Determinism in the 6G era

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About the Speaker

Antonio de la Oliva

- Involved in TSN activities since 5 years ago
- Proponent of IEEE 802.1CQ
- Currently Working on IEEE 802.11 standardization
  - IEEE 802.11be/bn
  - More than 25 patents on the area
- Coordinator of HE 6G-IA SNS PREDICT-6G project

What are we going to discuss about?

PREDICT-6G

- Quick recap on determinism
- PREDICT-6G
- Current lines of research

Current Status of determinism

Why our networks are not deterministic? (my view)

- First, what does deterministic means?
    - Reliable
    - Time sensitive
    - Predictable
- Reliable and Time sensitive have been tackled as special characteristics of niche technologies
    - All started with AVB (IEEE 1722)
    - Cars, manufacturing, fronthauling
    - Whole space of standards→IEEE 802.1 TSN family
    - Now IEEE 802.11 and 3GPP are also considered
- Predictability not considered at all
- Need new features in the network
- DiffServ vs IntServ problematic
    - Admission control

Related Standards

PREDICT-6G

Time-Sensitive Networking (TSN) Profiles (Selection and Use of TSN tools)

Audio Video Bridging	Fronthaul	Industrial Automation	Automotive In-Vehicle	Service Provider	Aerospace Onboard
[802.1BA/Revision]	[802.1CM/de]	[IEC/IEEE 60802]	[P802.1DG]	[P802.1DF]	[IEEE P802.1DP / SAE AS6675]

TSN Components

(Tools of the TSN toolset)

Synchronization

Reliability

Latency

Resource Management

Time synchronization:
Timing and Synchronization [802.1AS-2020]
(a profile of IEEE 1588)
Hot Standby [P802.1ASdm]
YANG [P802.1ASdn]
Inclusive Terminology [P802.1ASdr]

High availability / Ultra reliability:
Frame Replication and Elimination [802.1CB]
Path Control and Reservation [802.1Qca]
Per-Stream Filtering and Policing [802.1Qci]
Reliability for Time Sync [802.1AS-2020]

Bounded low latency:
Credit Based Shaper [802.1Qav]
Frame Preemption [802.1Qbu & 802.3br]
Scheduled Traffic [802.1Qbv]
Cyclic Queuing and Forwarding [802.1Qch]
Asynchronous Traffic Shaping [802.1Qcr]
Shaper Parameter Settings [P802.1Qdq]
QoS Provisions [P802.1DC]

Zero congestion loss = Bounded latency

Dedicated resources & API:
Stream Reservation Protocol [802.1Qat]
Link-local Registration Protocol [802.1CS]
TSN Configuration [802.1Qcc]
Foundational Bridge YANG [802.1Qcp]
YANG for CFM [802.1Qcx]
YANG for LLDP [P802.1ABcu]
YANG for 802.1Qbv/Qbu/Qci [P802.1Qcw]
YANG & MIB for FRER [P802.1CBcv]
Extended Stream Identification [P802.1CBdb]
Resource Allocation Protocol [P802.1Qdd]
TSN Configuration Enhancements [P802.1Qdj]
LLDPv2 for Multiframe Data Units [P802.1ABdh]
Multicast and Local Address Assignment [P802.1CQ]

Note: A 'P' in front of '802.1' indicates an ongoing Project.

Related Standards

- 3GPP -> TSC system already described since R16 in TS23.501
- IEEE 802.11 -> long list of proposed enhancements proposed in IEEE 802.11be and UHR
- Other family of SDOs-> 5G-ACIA, OPC, DetNet, Raw

- Main highlight: Work coordinated in multiple SDOs -> traction!

Use cases, why determinism is important

Current main drivers

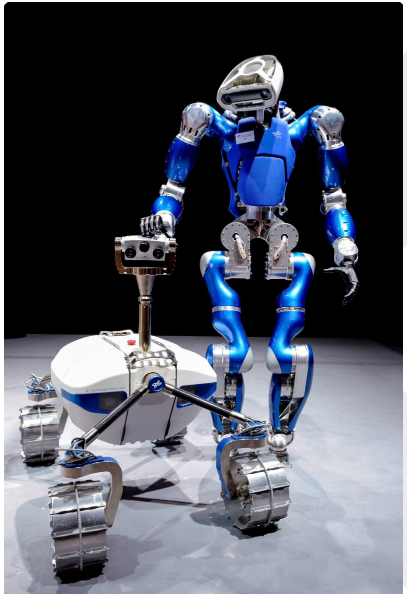


Photo d'illustration: TORO et DLR Moon Rover (crédits: DLR German Aerospace Center / Flickr Creative Commons Attribution 2.0 Générique (CC BY 2.0))

- Control automation, mainly at manufacturing
- AVB
- Cars, airplanes
- Fronthaul

Determinism?

- Increase in reliability for common technologies, even at home
- Time sensitiveness -> video games, AR
- Predict performance of your network, no more congestion losses?

Src: Microsoft

PREDICT-6G
Quick intro

The vision

Building a deterministic 6G network

RELIABLE

Availability
Low packet
Failure resilient

TIME SENSITIVE

Bounded latency
Low jitter

PREDICTABLE

Use of AI to predict events, states, demands, resources
Autonomous proactive actions based on predictions

The mission

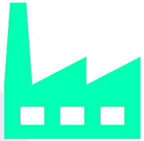
PREDICT-6G aims to **design, create and validate end-to-end (E2E) 6G solutions providing deterministic services over multiple interconnected domains and technologies** (incl. wired and wireless).

3 pillars

- To **extend the reliability and time sensitiveness features** of IEEE 802.11 and 3GPP networks, including APIs for the monitoring and control of such capabilities, enabling predictability.
- To **develop a multi-technology multi-domain Data-Plane** jointly with an AI-driven multi-stakeholder inter-domain Control-Plane (AICP)
- To **enhance the predictability** of the network through artificial intelligence, enabling the forecasting of the occupancy of network resources and the effect of accepting a new flow into the network

3 use cases

1. **Smart manufacturing**



2. **Multi-domain deterministic communications**
3. **Critical communications**

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3 use cases

1. **Smart manufacturing**
2. **Multi-domain deterministic communications**
3. **Critical communications**

Innovations

PREDICT 6G

Specific innovations

1. Improvement of L2 deterministic capabilities of IEEE 802.11 and 3GPP
2. Emulate deterministic network capabilities on top of non-deterministic network segments
3. Data-plane integration of multiple deterministic and non-deterministic domains
4. User, resource, and function mobility under deterministic constraints
5. Highly configurable monitoring platform for multi-technology deterministic networks
6. Cross-domain E2E deterministic service management automation
7. Predictability through Network Digital Twinning

Architecture overview

PREDICT-6G management scope

Networks (e.g., PM/CM)

Network services within one network (e.g., connectivity, det. SLA)

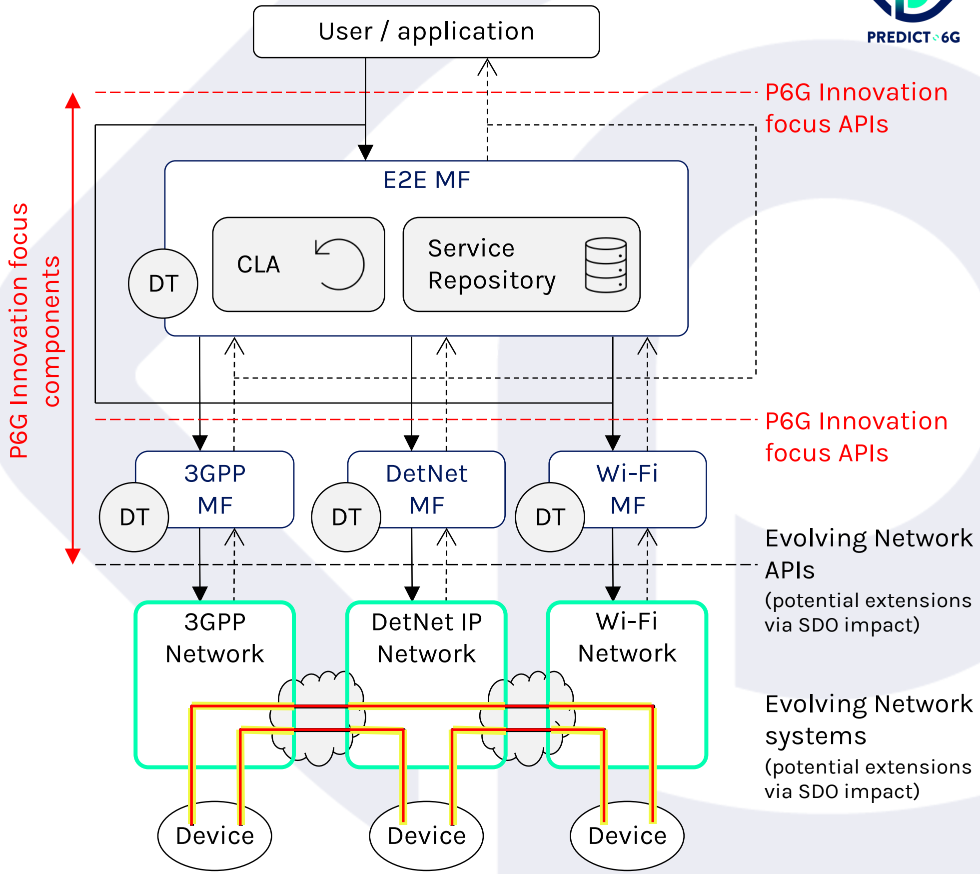
E2E services over multiple networks (e.g., between devices attached to different networks)

These are **Managed Entities (ME)** for the PREDICT-6G framework.

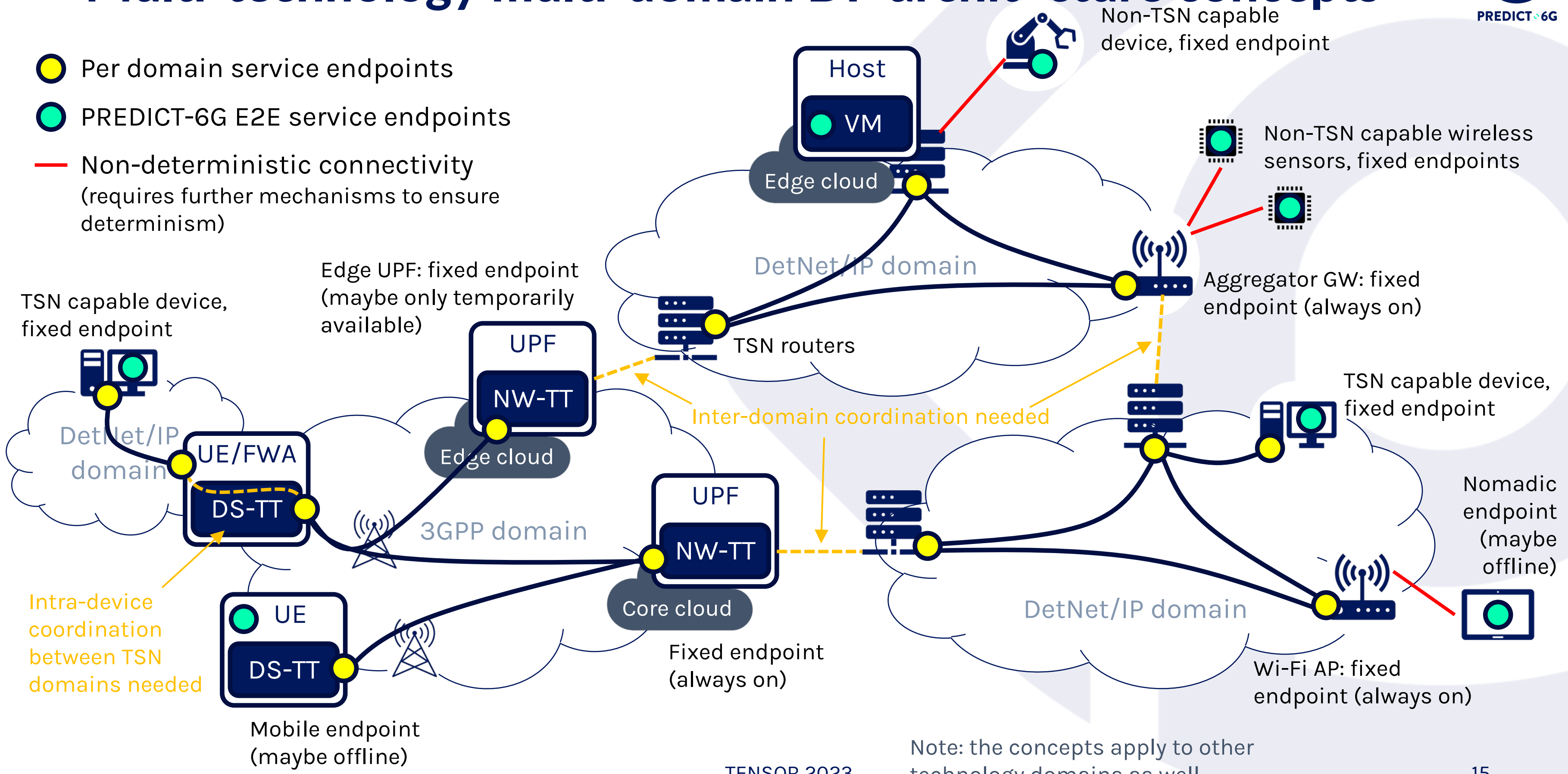
E2E deterministic service flow (MDP)

Request / configuration (AICP)

Measurement / status / insight (AICP)



Multi-technology multi-domain DP architecture concepts



Note: the concepts apply to other technology domains as well.

MDP

The integration concept within PREDICT-6G

- PREDICT-6G Integrates multi-domain layer-2 islands of deterministic technologies through layer-3 mechanisms (DetNet, RAW).

Fundamental research	Standalone demos	Integrated demos
Wireless Dynamic Scheduling →		Non-deterministic devices and networks
	Determinism for Localization & Sensing	Industrial cross-domain TSN
Technological solutions for TSN on Wi-Fi	Technological solutions for TSN on Wi-Fi	

Objectives

Articles SDOs PoCs

Experimentation plans and testbeds

- 3 key use cases
  - Deterministic services for critical communications
  - Multi-domain deterministic communication
  - Smart Manufacturing
- 2 main testsites
  - Budapest Open Lab
  - Madrid Open Lab (5TONIC)

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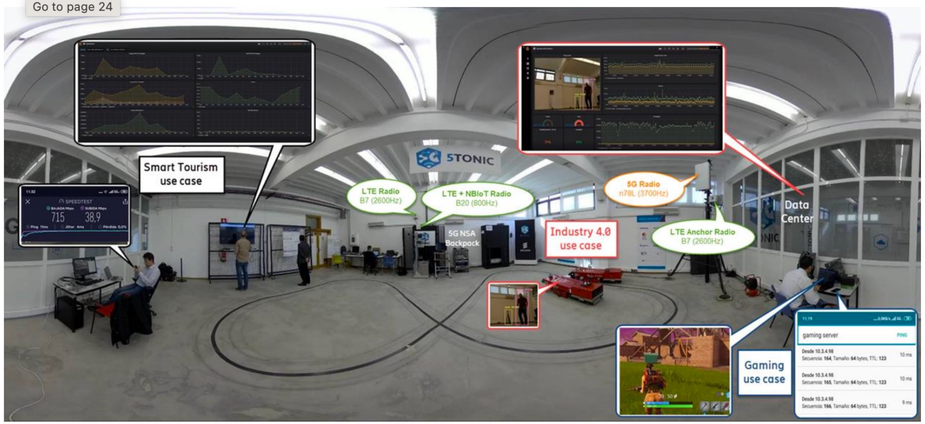

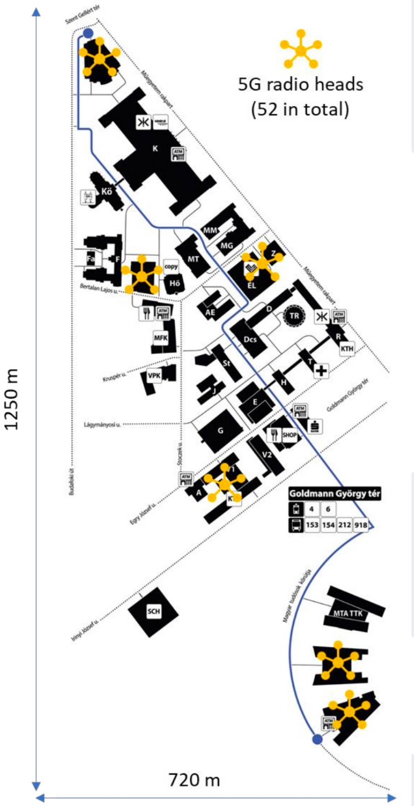

Current lines of research on determinism

Predictability

Predictability

PREDICT-6G

"Predictability is the ability to accurately predict parameters of stochastically evolving KPIs of a given communication system over a given time interval at run-time"

- Predictability is a desired feature for all kind of network and all kind of user and use cases. You ALWAYS want to know how your network is going to perform.
- This will led to new and improved capabilities of the network, reducing its **uncertainty**
- We use Digital Twins as key enabler for predictability in PREDICT-6G.

What is a Digital Twin?

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- A concept introduced in 2003, but recently it has been gaining increased relevance
- Many definitions have been suggested over the years
- Still, nowadays the most widely accepted definition states that:

"A Digital Twin consists a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision-making"

How Is It Going to Impact?

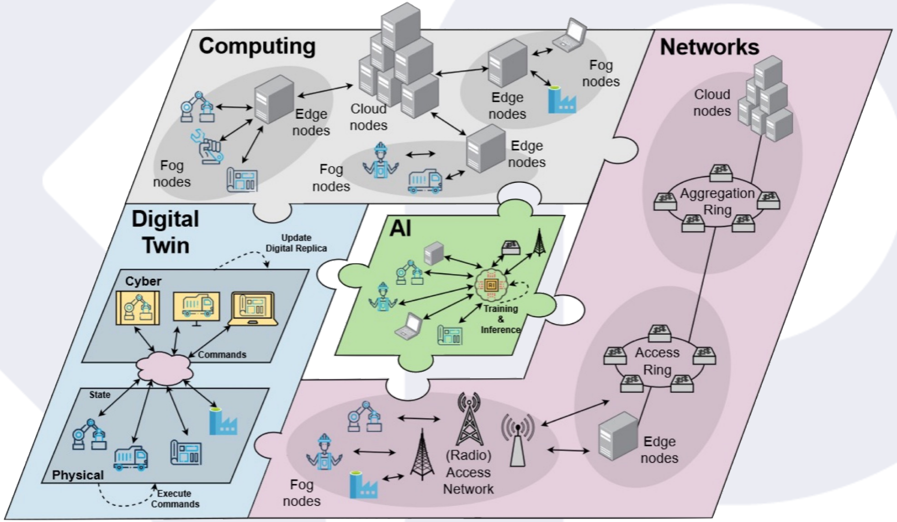
- How will the future networks be
  - Less over-provisioned
  - More intelligent
  - More flexible
  - More complex
- Opens the way for rethinking how networks are deployed and designed
  - Network deployed together with its digital twin
  - Experimentation provided through DT
- Changes in the network may be tested beforehand through its DT
- The key winning combination:
  - DT + AI

How Is It Going To Be Provided?

- By relying on different technological (e.g., networks and clouds) and administrative domains (e.g., across geographical areas),
  - Digital Twins might be provided as a service
  - Definition of SLAs and KPIs
  - Dynamic instantiation and termination of the service
  - Fully automated deployments
  - Fast service deployment times
- Vendors may provide the virtual assets together with the real hardware

Is AI The Missing Piece?

- The aforementioned challenges demand Digital Twins that:
  - Satisfy the expected real-time and secure performance.
  - Tackle the problems derived from its integration with the network and computing infrastructure.
- AI agents are strong candidates to handle such challenges
  - They can benefit from ML algorithms
  - Exploit existing data sources with context information at both the application, and infrastructure level



What Can You Do With AI?

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	AI agent	Input Data	Outcomes	ML algorithm(s)	Candidate Runtime Location
Application	Movement Prediction	Historic of commands, real-time commands	Predictions on the N next commands	VAR, TCN, GRU, LSTM	Fog, Edge
	Task Learning	Demonstrations of the task from different knowledge domains (e.g., physical object states)	Generalized task policy	IL, RL	Fog, Edge
	Risk Reduction	Sensor data, video streams, localization data and machinery states	Identification and forecasting unsafe situations	CNN	Fog, Edge
	Predictive Maintenance	Machinery and environmental sensor data (e.g., motors status, vibration, temperature)	Failure predictions	ARIMA, LSTM + LR, SVM	Edge, Cloud
Infrastructure (Computing and Networking)	Dynamic Scaling	Resource usage, date and time, task, number of instances, application KPIs and SLAs	Scale in/out or up/down suggestions	RL, RT, RF, MLP, BN	Edge, Cloud
	Privacy, Security and Intrusion Detection	Infrastructure and network context information, traffic flows patterns, service and infrastructure KPIs	Security breaches and suspicious flows	PCA, K-means, Autoencoders	Edge, Cloud
	Heterogeneous RAT Selection	Radio network information, available resources, mobility patterns, application KPIs and SLAs	RAT and handover candidate selection	RL, ANN, Fuzzy Logic	Fog, Edge

ANN: Artificial Neural Networks; ARIMA: Autoregressive Integrated Moving Average; BN: Bayesian Network; CNN: Convolutional Neural Networks; GRU: Gated Recurrent Unit; IL: Imitation Learning; LR: Logistic Regression; LSTM: Long-Short Term Memory; MPL: Multi-Layer Perceptron; PCA: Principal Component Analysis; RL: Reinforcement Learning; RF: Random Forest; RT: Random Tree; SVM: Support Vector Machines; TCN: Temporal Convolutional Networks; VAR: Vector Autoregressive.

What Are the Benefits For Applications? (1/2)

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Prediction

- Overcome unpredictable radio-frequency interference that introduce high jitter and packet loss.
- Predict effect of new traffic in network operation
- Predict side-effects of reconfigurations
- Improve reliability and avoid stalling events.

Task Learning

- Ease the automation of complex tasks.
- Better reaction unpredicted conditions and/or unforeseen events.
- Find optimal ways of executing a task or mimic human-based operations.
- E.g., Smart orchestration, automatic SFC

What Are the Benefits For Applications? (2/2)

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Risk Reduction

- Improving the reliability of the network will improve safety and reduce risks of critical applications, e.g., remote control operations.
- Operate autonomously to overriding risky actions or avoid obstacles.
- Act preemptively and coordinated with other physical processes.

Predictive Maintenance

- Avoid major failures in hardware.
- Minimizes (unplanned) downtime and emergency maintenance.
- Minimizes bad batches of produced goods.
- Reduce effect on time sensitive traffic

What Are the Benefits For Infrastructure?

Dynamic Scaling

- Accommodate just resources to support the service SLAs and KPIs.
- Increase resource allocation in case of increased demand.
- Decrease resource allocation for cost savings.

Heterogenous Network Selection

- Provide an always best connected experience.
- Selects the best available network for each kind of traffic.
- Decides and prepares seamless handovers.

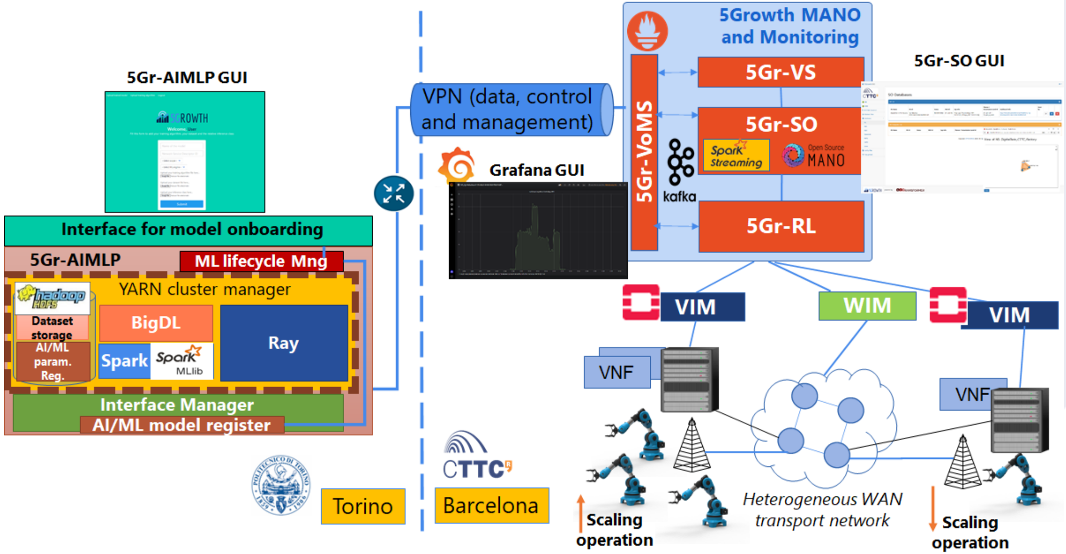
Privacy, Security, and Intrusion Detection

- Detect and diagnose security breaches and intrusion.
- Boost a collaborative training across different industrial players
  - without exposing private data.

Digital Twin: Dynamic Scaling

- **How do we did it?**

- Random Forest Classification
- Input:
  - Current Instantiation Level
  - Average CPU usage
- Output:
  - Instantiation Level to apply
- Model training and inference model creation
  - Real dataset taken with a Edge-based Digital Twin



Demo Paper: AIML-as-a-Service for SLA management of a Digital Twin Virtual Network Service [IEEE INFOCOM 2021]

Reliability

Reliability

- How reliable a network is:
  - Availability
  - % of packets lost
  - % of app layer failures (control messages lost or received out of time)
- Reliability is being tackled in multiple SDOs by mainly performing:
  - FRER (Frame Replication, Elimination and Re-ordering),
  - PAREO (Packet (hybrid) ARQ, Replication, Elimination and Ordering),
  - PREOF (Packet Replication, Elimination and Ordering Functions)
- 3GPP and WLAN are also working to improve this
- Improving reliability is also good for all networks, users and use cases
- **Our research focuses on improving reliability at higher layers through AI**

Digital Twin for Remote Operation of Robotic Arms

IMPROVING RELIABILITY OVER UNRELIABLE LINKS

Milan Groshev (UC3M)
Carlos Guimarães (UC3M)
Jorge Martín-Pérez (UC3M)

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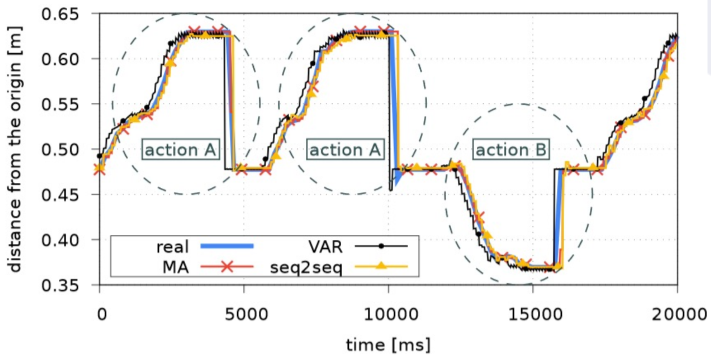
June 2021

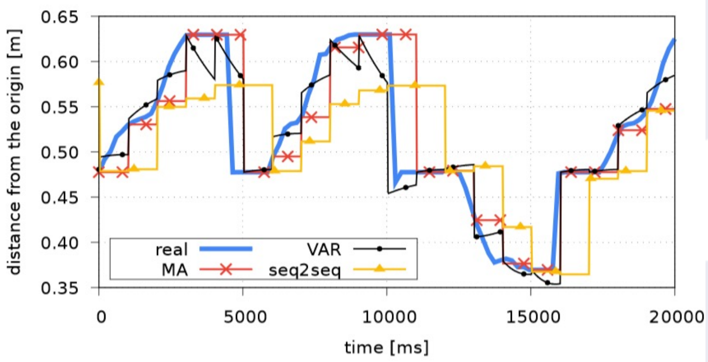
Digital Twin: Movement Prediction

How we did it?

- Forecasting algorithms:
  - LSTM (seq2seq) and VAR
- Trained with past movements executed by a human:
  - Real dataset of a pick and place task
- Predict:
  - 3-axis coordinates
  - 6-joints values
- 1-step ahead or N-steps ahead
- Both on-device and in-network intelligence is considered



(a) 5 movements ahead



(b) 50 movements ahead

Towards Intelligent Cyber-Physical Systems: Digital Twin meets Artificial Intelligence [IEEE COMMAG (in-press)]

Time Sensitiveness

Time Sensitiveness

- Time sensitiveness regards to the capacity of the system of forwarding traffic with defined delay and jitter boundaries.
- Only useful for a some use cases and users, but when required it is absolutely needed!
- Requires of scheduling across the network, support of TSN extensions, time synchronization and access control
- This is the part less mature of our work, just providing hints about it!

IEEE 802.11ax OFDMA vs. rTWT

OFDMA

- OFDMA was introduced in IEEE 802.11ax to provide UL/DL MU transmissions.
- Coordinated by the AP.
- Reduce the contention.

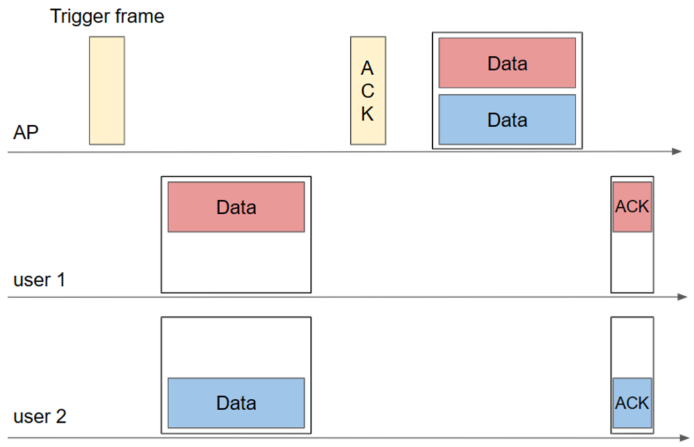
These features are very useful to provide determinism (i.e., TSN). Problems:

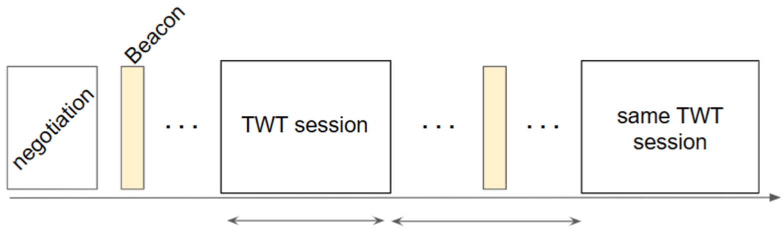
- Complex scheduling problem.
- Vendors implement basic solutions (e.g., Round Robin).

rTWT

TWT is a mechanism to save battery. It assign periods of time to users where they can transmit. rTWT, introduced in IEEE 802.be, extends TWT by providing secure windows.

- Created to reduce contention and provide determinism.
- Also coordinated by the AP.





IEEE 802.11ax OFDMA vs. rTWT

- Some works present solutions that improves the algorithms of the vendors. And some others develop solutions to the TWT allocation problem, increasing the performance of the network. However, determinism is not having into account.

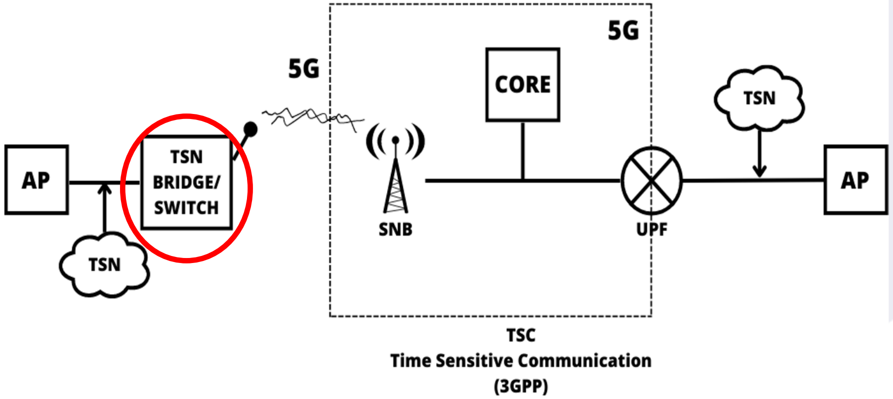
Our **goal** is to compare the performance in achieving TSN with IEEE 802.11 OFDMA MU:

- solving the scheduling problem in an intelligent way.
- solving the scheduling problem with the basic solution of the vendors, but implementing smart TWT allocation.
- solving the scheduling problem with the basic solution of the vendors, but implementing 802.1Qbv (the standard for wired TSN) on top of the 802.11 layers.

This will demonstrate if it is necessary to change the OFDMA scheduling solution vendors implement in order to provide TSN capabilities through IEEE 802.11.

Building an AF_XDP based TSN Switch

- Development of OS TSN-capable switch/bridge for testing queuing and prioritization techniques in a controlled and stable environment.
- Combination of eBPF and AF_XDP.
- **AF_XDP (Advanced eXpress Data Path)**
    - high-performance
    - bypass the traditional Linux kernel networking stack and process packets directly in the user space.
- **eBPF (Extended Berkeley Packet Filter)** framework to enable programmable and secure packet filtering and processing.



Building an AF_XDP based TSN Switch

What are we planning to do with it

- Main usage:
  - Develop and test new queueing policies for IEEE 802.1Qbv
  - Integration point for PREDICT-6G data plane
    - Wired
    - IEEE 802.11
    - 3GPP TSC

Conclusions

Summary

- We consider networks need to be enhanced to become more deterministic (i.e., predictable, reliable and time sensitive) to cope with emerging use cases
- The 6G network will be composed of multiple heterogeneous networks merged together
  - Not a single L2 solution will solve the problem
- We propose two main innovations in this area:
  - Multi-technology multi-domain Data-Plane (MDP)
    - Enhance L2 technologies
    - Integrate them into a single E2E data plane
    - Expose APIs for control and monitoring
  - AI-driven Multi-stakeholder Inter-domain Control-Plane (AICP)
    - AI-based network control plane framework
    - Network digital twins for predictability
    - Monitoring platform
- We think DTs will play a key role in this area

Where To Find More Information?

PREDICT-6G

- PREDICT-6G web page: https://predict-6g.eu
- Publications:
  - Towards Intelligent Cyber-Physical Systems: Digital Twin meets Artificial Intelligence [IEEE COMMAG (in-press)]
  - An Intelligent Edge-based Digital Twin for Robotics [IEEE Globecom WS 2020]
  - Demo Paper: Assessing the need for 5G driven Edge and Fog solution for Digital Twin systems [ACM WiNTECH 2020]
  - Demo Paper: AIML-as-a-Service for SLA management of a Digital Twin Virtual Network Service [IEEE INFOCOM 2021]
- Live Demos:
  - Digital Twin Service Demo: https://youtu.be/MIvcJWb0YVE
  - Digital Twin Application Demo: https://youtu.be/yGvzHteOcSU
  - Digital Twin Dynamic Scaling Demo: https://youtu.be/K5GyrAD7h_Q

PREDICT-6G

Thank you!

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