Hexa-X: WP7 - Deliverable D7.3

Special-purpose Functionalities: Final Solutions

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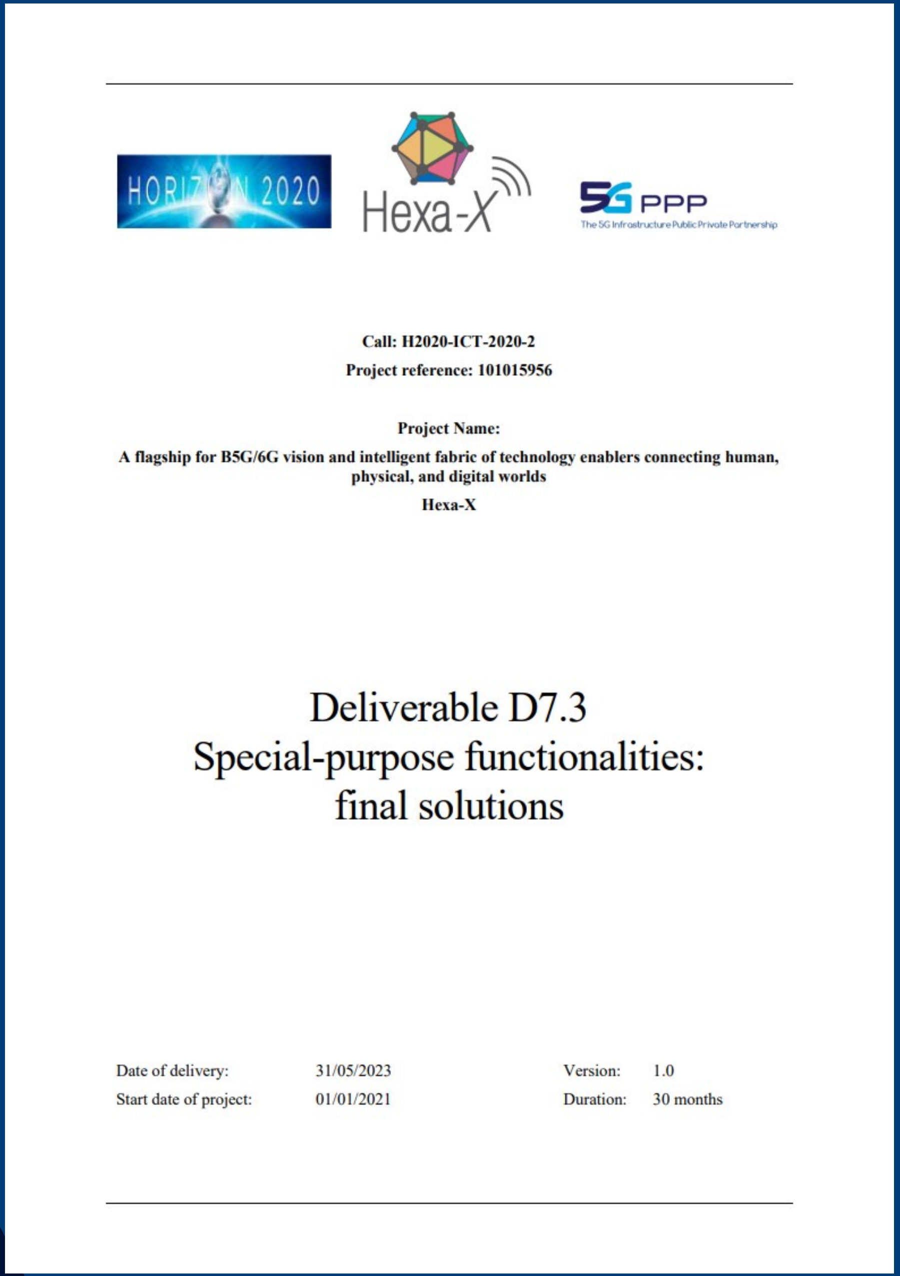
Mission and scope

- WP7 studies enablers for **increased dependability** and **sustainable coverage**, including **Digital Twins** and **novel HMIs** to enable extreme experiences
- It contributes to the project objective “**network evolution and expansion towards 6G**”

- **D7.3 contains final solutions and their relation to project objectives, other Hexa-X technical enablers, KPIs, and KVIs**



HORIZON 2020 Hexa-X 5G PPP The 5G Infrastructure Public Private Partnership

Call: H2020-ICT-2020-2
Project reference: 101015956

Project Name:
A flagship for B5G/6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds
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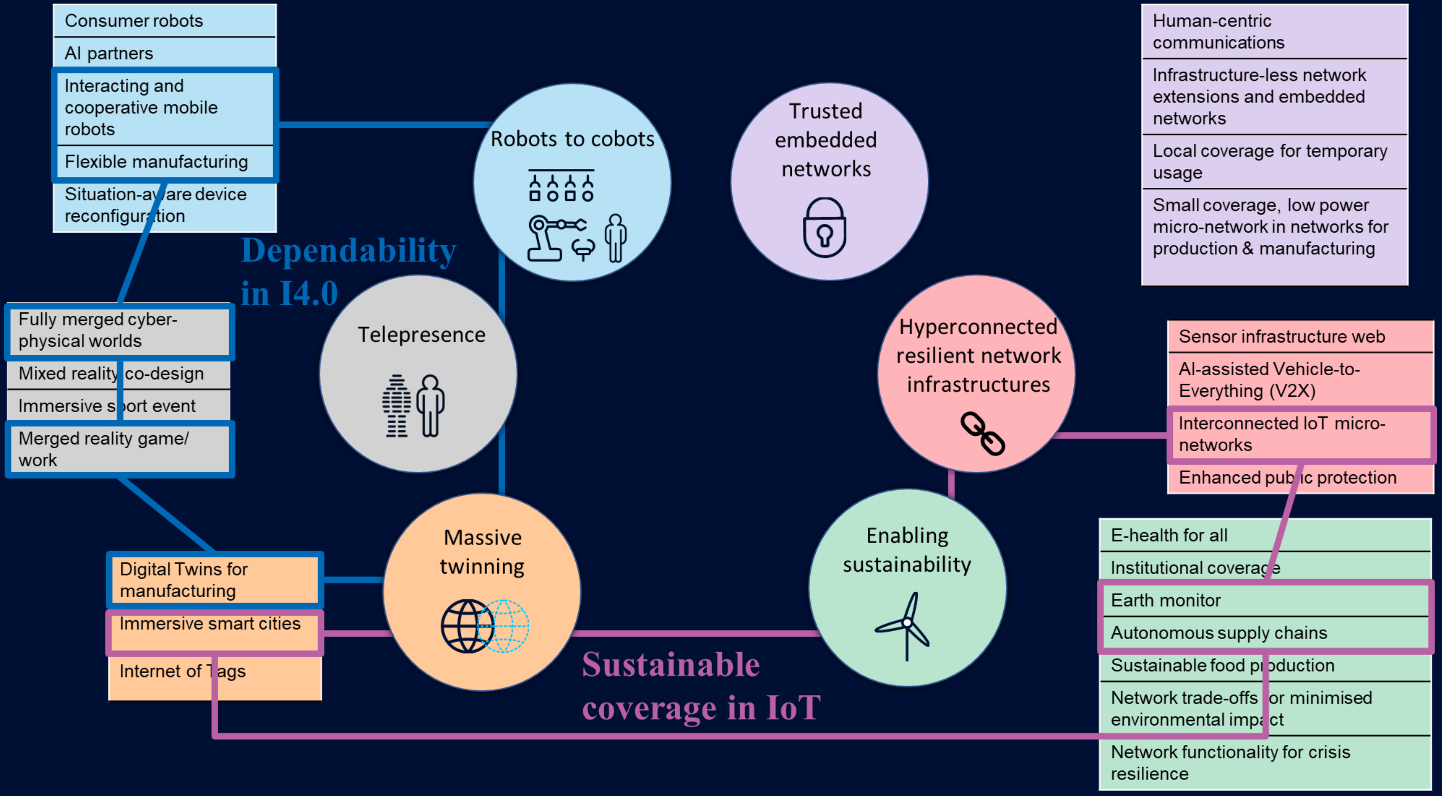
Deliverable D7.3
Special-purpose functionalities:
final solutions

Date of delivery:	31/05/2023	Version:	1.0
Start date of project:	01/01/2021	Duration:	30 months

Identification of key use cases for extreme experiences

(Recap of D7.1, updated with D1.3 content)

- Analysis of Hexa-X use cases, focusing on two groups
- Sharpened requirements (KPI and KVI definitions and target values in use cases)



Three focus topics for special-purpose functionality

(Recap of D7.1)

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Ultra-flexible resource allocation (Task 7.2)

Ultra-flexible resource allocation procedures in **challenging environments** such as those populated by mobile devices with special requirements and in need of coverage.

Dependability in I4.0 (Task 7.3)

Mechanisms and enablers for **high dependability** in vertical scenarios, enabling efficient resource support of complex and dynamically changing availability requirements.

HMIs and digital twins (Task 7.4)

Convergence of the biological, digital and physical worlds with human interaction through **novel HMI** concepts and a **privacy-preserving high-availability Digital Twin**.

Outline

- **Overview of contributions**
  - WP7 in Hexa-X: relation to architectural enablers
  - Contributions in relation to KPIs and KVIs
- **Final solutions**
  - for flexible resource allocation
  - for dependability in I4.0
  - for HMIs and Digital Twins
- **Demonstrator**
  “extreme performance in handling unexpected situations in industrial contexts”
- **Conclusion**

Overview of contributions

Overview of contributions in D7.3

Ultra-flexible resource allocation

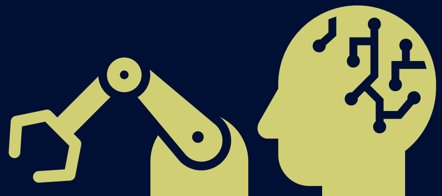
- In^2-X communication model
- Radio-aware trajectory planning
- Functional-split-aware trajectory planning
- O-RAN compliant resource provisioning for federated learning
- Ambient backscatter communications

Dependability in I4.0

- Technical enablers:
  - RRM with DTs
  - UAV-assisted mMTC
  - data- and control-plane guarantees
  - RAN intelligence
- CoCoCoCo framework:
  - model-based vs. data-driven approach
  - bottleneck identification
  - loss-aware resource allocation

Digital Twins and novel HMIs

- Overview on novel HMIs
- Modeling the impact of human presence
- DT-empowered cobots
- DT-based functional split adaptation
- DTs for Emergent Intelligence



Overview of contributions in D7.3

Demonstrator

- “extreme performance in handling unexpected situations in industrial contexts”

Relation to technical enablers

(list of enablers based on D1.3)

Enabler (c.f. list in D1.3)	Related contribution	Details
Distributed large MIMO	Dependability in distributed large MIMO	D7.2, Sec. 4.3
Localization and Sensing	Formulation of requirements in DT and I4.0 / factory automation use case	D7.1 for use case / requirements D7.2 Sec. 4.4, 5.3, 5.6
UE, network, and service programmability	UEs not explicitly considered - can be an enabler for novel HMI functionality or retrofitting. Network programmability with data and control plane guarantees	 D7.3 Sec. 4.1.3
Network automation	Orchestration and handling of unexpected situations (demonstrator) Flexible functional split adaptation and joint trajectory optimization Data analytics assisted AI operation	D7.3 Sec. 6 (Demonstrator) D7.3 Sec. 3.3 D7.3 Sec. 4.1.4
AI and AI as a Service	Special-purpose case of federated learning in IoT AI and Emergent Intelligence in digital twins	D7.2 Sec. 3.4, D7.3 Sec. 3.4 D7.2 Sec. 5.7, D7.3 Sec. 5.5
Dynamic function placement	Utilized as enabler for resource allocation in challenging environments Impact on dependability	D7.2 Sec. 3, D7.3 Sec. 3 D7.2 Sec. 4.5
NTN	No direct NTN works. Utilization of drones for sustainable coverage extension in mMTC	D7.3 Sec. 4.1.2
Mesh / Device-to-device	In2-X networks in factories	D7.2 Sec. 3.1, D7.3 Sec. 3.1
Architectural transformation	Reduced dependencies between network functions enables flexible placement Potential utilization in flexible functional split adaptation and joint trajectory optimization	D7.2 Sec. 5.6 D7.3 Sec. 3.3
Compute as a Service	Availability of (trustworthy) compute capabilities for the execution of digital twins Can be enriched with allocation strategies, e.g., for federated learning in IoT scenarios Further studies in relation to CoCoCoCo	D7.2 Sec. 5 D7.2 Sec. 3.4 D7.3 Sec. 4.2
Automation & Data-driven M&O	Exposure of local (domain-)knowledge through network-aware collaborating digital twins Formulation of an ecosystem of digital twins to allow cross-domain optimization and collaboration in a privacy-preserving fashion Enabler for resource allocation, e.g., in In-X networks and networks-of-networks	D7.2 Sec. 4.4, 5.6 D7.2 Sec. 5 D7.2 Sec. 3.1

Relation to targeted KPIs
(based on definitions in D1.3)

		KPI	Contributions
Communication	Dependability	Availability	Understand and model the impact of packet losses etc. on application performance with Communication(-Computation)-Control-Codesign (D7.2 Sec. 4.1; D7.3 Sec. 4.2) for industrial control applications in I4.0. Quantification of end-to-end dependability and measurement approaches (D7.2 Sec. 4.5). Modelled for the CoCoCoCo approach in D7.3 Section 4.2.1. Extended to UAV-assisted mMTC use case in D7.3 Section 4.1.2, allowing for dependability within sustainable coverage use cases. Additional technical enablers for dependability in D7.3 Section 4.1. *All contributions mentioned under "Quality of Service (QoS) Attributes"*
		Reliability	
		Safety	*No dedicated contributions*
		Integrity	
		Maintainability	Observability with dependability monitoring (D7.2 4.5) Mechanisms for error identification (D7.2 4.2)
	QoS Attributes	Service latency	Deterministic latency with control and data plane guarantees (D7.2 4.5, D7.3 4.1.2)
		Data rate	Increasing efficiency of Radio Resource Management (RRM) with DTs (D7.2 Sec. 4.4), D7.3 Section 4.1.1. AI based joint application and RAN resource optimization in D7.3 Sec. 4.1.4. Dependability in Massive MIMO ([Hexa-X D7.2]: Sec. 4.3), D7.3 Section 4.1.2. Utilizing ambient backscatter communications for resource constrained devices ([Hexa-X D7.2]: Sec. 3.5), Updated in D7.3 Section 3.5. Interference management ([Hexa-X D7.2]: Sec. 3.1), further modelled and simulated in D7.3 Section 3.1.
		Resource constraints	
		Scalability	

Relation to targeted KPIs (cont'd)

(based on definitions in D1.3)

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		KPI	Contributions
AI and computation	Dependability	Agent availability	Inclusion of "Computation" in Communication-Control-Codesign (CoCoCo) (D7.2 Sec. 4.1), final solutions on compute aspects are included in D7.3 Section 4.2.2. Resource provisioning for Federated Learning in IoT (D7.2 Sec. 3.4) showing that in a distributed environment, such as an urban IoT one, FL can be affected by latency and bandwidth. This was further extended towards a realization of a V2X use case in the O-RAN compliant COLOSSEUM emulator in D7.3 Section 3.4.
		Agent reliability	
		Safety	*No dedicated contributions*
		Integrity	*No dedicated contributions*
		Maintainability	Observability with dependability monitoring (D7.2 Sec. 4.5) Mechanisms for error identification (D7.2 Sec. 4.2)
	QoS Attributes	AI service RTT	Optimal resource allocation and redistribution (D7.2 Sec. 3.3) Resource provisioning for Federated Learning in IoT (D7.2 Sec. 3.4), showing the impact of RTT on a testbed FL implementation.
		Inferencing accuracy	*No dedicated contributions*
		Interpretability level	
		Training/model transfer latency	Optimal resource allocation and redistribution (D7.2 Sec. 3.3) Resource provisioning for Federated Learning in IoT (D7.2 Sec. 3.4), showing that increased latency for few selected FL agents leads to worse overall performance. Emulation in a V2X O-RAN scenario (D7.3 Section 3.4) highlights the magnitude of this problem. Digital Twins for Emergent Intelligence (D7.2 Sec. 5.7)
		Resource constraints	
		Scalability	

Relation to targeted KPIs (cont'd)

(based on definitions in D1.3)

Localization and Sensing	Utilization of location information in digital twins (e.g., for trajectory optimization) to allow for more efficient resource utilization (D7.2 Sec. 3.2, 4.4), extended in D7.3 Section 3.2 and 3.3 for the case of radio-aware trajectory planning and for split-aware trajectory planning in the case of flexible functional splits. Modelling the impact of human presence, potentially augmented by sensing capabilities of 6G (D7.2 Sec. 5.3), extended in D7.3 Section 5.2 for the case of industrial environments. Additionally, human pose detection is described in D7.3 Section 5.3.2.2 for the use case of collaborative robots.

Relation to targeted KVIs
(based on definitions in D1.3)

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KVI area	Contribution	Remarks
Sustainability	Ambient backscatter communication (D7.3 3.5)	Novel zero-energy devices for massive IoT scenarios (e.g., earth monitor). Energy autonomy under optimistic assumptions is shown. The impact of potential integration into the mobile network is discussed.
	Efficient resource allocation (D7.3 Sec. 3)	Efficient utilization of infrastructure, adapted to current load and conditions (c.f. flexibility KVI). Also impacted by results on dependability, as e.g., CoCoCoCo enables high application productivity at lower demands on the underlying network by utilizing cross-layer optimization.
Trustworthiness	Dependability-related contributions (D7.3 Sec. 4)	Increased and observable/quantifiable dependability is expected to contribute to the overall level of trust as an indicator of trustworthiness [Hexa-X D1.3].
	Trustworthy Digital Twin platform (D7.2 5.1, 5.6, 5.7)	Privacy-preserving collaboration among digital twins, benefiting from novel 6G capabilities (e.g., localization, sensing).
Inclusiveness	Novel HMIs (D7.2 5.2) and interaction with Digital Twins (D7.2 5.4, 5.5)	Enable remote interaction, enable inclusion of a more diverse (remote/on-site) workforce. Reduced human exposure to hazardous/dangerous situations. Example shown in the demonstrator (D7.3 Sec. 6) and for DT-empowered collaborative robots (D7.3 Sec. 5.3).
Flexibility	Flexible resource allocation (D7.2 Sec. 3, D7.3 Sec. 3)	Mechanisms to adapt to changing requirements, mobility, device constraints, …

Overview of contributions

Final solutions

- for flexible resource allocation
- for dependability in I4.0
- for HMIs and Digital Twins

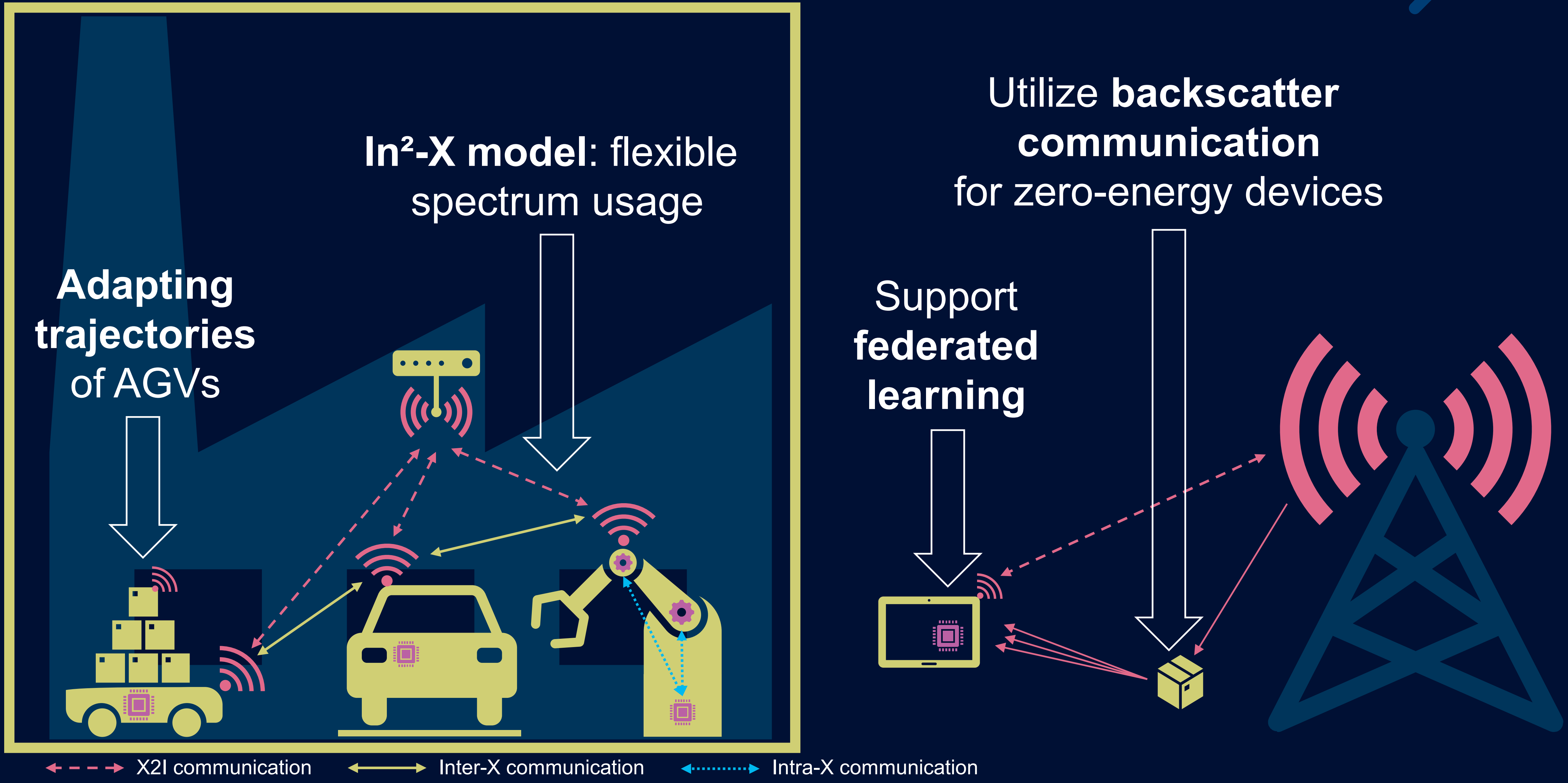
Demonstrator
"extreme performance in handling unexpected situations in industrial contexts"

Conclusion

Flexible resource allocation

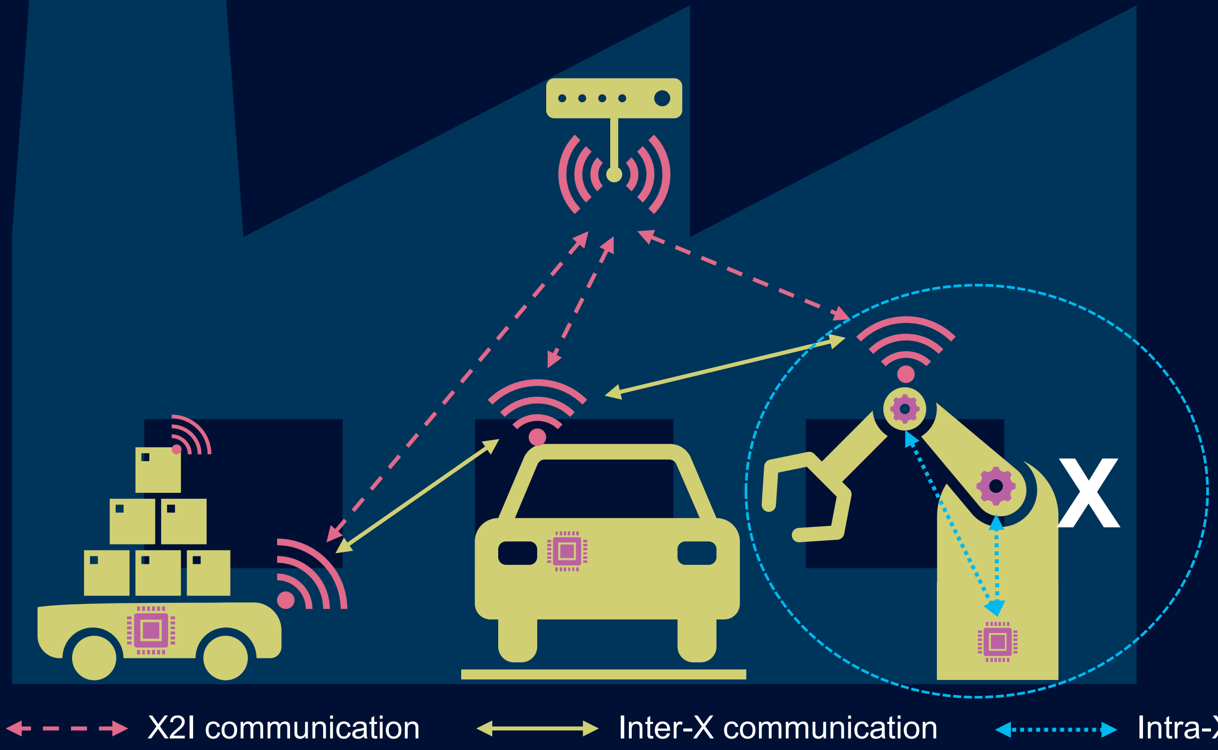
Final solutions

Flexibility-related contributions



Flexibility in spectrum usage: the In²-X model

- Different coverages and traffic patterns
  → **spectrum management is challenging**
  - Mixed standards/protocols by different underlay networks
  - Interference between sub-networks



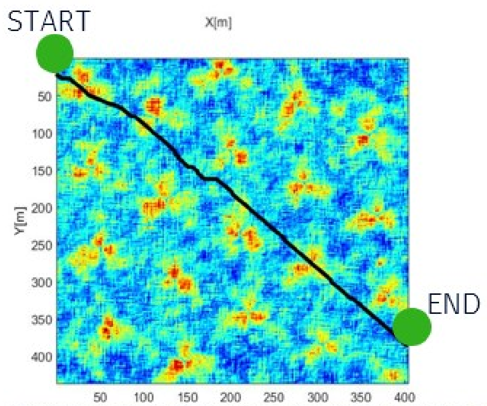
- Proposed framework
  - For intra-X traffic, recommend to use SS
    (low complexity, low interference, good spectral efficiency)
  - For inter-X and X2I, each X measures the overall power leakage of other intra-X traffic
    (each intra-X protocol individually creates a radio pattern, but only the superposition is observable)
  - Mutual scheduling
    Each X estimates the overall pattern, predict the channel occupation, and opportunistically schedule its own traffic.

- Preliminary result:
  - **33% prevention of collisions**

Flexibility by adapting trajectories of AGVs

Radio-aware trajectory planning utilizing Digital Twins

- Utilize the radio-aware Digital Twin (c.f. D7.2) to optimize trajectories of controllable entities (UAVs, AGVs)
- Supports different target quality metrics depending on application scenario

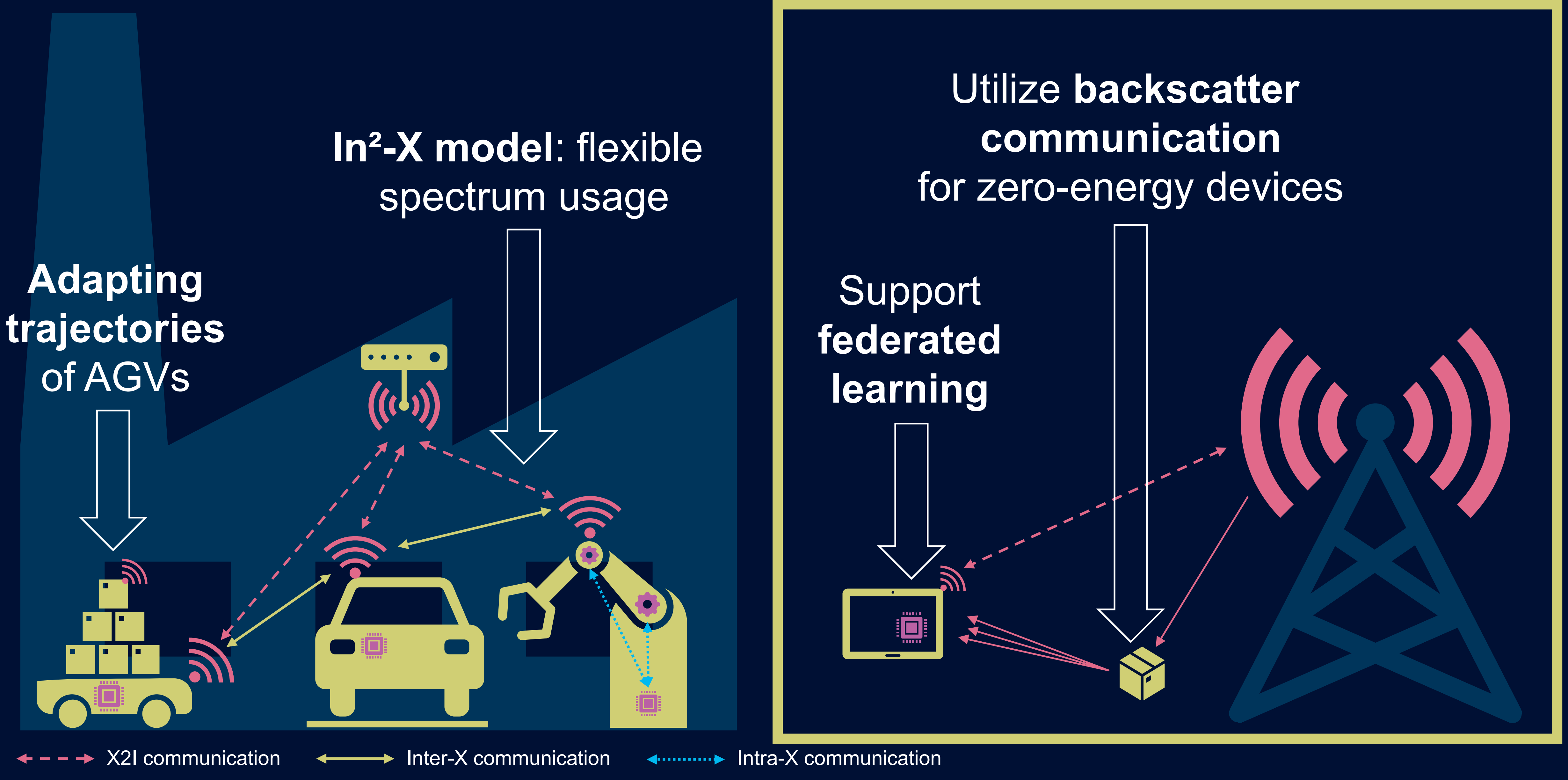


Optimal energy efficiency routing while satisfying minimum throughput constraint

Functional-split-aware trajectory planning

- AGVs are enabled to plan routes based on minimizing the Risk of Interference
- Utilize information about split and centralization of network functions

Flexibility-related contributions



Flexible resource provisioning for Federated Learning

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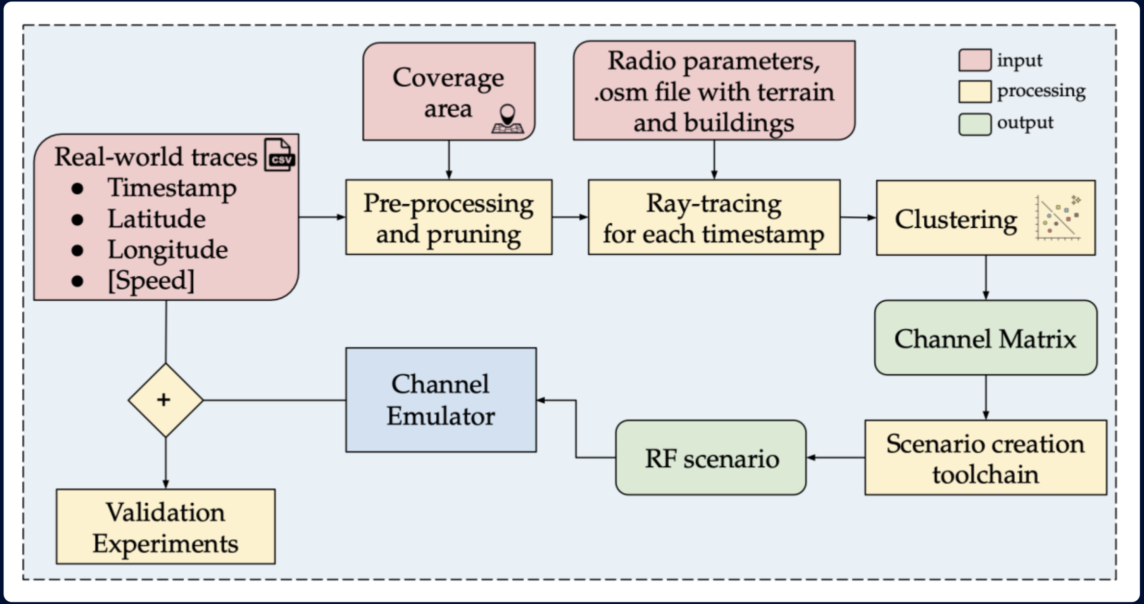
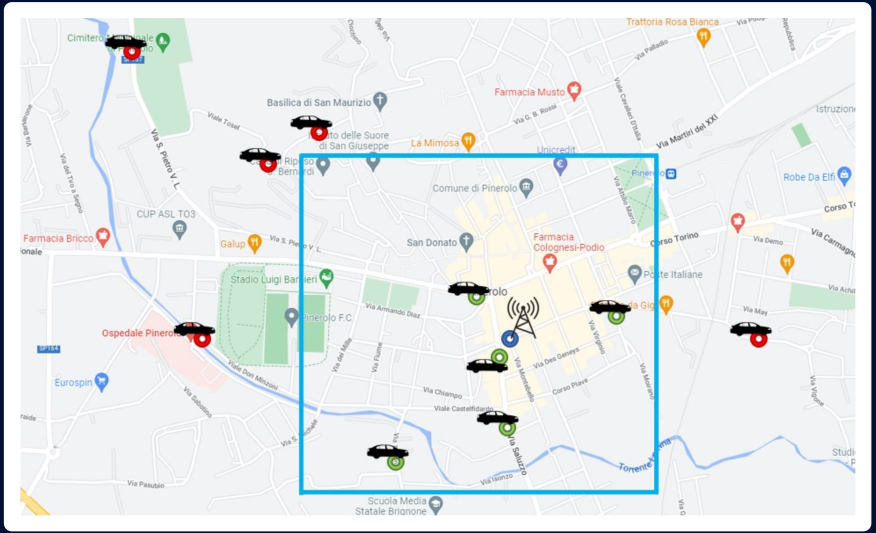
- Framework for creating RF scenarios for large scale Radio Frequency (RF) emulators
  - Signals are processed by channel emulators to generate a realistic path loss and phase shift, as if the SDRs were placed inside the actual physical environment
  - Dataset composed by dynamic data of 19 vehicles travelling in a 1km^2 area around Pinerolo (near Torino, Italy); collected by the NavSAS group at PoliTO
  - Data collected with a high-end GNSS device with ~10 Hz update rate, including IMU for gathering additional dynamic information (e.g., acceleration)





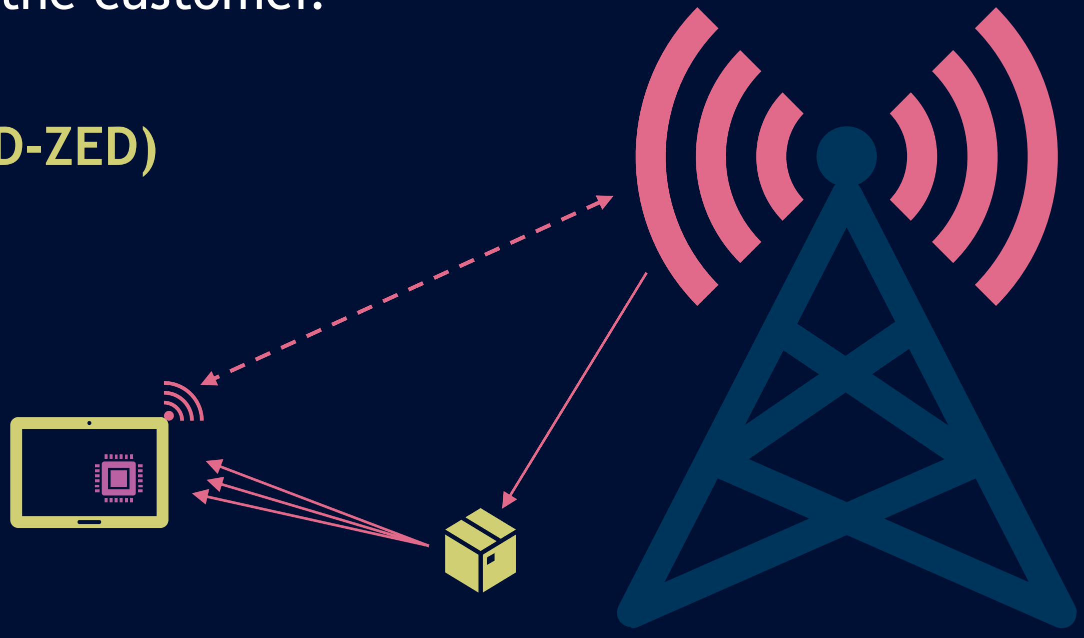
Flexible asset tracking with zero-energy devices

Motivation: offer a “Tracking Out-of-Thin-Air service”

- The network operator sells a tracking service to a company or individual customer, and rewards smartphones participating anonymously to crowd-tracking.
- 3 steps:
  - The customer puts a Zero Energy Device (ZED) on a package,
  - Each time the package is close to a smartphone connected to the network and geo-localised, the ZED is horodated and geolocalised by the network,
  - The network provides the traces of the ZED to the customer.

Solution: Crowd-detectable Zero-Energy Device (CD-ZED)

- Zero added waves: backscatters ambient (DL and UL) waves
- Zero added energy: harvests ambient energy (solar or indoor light)
- Zero dedicated network infrastructure or readers: it can be read by 6G equipment (Smartphone in DL and Base Station in UL)



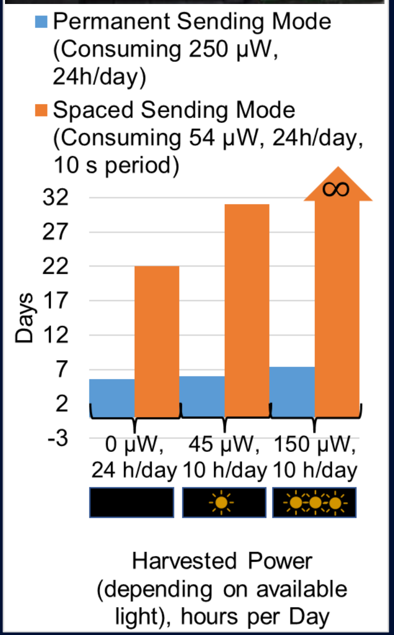
Flexible asset tracking with zero-energy devices

Experimental Proof-of-Concept

ZED prototype backscatters 96 bits in ~0.5 second, 24H/Day

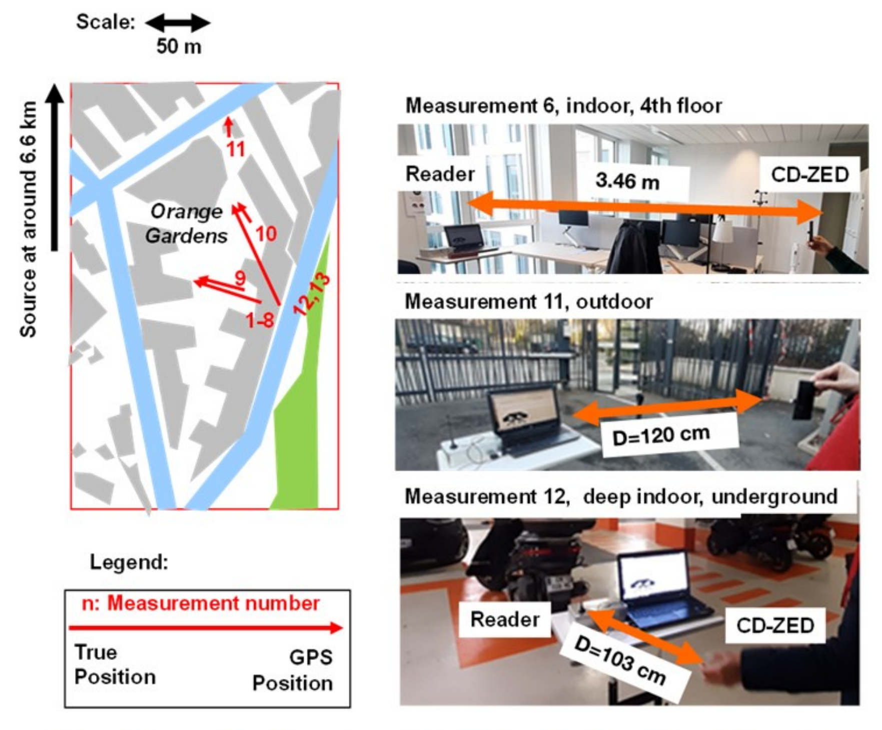
Autonomy:

- Minimum is 5 days, in the dark, with continuous sending.
- Maximum is **unlimited** time, with 10h of bright light per day, and sending every 10 seconds.



(a) Energy autonomy in days, assuming initially full battery

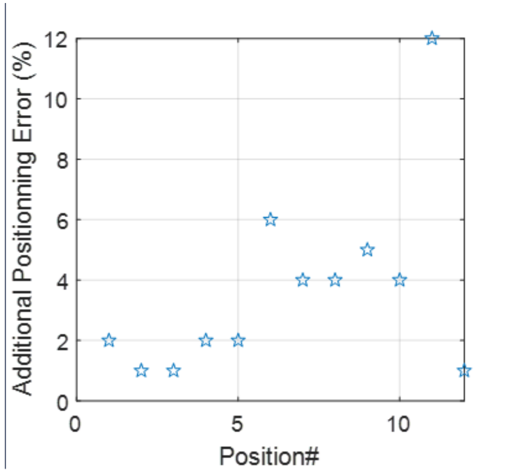
ZED is localised with an accuracy that is in the same range of a smartphone localisation.



a) Smartphone Positionning Error

b) ZED-to-Reader (Smartphone) distance

Experiments show that ZED detection by smartphone adds up to 12% of positioning error, to the smartphone's own positioning error.



(c) Additional Positionning error due to tag-reader distance

Overview of contributions

Final solutions

- for flexible resource allocation
- for dependability in I4.0
- for HMIs and Digital Twins

Demonstrator
"extreme performance in handling unexpected situations in industrial contexts"

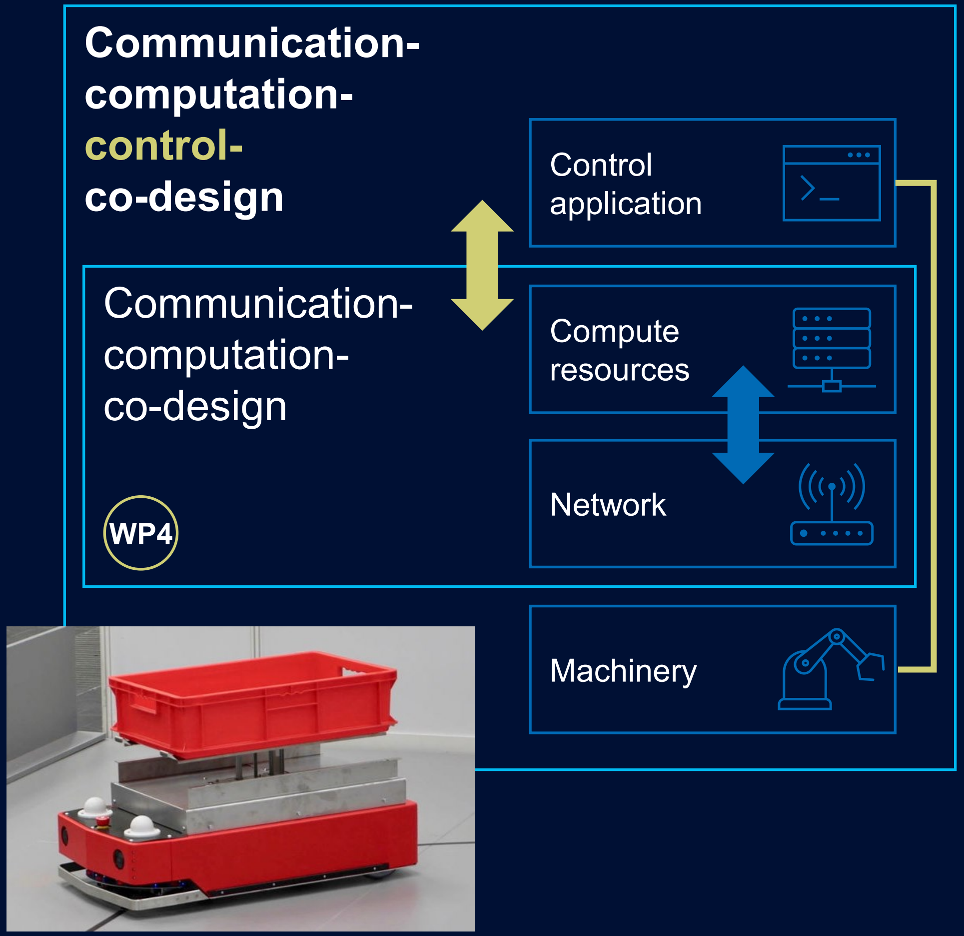
Conclusion

Dependability in I4.0

Final solutions

Contributions for dependability in I4.0

Communication-Computation-Control-Co-Design framework



Technical enablers for network dependability in I4.0

- Radio resource management with DTs
- Dependability in UAV-assisted mMTC
- Data and control plane guarantees in programmable industrial networks
- Utilizing network data for AI operations in factory networks

Model-based vs. data-driven approaches of CoCoCoCo

- Classical approach that takes a statical approximation of communication model fails in CoCoCoCo scenario, **a joint model is required**
- A novel formulation of the overall CoCoCoCo optimization problem:

$$
\begin{aligned}
\min_{z} \quad & \mathbf{E}_{P_1}\left[Q_1(z,\omega_1)\right] \\
s.t. \quad & f(z) \le 0, \\
& \mathbf{E}_{P_1 \times P_2}\left[Q_2(z,\omega_1,\omega_2)\right] \le 1 - R_{app}(0) \\
& z \in \boldsymbol{R}^n
\end{aligned}
$$

Outer stage: communication subsystem design

$$
\begin{aligned}
Q_1(z,\omega_1) = \min_{z} \quad & \boldsymbol{E}_{P_2}[J(u)] \\
s.t. \quad & g(\dot{x},x,u,\omega_1,\omega_2) = 0, \\
& (x_0,t_0) = v(z,\omega_1), \\
& u \in \boldsymbol{R}^m
\end{aligned}
$$

Inner stage: control/computing subsystems design

$$
\begin{aligned}
Q_2(z,\omega_1,\omega_2) &= 1 - I(y) \\
y &= h[x,u,v(z,\omega_1),\omega_2] \\
I(y) &= \begin{cases} 1, & y \in D_{app} \\ 0, & o.w. \end{cases}
\end{aligned}
$$

Application-layer system reliability assessment

Approaches to the complex multi-level program

Application-oriented in-loop design (iterative)

- Pro: simplicity
- Cons: requires collective expertise across domains (time & cost); no flexibility

Decomposition into domain-specific subproblems coupled with each other

- Pros: more flexible development cycle, lower cost, allowing adaptation of domain-specific tools
- Cons: requires deep understanding of the dependability coupling across different domains

Data-driven black-box approach

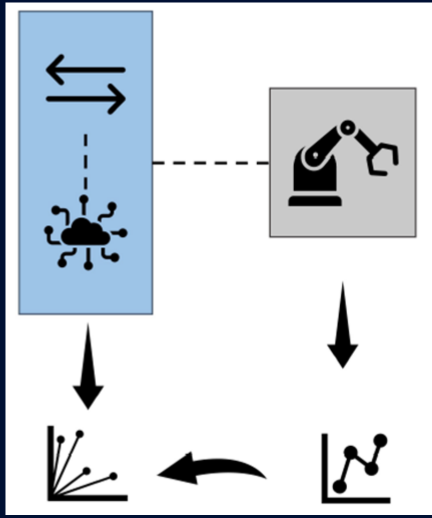
- Pros: flexibility in reusing the same CoCoCoCo infrastructure on different applications
- Cons: less capable of revealing the fundamental mechanism, cannot guarantee global optimality

Insights gained for modelling CoCoCoCo

- Towards model-based: error propagation chain analysis

Error category	Examples	Impact
Value errors	Sensing error, computation error, source coding noise, quantization noise, system disturbance, etc.	System state diverged from optimum
Transmission errors	HARQ NACK, packet loss	Increased inter-arrival interval
Application errors	System outage, service failure	Reduced dependability

- Towards data-driven:
  - Framework proposed
    - CoCoCoCo infrastructure as a black-box, characterized by a feasible domain of the "generic QoS vector"
    - Each application characterized by a function that maps the generic QoS vector onto its system-level performance
  - Use cases identified: Flexible manufacturing, Open manufacturing system, SLA design

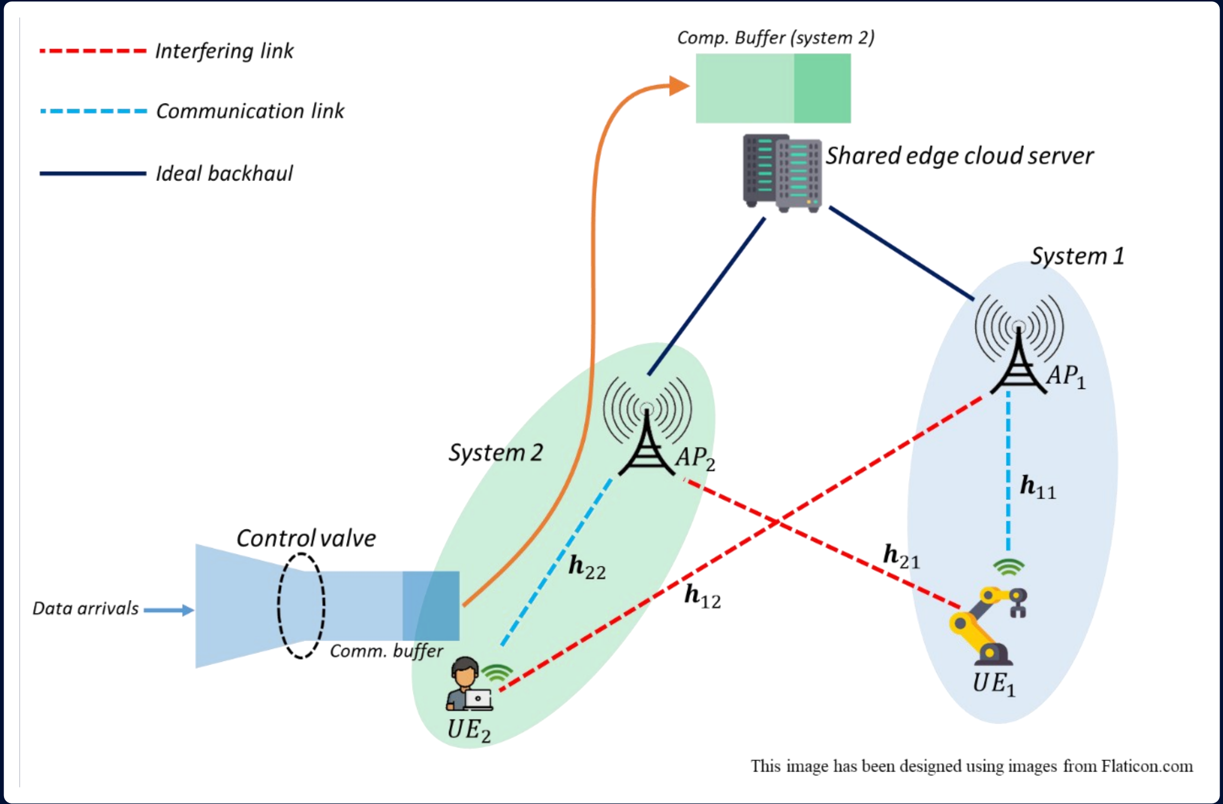


Bottlenecks of coexisting connect-compute services

Motivation: hidden bottlenecks of connect-compute services (e.g., computation offloading) in different segments of future systems, due to energy constraints at wireless or computing entities (e.g., edge cloud servers), EMF exposure, interference, etc.

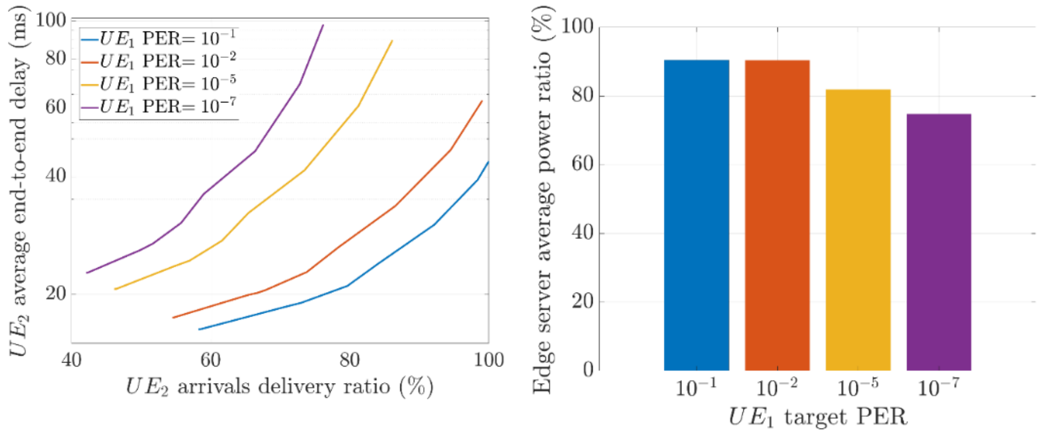
Scenario

- System 1: UE 1 offloading tasks through AP 1 in a per-slot basis, without buffering
- System 2: UE 2 offloading tasks through AP 2 in a per-slot basis, with buffering
- Both use the same spectrum (carrier) and computing resources (edge cloud server)
- Optimisation variables:
    - System 2 transmit power
    - System 2 proactive arrivals drop
    - Edge cloud CPU frequency scheduling among the two systems



Bottlenecks of coexisting connect-compute services

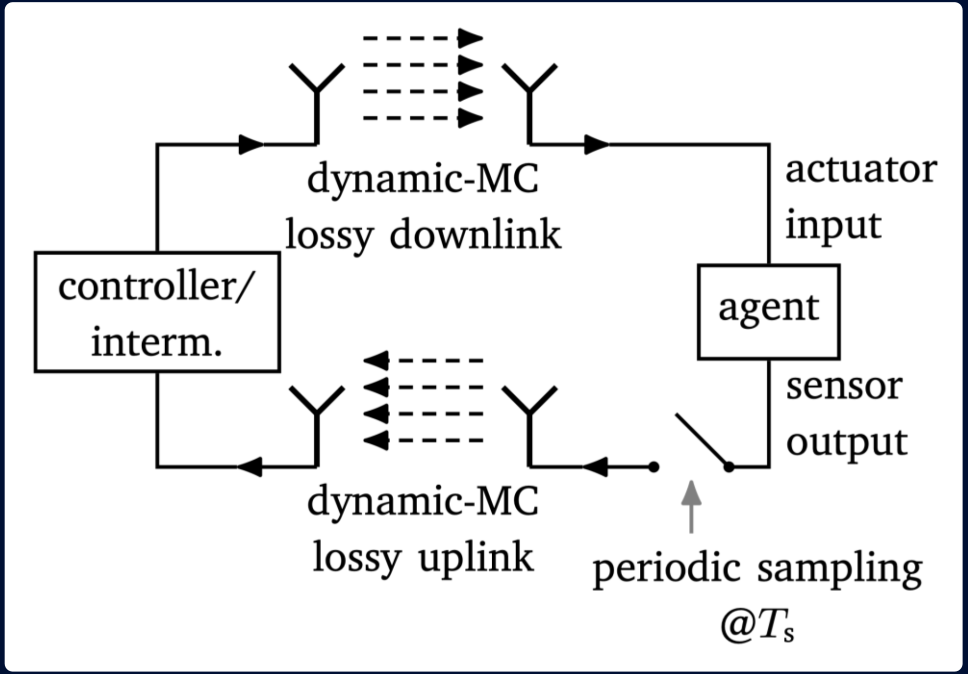
- Numerical results (in case no power constraints are imposed at the edge cloud server)
  - Trade-off between UE 2 data offloading rate (or, packet arrivals delivery ratio) and UE 2 end-to-end delay
  - Different PERs for UE 1 determine different trade-offs
  - Higher PER for UE 1 leads to higher data offloading rate for UE 2, with the same end-to-end delay
  - Lower edge server power consumption is achieved for lower System 1's PER, as system 2 bottleneck is stricter
  - Results show the inherent coupling between wireless and computing resources and the resulting bottlenecks



(a) trade-off between UE_2 average end-to-end delay and arrivals delivery ratio, for different UE_1 target PER values

(b) edge server average power consumption ratio vs. target PER

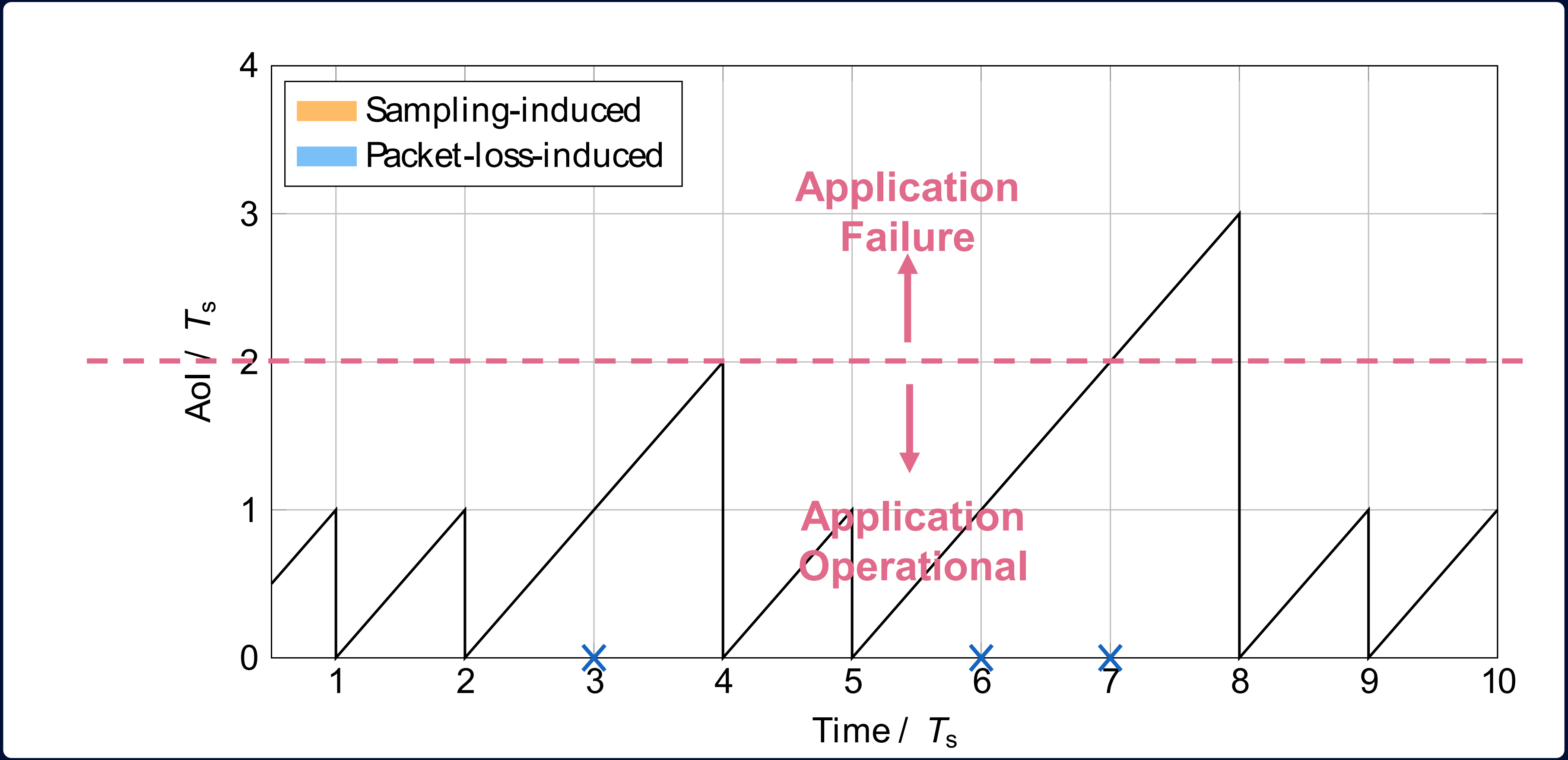
Packet-loss-aware resource allocation



- In [D7.2], only single-hop networks were investigated
- However, typically information must traverse multiple hops before it is consumed
- Resource allocation based on the “packet loss history” must include the whole chain of data flow
- A different metric for valuing a packet’s importance must be used for resource allocation purposes … (see next slide)

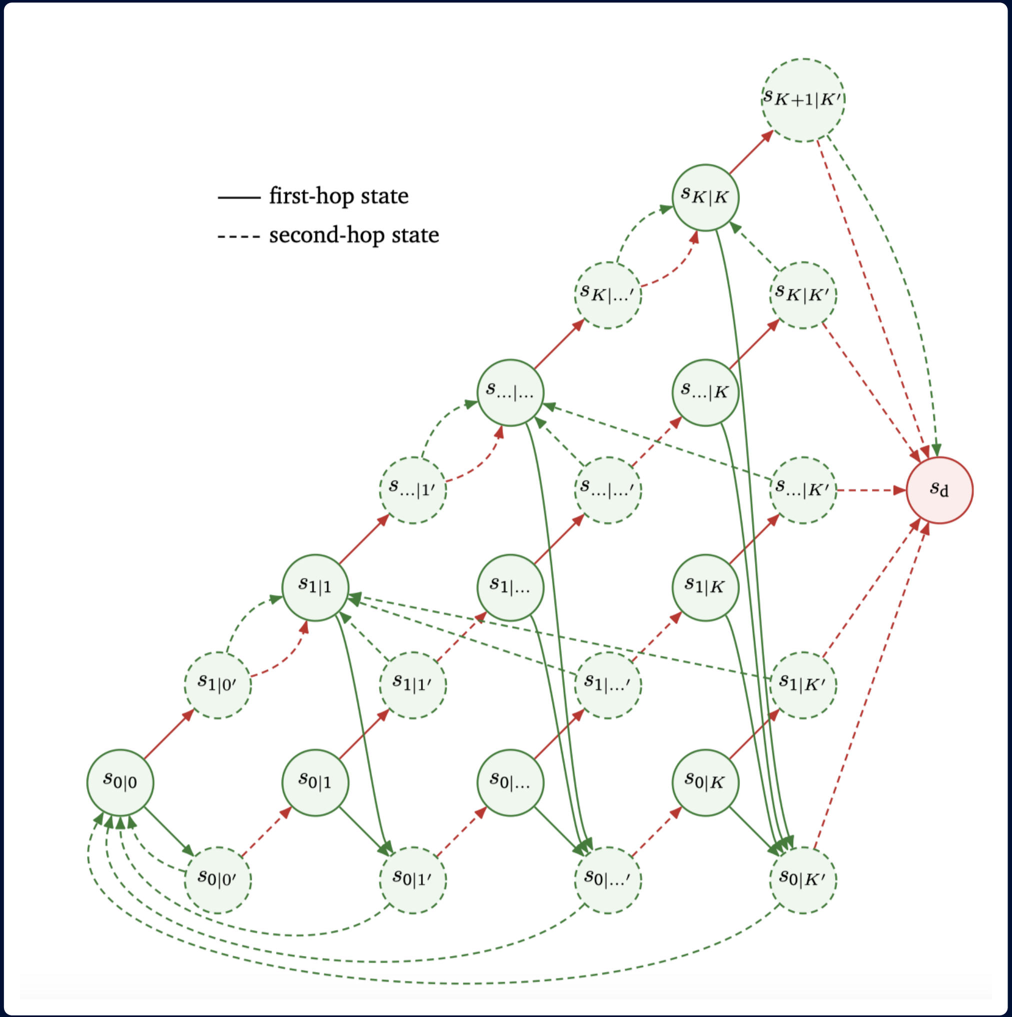
Packet-loss-aware resource allocation

- Definition: The **Age of Information** is the time that has passed since the generation of the last successfully received packet.



Classification whether application has failed based on the information freshness.

Packet-loss-aware resource allocation



- Based on a Markov Chain modeling approach, the freshness of the information at the data sink and all intermediate nodes determines the target success probabilities on every i-th hop transmission
- Reaching the failure state (red) means that an AoI-threshold at the data sink is exceeded

Packet-loss-aware resource allocation

- Based on this model, an optimization can be performed

Individual penalty functions

Combination function of the individual penalty values

"Status update age": A different term for AoI

Average resource consumption

$$\boldsymbol{l}^{\text{opt}} = \arg\min_{\boldsymbol{l}} \left\{ \Gamma \left(g_{\text{MTTF}} \left(\text{MTTF} \left(\boldsymbol{l} \right) \right), g_{\text{SUA}} \left(f_{\text{SUA}} \left(\text{SUA} \left(\boldsymbol{l} \right) \right) \right), g_{\bar{l}} \left(\bar{l} \left(\boldsymbol{l} \right) \right) \right) \right\}$$

$$\text{subject to } l_k \in \left\{ 1, \ldots, \hat{l} \right\}$$

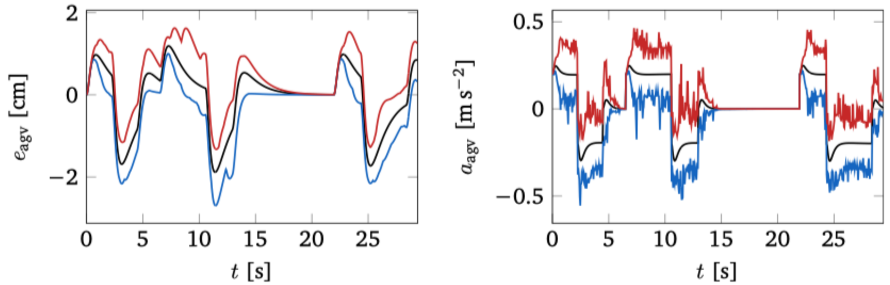
How many resources to assign in each state

An integer number of simultaneous links (resources)

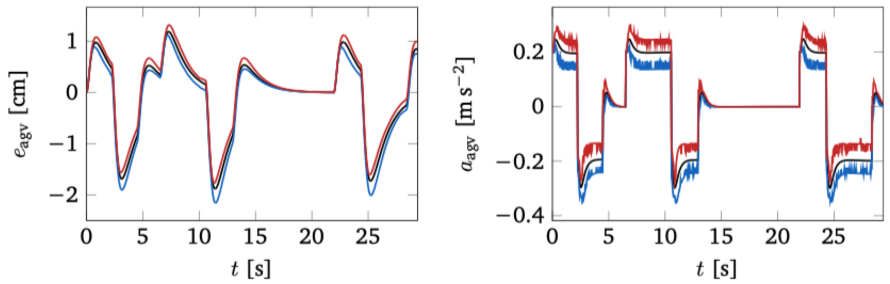
Packet-loss-aware resource allocation

- Maximum
- Minimum
- No Packet Losses

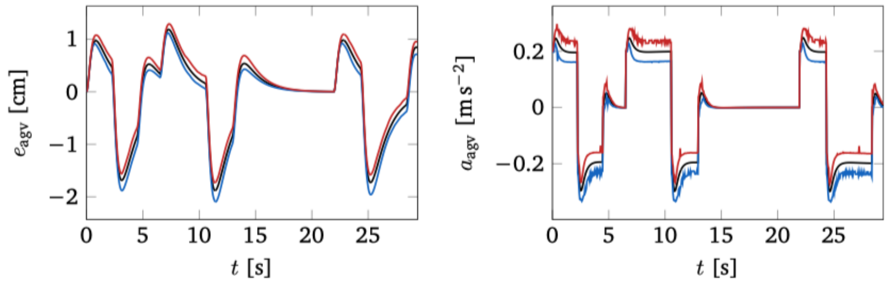
Position offset for AGV position control application



(a) Static single-connectivity: with a single channel ($\bar{l} = 1$) the acceleration is jerky and the agent does not operate dependably (MTTF = 2 minutes).



(b) Static dual-connectivity: doubling the number of channels ($\bar{l} = 2$) results in significantly more determinism, however, the agent is still not very dependable (MTTF = 10 days).



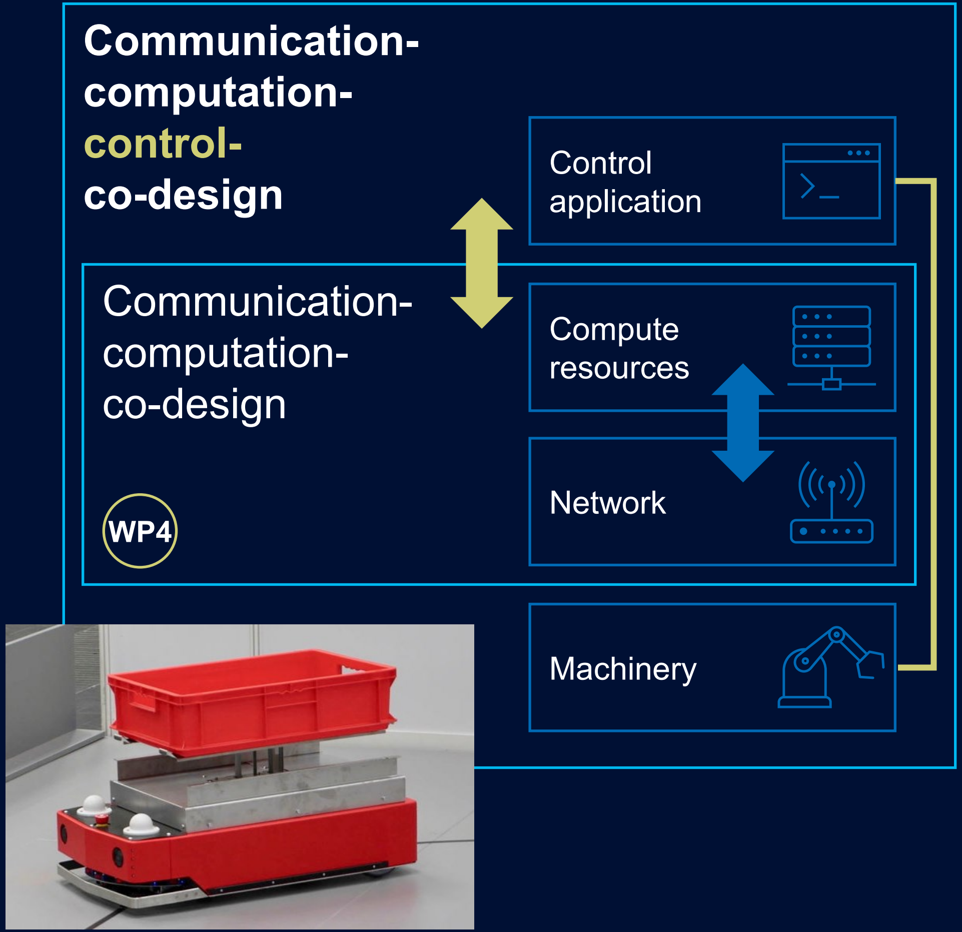
(c) $p_{\text{loss}} = 10\,\%$, T_{ref}, $K = 3$: With SARA, the average number of channels reduces to $\bar{l} = 1.18$, the determinism is comparable to that of static dual-connectivity, and the agent's dependability increases drastically to MTTF = 74 years.

Acceleration (control value)

→ Only +18% more resources for 2×10^7 application reliability improvement!

Contributions for dependability in I4.0

Communication-Computation-Control-Co-Design framework

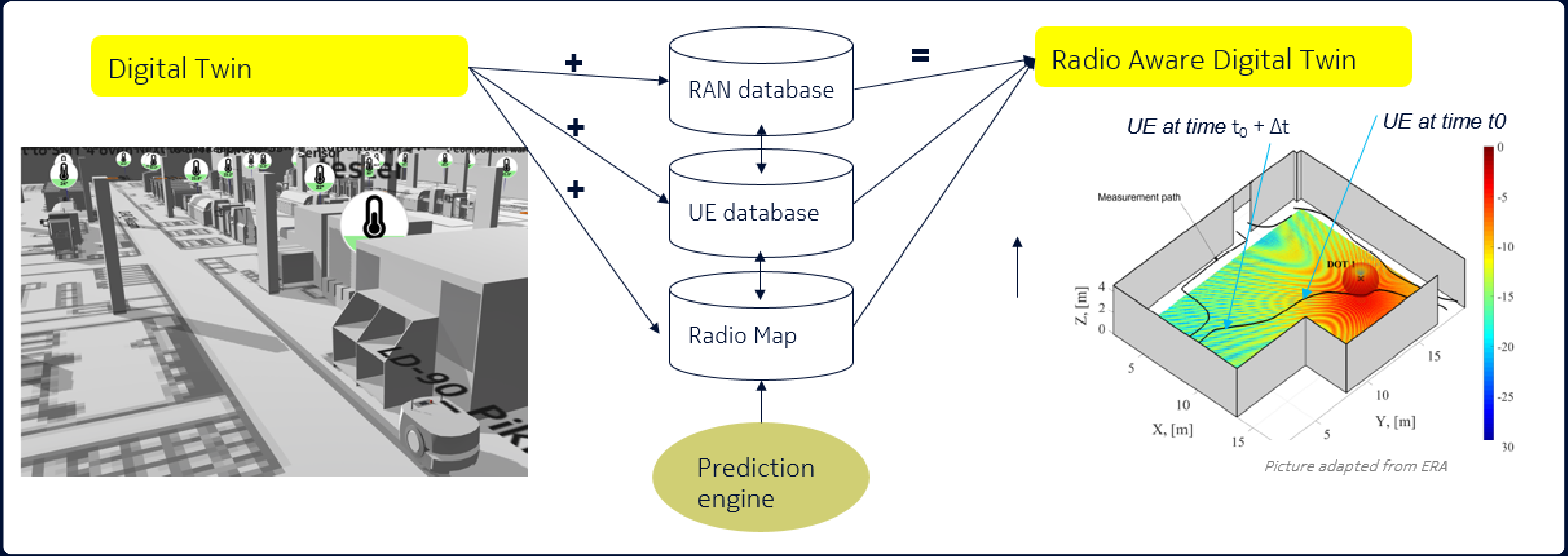


Technical enablers for network dependability in I4.0

- Radio resource management with DTs
- Dependability in UAV-assisted mMTC
- Data and control plane guarantees in programmable industrial networks
- Utilizing network data for AI operations in factory networks

Radio Resource Management with Digital Twin

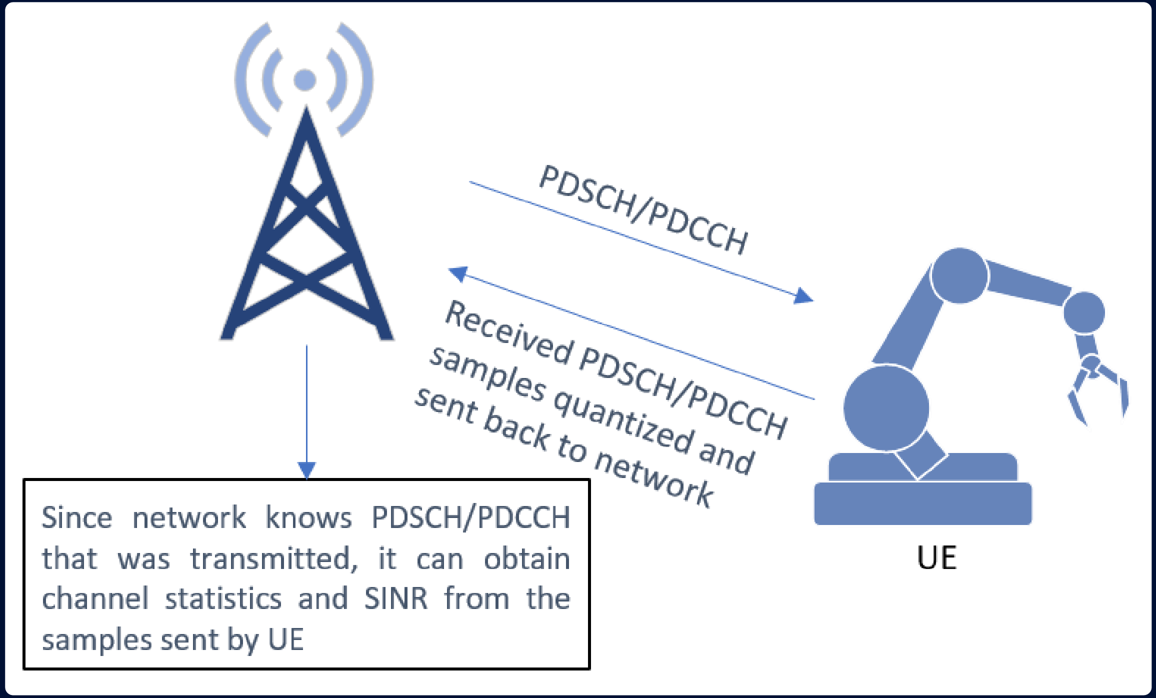
- Controlled factory environment (UE trajectories, UE types, operations)
- Propagation environment and scenario layout is known very well
  - Accurate prediction with ray-tracing, EM and other tools
  - 3D plan of the network and Digital Twin representation of it
- **Enables pro-active, intent-based resource allocation and decision making**



Picture adapted from ERA

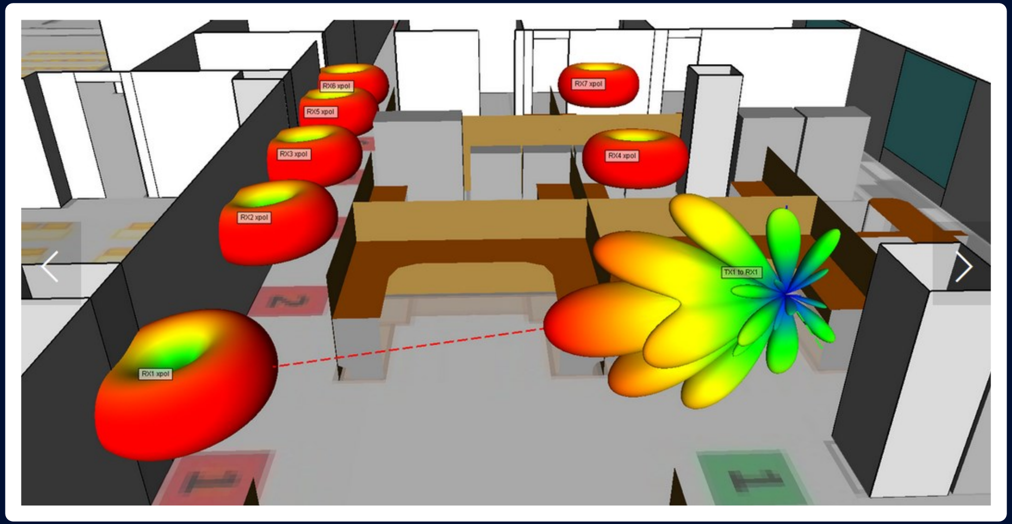
Efficient radio resource map generation for network DT

- ML model of radio environment requires active downlink measurements (overhead)
- **Instead, rely on latency-insensitive samples of DL by UE**
- Given these samples, network estimates the channel as follows
  - Network is aware of the DL signal
  - Network also knows the interfering DL signal (in a controlled environment)
  - Only unknowns are the channel matrices (estimated from the samples by treating the DL data as pilots)
- To further minimize overhead, received symbols are fed back when the network traffic is low



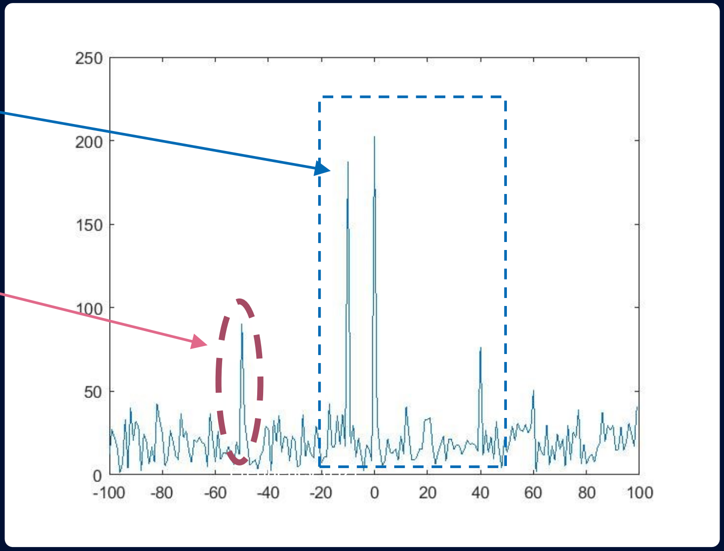
Beam training interval adaption with radio-aware DT

- **Goal: adapt beam training interval to mobility characteristics of environment**
- Addresses UEs where movement is not known/controllable (e.g., human-driven)
- Main idea: Doppler spectrum estimation at the receiver to capture relative movement
  - Receiver estimates the doppler spectrum from channel measurements
  - Radio-aware DT provides receiver with calculated doppler spectrum
  - If estimated and calculated doppler spectrum are same, then beam training interval is set by DT
  - Else, beam training interval set according to the largest unknown doppler frequency



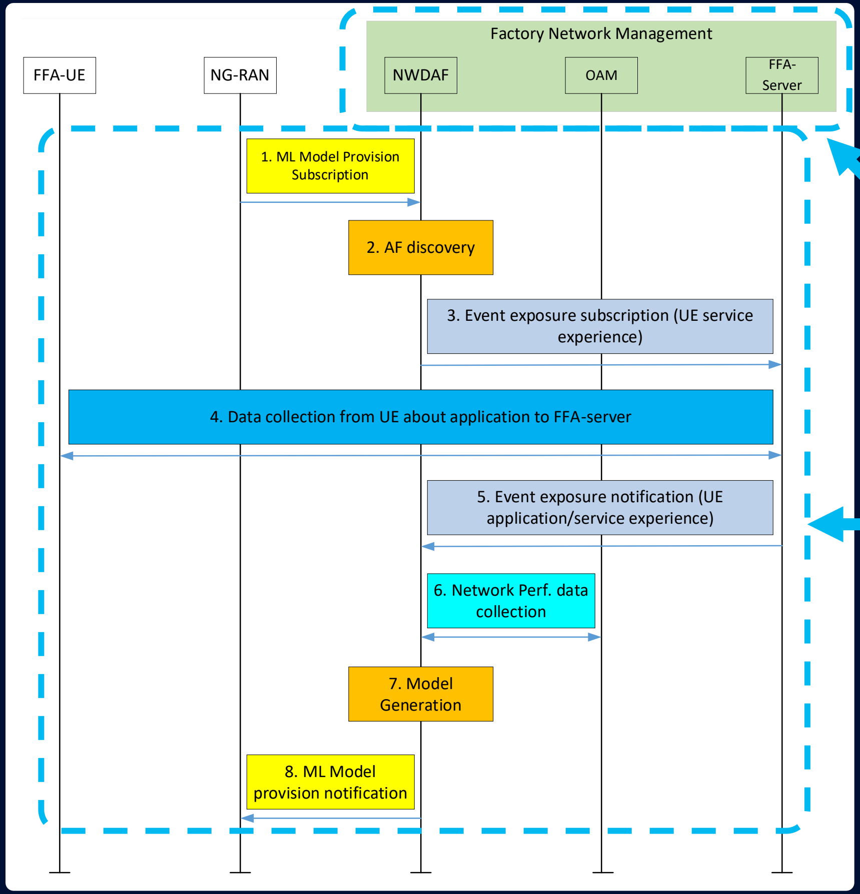
Peaks calculated by DT

Peaks corresponding to unknown object



Network data analytics assisted AI operation

- Unified functional framework for AI enabled 5G radio access network intelligence studied in 3GPP [37.817]
  - Opt-1) AI/ML Model Training in OAM) and AI/ML Model Inference in the gNB
  - Opt-2) AI/ML Model Training and AI/ML Model Inference both in the gNB



Factory NW management system (FNMS) comprised of NWDAF, OAM and future factory application server (FFA-server) can determine and update the AI/ML model configured in NG-RAN nodes.

AI/ML model is used to create analytics data used for joint application and RAN optimization. Proposed signalling procedure enables the information collection from UE and NG-RAN nodes and the delivery of the collected information to NWDAF.

Overview of contributions

Final solutions

- for flexible resource allocation
- for dependability in I4.0
- for HMIs and Digital Twins

Demonstrator
"extreme performance in handling unexpected situations in industrial contexts"

Conclusion

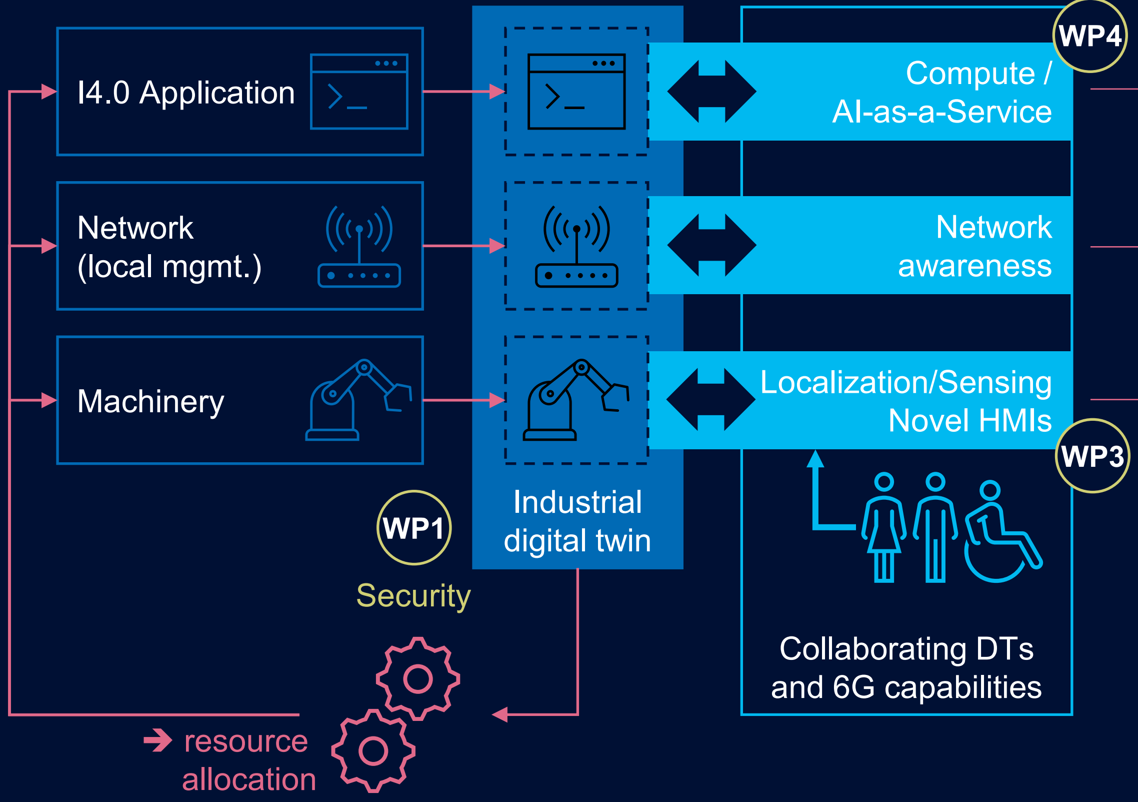
Hexa-X

HMIs and Digital Twins

Final solutions

HMIs and digital twins

Ecosystem of collaborating DTs in human-centric industrial environments

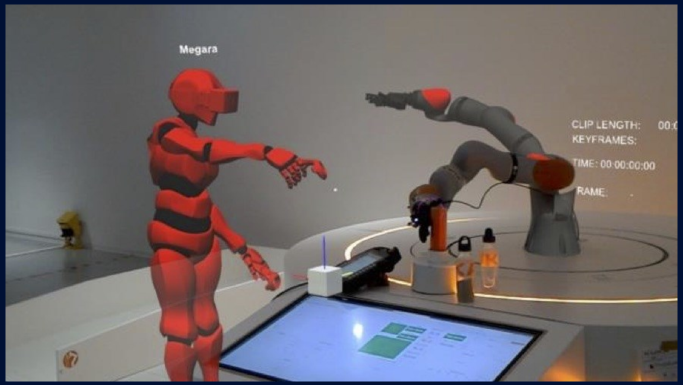


Focus topics

DT empowered collaborative robots
DTs for emergent intelligence

Impact of human presence on industrial deployments
Network-aware DTs for local insights

Novel HMIs for mobile human-machine interaction
Bringing the human in the loop



Applications, requirements, key enablers for novel HMIs

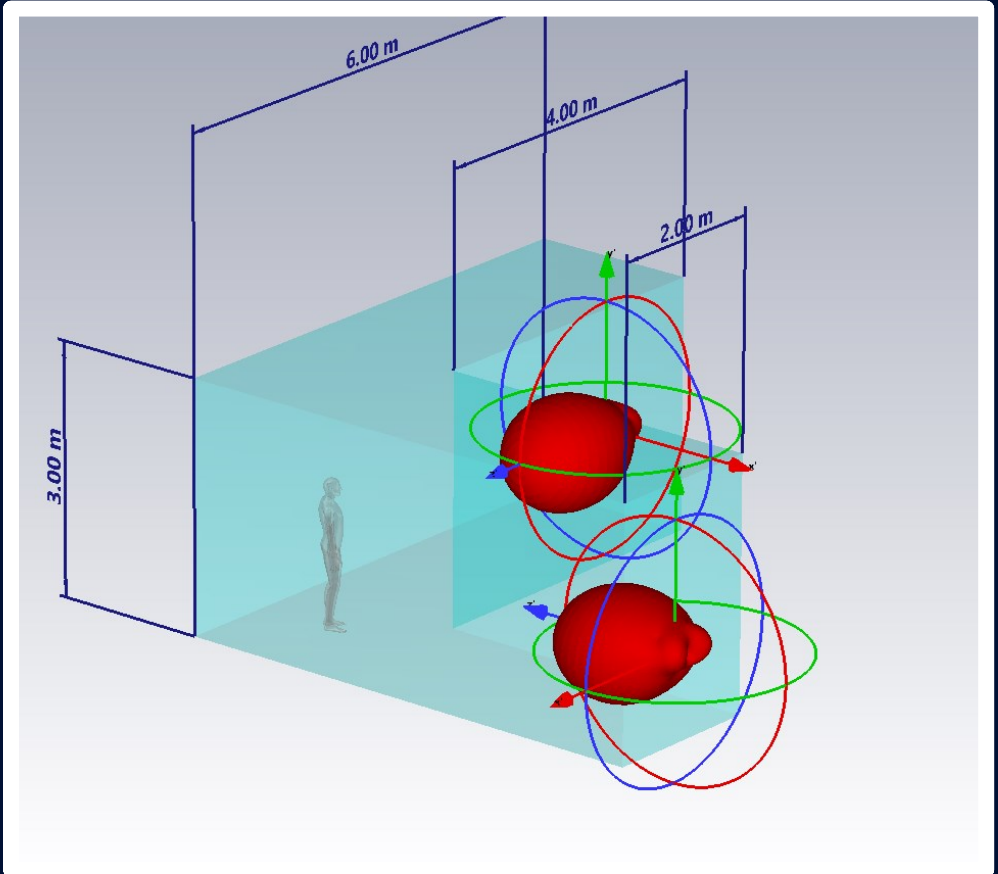
- Novel applications: human-context-aware industry, telepresence collaboration with multi-sensory MR, accompanying DT
- Requirements: safety and health-friendliness, comfort and convenience, dependability, EMC, sustainability, security and privacy
- Key enablers:
  - Sensing mental status: speech voice, facial expression, galvanic skin response, bioelectric signals
  - Multi-sensory feedback: holographic vision, tactile, spinal cord and brain stimulation, synesthesia-based stimulation
- **Case study:** effective perception of feelings triggered by both recorded and synthesized ASMR audios

Perceived Feeling	Average of recorded clips		Average of synthesized clips	
	Mean score	Deviation	Mean score	Deviation
Negative[1]	1.6244	0.7302	1.5827	0.6353
Positive[1]	1.5527	0.9109	1.2521	0.3605
Relaxed[1]	1.6489	0.9953	1.3924	0.5093
Attentive[1]	2.4112	1.6582	2.0072	1.1980
ASMR experience[2]	0.6552	0.7727	0.5093	0.6232

1: graded into one of five levels, from 1 (not at all) to 5 (extremely)
2: graded into one of three levels:0 (no), 1 (almost), or 2 (yes)

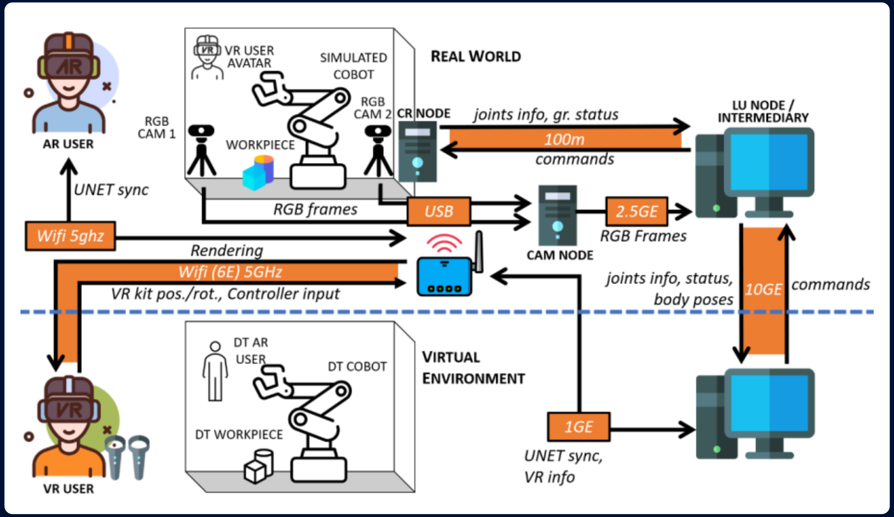
Modelling human presence in a network DT

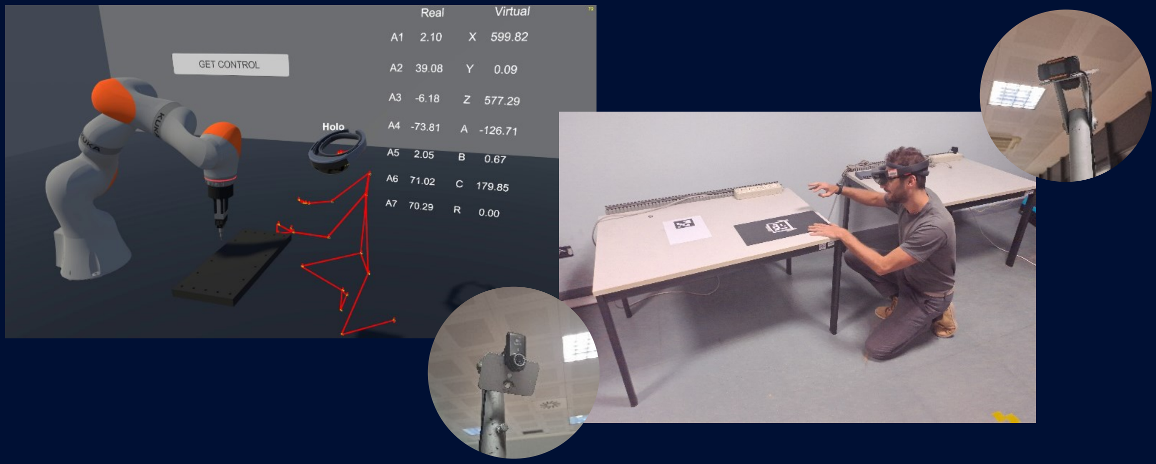
- Goal: cater for the uncontrollable influence of human presence on the DT
- Approach: Utilize geometrical optics (ray tracing) and physical optics solvers for modelling impact of humans on propagation environment
  - Human tissue modelled as perfect electric conductor
  - Human body as an empty shell
  - Simplifications valid at mmWave frequencies
- Results from simulation study
  - Difference in pathloss (order of a few dBs) with human presence and absence
  - Pathloss changes with orientation of human
  - Advanced solvers such as physical optics required to capture all paths
  - Human presence in NLoS needs to be modelled

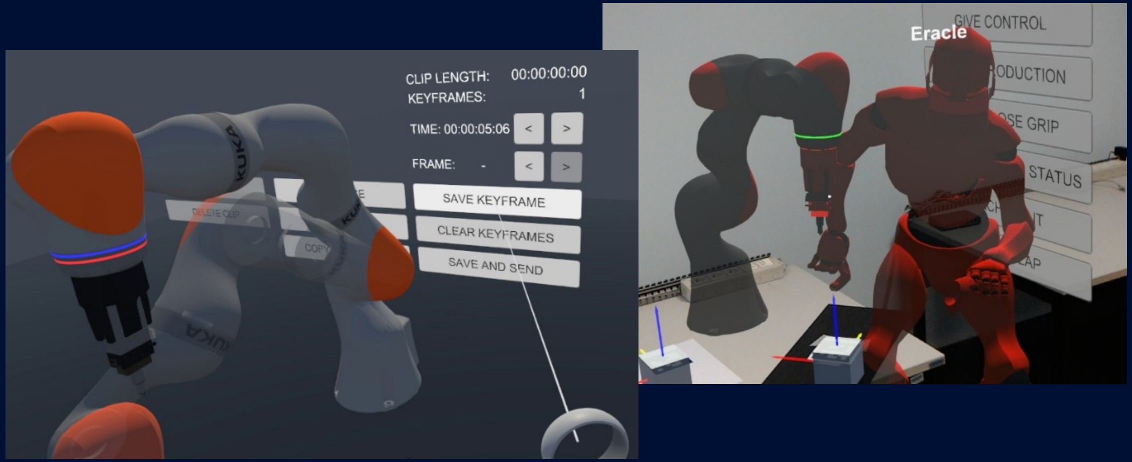


DT-empowered collaborative robots (cobots)

- Analysis on support of remote programming of a cobot featuring DT- and eXtended Reality (XR)-based tele-presence capabilities in 6G
- **Scenario: local user has no experience with cobot, remote user teaches via XR platform**
  - Supporting new CV- and AI-based functionalities (human-pose estimation and workpiece tracking)
  - Built on laboratory setup from D7.2



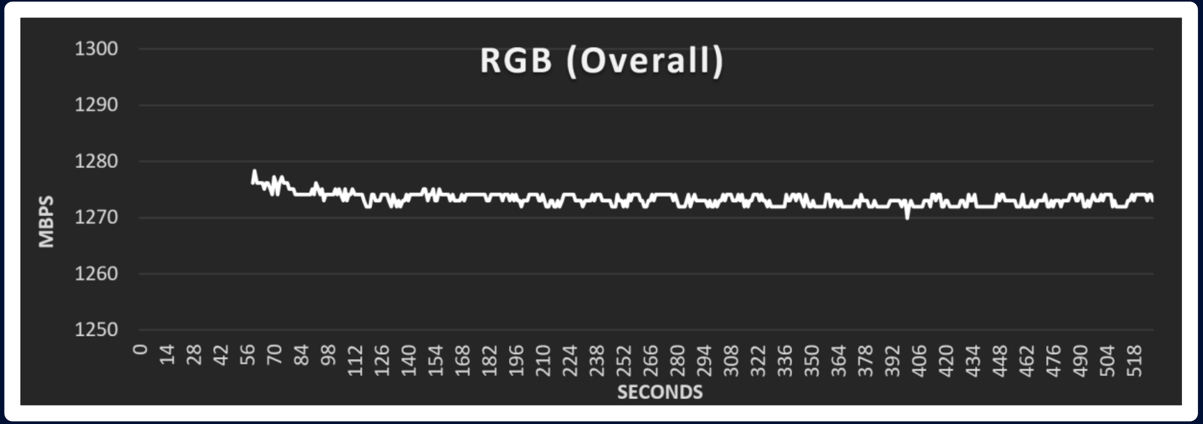




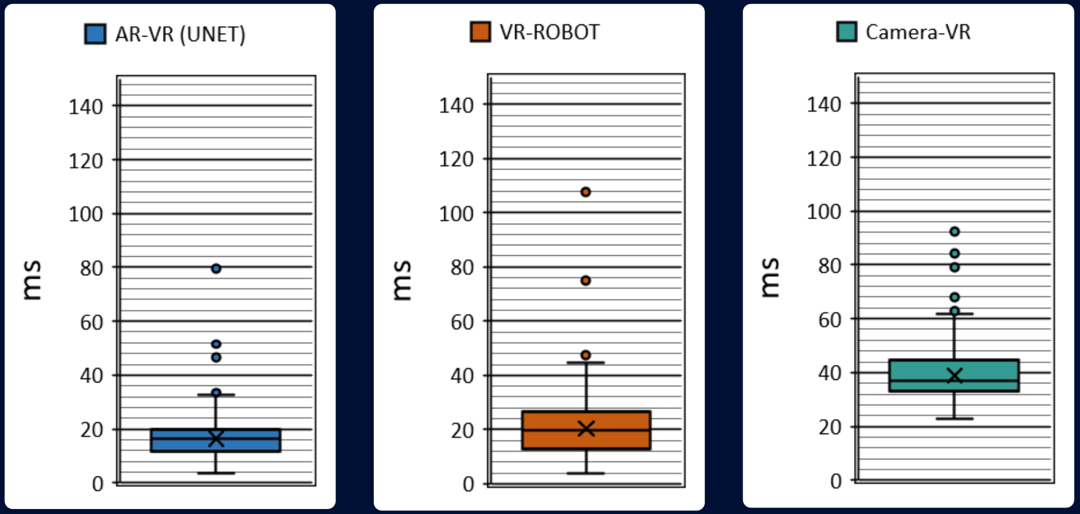
DT-empowered collaborative robots (cobots)

- **Bandwidth:** current 5G mobile networks cannot completely support the use case
  - Main limitation: required bandwidth
  - Exceeding the peak bandwidth of today's real-world 5G networks (1Gbps)
  - Way below the minimum for the considered setup (1.23Gbps for the sole RGB data)

- **Latency:** performance of 5G is sufficient



Message bandwidth for the ZMQ network layer (LU-RU), considering only the RGB data streaming



Utilize DTs to assist in functional split adaptation

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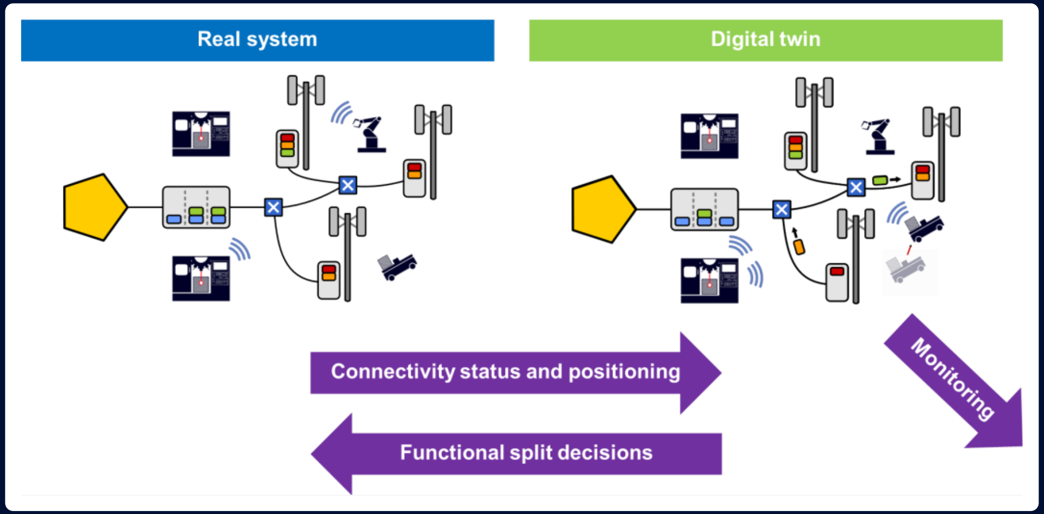
Goal: develop a DT of the RAN

- Activity of fixed stations, AGVs, and current state of the functional split for base stations
- Real system provides up-to-date information about the instantaneous state of the network

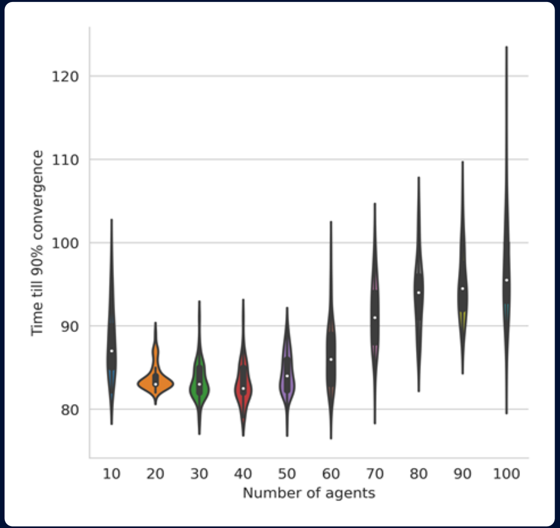
DT decides on the functional split adaptation

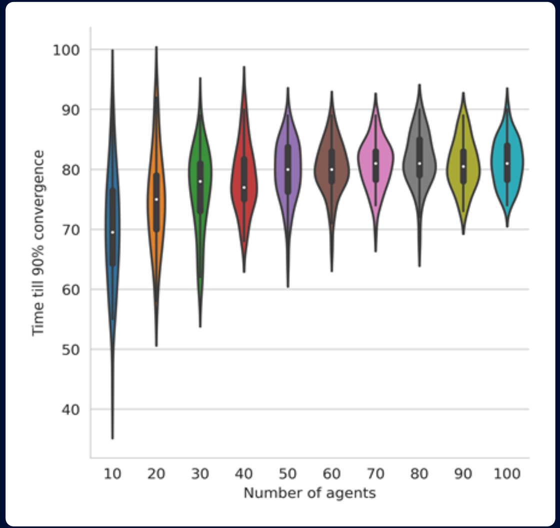
- When network capacity or computational constraints may be violated
- When there is a better valid state
- To assist in decision-making, consider:
  - Cost of deploying an adaptive network
  - Cost of operating the network and those of a possibly better state
  - Cost or risk of changing the functional split
  - Cost or risk of erring the positioning/activity prediction, adapting too late, failing to adapt, or otherwise producing an undesired effect



DTs for emergent intelligence (EI)

- EI as a potential-rich approach to decentralized intelligence in 6G
- **Expectation: DT can further improve the performance of EI by means of**
  - Reducing the communication load in information exchange among agents
  - Protecting the system from data-injection attacks with trust-awareness
- **Evaluation with a PSO-based multi-UAV localization use case**
  - DT-gain in communication efficiency evaluated regarding number of agents
  - Security risk caused by data-injection attack assessed
  - Trust-aware PSO to countermeasure this risk, trust information well supported by the DT framework





Convergence of the PSO algorithm with (left) and without (right) DT

Demonstrator

Extreme performance in handling unexpected situations in industrial contexts

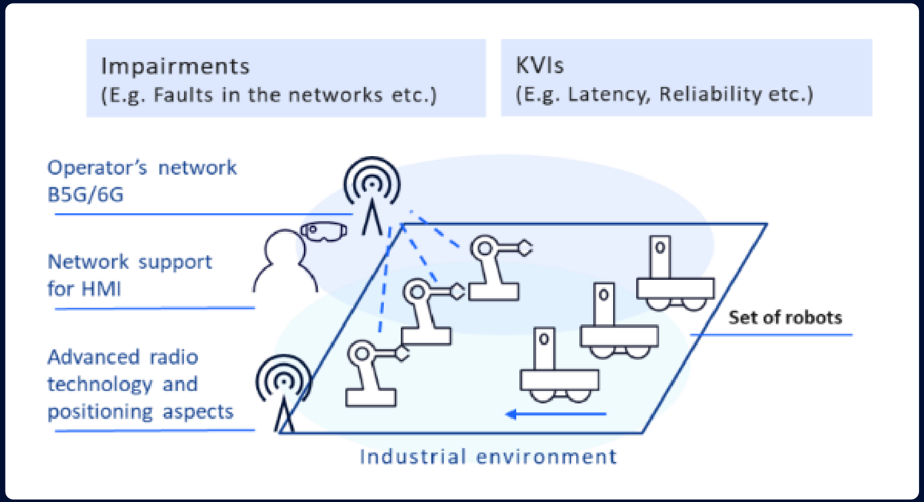
Problem description

Ensure dependability in industrial environments by handling unexpected situations involving

- Monitoring and identifying key parameters e.g., latency, throughput, application-layer indicators
- Infrastructure and mechanisms for emulating impairments
- The infrastructure has a set of collaborative cobots, cooperating on a task, and B5G/6G connectivity
- Impairments are faults in the network, robotic devices, or functionality

Several cases are shown

- Using advanced network infrastructures for mitigating impact of a faulty device by redistributing functionality and roles
- Using B5G/6G to deliver high rate, low latency, and reliability supporting HMI
- Using advanced radio and positioning to address impairments



Challenges

- Collaborative Robots
- Massive twinning application in industrial environments
- Impairments
- Automated redistribution of functionality to non-faulty AGVs
- Enabling “Human In The Loop”, e.g., for repairs, through advanced Human Machine Interfaces (HMI)

Demo scenarios

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Scenario 1: Unified orchestration across the Cloud - Extreme edge continuum

- Exploits the benefits of B5G/6G on performance and efficiency of production lines with the utilisation of a unified orchestration process which provides automation, reconfigurability and reduces human interventions.
- Digital twin, VR application, HMI, and teleoperation allowing human-in-the-loop activities was developed

Scenario 2: Functionality Allocation

- Studies and demonstrate the fast and close to optimum management and redistribution of functionality in an automated way.
- Functionality allocation and AI/ML based anomaly detection and performance degradation analysis are the key components
- Of great importance in the case of an unexpected situation, a problem in the flow of industrial production

Scenario 3: Predictive orchestration and maintenance

- Aims to anticipate situations and predict the behaviour of services and the various components of the production cycle, with the use of AI/ML enablers
- Use of monitoring data from selected services or components, predictive models are trained to be able to identify accurately upcoming critical events

System components

Monitoring

- Monitoring as a Service (MaaS) platform developed by NOF (WP6)

Performance diagnosis

- Detects anomalies and can identify the root cause of possible problems

Predictive Orchestration (WP6)

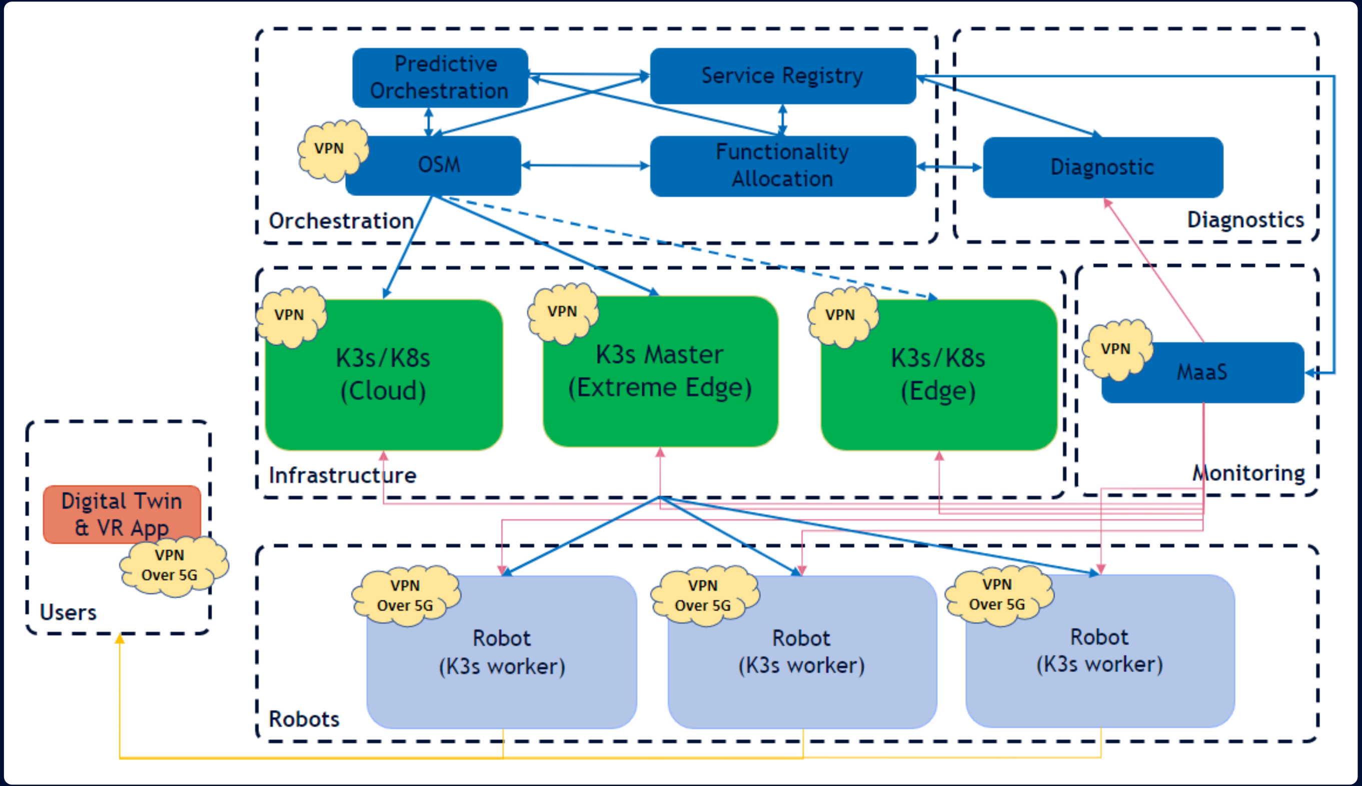
- Predicts the behaviour and performance of monitored services and nodes across the infrastructure
- AI/ML model for time series forecasting

Service Registry

- Python Flask API that stores and updates services and resource pools from a MongoDB database.

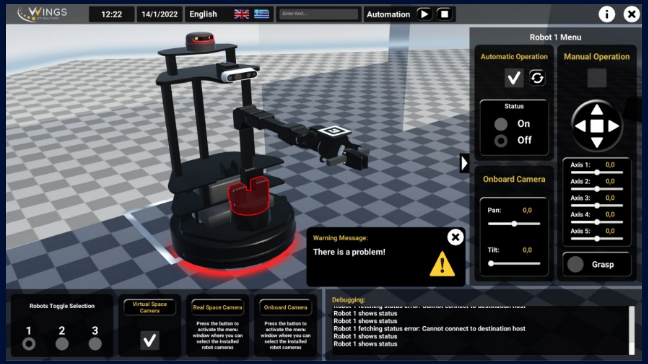
Functionality allocation

- Metaheuristic optimisation placement algorithm



Summary of demonstrator results

- Seamless reallocation of functionality among cobots, along with ability to measure the real energy consumption needs for the various robot roles and the system as a whole, enables effective design of the system, considering the various energy consumption – operation cycles trade-offs.
- System continues to operate, with a higher fatigue / energy consumption for the devices that remain in operation
- Measurements around the energy consumption confirm initial expectations
- **More detailed findings and measurements described in D7.3**



Error outline popup to digital twin's user interface.

Digital twin interface showing the moment a product is exchanged between two robots.

The VR application interface with the user wearing the VR headset utilised.

Conclusion

Conclusion

Hexa-X

- Final deliverable of WP7, contributing to the **network evolution and expansion towards 6G**
- Applicability of Hexa-X key enablers (functionality and architecture) to use cases for increased dependability and sustainable coverage
- Addressing Hexa-X KPIs and KVIs
- Key aspects and contributions showcased in demonstrator

Thank you!

HEXA-X.EU

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