



HEXA-X-II

First Insights from the Hexa-X-II PoC activities



6G SNS



Co-funded by
the European Union

EUCNC | 6G Summit
Antwerp, Belgium • 3-6 June 2024

Preamble - PoC work in a nutshell



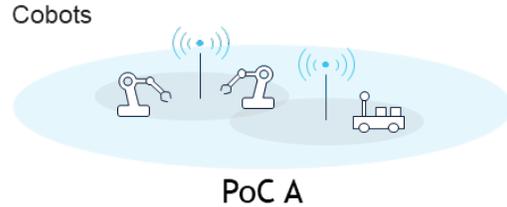
1. **Goal**: Early glance of 6G capabilities in terms of functional and performance (non-functional) aspects
2. Support **applications**: enrich with **cobots**, **massive twinning**, **XR**, secure spaces
3. Show benefits from enhanced **functional** capabilities:
 - **Exposure** functions: infrastructure, data aspects, domains
 - Infrastructure: Networks **beyond Communications**, "**Compute as a Service**", On the need for "**AI as a Service**", data insights, localization / **sensing** information
 - Management: Intent; Management & Orchestration (**M&O**): flexibility, full continuum, from far-edge devices to secure core servers, multi-domain
4. **Performance** aspects:
 - In particular cases: need for extreme performance: video, real-time video analytics, command and control
 - E.g., order of hundreds of Gbps per "cell", lowest possible RTT to enable remote control of devices at the cm level, reliability
5. **Social** impact: economic, environmental, social
6. Key **messages** / outcome: wealth of capabilities, "more than the sum of its parts"

System-PoCs outline



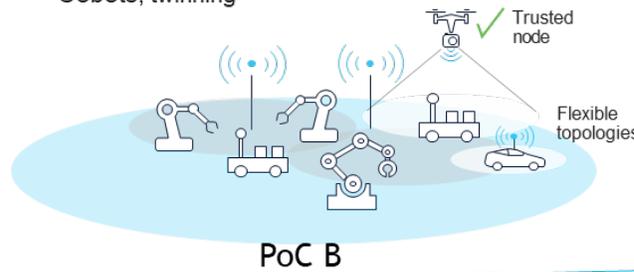
Sustainability Aspects	Social	Environmental	Economic
	Trustworthiness; Time related KPIs	Energy efficiency / Power consumption	Resilience / limited downtime; OPEX

Key enablers	Management and orchestration	Diagnostics intent
	Network architecture and transformation Trustworthy flexible topologies, Beyond communications	
	6G device components	6G radio aspects



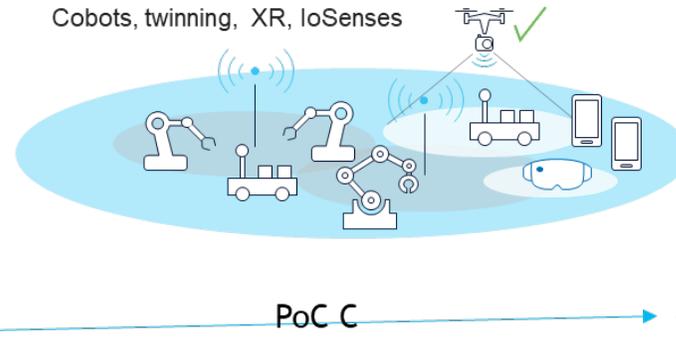
Social	Environmental	Economic
Trustworthiness; Exposure, security / privacy; Digital inclusion	Energy efficiency / Power consumption	Resilience / Limited downtime; OPEX; CAPEX
Management and orchestration	Diagnostics intent	
Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
6G device components	6G radio aspects	

Cobots, twinning



Social	Environmental	Economic
Trustworthiness; Exposure, security / privacy; Digital inclusion	Energy efficient radio, zero-energy devices	Resilience / Limited downtime; OPEX; CAPEX
Management and orchestration	Diagnostics intent	
Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
6G device components	6G radio aspects	

Cobots, twinning, XR, IoSenses



6G

Plan:

- **Three waves.** Currently in PoC B (PoC A laid a foundation, PoC B evolves and introduces new features, PoC C will evolve the previous two)
- In each wave: gradual addition of **technical** enablers. M&O, network enablers (flexible technologies, beyond coms), radio aspects, with respective KPIs
- Gradual placement of focus to additional **sustainability** (societal) aspects. **Environmental**, also **social** (Trust, Inclusion), accompanied by **economic**, with certain indicators

Gradual addition

System-PoCs / Scenarios



PoC A: Baseline Scenario 1 single-domain

Leveraging Hexa-X PoC introducing new features towards trustworthiness.

Use Case

- **Cooperating Mobile Robots**
 - Cobot-powered warehouse operations, towards inventory management

Enablers

- Management &Orchestration (Pervasive Functionality)
 - Trust aspects
 - AI-driven assessment for participating resources: performance, reliability, capabilities, vendor, ...
 - Sustainable AI-control
 - AI for Functionality allocation towards energy efficiency

Sustainability Aspects

- Social: trustworthiness
 - Time related KPIs (handling event)
- Environment: Energy
 - Power consumption
- Economic: financial (resilience, limited downtime), OPEX (energy)

PoC B: Scenario 2: multi-domain aspects

Use Cases

- **Cooperating Mobile Robots**
- **Human centric services** (Public safety services, Safe environments)

Enablers

- Pervasive technologies
 - Intent-driven multi-criteria role selection
 - M&O: Enhanced trust-/energy-driven functionality allocation supporting physical robotic task planning
 - M&O: Cross-domain synergetic monitoring & orchestration
- Network functions
 - Trustworthy flexible topologies
 - Network beyond communications: compute resources, exposure

Sustainability Aspects

- Economic: Intelligence / automation in complex tasks, time to handle (also unexpected situations), CAPEX aspects;
- Environment: Energy/Power consumption
- Social: Trust, Digital inclusion, Security / privacy.

PoC C (To be elaborated): Scenario 3 Intent-driven, multi-domain

Use Cases

- **Cooperating Mobile Robots**
- **Human centric services** (Public safety services, Safe environments)

Enablers

- Evolved Management & Orchestration (Pervasive functionality)
- Evolved Trustworthy flexible topologies
- Evolved Network beyond communications: Exposure, compute, sensing
- 6G Device components
- 6G Radio aspects
- Intent-Based Network aspects
- Cobots, XR, Twinning Sensing

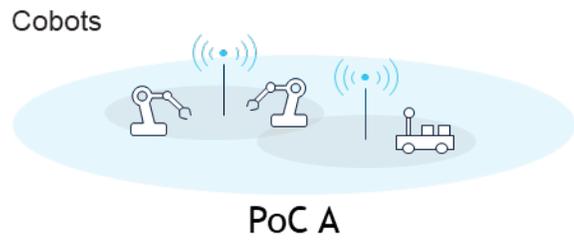
Sustainability Aspects

- Social: trustworthiness: Time to handle; Data exposure security, privacy mechanisms; Digital inclusion
- Environment: Energy/Power consumption; Dynamic replanning of available device roles
- Economic: OPEX; CAPEX

System-PoC A



Sustainability Aspects	Social	Environmental	Economic
	Trustworthiness; Time related KPIs	Energy efficiency / Power consumption	Resilience / limited downtime; OPEX
Key enablers	Management and orchestration		Diagnostics intent
	Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
	6G device components		6G radio aspects



PoC A: Baseline Scenario 1 single-domain

Leveraging Hexa-X PoC introducing new features towards trustworthiness.

Use Case

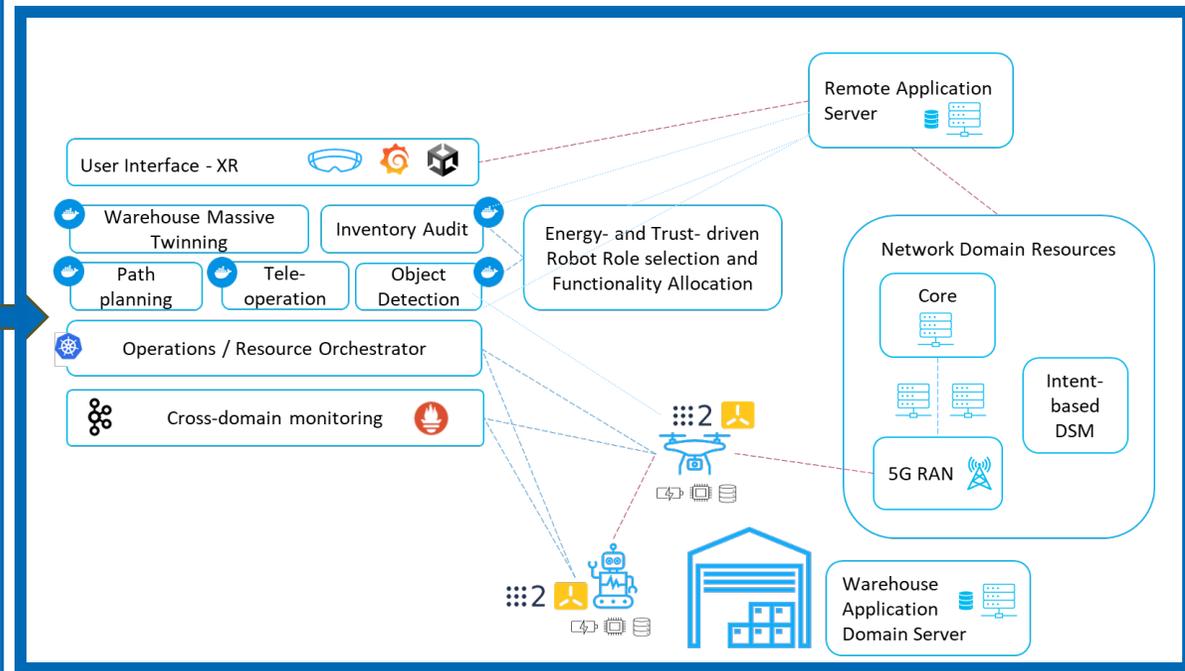
- Cooperating Mobile Robots**
 - Cobot-powered warehouse operations, towards inventory management

Enablers

- Management & Orchestration (Pervasive Functionality)**
 - Trust aspects
 - AI-driven assessment for participating resources: performance, reliability, capabilities, vendor, ...
 - Sustainable AI-control
 - AI for Functionality allocation towards energy efficiency

Sustainability Aspects

- Social:** trustworthiness
 - Time related KPIs (handling event)
- Environment:** Energy
 - Power consumption
- Economic:** financial (resilience, limited downtime), OPEX (energy)

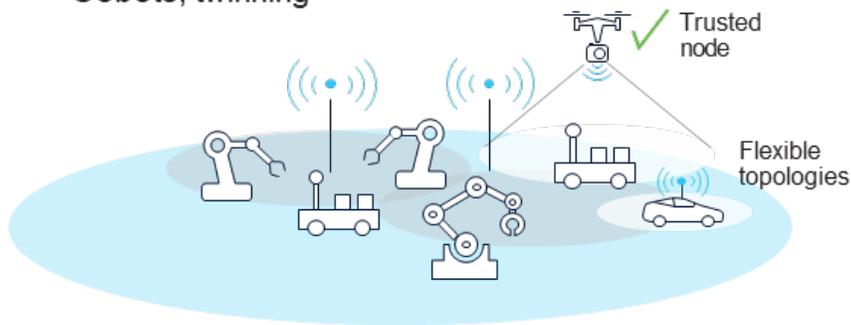


System-PoC B and Component-PoC #B.3 main elements



Social	Environmental	Economic
Trustworthiness; Exposure, security / privacy; Digital inclusion	Energy efficiency / Power consumption	Resilience / Limited downtime; OPEX; CAPEX
Management and orchestration	Diagnostics intent	
Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
6G device components	6G radio aspects	

Cobots, twinning



- **Application: Inventory audit**
 - **Swarms of devices (AMRs, UAVs)**
- **Advanced M&O leveraging**
 - **Intent:** end user-oriented high-level commands
 - Semantic definition of warehouse zones of interest (corridors, shelves) to be inspected
 - Max performance / minimum Time *OR* minimum resource consumption
 - Dynamic planning of node roles / function allocation
 - Diagnostics features: observability, diverse resources monitoring (network, compute H/W, battery, robotic modules, etc.),
- **Network beyond communications**
 - Exposure of network beyond communication capabilities
 - Compute resources
 - Flexible topology formulation upon service disruption via UAV-powered nodes with communication and compute capabilities



Application

1. **Intent:** Conduct inventory in site X, transfer production to site Y
2. **Swarm planning**
 - Role allocation: area to cover, functions
3. **Swarm management**
 - Centralized and Distributed control
4. **Inventory realization**
 - Computer vision, Video analytics
5. **End task**, return to "initial" position

Note: Component PoCs complement application capabilities

Infrastructure exhibits

1. **Intent mechanisms:** Trigger for infrastructure management, multi-domain / cross-layer aspects
2. **M&O:** Enforce decisions
3. **Networks beyond communications involvement:** compute as a service, AI as a Service, Localization, Sensing.
4. **Flexible topologies:** support for application task.
5. **Extreme performance:** volume, latency, dependability

Note: component PoCs enhance the capabilities

Elements



Application

1. Intents

**2. Swarm
planning**

**3. Swarm
management**

**4. Inventory
realization**

**5. End
task**

Infrastructure Exhibits

**1. Intent-driven
triggers**

**2. M&O / Decision
enforcement**

**3. Network beyond
communications**

**4. Flexible
topologies**

**5. Extreme
performance**

Evaluation axes



6G Performance requirements

- **Extreme connectivity:** bitrate, latency, reliability, jitter, coverage
- **Flexible connectivity:** flexible selection of communication resources, reduced connectivity set-up times, compute capabilities at the extreme edge
- **Multi-domain, synergetic monitoring and orchestration** capabilities: resource optimisation, reduced service migration times leveraging predictive and intent-based features

Sustainability Aspects

- **Social:** Trustworthiness; Ability to handle unexpected situations; Time to handle; Data exposure security, privacy mechanisms; Digital inclusion
- **Environmental:** Energy/Power consumption; Dynamic replanning of available device roles; functionality allocation based on availability of renewable energy/energy grade
- **Economic:** Resilience, reduced downtime, OPEX (energy), CAPEX (infrastructure needs reduction via flexible topologies)

Evaluation: AI-powered Functionality Allocation optimisation



System-PoC A & B current KPIs measured

Execution time of FA algorithm for allocating the workloads to devices

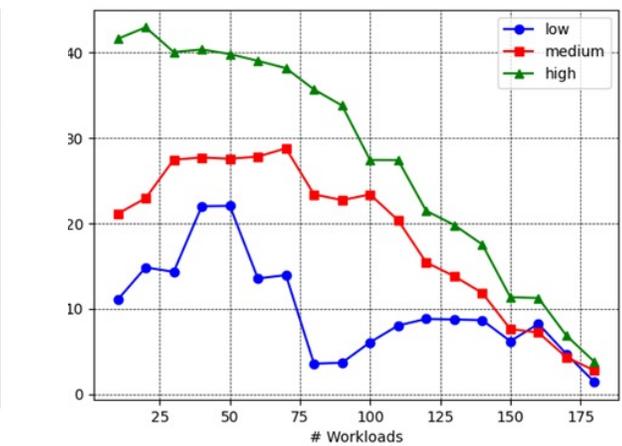
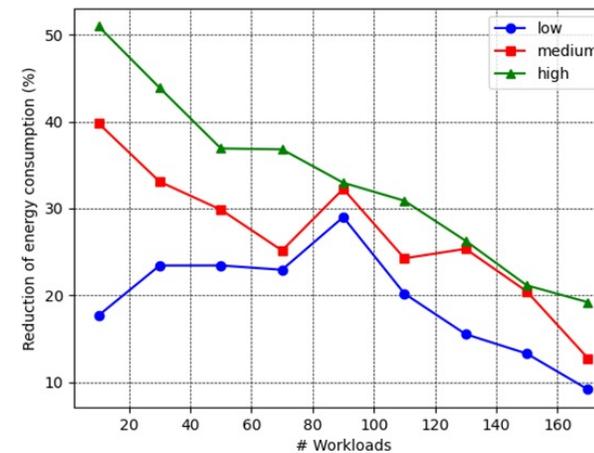
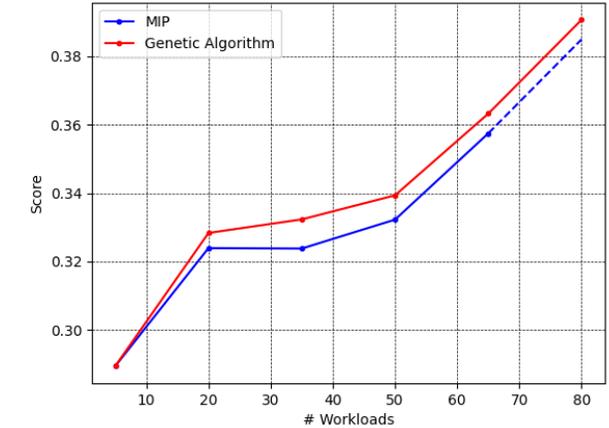
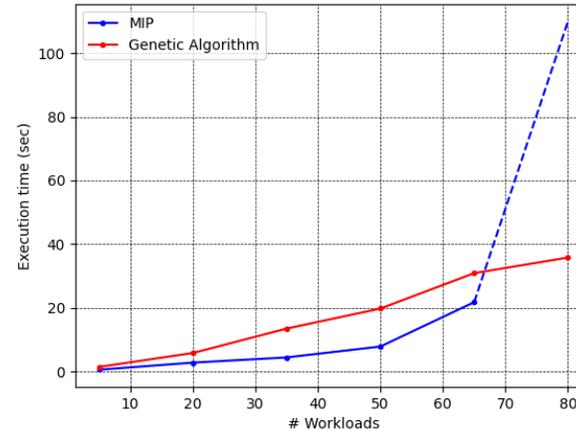
Linear growth (compared to the nearly exponential growth of the optimal mixed-integer programming algorithm)

Energy consumption gains of FA algorithm (Genetic algorithm capabilities)

Up to **50%**

Trustworthiness (Quantified) of FA algorithm (Genetic algorithm capabilities)

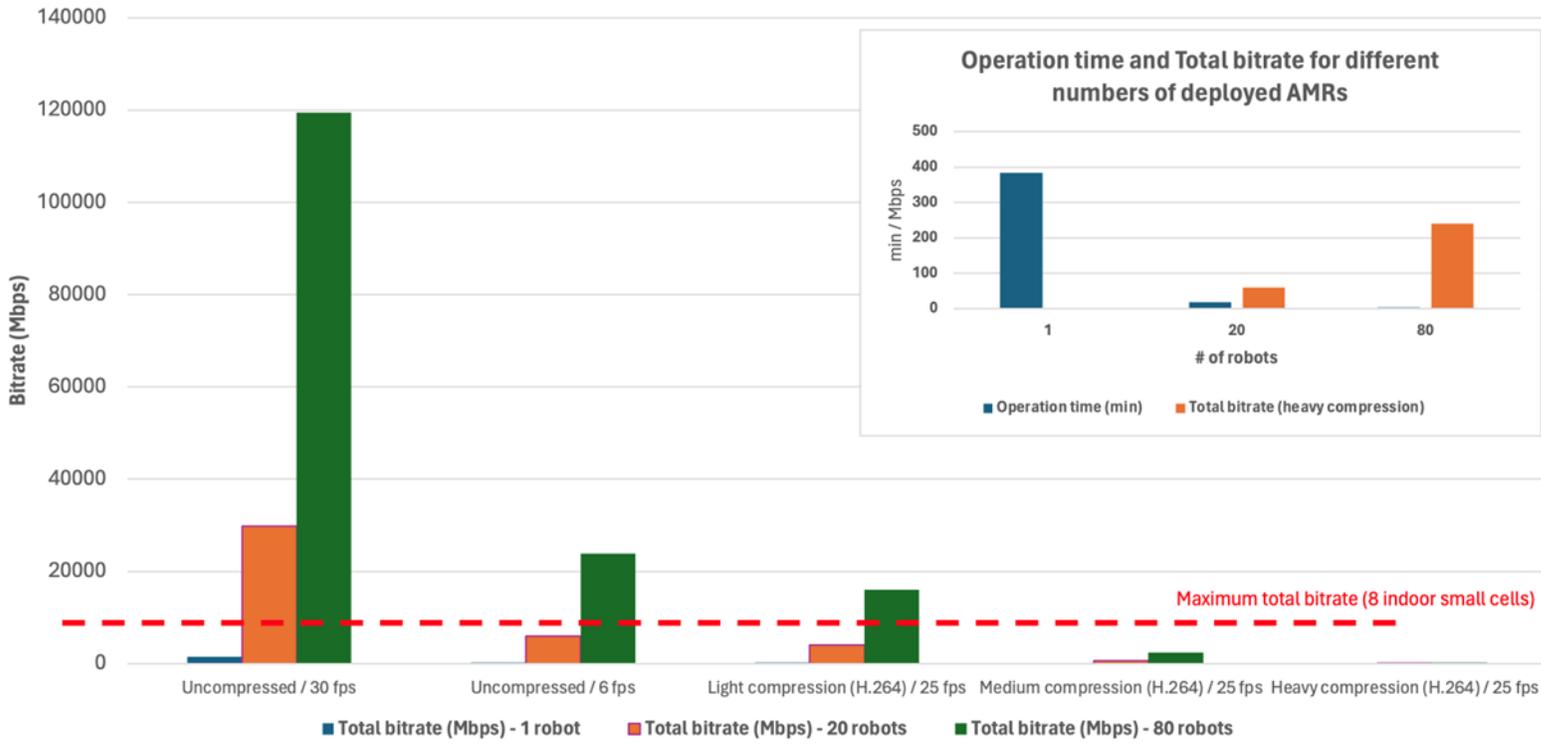
Up to **45%**



Non-functional aspects



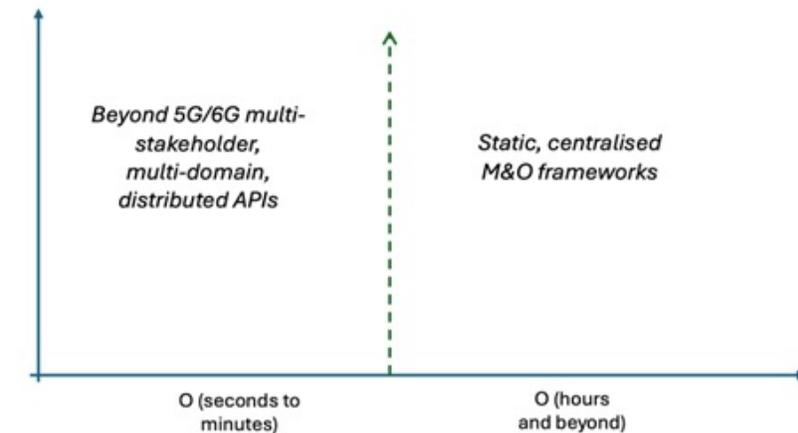
Total bitrate requirements for different robot swarm / video configuration scenarios



Warehouse equipped with indoor small cells (assuming ~20m range, 100 MHz bandwidth, at least 8 indoor cells with max. 1Gbps of bitrate are assumed)

Configuration	Total bitrate (Mbps)		
	1 robot	20 robots	80 robots
Uncompressed / 30 fps	1493	29860	119440
Uncompressed / 6 fps	299	5980	23920
Light compression (H.264) / 25 fps	200	4000	16000
Medium compression (H.264) / 25 fps	30	600	2400
Heavy compression (H.264) / 25 fps	3	60	240

of exposed M&O domains capabilities, distributed APIs



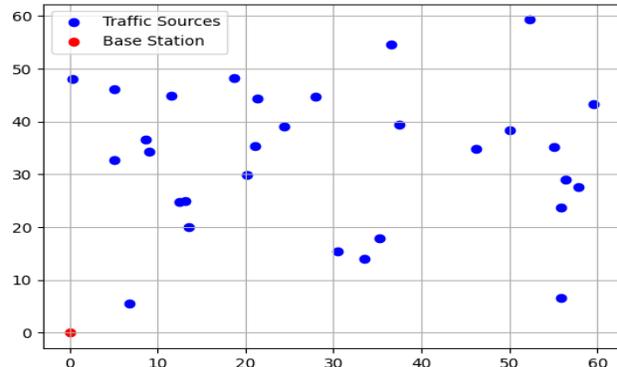
Trustworthy Flexible Topologies



Flexible topology instantiation

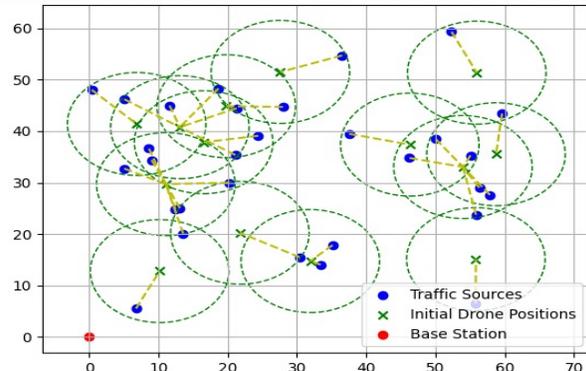
A. Isometric Grid Integration

Traffic Sources and Base Station



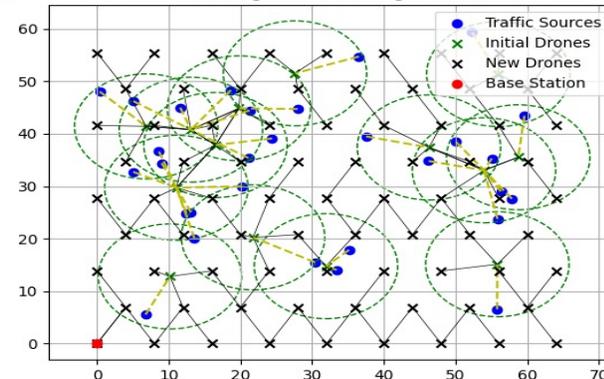
B. Minimum Spanning Tree (MST)

Initial Drone Positions, Radii, and Their Connections to Traffic Source



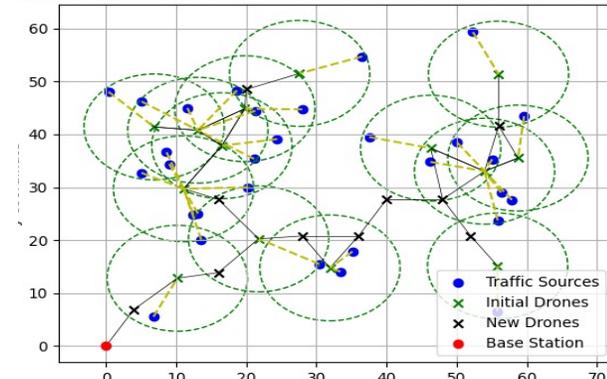
C. Pruning

MST Before Pruning and Removing Redundant Drones

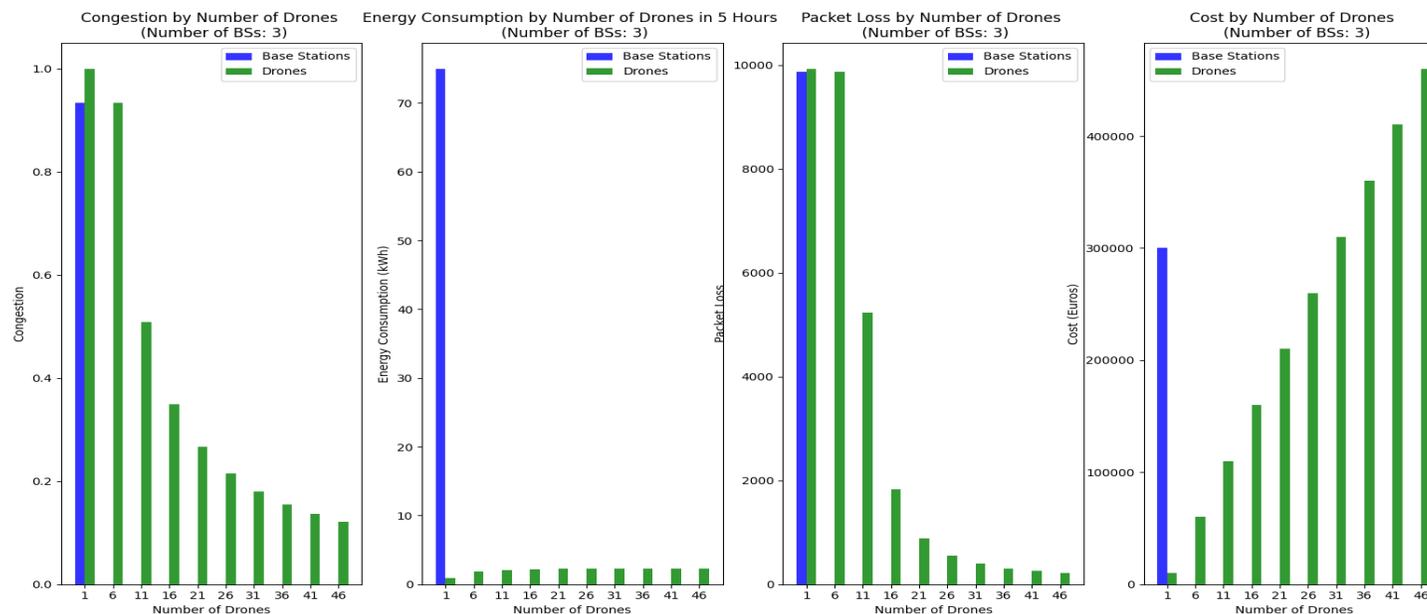


D. Redundancy Elimination

Final Optimized MST after Pruning and Removing Redundant Drones



Influence on various KPIs/KVIs



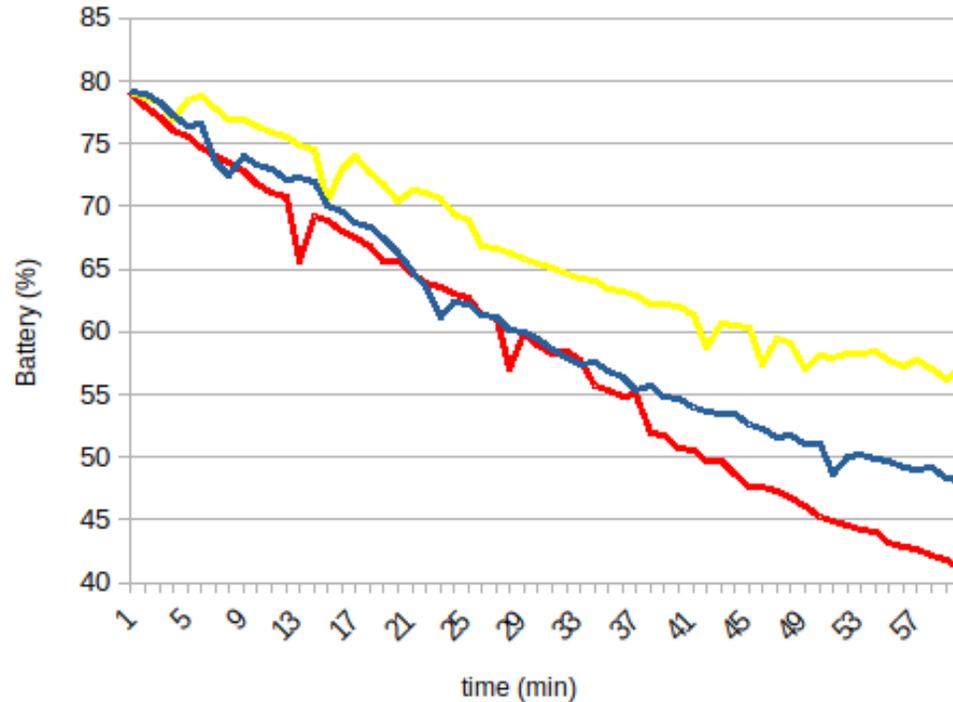
Power Consumption comparison On-device vs Edge Computing Setup



Enhanced Battery Efficiency and Operational Time Extension:

Offloading computational tasks leveraging edge resources reduces device battery depletion by approximately 20% over 60 minutes.

Extending the uptimes among the device-specific inventory audit operations minimises the need for inter-robot synchronization.

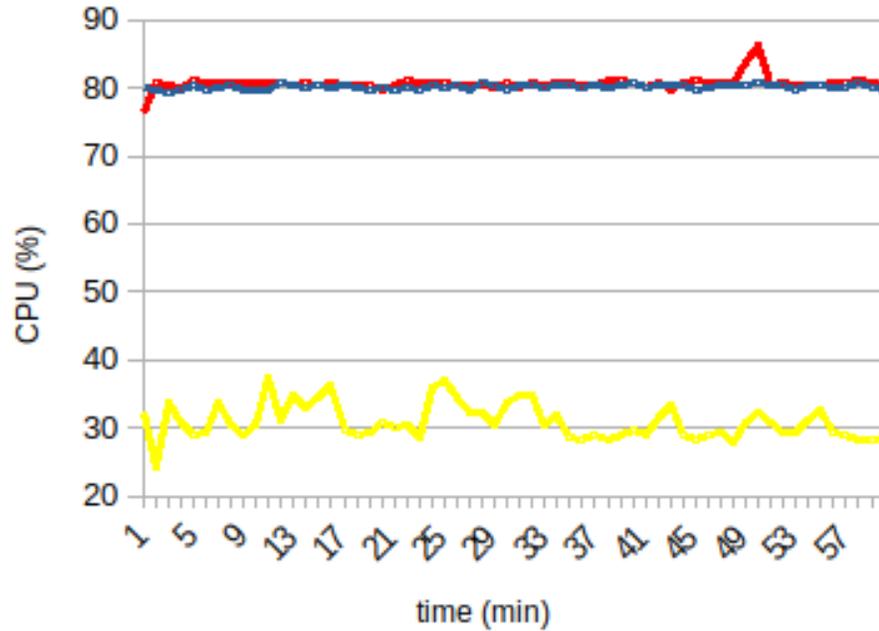


- On-device processing + data transmission
- On-device processing
- Offloading enabled (processing at the edge)

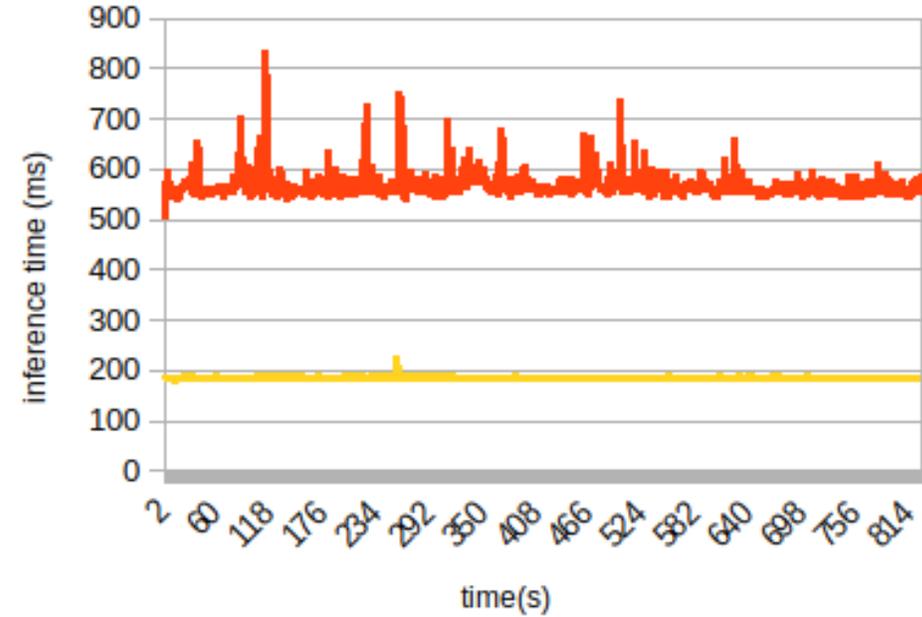
Sustainability Aspects

- **Social:** Trustworthiness; Ability to handle unexpected situations; Time to handle; Data exposure security, privacy mechanisms; Digital inclusion
- **Environmental:** Energy/Power consumption; Dynamic replanning of available device roles; functionality allocation based on availability of renewable energy/energy grade
- **Economic:** Resilience, reduced downtime, OPEX (energy), CAPEX (infrastructure needs reduction via flexible topologies)

Performance Benefits of Offloading Computation via 5G: CPU Utilization and Inference Time Analysis



- On-device processing + data transmission
- On-device processing
- Offloading enabled (processing at the infrastructure / edge)



- On-device inferencing latency
- Edge inferencing time

Evaluation: Application features-induced KPI requirements

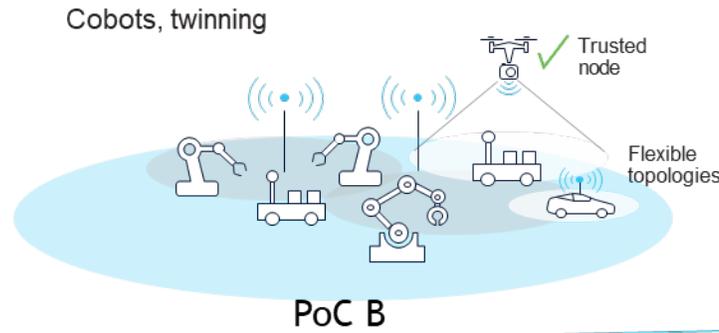
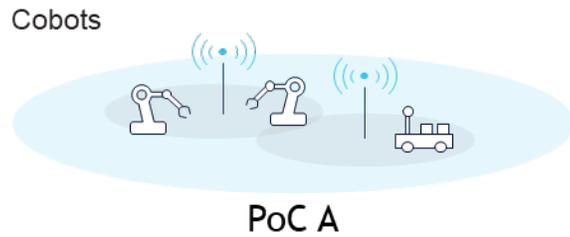
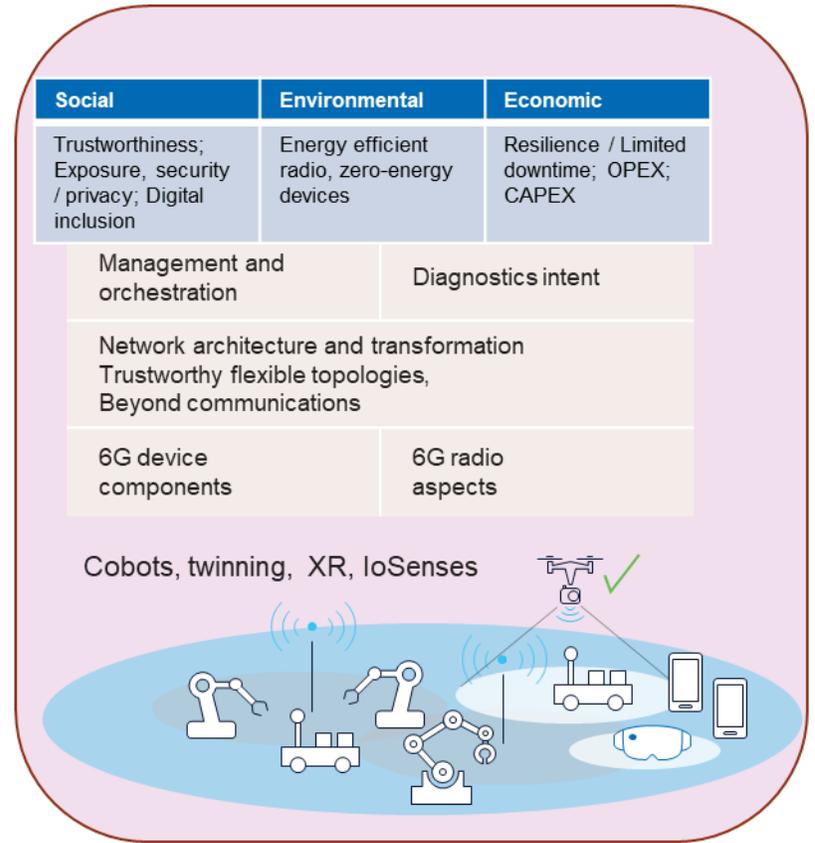
- the communication between the robotic devices, the infrastructure sensing devices (if available) and the edge/remote backend server AFs [UL & DL bitrate, network latency]
- the swarm management operations (processing of exposed data, path planning, navigation) [UL & DL bitrate, latency, processing latency at the edge/remote server]
- robotic platforms' tele-operation features, requiring ultra-low latency between the remote user (tele-operator) and the robotic platforms in the field [UL & DL network latency]
- the computer vision-related operations:
 - the compression of the real-time high-definition video streams [processing on-board (device) latency]
 - the transmission of the (compressed) video streams [UL bitrate, network latency]
 - the processing, inferencing and decision-making operations [processing latency at the edge/remote server]
 - the response (enforcement) back to the robotic devices [DL bitrate, network latency]



Next steps

Sustainability Aspects	Social	Environmental	Economic
	Trustworthiness; Time related KPIs	Energy efficiency / Power consumption	Resilience / limited downtime; OPEX
	Management and orchestration	Diagnostics intent	
	Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
Key enablers	6G device components	6G radio aspects	

Social	Environmental	Economic
Trustworthiness; Exposure, security / privacy; Digital inclusion	Energy efficiency / Power consumption	Resilience / Limited downtime; OPEX; CAPEX
Management and orchestration	Diagnostics intent	
Network architecture and transformation Trustworthy flexible topologies, Beyond communications		
6G device components	6G radio aspects	



Gradual addition

PoC C: introducing elaborated network enablers (WP3), 6G device components (WP5), 6G radio aspects(WP4), and intent-driven M&O (WP6)

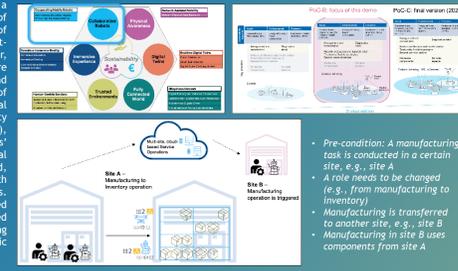
6G

Demonstration sequence

- Use Cases
- Enablers
- Sustainability Aspects
- Architecture
- Results
- Benefits - Impacts

Overview

Hexa-X-ii aims at building a system blueprint of a sustainable trustworthy 6G platform. Within the scope of evaluating and validating this E2E system, the use case of collaborative robots (robots) conducting inventory audited-related operations in a warehouse is studied. In particular, autonomous mobile robots (AMRs) & drones (UAVs) are cooperating in conducting automated i.e., scanning and identifying cartons, keeping track of real-time location of goods, etc. Numerous challenges related to functional aspects, namely intelligent and dynamic MBO (functionality allocation to robots, multi-site, synergistic orchestration), flexible network topologies, data and device capabilities' exposure, compute offloading, as well as non-functional aspects (throughput, E2E latency, reliability) are addressed, towards robust and resilient industrial operators with reduced downtimes, energy efficiency and trustworthiness. Moreover, intent-based features offering automated translation and orchestration of high-level, user-oriented commands, as well as key application functions leveraging powerful AI/ML capabilities (swarm management of robotic devices, computer vision algorithms, etc.) are showcased.



Enablers

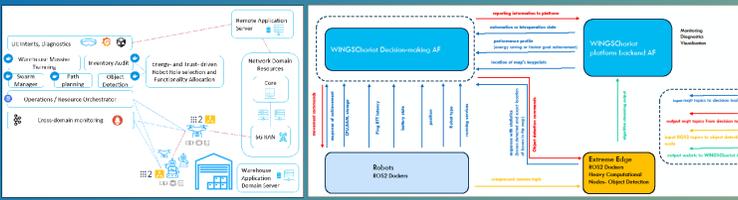
- Advanced Management and Orchestration
- Trust aspects
- AI-powered sustainable operations
- Exposure of data and capabilities beyond communications
- Flexible, trustworthy network topologies
- Intent-based features

Sustainability Aspects

- Social: trustworthiness, inclusion
- Time related KPIs (handling event)
- Data exposure security
- Environments Energy
- Power consumption
- Dynamic replanning of available device roles
- Economic: financial (resilience, limited downtime), OPEX (energy), CAPEX

Pre-condition: A manufacturing task is conducted in a certain site, e.g., site A.
A role needs to be changed (e.g., from manufacturing to inventory).
Manufacturing is transferred to another site, e.g., site B.
Manufacturing in site B uses components from site A.

Architecture



Robotic Layer:

- Utilizes ROS2 for communication among robots.
- Deploys Docker containers for modularization and ease of deployment on diverse robotic platforms.

Edge Compute Device:

- Manages high CPU-GPU demanding nodes critical for robotic tasks.
- Serves as a central hub for robot communication and computation.
- Performs real-time AI/ML based video analytics (Input: ROS2/Output: WebRTC, MQTT to Wings Chariot Fleet Manager/Platform)

WINGSChariot Platform:

- Leverages MQTT for communication.
- Monitors, diagnoses, and acts as the user interface for the entire robotic system.
- Provides comprehensive insights and control over the robotic fleet.

Testbed

- Two AMRs equipped with advanced components (Intel NUC Single D3 processor; 16GB RAM; 250GB SSD; Slamtec RPLIDAR S2-18m for precise mapping and navigation, RealSense D435 camera for visual perception).
- 1 UAV equipped with 8-core chipset, 3.091 GHz, 8GB LPDDR5, PMD time-of-flight (ToF) module for indoor depth mapping, CV tracking image sensor for visual inertial odometry (VIO) localization, 4K Hi-Res camera for real-time streaming, RGB image capture, and video recording).
- Private 5G NSA and SA Networks

Video Feeds Capture and Transport:

- Utilizes low-latency WebRTC protocol for capturing and transporting video feeds from robots.
- Custom software component captures image sequences from ROS Camera topics.
- Packages images using an efficient video codec/WebRTC server for BE processing.

Orchestration Tool - WINGSChariot Fleet Manager:

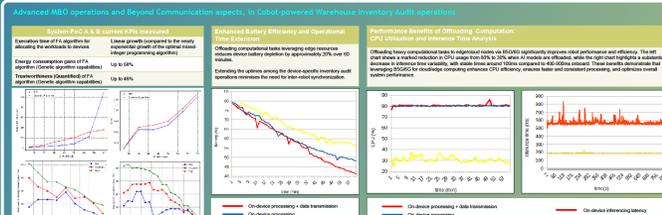
- Resides on the cloud for centralized control and management.
- Employs MQTT protocol to collect data from robots using an MQTT to ROS2 bridge.
- Issues commands to robots based on intelligent decision-making processes.

Results

Advanced MBO operations and Beyond Communication aspects, in Intent-powered Warehouse Inventory Audit operations.

Enhanced Battery Efficiency and Operational Time Extension:

Performance Benefits of Offloading, Computation, CPU Utilization and Inference Time Analysis:



AI enablers impact:

- Flexible topologies: CAPEX reduction
- Beyond communications: Sophistication / Efficiency gains
- Insights, e.g., localisation information, sensing.
- Trusted (local) computation.
- Latency improvements, e.g., in inference time, compared to on-device processing or core cloud computations

Management and Orchestration / Exposure: Service management towards order of seconds / minutes, dynamic replanning of available device roles.

Performance aspects (as far supported by system):

- Optimization: warehouse size, target time to complete a task, number of devices and associated video-induced throughput (Gbps), infrastructure elements.

Additional social impacts:

- Environmental sustainability

Benefits - Impacts

Benefits from advanced performance back-end-edge synergy:

Enabling trustworthy network topologies:

Trustworthy Flexible Topologies:

Trustworthy Resilient Topologies enable efficient and optimized network sharing efficient resource use and minimized latency.

These topologies dynamically improve KPIs such as energy consumption and cost effectiveness, making them ideal for application in the warehouse inventory management.

The system's continuous trial evaluation and node recovery mechanisms ensure robust and reliable operations, meeting critical low latency and security requirements.

Parameter table:

Parameter No.	Parameter	Value
1	Transmission Load	0.2 / 700 Mbps
2	CPU Utilization	20% / 10%
3	CPU cores	7
4	Battery Autonomy	0.28 (E-W) / 0.2 (S)

Table 1: Metrics

Transmission Load	CPU Utilization	CPU cores	Battery Autonomy
1	Transmission Load: 100Mbps, CPU Utilization: 20%, CPU cores: 7, Battery Autonomy: 0.28		
2	Transmission Load: 100Mbps, CPU Utilization: 20%, CPU cores: 7, Battery Autonomy: 0.28		
3	Transmission Load: 100Mbps, CPU Utilization: 10%, CPU cores: 7, Battery Autonomy: 0.28		



Hexa-X-II booth



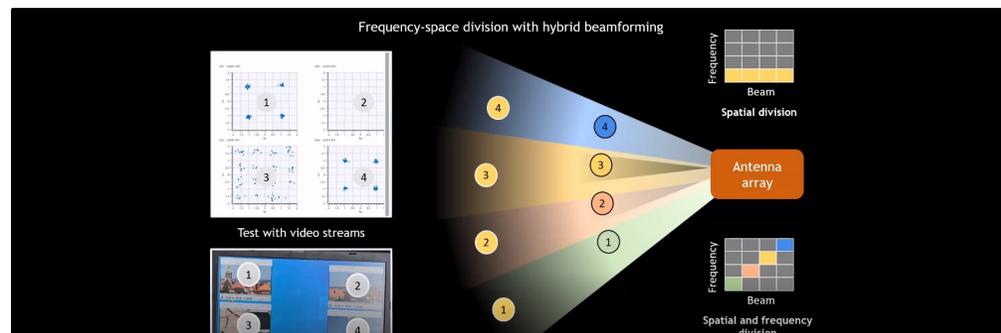
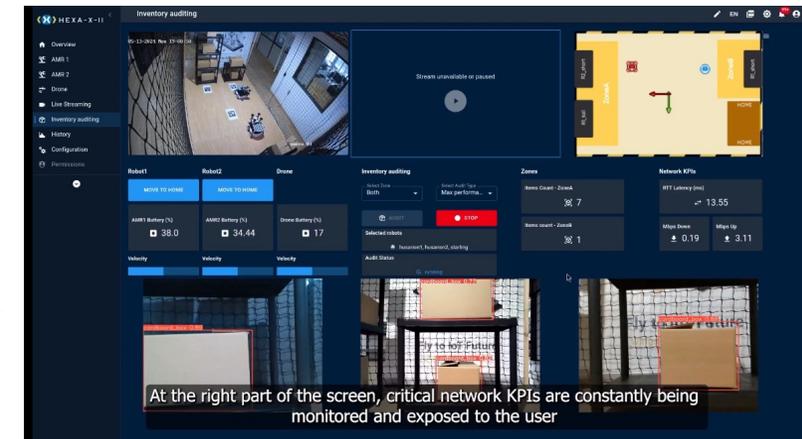
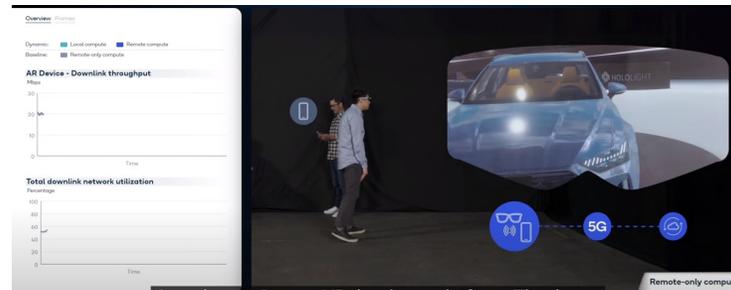
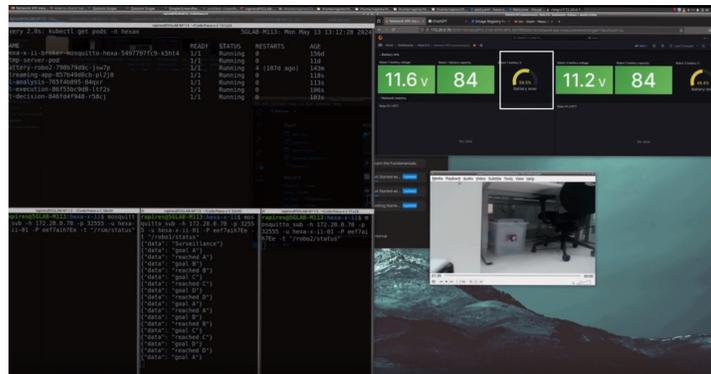
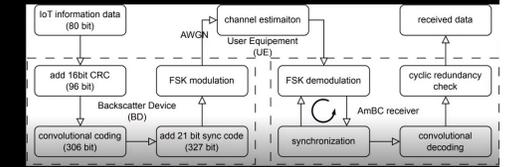
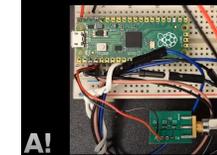
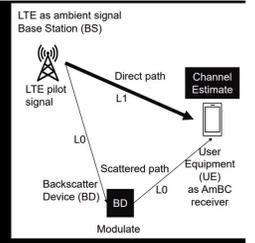
Come visit us at booth 32 & 34 to see our live and video demos!



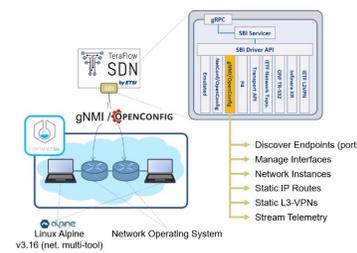
A practical Ambient Backscatter

based on LTE downlink Cell Specific Reference Signal (CRS), channel estimation

- Battery-free energy-autonomous device.
- Integrated convolutional channel coding and cyclic redundancy check (CRC) into an Ambient Backscatter Communication (AmBC) system that relies on LTE downlink pilots.
- Reused channel coding and CRC algorithm existing in LTE.



ETSI TeraFlowSDN integration



- Several extensions and a new TeraFlowSDN SBI driver is introduced for controlling NOS with gNMI/OpenConfig
- It includes Endpoint discovery
- Interface Management
- Set-up of static IP routes
- L3-VPNs through static routing
- Streaming telemetry