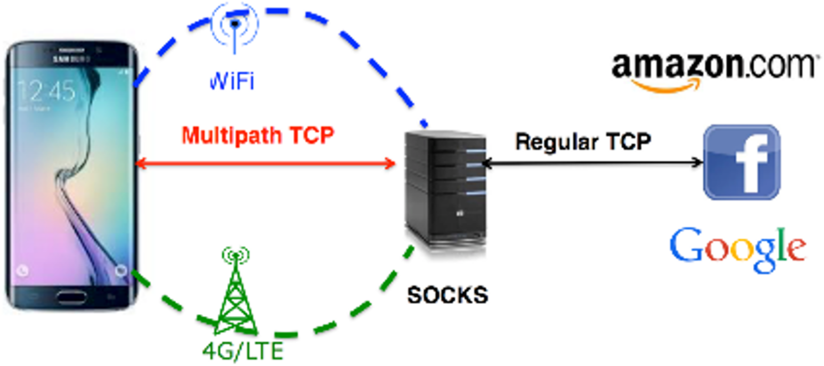
The problem

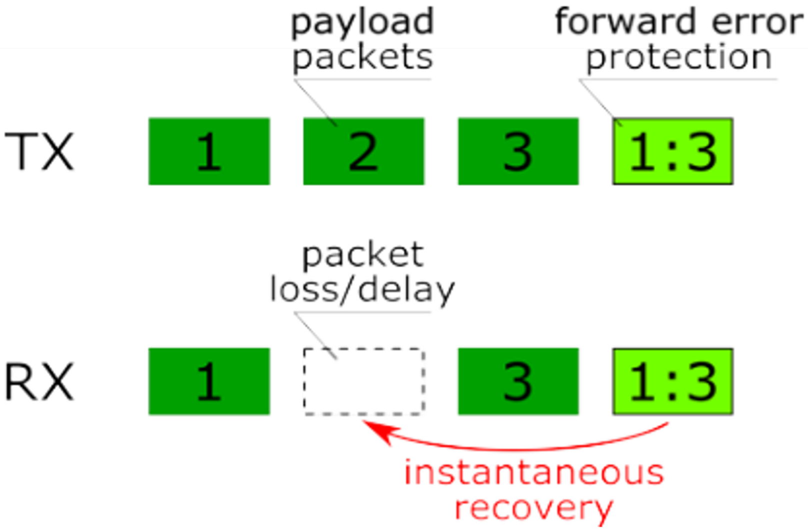
- Advanced applications want bounded latency (max 50 ms)
- Reliability: no more than 2% late frames
- Inflexibility: we may have no control over video frame size
- Transparency: we can only work end-to-end at L7

How do we do it?

A solution: multipath

- Using multiple unreliable paths in parallel…
- and wisely adding inter-path redundancy (FEC)
- … we can improve reliability
- … in a mathematically provable manner!



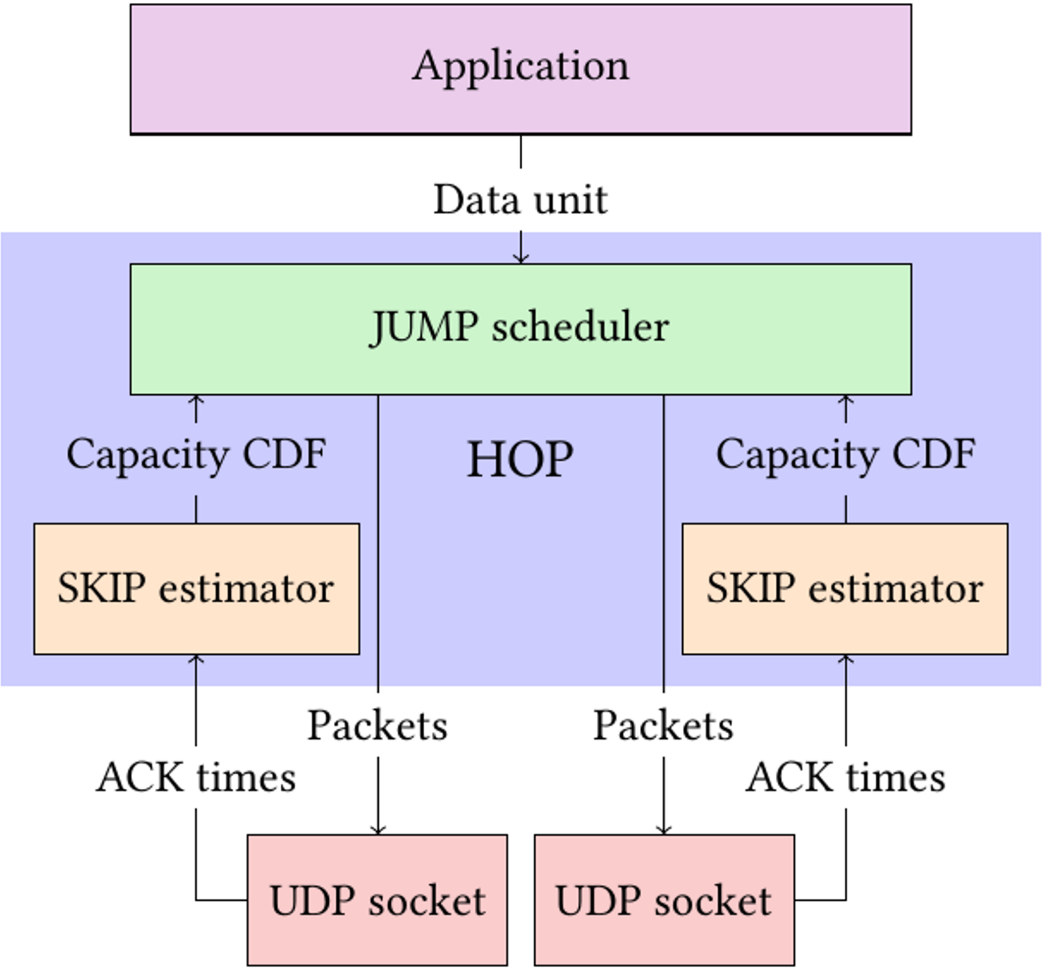


Our solution… HOP!

- **H**igh-reliability latency-bounded **O**verlay **P**rotocol
- We need 3 parts for the protocol to work:
  - Short-term capacity estimation for each path
  - Distribution prediction (Kalman-like) for each path
  - Multipath scheduling
- SKIP: Sender-side Kalman Inference Procedure
- JUMP: Joint Unit Multipath Protection

F. Chiariotti, A. Zanella, S. Kucera, K. Fahmi and H. Claussen, "The HOP Protocol: Reliable Latency-Bounded End-to-End Multipath Communication," in *IEEE/ACM* TNET 2021

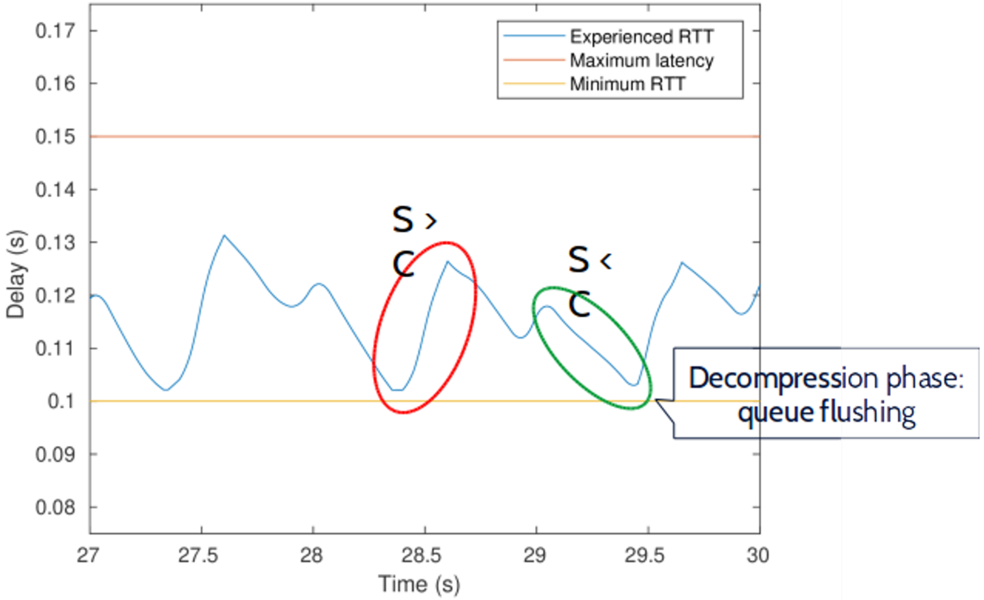
HOP components



SKIP: modeling capacity

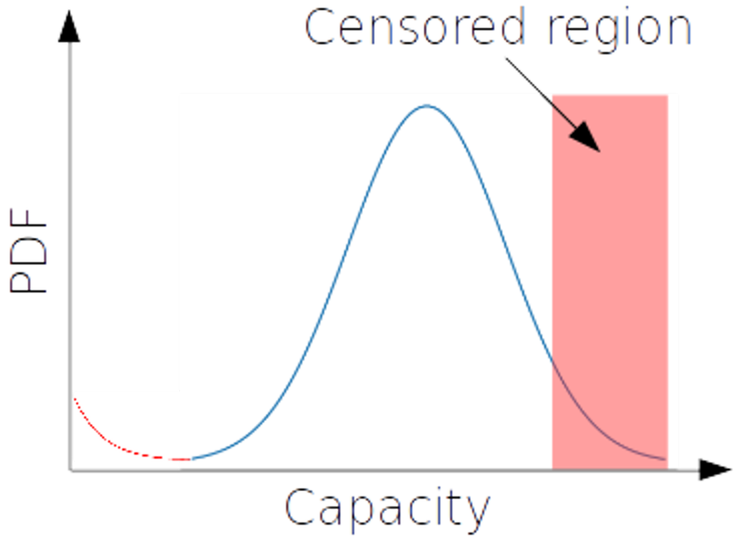
If there is queuing, we can use changes in RTT to infer the difference between the capacity and the sending rate

→We need a high send rate to see capacity, or we won’t have any queuing



SKIP: tracking capacity

- We introduce a “drop mode” in the Kalman filter (exponential)
- Drop mode samples do not affect Kalman operation
- We modify the filter to work for censored inputs (the capacity measures cannot go higher than the send rate)



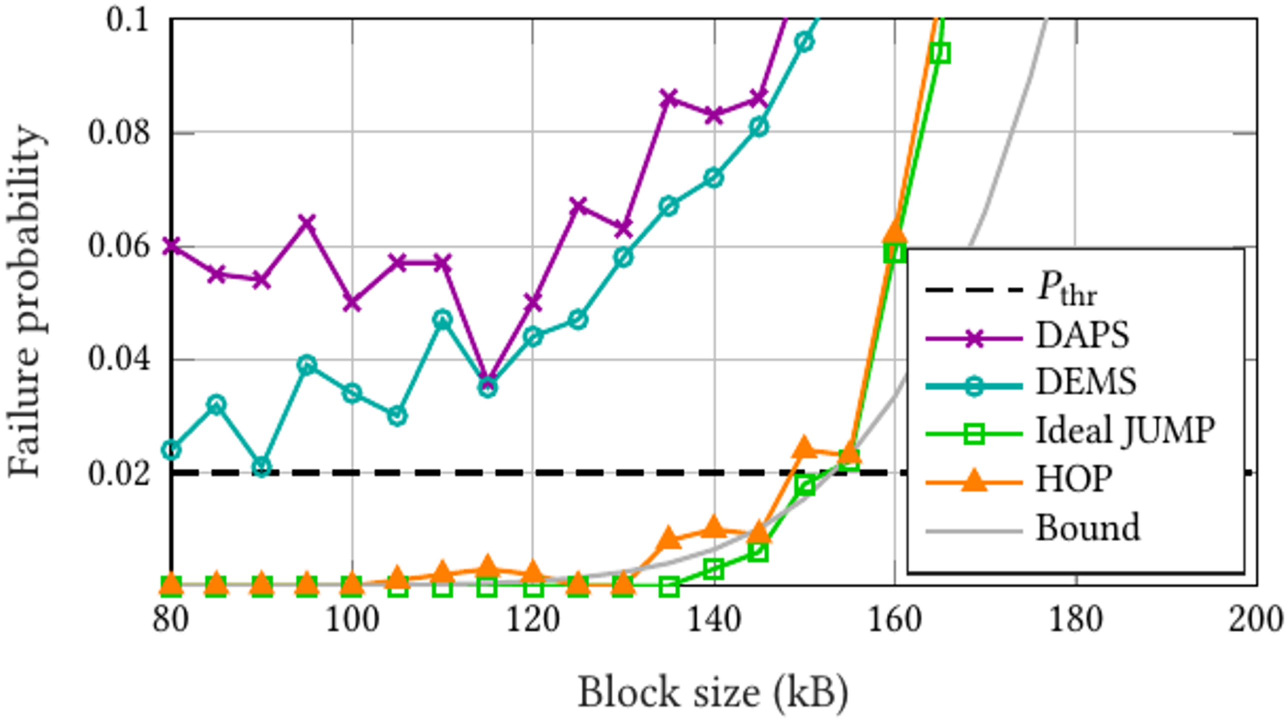
JUMP: building schedules

- Using the slope model we can estimate the capacity it would take to deliver the next packet on time, given the standing queue

We can then build the schedule iteratively, choosing the path with the highest delivery probability for each packet

Results: synthetic traces

- HOP is very close to the performance bound
- SKIP is almost perfect in this scenario: achieved performance close to ideal (perfect estimate) JUMP



Outline

- Motivations
- The S^3 approach: Smart Sensing and Sending
  - Modelling, tuning and using LoraWAN
  - Delay-constrained Transport Protocols
- Scalable and Dynamic Network slicing
- Conclusions

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

1222·2022 800 ANNI

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

SIGNET
signet.dei.unipd.it

Scalable and Dynamic Network slicing

Federico Mason
masonfed@dei.unipd.it

Prof. Andrea Zanella

University of Padova
Department of Information Engineering

INTRODUCTION

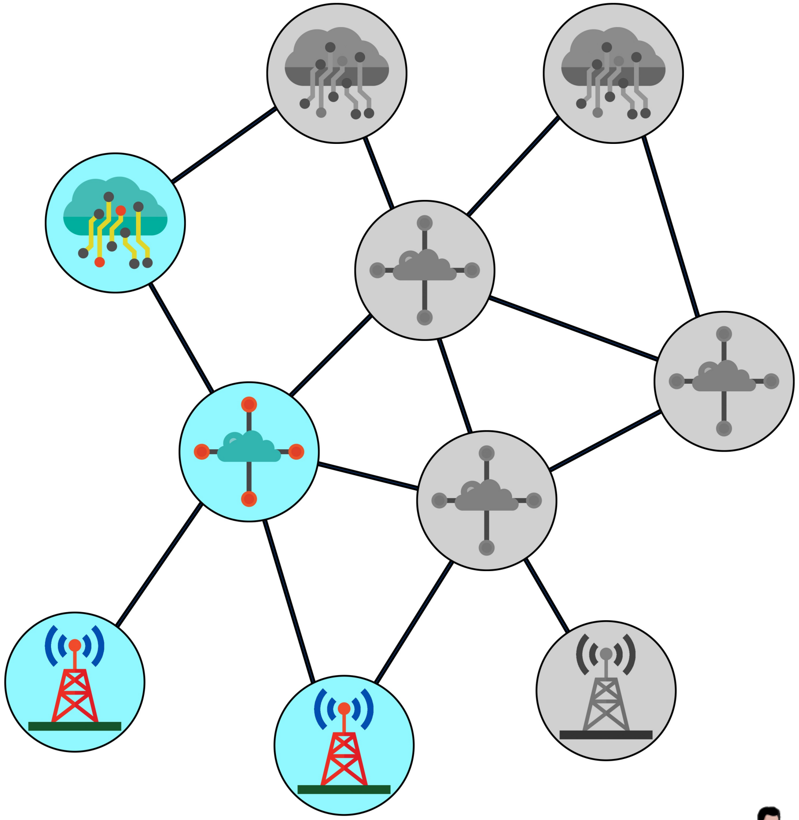
Future telecommunication systems will be characterized by **heterogeneous** applications with very **specific requirements**

Federico Mason <masonfed@dei.unipd.it>

NETWORK SLICING

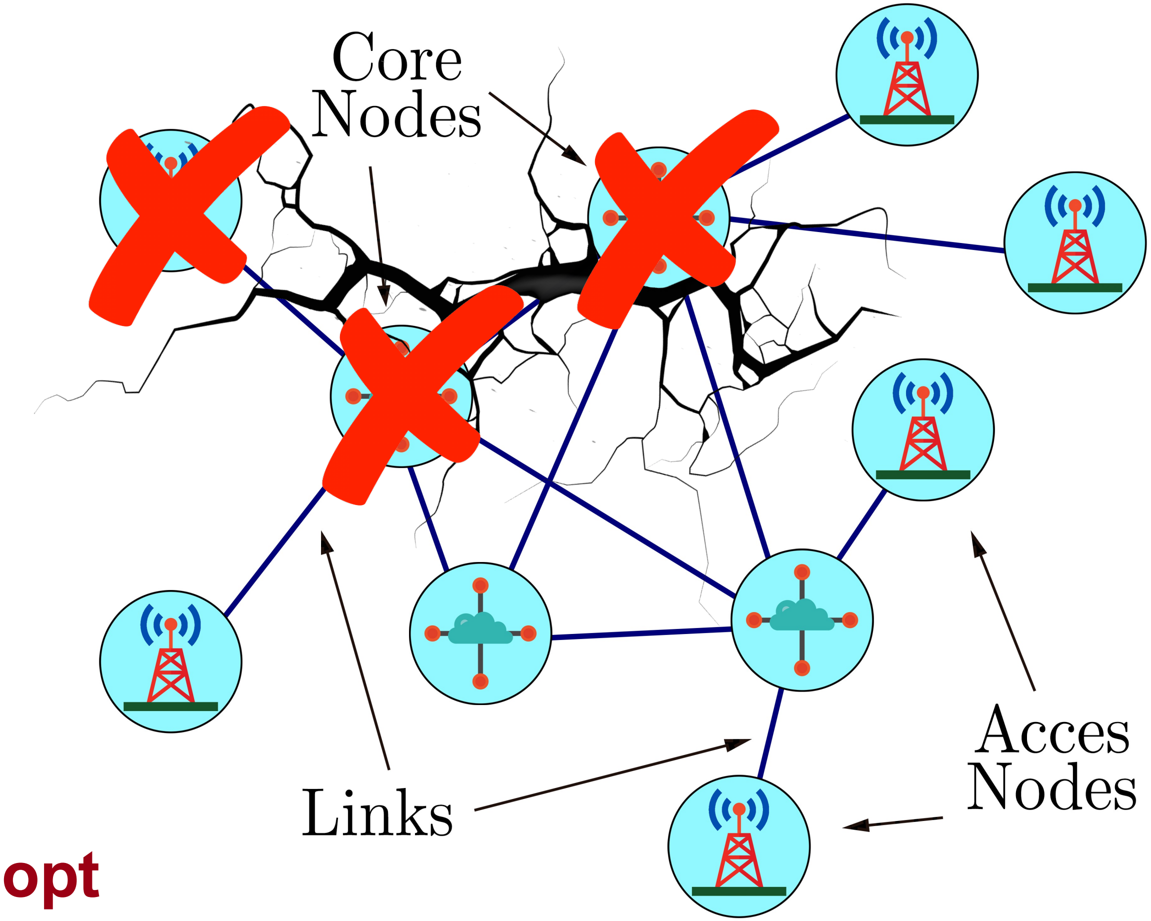
We can initialize multiple **logical networks** over the same infrastructure

- **Service isolation**
- **Resource optimization**
- **High adaptability**



PUBLIC SAFETY

- Volatile resources
- Activation of new services
- Fast dynamics



It is difficult to adopt a centralized approach!

PROBLEM FORMULATION

We want to **allocate network resources** among different slices with a **distributed approach**

- Very complex system
- Partially observable

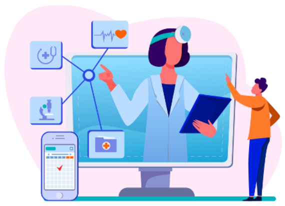
We attack the problem by a **Deep Reinforcement Learning (DRL)** strategy

SYSTEM MODEL

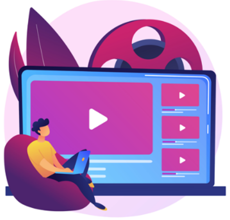
We consider a network with multiple **traffic flows** contending for the same resources

Each flow is characterized by:

- Time-varying **requirements**
  - **Performance** function



That depend on the slice which the flow belongs to...



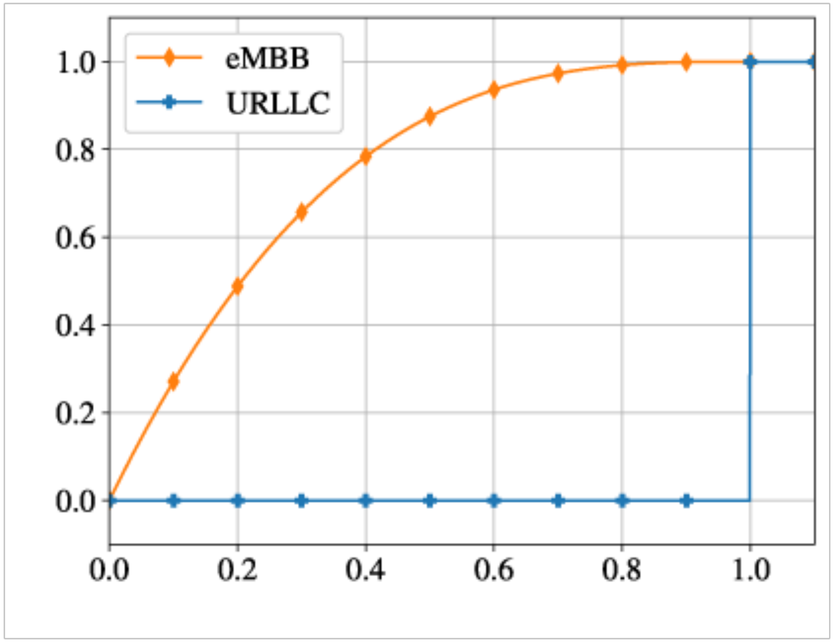
SYSTEM MODEL

There are two kinds of network elements

The **links** provide the communication bandwidth that determine the flows' **throughput** and **delay**

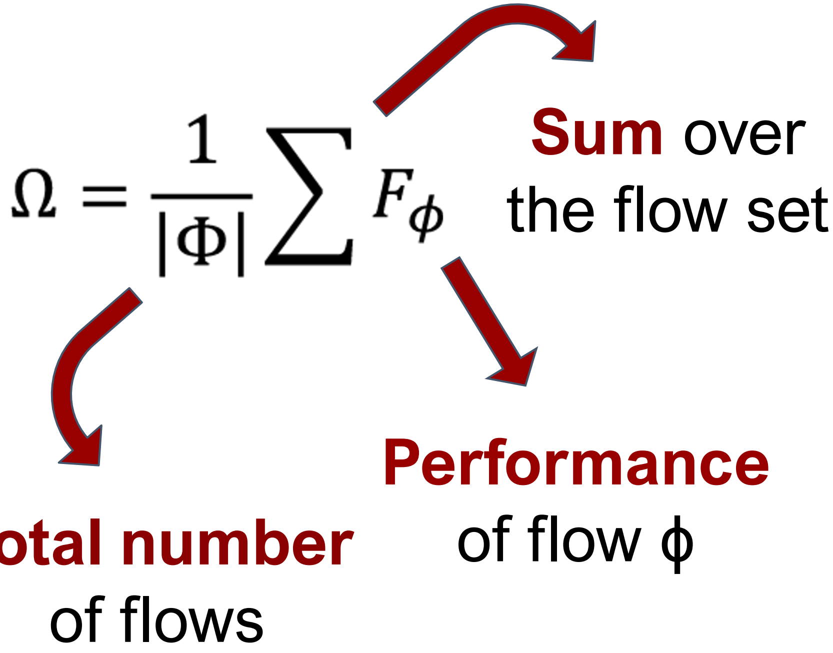
The **nodes** provide computational and memory capacity to support **virtual network functions**

SYSTEM MODEL



We consider two slice classes: **eMBB** and **URLLC**

The goal is to maximize the **system utility**:



$$\Omega = \frac{1}{|\Phi|} \sum F_\phi$$

Sum over the flow set

Total number of flows

Performance of flow ϕ

REINFORCEMENT LEARNING

1) Observation: the agent observes the local status of the flows crossing a network element

2) Action: the agent computes the amount of resources required by each of the flows

3) Reward: the agent is rewarded according to the performance of the flows crossing the element

LEARNING FRAMEWORK

Problem:

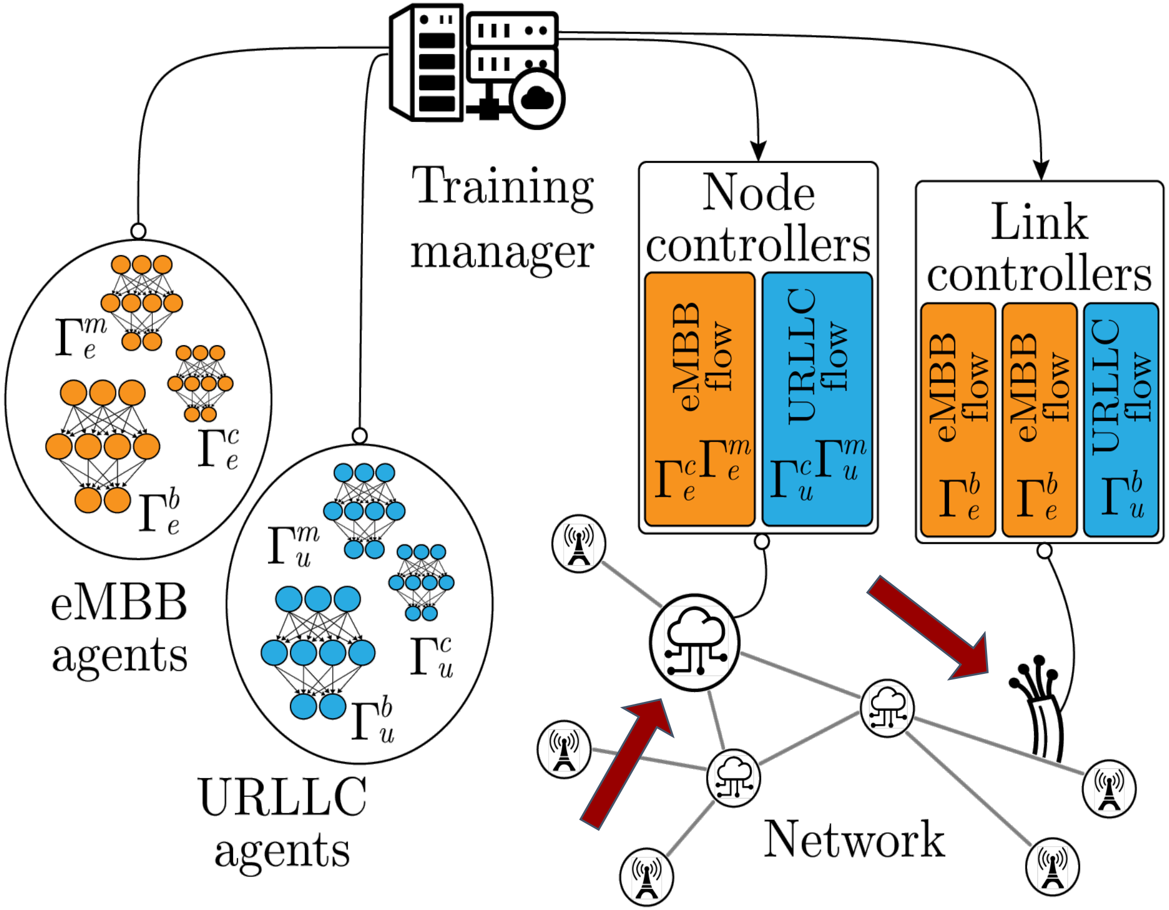
- The agent action and state spaces depend on the number of flows…

Solution:

- We deploy a different agent for each flow
- The agents must cooperate to distribute resources among the flows

We obtain a **Multi-Agent** system,
which makes the training more instable!

LEARNING FRAMEWORK



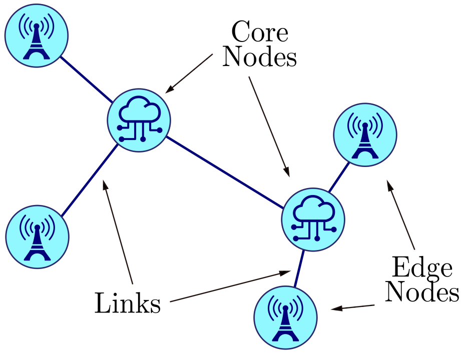
The number of deployed agents depends on the network topology…

…but we train only one set of learning agents per slice!

BENCHMARK

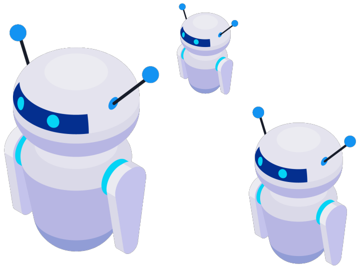
Static Strategy	**Empirical Strategy**
Centralized approach	Distributed approach
Consider the average flow demands	Consider the instantaneous flow demands
It does not handle dynamic requirements	It does not handle slice diversity

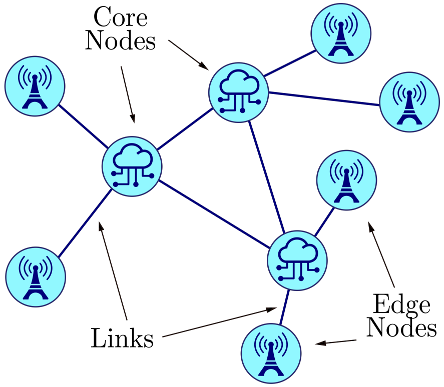
SYSTEM EVALUATION



Dumbbell Network

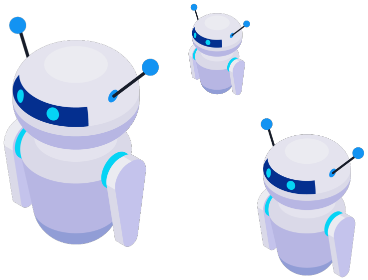
DRL-D





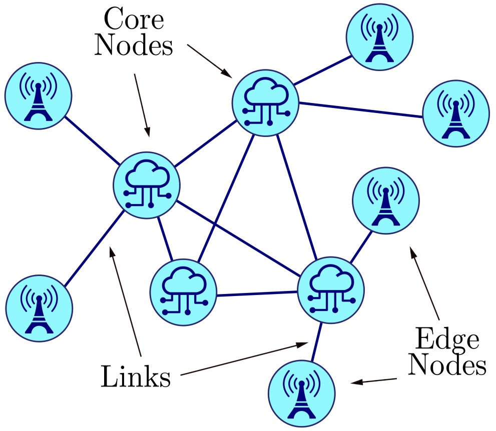
Triangle Network

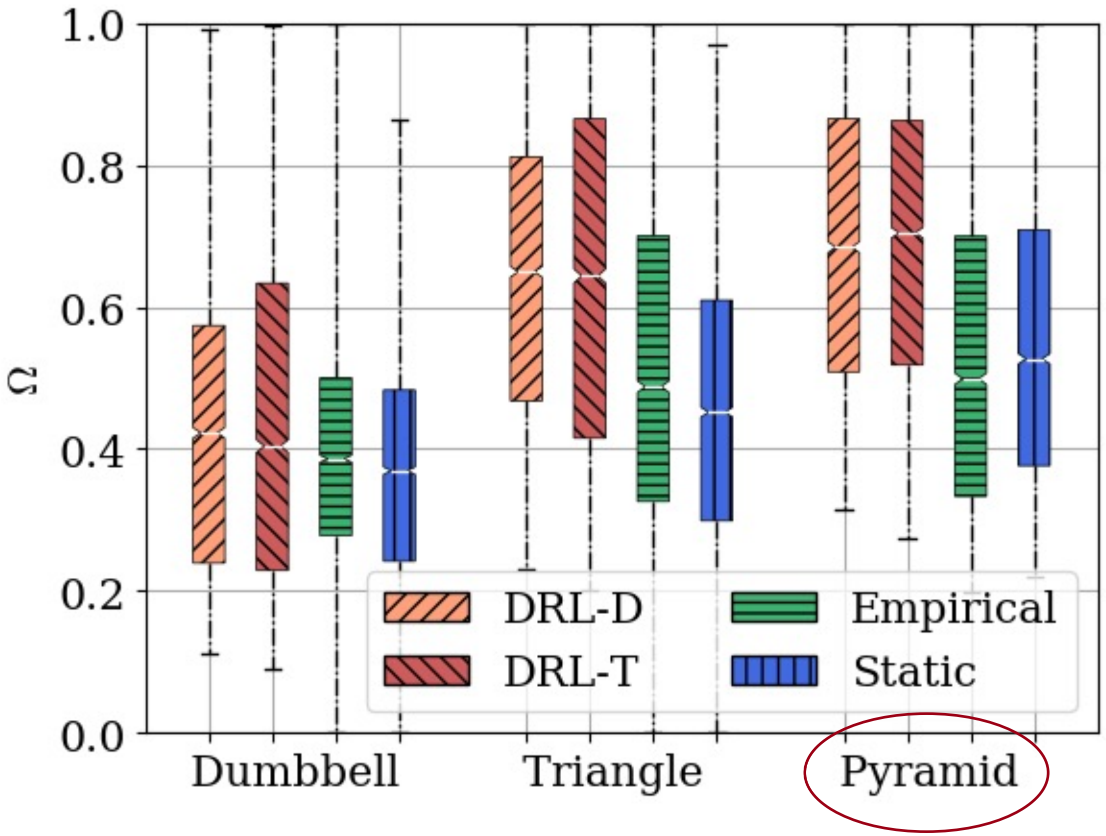
DRL-T



Federico Mason <masonfed@dei.unipd.it>

SYSTEM EVALUATION



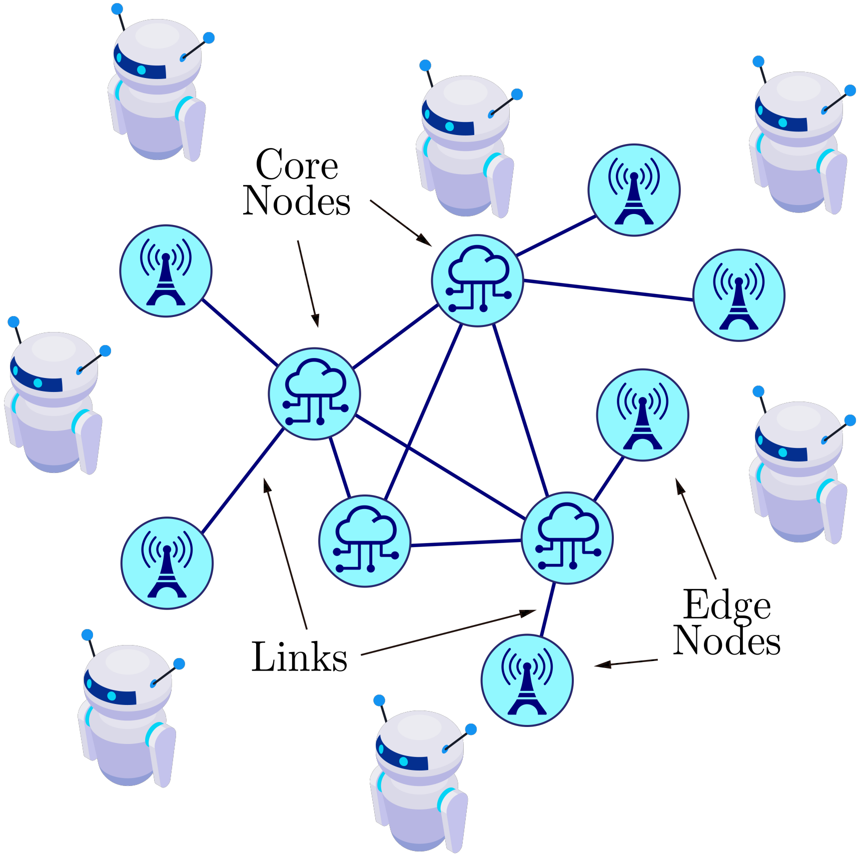


We experience high performance even in different network scenarios!

TRANSFER LEARNING

Each agent is trained to operate in a specific network location

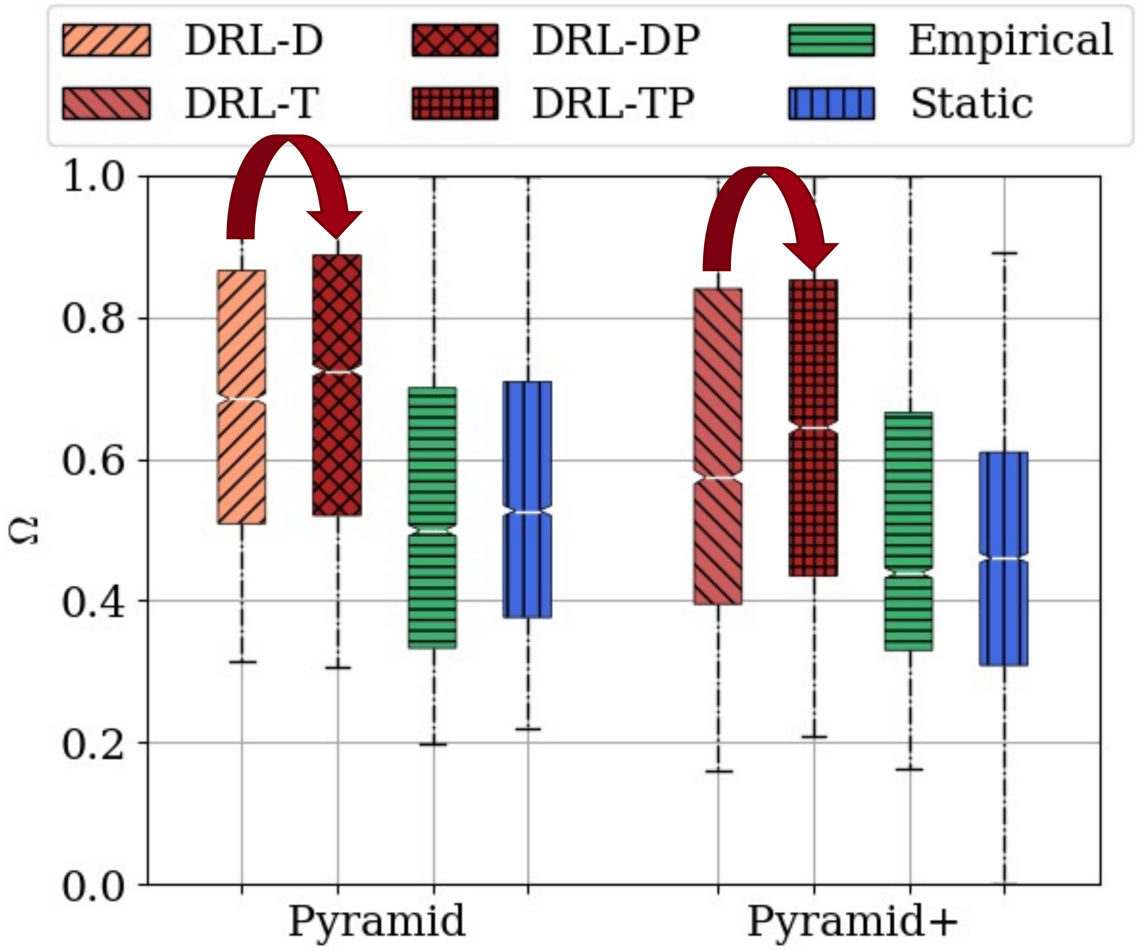
- The number of agents increases!



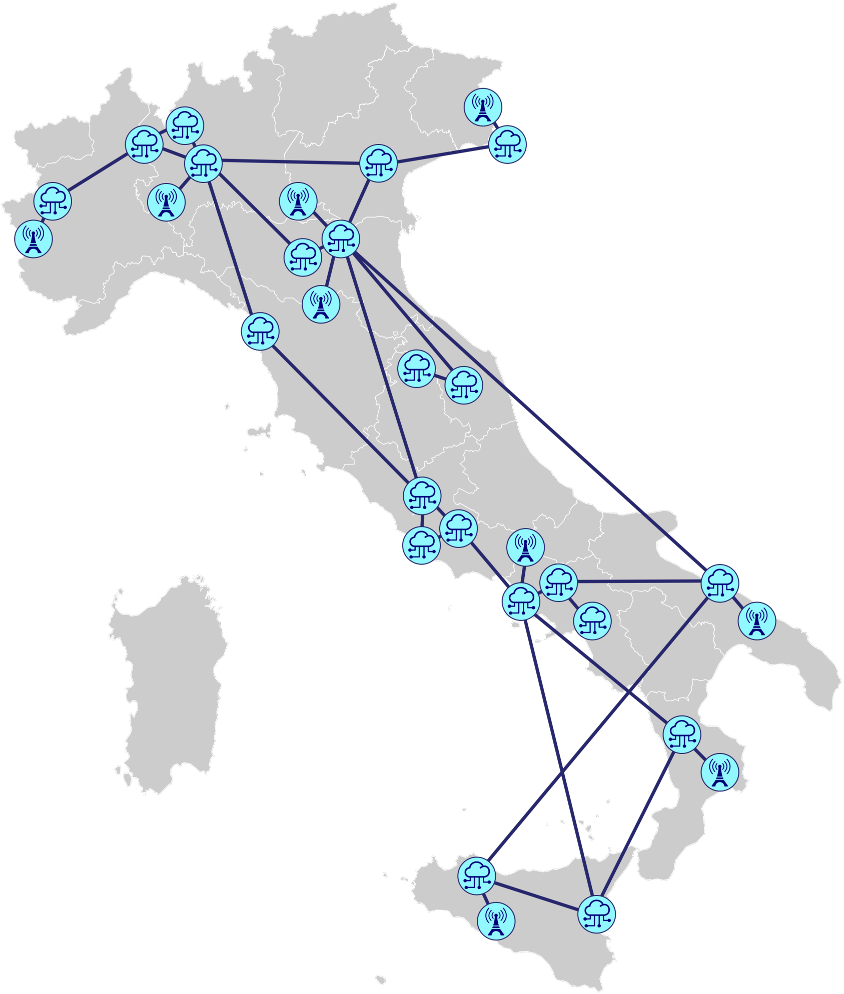
It is **more performant**…

…but **less flexible!**

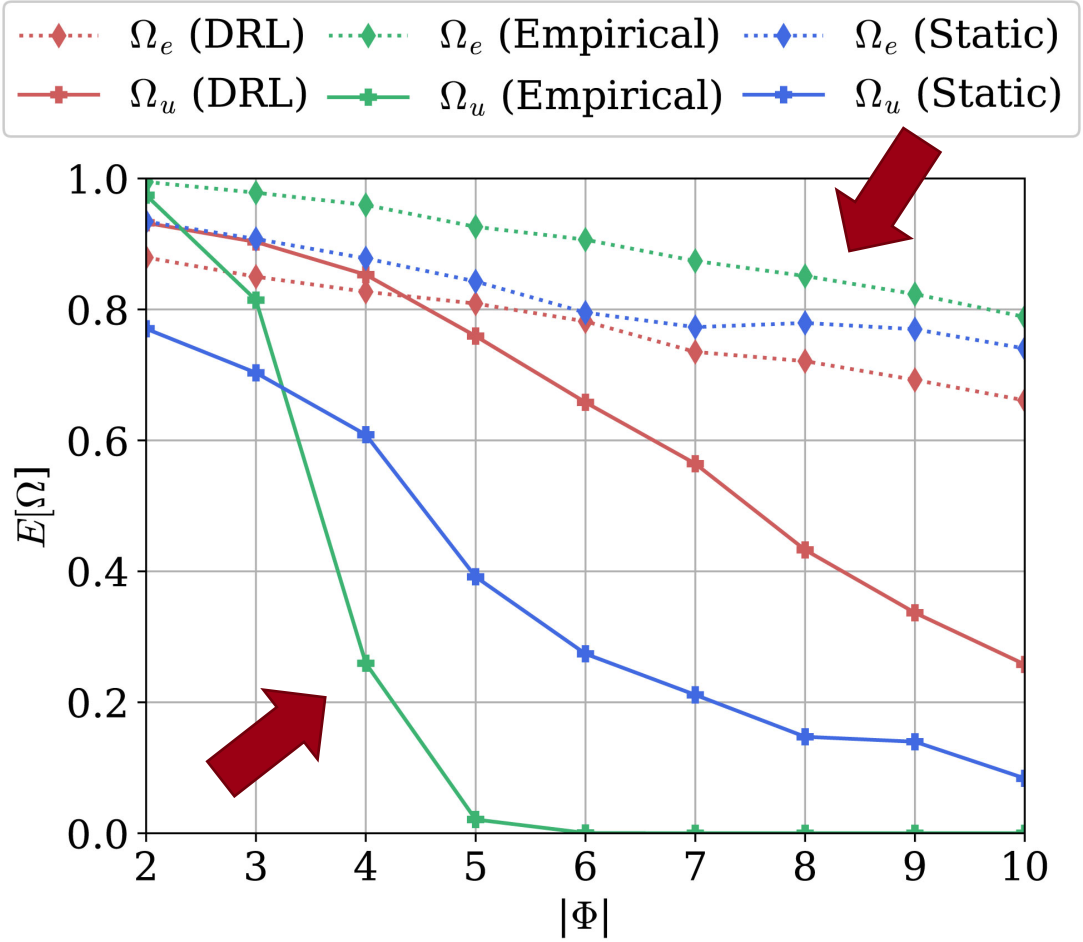
TRANSFER LEARNING

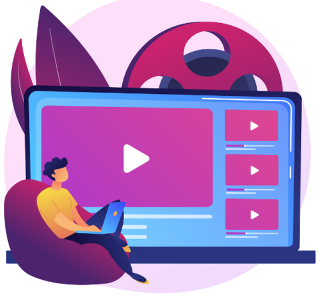


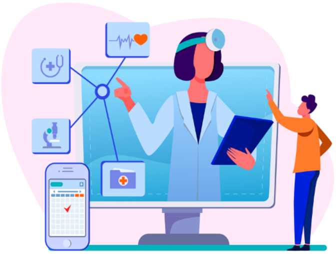
GARR NETWORK SCENARIO



GARR NETWORK SCENARIO







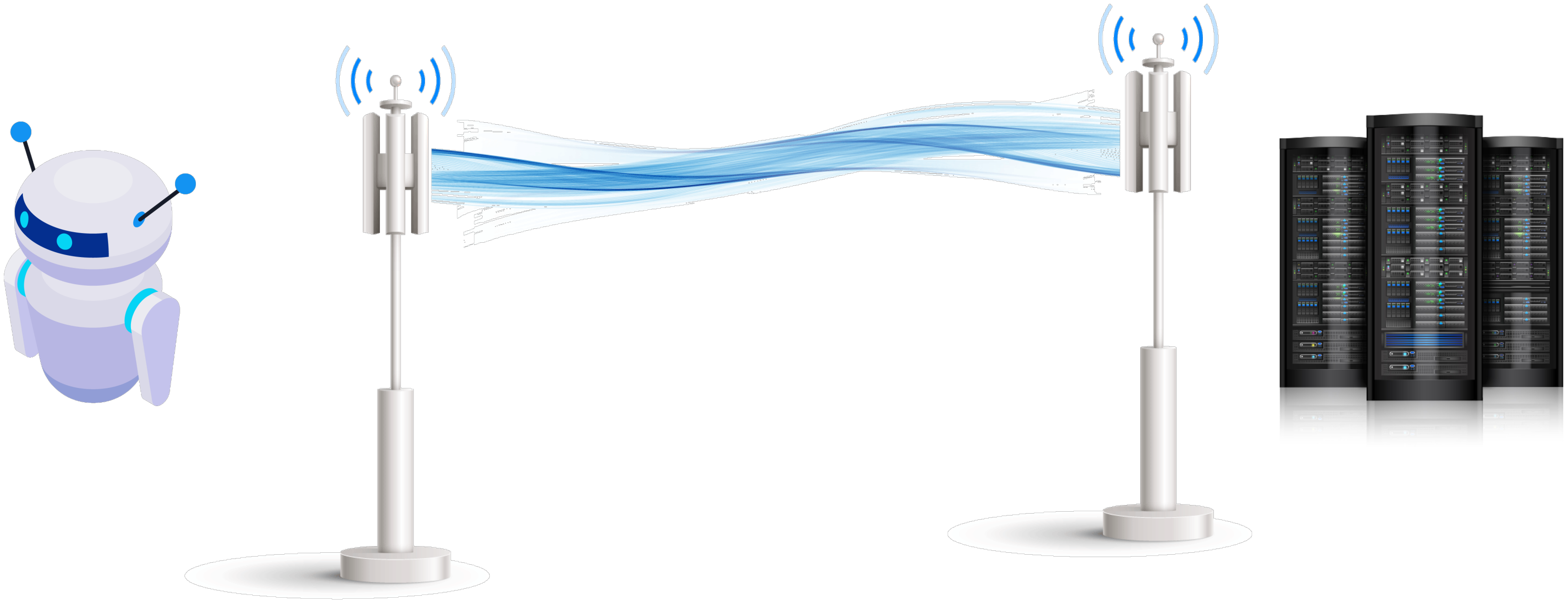
LEARNING vs EXPLOITATION

- We consider to train the agents **online**, to adapt the system to different scenarios in real-time
- Part of the network resources (computation, bandwidth) are used to support the training

The current system performance becomes **inversely proportional** to the training speed!

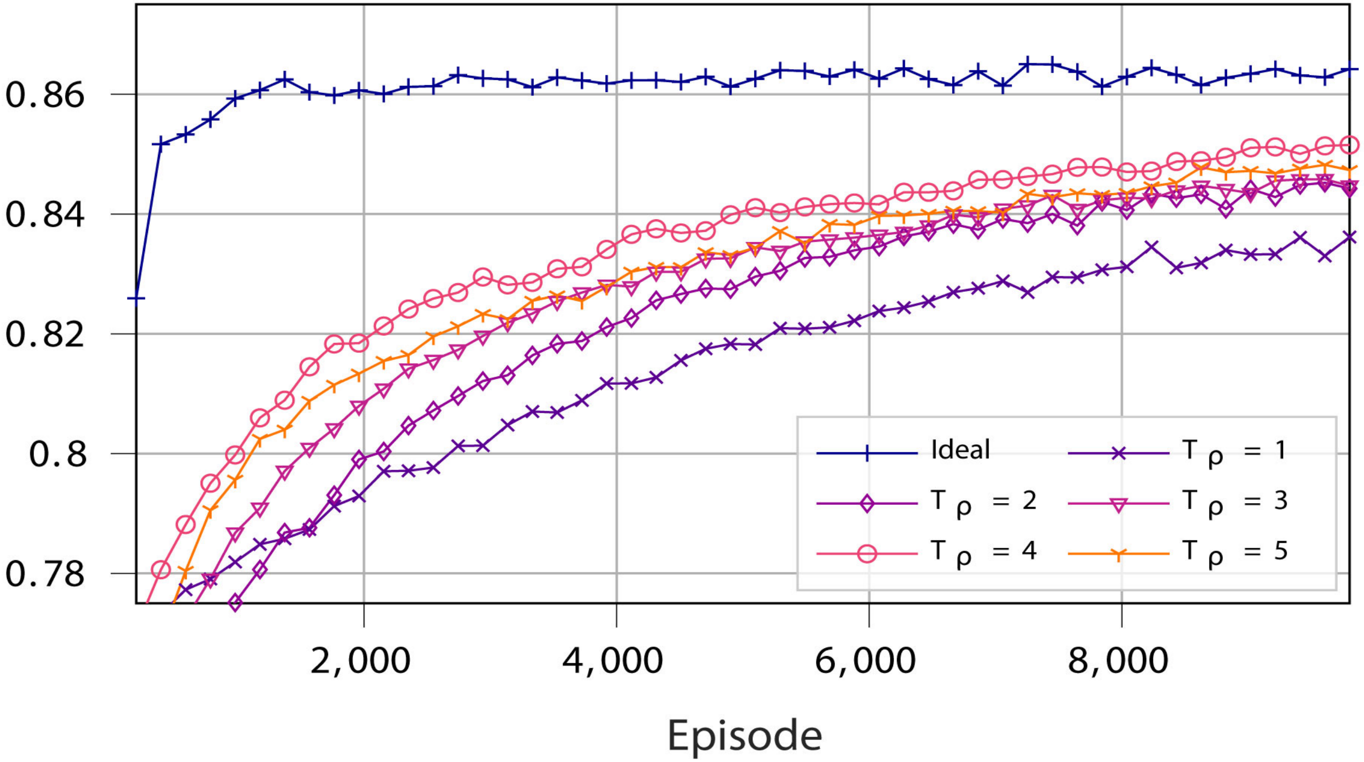
LEARNING vs EXPLOITATION

We denote by T_ρ the percentage of time during which the channel is used to train the agent



RESULTS

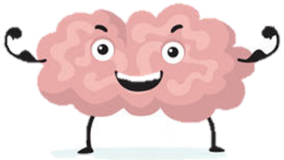
The optimal number of resources to be assigned to the agent training is not trivial!



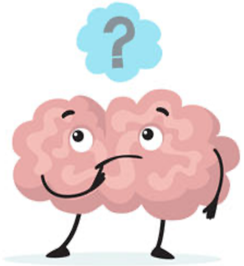
CONCLUSIONS

DRL **improves the orchestration** of network resources, especially when the system **complexity increases**

The **transfer learning** paradigm can be used to further improve the system adaptability



The balancing between **learning** and **exploitation** is a critical problem that need further investigation



Conclusions

- Off-the-shelf technologies may be suitable for novel applications, but often they **need proper and dynamic tuning**
- **Mathematical modeling and machine learning** can be used to self-tune the system parameters and adapt to the context (but they need experise)
- This broad concept can be applied to a number of different scenarios…

Conclusions (cont)

- Smart Mobility
  - Optimizing collection and replacing of shared bikes/kick-scooters
  - Designing incentive schemes to promote self-balancing of sharing services
  - Coordinate on-board sensor data exchange among vehicles to maximize context awareness
- Smart Industry
  - Support intelligent environmental monitoring
  - Offer suitable transport protocols for interactive applications
  - Provide service-specific network slices

Conclusions (cont II)

- X-reality
  - Estimate rate-distortion curve and adapt streaming parameters to maximize quality of experience
  - Predict head motion for content pre-fetching
- Emergency scenarios
  - Control flying BS to offer optimal ground coverage
  - Develop self-coordination capabilities of autonomous mobile robots to achieve a task in hostile conditions
  - Dynamically reconfigure the communication network to offer better support to rescue teams

Some related ref. from my group

IoT & Smart Cities

- F. Michelinakis, A. S. Al-selwi, M. Capuzzo, A. Zanella, K. Mahmood and A. Elmokashfi, **Dissecting Energy Consumption of NB-IoT Devices Empirically** IEEE Internet of Things Journal 05 August 2020,
- D. Magrin, M. Capuzzo, A. Zanella. **A Thorough Study of LoRaWAN Performance Under Different Parameter Settings** IEEE Internet of Things Journal vol. 7, no. 1, pp. 116-127, Jan. 2020
- C. Pielli, D. Zucchetto, A. Zanella, M. Zorzi**. An Interference-Aware Channel Access Strategy for WSNs Exploiting Temporal Correlation.** IEEE Transactions on Communications vol. 67, no. 12, pp. 8585-8597, Dec. 2019
- M. Polese, M. Dalla Cia, F. Mason, D. Peron, F. Chiariotti, M. Polese, T. Mahmoodi, M. Zorzi, A. Zanella, "**Using Smart City Data in 5G Self-Organizing Networks,"** IEEE Internet of Things journal, vol. 5, no. 2, pp. 645-654, April 2018.
- F. Chiariotti, M. Condolucci, T. Mahmoodi, A. Zanella, "**SymbioCity: Smart Cities for Smarter Networks**" Transactions on Emerging Telecommunications Technologies, Wiley Jan. 2018; 29:e3206
- M. Centenaro, L. Vangelista, A. Zanella, M. Zorzi, ``**Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart City Scenarios**" IEEE Wireless Communications, pp. 60 - 67, Volume: 23, Issue: 5, October 2016

Some related ref. from my group

Smart mobility

- F. Pase, F. Chiariotti, A. Zanella, and M. Zorzi, **Bike Sharing and Urban Mobility in a Post-Pandemic World** IEEE Access, vol. 8, pp. 187291-187306, 2020.
- F. Mason, M. Giordani, F. Chiariotti, A. Zanella, and M. Zorzi, **An Adaptive Broadcasting Strategy for Efficient Dynamic Mapping in Vehicular Networks** IEEE Transactions on Wireless Communications , vol. 19, no. 8, pp. 5605-5620, Aug. 2020
- F. Chiariotti, C. Pielli, A. Zanella, and M. Zorzi, **A Bike-Sharing Optimization Framework Combining Dynamic Rebalancing and User Incentives**. ACM Transactions on Autonomous and Adaptive Systems (TAAS) , vol. 14, no. 3, pp. 1-30, Mar. 2020,
- Marco Giordani, Mattia Rebato, Andrea Zanella, Michele Zorzi "**Coverage and Connectivity Analysis of Millimeter Wave Vehicular Networks"** AD HOC NETWORKS Journal, Elsevier, vol. 80, pp. 158-171, Nov. 2018
- F. Chiariotti, C. Pielli, A. Zanella, and M. Zorzi, "**A Dynamic Approach to Rebalancing Bike-Sharing Systems**," Sensors journal, MDPI 18(2), 512; Feb. 2018.

Some related ref. from my group

Drones management

- Federico Mason, Martina Capuzzo, Davide Magrin, Federico Chiariotti, Andrea Zanella, and Michele Zorzi, **Remote tracking of UAV swarms via 3D mobility models and LoRaWAN communications** IEEE Transactions on Wireless Communications Accepted for publication. Sep. 2021.
- Federico Venturini, Federico Mason, Francesco Pase, Federico Chiariotti, Alberto Testolin, Andrea Zanella, and Michele Zorzi **Distributed Reinforcement Learning for Flexible and Efficient UAV Swarm Control** IEEE Transactions on Cognitive Communications and Networking Early Access - Mar. 2021.

XR Services

- Mattia Lecci, Matteo Drago, Andrea Zanella, and Michele Zorzi, **An Open Framework for Analyzing and Modeling XR Network Traffic** IEEE Access Sep. 2021. Early access available.
- M. De Filippo De Grazia, D. Zucchetto, A. Testolin, A. Zanella, and Ma. Zorzi, and M. Zorzi, "**QoE Multi-Stage Machine Learning for Dynamic Video Streaming**," IEEE Transactions on Cognitive Communications and Networking (TCCN) vol. 4, n. 1, pp. 146 - 161, March 2018.
- M. Gadaleta, F. Chiariotti, M. Rossi, and A. Zanella, "**D-DASH: a Deep Q-learning Framework for DASH Video Streaming**," IEEE Transactions on Cognitive Communications and Networking in IEEE Transactions on Cognitive Communications and Networking, vol. 3, no. 4, pp. 703-718, Dec. 2017.

Some related ref. from my group

Latency-bounded transport protocols

- Federico Chiariotti, Stepan Kucera, Holger Claussen, Kariem Fahmi, and Andrea Zanella, **The HOP Protocol: Reliable Latency-Bounded End-to-End Multipath Communication** IEEE/ACM Transactions on Networking Accepted for publication. May 2021.
- Federico Chiariotti, Stepan Kucera, Holger Claussen, and Andrea Zanella, **BBR-S: A Low-Latency BBR Modification for Fast-Varying Connections** IEEE Access Accepted for publication. May 2021.
- M. Polese, F. Chiariotti, E. Bonetto, F. Rigotto, A. Zanella, and M. Zorzi, **A Survey on Recent Advances in Transport Layer Protocols** IEEE Communications Surveys & Tutorials (COMMST), in press, 2019.
- F. Chiariotti, S. Kucera, A. Zanella, and H. Claussen, **Analysis and Design of a Latency Control Protocol for Multi-Path Data Delivery with Pre-Defined QoS Guarantees**. IEEE/ACM Transactions on Networking (TNET), vol. 27, no. 3, pp. 1165-1178, Jun. 2019

Industrial scenarios

- Federico Chiariotti, Anay Ajit Deshpande, Marco Giordani, Kostantinos Antonakoglou, Toktam Mahmoodi, Andrea Zanella **QUIC-EST: A Transmission Scheme to Maximize VoI of Multi-Stream Correlated Data Flows** IEEE Communications Magazine, vol. 59, no. 4, pp. 30-36, Apr 2021.
- D. Magrin, M. Capuzzo, A. Zanella, L. Vangelista and M. Zorzi, **Performance Analysis of LoRaWAN in Industrial Scenarios**, IEEE Transactions on Industrial Informatics, vol. 17, no. 9, Sep. 2021

Contacts

Andrea Zanella – zanella@dei.unipd.it