Hexa-X-II D2.5 Deliverable

D2.5 summary slides: Final overall 6G system design

Hexa-X-II

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Document editor	NFR: Nicolas Le Sauze, Sylvaine Kerboeuf
Authors	**APP:** Alperen Gundogan, Sameh Eldessoki, Panagiotis Botsinis, Christian Drewes; **ATO:** Ignacio Labrador Pavón; **BI:** Prajnamaya Dass, Stefan Köpsell, Amitha Mayya, Ali Khandan Boroujeni, Maximilian Matthé; **CTT:** Pol Alemany, Raul Muñoz, Ricard Vilalta, Behnam Ojaghi; **EAB:** Zhenhua Zou, Hamed Farhadi, Flávio Brito, Patrik Rugeland, Josué Castañeda Cisneros, Remi Robert, Mårten Ericson (EAB); **EBY:** Elham Dehghan Biyar, Merve Saimler, Betül Güvenç Paltun, Ferhat Karakoç; **ICC:** Ioannis Tzanettis, Grigorios Kakkavas, Anastasios Zafeiropoulos; **LMF:** Sonika Ujjwal (LMF); **NDK:** Pilar Andres Maldonado; **NFI:** Akshay Jain (NFI); **NFR:** Abdelkader Outtagarts, Dinh Thai Bui, Sylvaine Kerboeuf, Nicolas Le Sauze, Huy Tran, Mathieu Boussard; **NGE:** Markus Staufer; **NXW:** Pietro G. Giardina, Giada Landi, Giacomo Bernini; **OPL:** Halina Tarasiuk, Marcin Ziółkowski, Karol Kuczyński; **OPT:** Xose R. Sousa ; **TID:** Diego López, Riccardo Nicolicchia; **TUD:** Ana Belen Martinez, Anton Schösser, Philipp Schulz, Carl Collmann, Ahmad Nimr ; **UMU:** José María Jorquera Valero, Manuel Gil Pérez, Gregorio Martínez, Pérez, Noelia Pérez Palma ; **VTT:** Pawani Porambage, Dinaj Attanayake, Rafael Pires, Henry Blue; **WIN:** Sokratis Barmpounakis, Vasiliki Lamprousi, Vasilis Tsekenis, Panagiotis Demestichas

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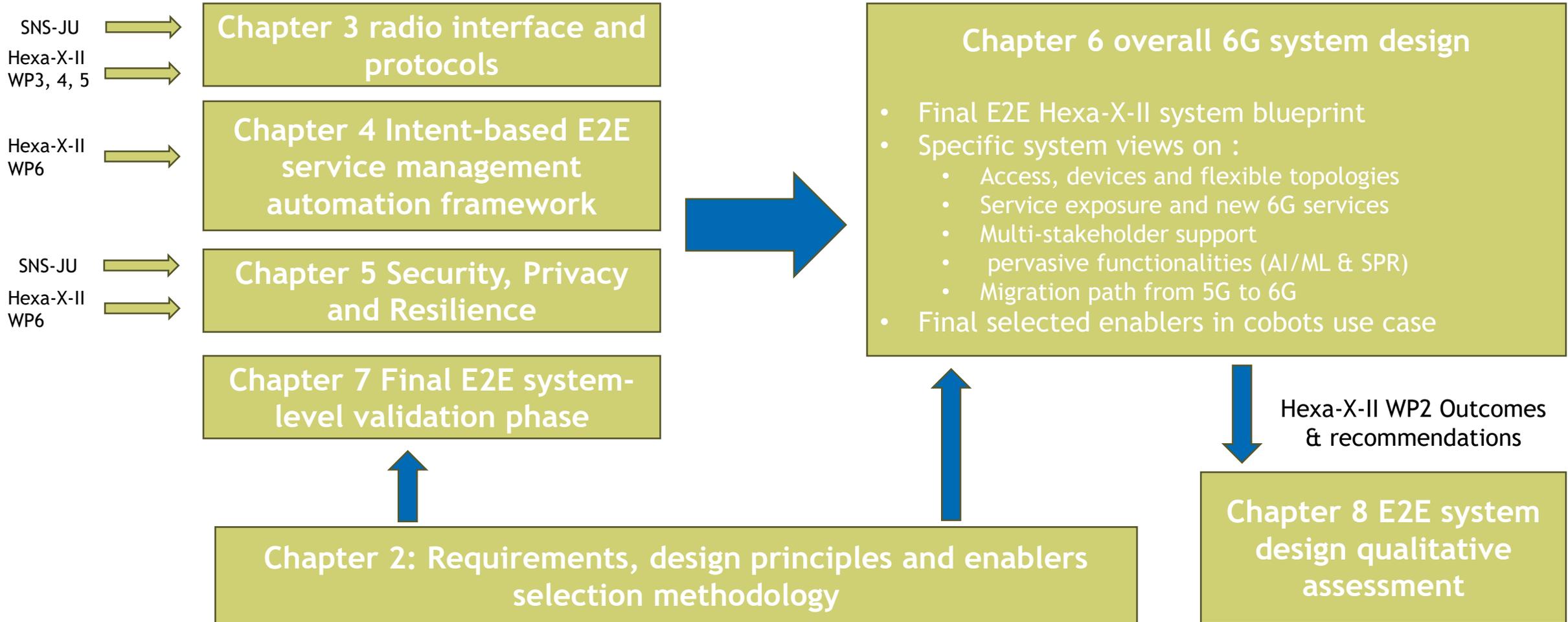
Deliverable structure

Hexa-X-II WP2 enabler analysis and recommendation

X-WP and SNS-JU enabler analysis & selection for coordinated system views + illustration on a PoC-related practical use-case

SNS-JU →
Hexa-X-II WP3, 4, 5 →

Chapter 3 radio interface and protocols

Hexa-X-II WP6 →

Chapter 4 Intent-based E2E service management automation framework

SNS-JU →
Hexa-X-II WP6 →

Chapter 5 Security, Privacy and Resilience

Chapter 7 Final E2E system-level validation phase

Chapter 2: Requirements, design principles and enablers selection methodology

Chapter 6 overall 6G system design

- Final E2E Hexa-X-II system blueprint
- Specific system views on :
  - Access, devices and flexible topologies
  - Service exposure and new 6G services
  - Multi-stakeholder support
  - pervasive functionalities (AI/ML & SPR)
  - Migration path from 5G to 6G
- Final selected enablers in cobots use case

Hexa-X-II WP2 Outcomes & recommendations

Chapter 8 E2E system design qualitative assessment

Chapter 2
Requirements, design principles and technical enablers selection methodology

Summary of system requirements

Summary of functional requirements based on [HEX223-D22], [HEX224-D23]

- Functional requirements focus on functionalities (what) for the use cases (user perspective).
- Detailed description of all the functional requirements is provisioned in [HEX223-D22] and [HEX224-D23]
- Examples of advanced communication and computation requirements are:
  - Positioning and Sensing: cost-efficient and accurate positioning and sensing capabilities, with accurate time synchronization for immersive experiences
  - Pervasive AI/ML: integrate Artificial Intelligence (AI)/Machine Learning (ML) for immersive experiences, robot coordination, and real-time sensor data processing, ensuring explainability and sustainability
  - Compute capabilities: support reliable compute for complex digital twin models and AI-driven simulations, including compute offloading from devices
  - Ubiquitous coverage: provide global connectivity, integrating terrestrial and non-terrestrial networks for seamless indoor and outdoor service coverage
  - Local Ad-hoc connectivity: enable local ad hoc connectivity for collaborative tasks, forming task-specific subnetworks to optimize latency and reliability
  - High Privacy protection: prioritize privacy protection, defining and verifying privacy requirements in service level agreements to prevent malicious disruptions

Summary of non-functional requirements based on [HEX223-D12], [HEX223-D22], [HEX224-D23]

- Non-functional requirements relate to how the 6G system behaves
- It covers two aspects: System operations and performance of services
- Key non-functional requirements are:
  - System Scalability: flexibly reconfigure network topologies and automate dynamic scaling to manage increasing demand, integrating edge intelligence for lower latency and localized decision-making
  - Resilience and Security: include redundancy, self-healing mechanisms, cryptographic protocols, confidential computing, and AI-enabled automated responses to enhance resilience and security
  - Efficient Automation: autonomously configure networks based on user intents, using ML-based closed-loops and real-time adaptation for optimal performance in dynamic environments
  - Flexible radio protocols: introduce a flexible protocol stack in RAN, optimizing radio resource control, data recovery, security features, and ensuring maximum flexibility
  - Mobility procedures: should be unified, agnostic to network architecture, optimized for FR3, and enhanced with AI/ML and Joint Communications and Sensing (JCAS)
  - Environmental, Social and Economic Sustainability: optimize power consumption, bridge the digital divide, ensure privacy, provide trustworthy AI frameworks, and justify costs through automation and resilience in system operations
  - Performance requirements: diverse and complex performance requirements for 6G, including low latency, high data rates, precise positioning, reliability, and coverage, tailored to specific use cases such as immersive experiences, collaborative robots, physical awareness, digital twins, ubiquitous connectivity, and trustworthy environments

Summary of design principles: Top priorities

Principle 1	Principle 2	Principle 3	Principle 4
Support and exposure of 6G services and capabilities	Full automation and optimization	Flexibility to different network scenarios	Network Scalability

Principle 5	Principle 6	Principle 7	Principle 8
Resilience and availability	Persistent security and privacy	Internal interfaces are cloud optimized	Separation of concerns of network functions

Top Priority

Principle 9
Network simplification in comparison to previous generations

Top Priority

Principle 10
Minimizing environmental footprint and enabling sustainable networks

Top Priority

- Achieving the 6G Key Values (KV) realization of environmental, social, and economic sustainability
- Crystallized around simplification, security/privacy, and sustainability

Revision of technical enabler selection methodology

Updated methodology accounts for the Key Performance Indicators (KPIs) as well as the subjective nature of KVs/KV Indicators (KVIs)

A multi-stage process is employed wherein:
- Meta-data collection is done [HEX2-JOK+25]
- Noisy/Full Knowledge Graph (KG) is constructed
- Pruning and hence, initial selection of enablers based on migration, maturity level and KPIs is performed
- A KVI to technical requirement to enabler mapping is done
- A KVI-based analysis and final selection of enablers is done
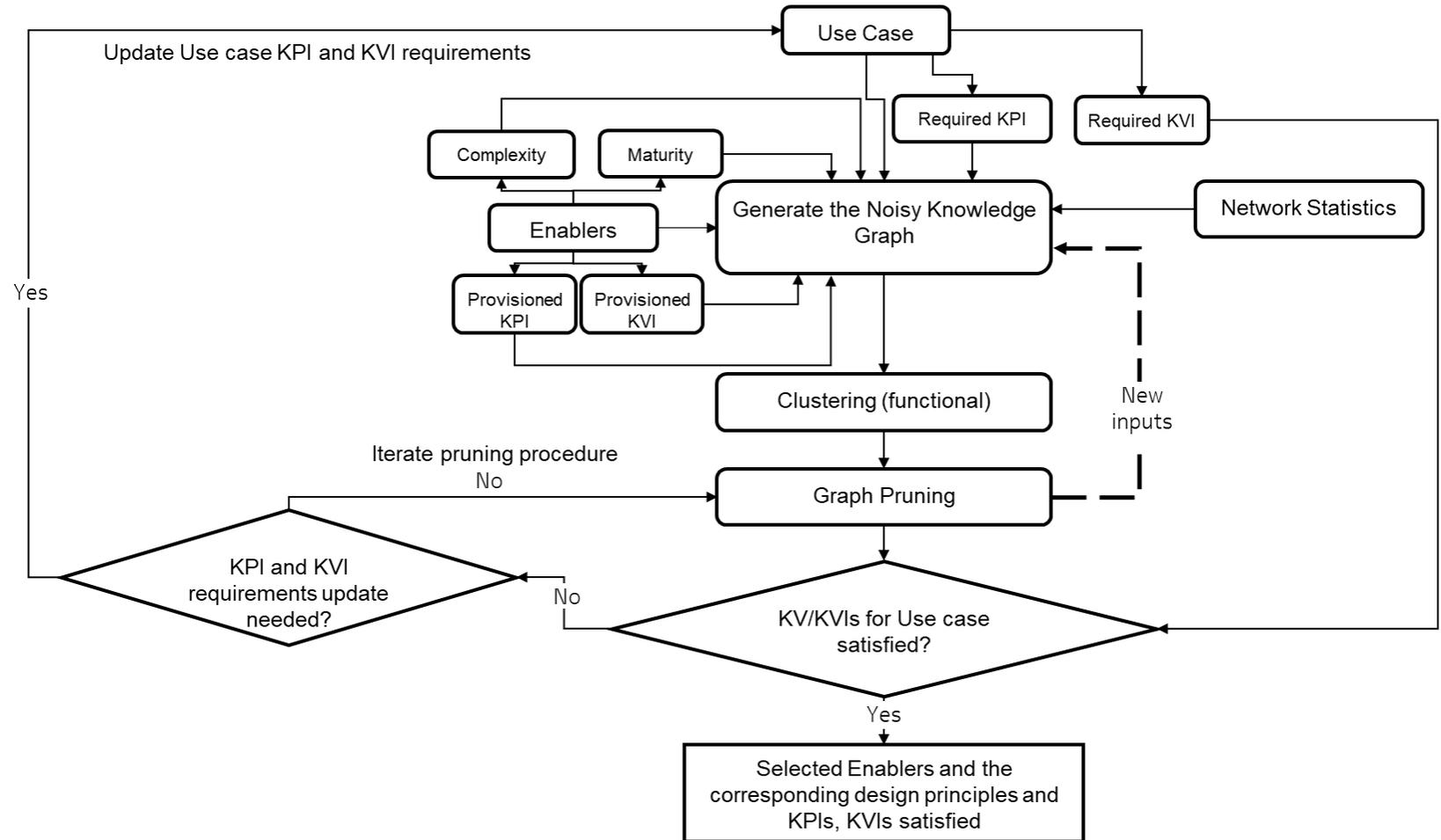
Chapter 3
Radio interface and protocols

Radio user plane protocols

6G Medium Access Control (MAC) retransmission technique

- Hybrid Automatic Repeat request (HARQ) retransmissions may not always improve the Transport Block (TB) decoding probability TB (e.g., highly degraded channel conditions for initial TB).
- MAC shall determine such conditions and reset the transmission of the TB instead of wasting resources.
- MAC layer can have a new function "MAC segmentation for HARQ retransmissions" to aid with such retransmissions.
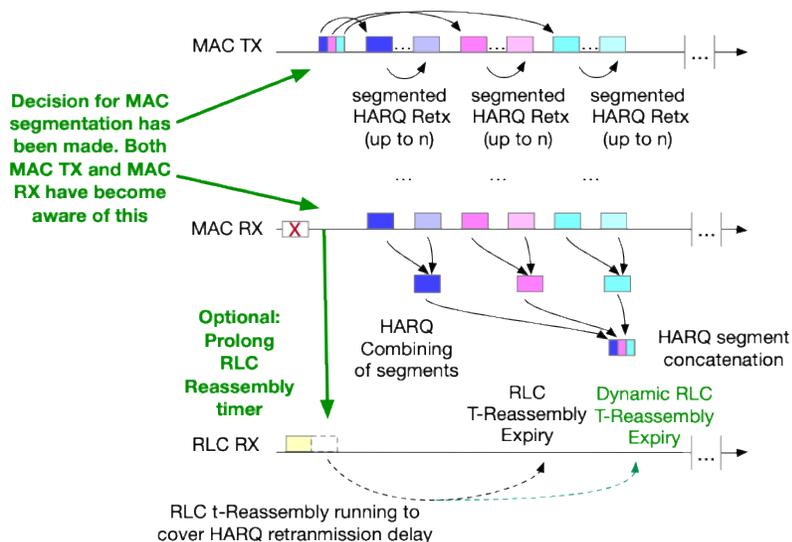
Asymmetric Radio Link Control (RLC)

- Issues with HARQ in downlink (DL) (i.e., discontinuous transmission interpreted as acknowledgment (DTX-to-ACK), and negative ACK to-ACK).
- User Equipment (UE) would only require RLC unacknowledged mode (UM) functionality for both uplink (UL) and DL with some RLC Acknowledged Mode (AM) related functionality only for the DL path. It should be noted that Asymmetric RLC can also be applied in the UL direction, if seen needed.
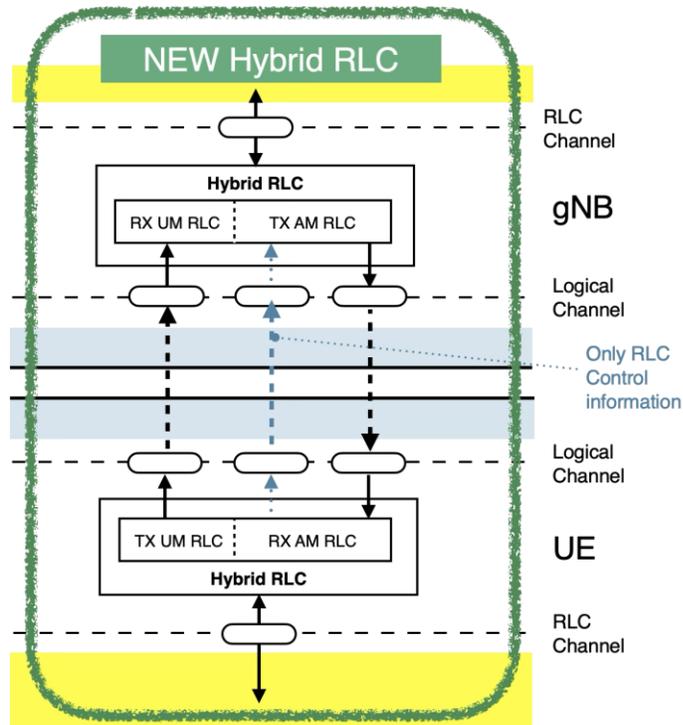
Modular user plane design for different UE types

- Modular user plane design (i.e., based on an anchor module and additional modules) can enable native support of various device types optimized for different purposes.
- For the lowest device type like Low Power Wide Area (LPWA) type devices, only the anchor module can be used to support the necessary Control Plane (CP) functions and User Plane (UP).
- For the mainstream device type, in addition to the anchor module, a few more modules can be included for supporting higher data rate.
- For high-end device types, even more additional modules can be included to further boost the supported maximum data rate.
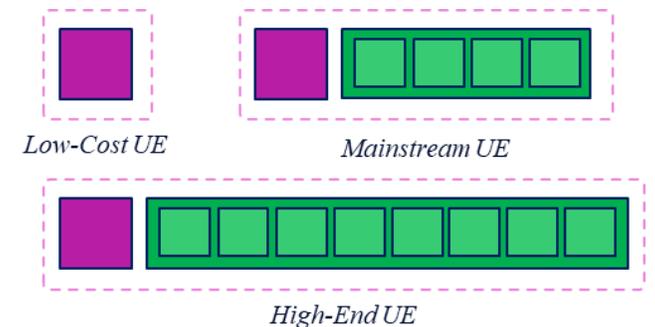
Mobility procedures (1)

Methods for cellular data transfer within connected measurements radio gaps

- During the measurement gaps, the DL/UL data transfer between the UE and the cellular network is interrupted.
- To overcome this problem, the cellular network may exchange data with the UE via one of the neighbour cells to be measured by the UE during a connected mode measurement radio gap.
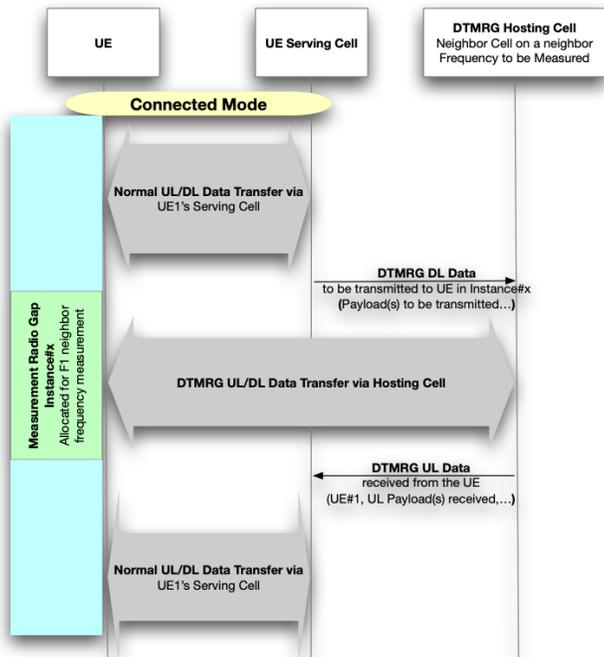

Data driven mobility

- The UE and the network collaborate to enhance the connectivity control decisions by leveraging information from the other sensors of the UE, utilizing the UE traffic pattern, and using the history of connectivity experiences of itself and other UEs.
- UEs will not share any privacy sensitive data with the network, i.e., the first column of the following table "on-device understanding", the network will only receive the event definitions (e.g., Z2, Z3) when an event is satisfied.

User contextual event	Impact on user connectivity	Mobility contextual event type	Possible NW mobility decisions	3GPP predictive event definition (equivalent to A3, etc..)
User in a car entering a tunnel (passengers in the car are watching 4K video, downloading a large file, etc.), given the speed the tunnel will last 10 seconds	User will be on a phone call inside the tunnel	Radio environment event: high loss expected on this band	-> Change band ->Increase Radio Link Failure (RLF timers) ->Increase number of ReTx	Z2: RSRP in Current band will drop momentarily
User is going for a cross biking for at least 30 mins	User does not use the phone during this activity	Data Traffic event: Low traffic expected	->Handover to offload the cell	Z3: traffic on this band from this user will decrease for an extended period

Computation aware mobility

- The UE should evaluate its own computation requirements as well as the computation capabilities of the Base Station(s) (BS) before initiating
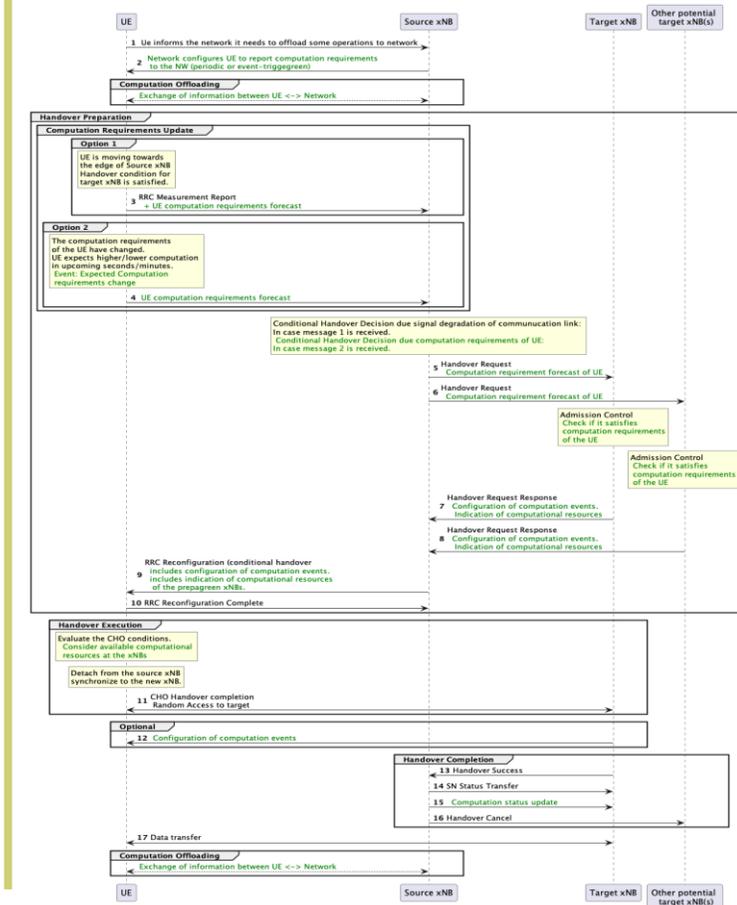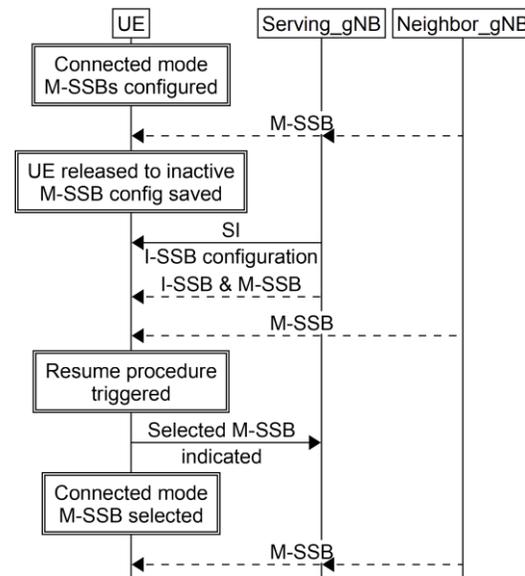
Mobility procedures (2)

Terrestrial Networks (TN) / Non-Terrestrial Networks (NTN) handover

- **Quality-of-Service (QoS) aware omission of Handover (HO) common information**
  - Handling of HO common information based on knowledge of the QoS or traffic patterns
- **Random time-based conditional HO**
  - Reduction of signalling during HO execution by introducing randomness into the HO initiation time
- **Satellite switching with "physical cell indicator (PCI) change only"**
  - Reduction of HO-related interruption time
  - Cell configuration remains unchanged, only target cell identifier is updated

Lean system mobility

- Two types of Synchronization Signal Blocks (SSBs) for energy efficiency
  - Always-on SSB for Radio Resource Control (RRC)_IDLE mode/coverage
  - On-demand SSB (can be turned-off) from capacity node
- Enhancement on transition from RRC_INACTIVE to RRC_ACTIVE when a UE last served by capacity node: Direct resume on the capacity node assuming the same system information unless a validity timer is expired .

https://gitlab.com/msc-generator v8.2

Mobility procedure harmonization

- A unified mobility procedure to harmonize enhancements introduced in 5G, e.g., Layer 1 (L1)/Layer 2 (L2) trigged mobility, conditional handover.
  - Pre-configuration
  - Pre-synchronization
  - Execution
- Relies on the flat RRC structure and redesign of the 5G multiple-level DL control
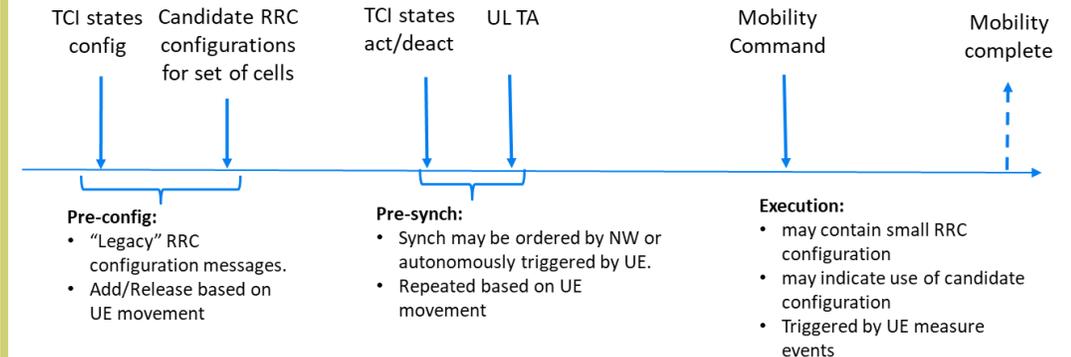
Mobility procedures (3)

Unprepared handover

- Mobility procedure that skips the full preparation before HO command and configures the UE with cell common configuration while preparing the full configuration for a given UE in parallel.
- This approach can provide the robustness level that Conditional HO targeted, but with no/low risk that the early prepared configuration becomes invalid.
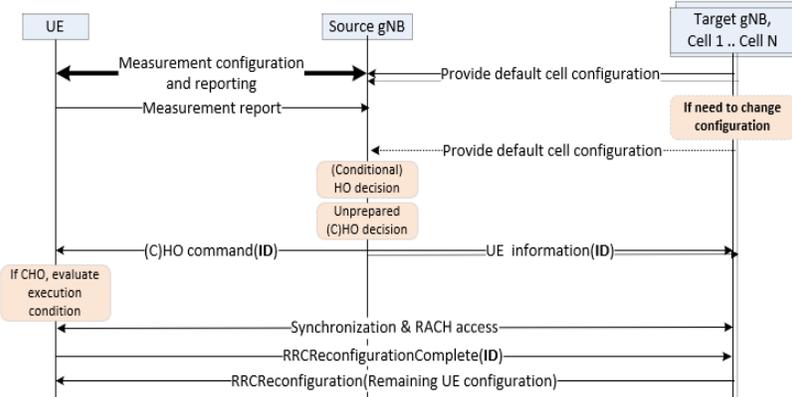

Mobility configured and managed by lower layers

- 6G mobility procedures can delegate more autonomy to lower layers (PHY and MAC), enabling the MAC layer to control more over RRC layer operation for mobility management such as configuration and triggering for cell switch.
- Delegating autonomy to MAC achieves the benefits of offered by L1/L2 Triggered Mobility (LTM) and slim operation with minimum redundancy.
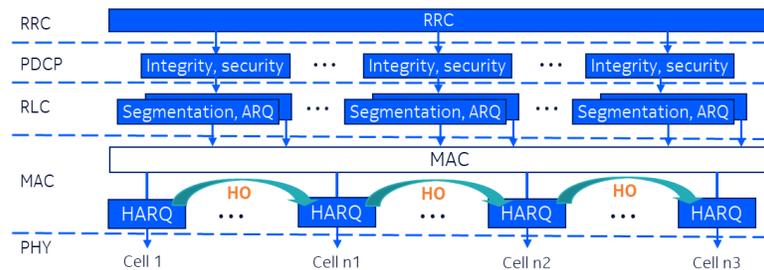
Random Access Channel (RACH)-less baseline HO with early Timing Advance (TA) acquisition

- To reduce interruption time, 6G HO procedures to consider early TA part of the basic HO procedure, beyond LTM case in 5G. That is, to have in 6G RACH-less baseline handover.
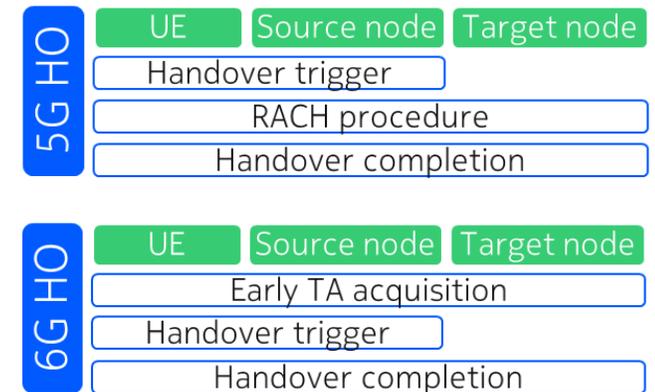
Application-Network interactions

Ad-Hoc Radio Bearer and Inline Signaling

- In [HX224-D23], a new mechanism, via inline MAC Control Element (CE) signalling, for the setup, reconfiguration, and release of Radio Bearers (RBs) in a more dynamic fashion based on application or service requirements was introduced.
- Another way to realize this is using the Service Data Application Protocol (SDAP) layer and header, requiring split of the SDAP functionality moving the labelling and SDAP header part below RLC, while QoS flow mapping remains as in 5G.
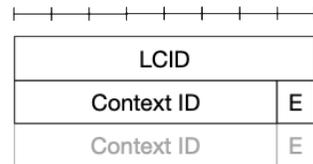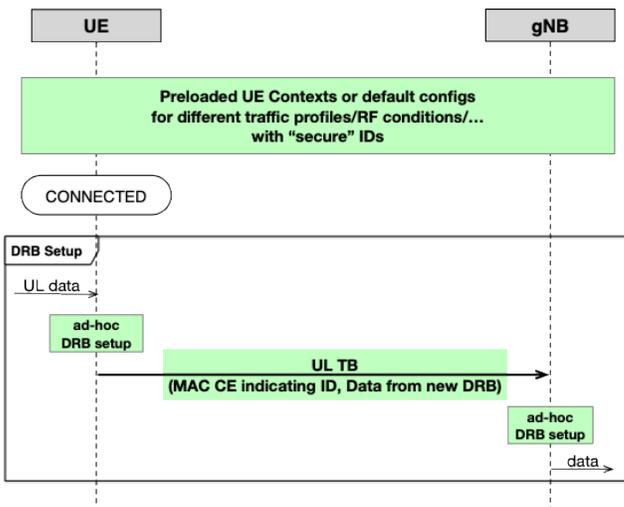
Data Radio Bearer (DRB) setup example: (a) message sequence chart, (b) MAC CE.

UE Quality Level-aware Scheduling

- In the current QoS framework there is no quick method for UE and network (NW) to align and rapidly adjust the provided NW UL grants and the UE's target bitrate, leading to buffer bloat and resource waste.
- Proposed new procedure is formed of two stages:
  - **Stage#1 – UE indicated Quality-Levels;** the UE agrees with the NW on multiple different quality levels that can then be used as a reference for Stage#2.
  - **Stage#2 – Level-aware Scheduling;** the UE is informed on a regular basis about the quality level the NW can serve to this UE currently and/or in the future steering the UE to known and sustainable levels.
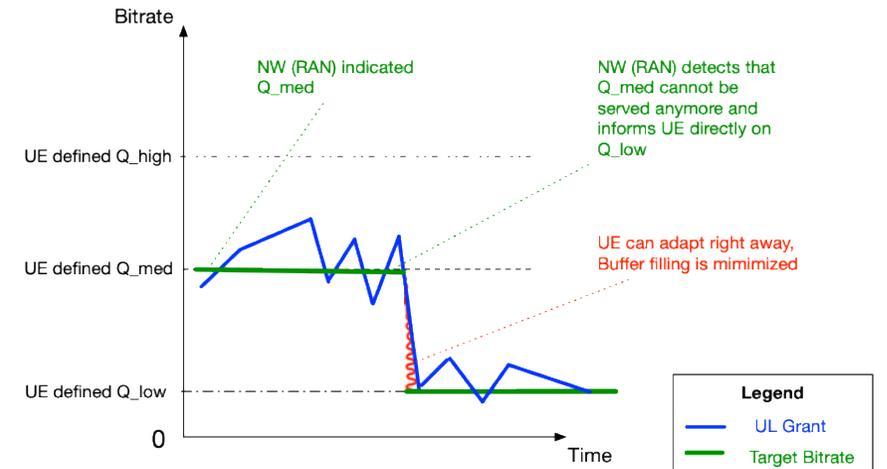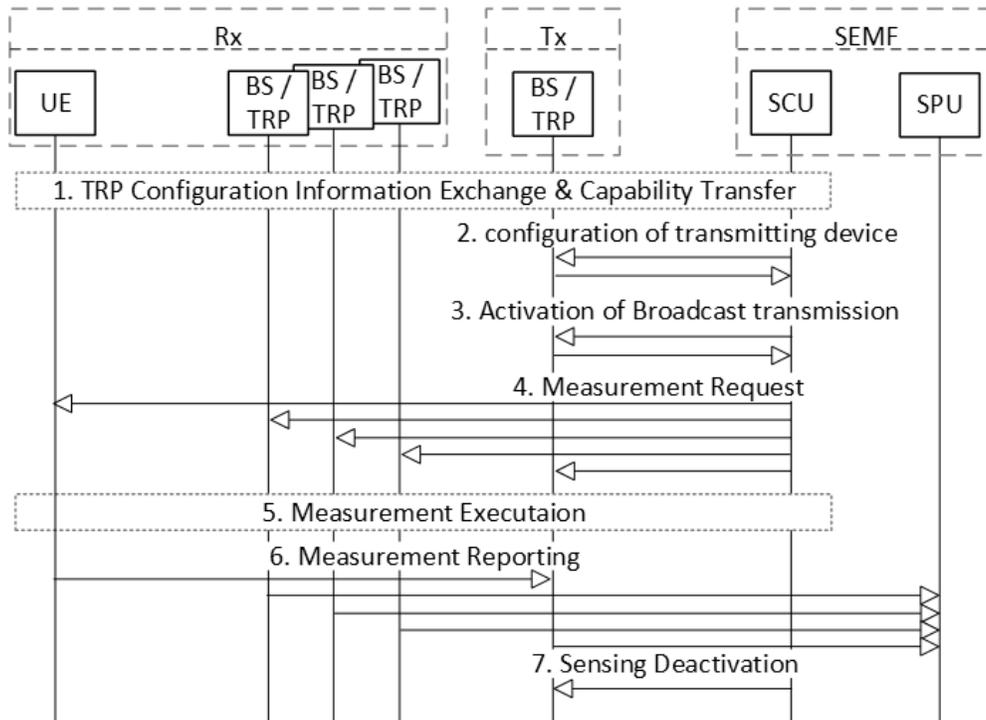
Integration of JCAS

JCAS radio protocols and procedures

- [HEX223-D33] has purposed novel network functions to support JCAS Integration into 6G networks. In this work, a multistatic sensing procedure defines key protocol steps: Transmission/Reception Points (TRPs) configuration, capability negotiation, synchronized transmission, measurement execution, and reporting.

- Due to similarities with existing 5G positioning protocols (LTE Positioning Protocol –LPP, new radio positioning protocol a –NRPPa), extending these protocols may simplify 6G sensing implementation.

```
             Rx                    Tx              SEMF
  ┌─────────────────────┐   ┌─────────┐   ┌─────────────────┐
  │      BS/ BS/ BS/     │   │  BS/    │   │  SCU      SPU   │
  │ UE   TRP TRP TRP     │   │  TRP    │   │                 │
  └─────────────────────┘   └─────────┘   └─────────────────┘

  1. TRP Configuration Information Exchange & Capability Transfer

              2. configuration of transmitting device

              3. Activation of Broadcast transmission

              4. Measurement Request

  5. Measurement Executaion

  6. Measurement Reporting

              7. Sensing Deactivation
```

Radio bearer for sensing measurements in Uu interface

- Radio protocol framework is flexible to support potential needs, e.g., a new radio bearer type other than signalling radio bearer(SRB) and data radio bearer (DRB) is needed (and can be supported) in one scenario:
    - measurements are not processed at the UE but forwarded to the network.
    - measurements are raw sensing data with a potentially very large size.

| Signalling radio bearer |

| Sensing radio bearer |

| Data radio bearer |

Integration of NTN

- **Integration of NTN with TN** is a key aspect from spectrum and coverage point of view
  - **Coverage enhancement:** Extension of existing cellular deployments towards full global coverage
  - **Spectrum reuse:** Cost minimization and efficient deployment

- **Performance considerations**
  - Urban areas experience less degradation when TN and NTN downlinks share the same band
  - Low-Earth-Orbit (LEO) satellite altitude has a higher impact in rural areas
  - Reverse duplex schemes (NTN uplink using TN downlink band) can severely affect cell-edge users

- **Interference mitigation**
  - Defining separation distances and power limits to protect TN users
  - User equipment-level techniques: TN-NTN handshaking, optimized antenna patterns, circuit designs, and digital signal processing

- **High-Altitude Platforms (HAPS) vs. satellites**
  - HAPS-mounted gateways provide lower path loss and better predictability than satellites

- **Handover challenges**
  - New TN/NTN HO strategies to reduce signaling overhead and minimize service interruption time

Integration of AI-ML for radio interface optimization

- The AI-ML-driven air interface integrates AI-ML-based methods to enhance lower-layer functionalities in transmitters and receivers. Solutions optimizing air interface design are categorized as:
  - Learning for waveform, modulation, and coding
  - AI-based Channel-State-Information (CSI) acquisition
  - AI-enhanced Multiple Input Multiple Output (MIMO) transmissions
  - AI solutions for Hardware (HW) impairments

- The integration of AI-ML-driven air interfaces into radio access networks requires new radio procedures, protocols, and signalling mechanisms. The following points highlight the need of such mechanisms:
  - AI-ML model life cycle management
  - Revision of signals and waveforms
  - Signalling and protocols for physical layer integration
  - Reduction of reference signals
  - Revision of requirements based on AI-ML capabilities
  - Testing procedures for regulatory compliance
  - Trustworthiness

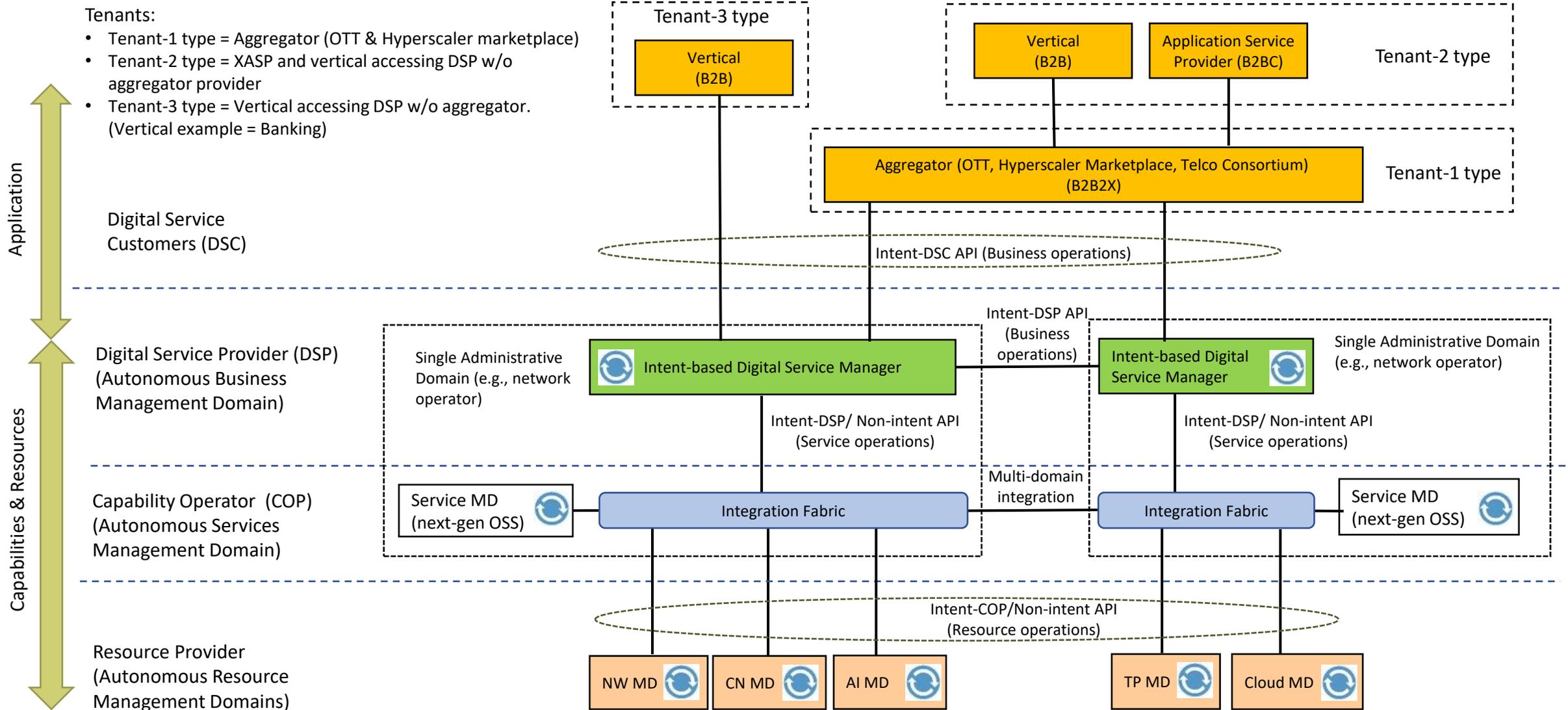# Conclusions and recommendations on radio interfaces and protocols

- Three areas have been the focus of 6G innovations in D2.5 complementing and extending the work of previous deliverables:
    - Radio user plane protocols: extending the functionality at MAC and/or RLC layers, native support of different types of devices based on user plane modularization.
    - Mobility procedures: mechanisms to minimize interruption time, scheme to harmonize mobility procedures, and information for evaluating mobility events, etc.
    - Application-network interactions: UE and the base station to optimize service provisioning in 6G.

- The updated analysis of the integration of other 6G capabilities such as JCAS into the radio protocols has identified the need for extending current procedures for new cases foreseen, updating reference signals and radio bearers, and adding additional capabilities to be exchanged between the UE and the network, etc.

- As recommendation, 6G radio design is seen as an evolution of 5G. Innovations in this area utilize the existing ecosystem of devices and infrastructure.

- Key take aways for 6G radio design: i) radio protocols simplification, ii) tighter coordination between protocol layers and their operation, and iii) more adaptiveness in the radio interface operation for service provisioning.
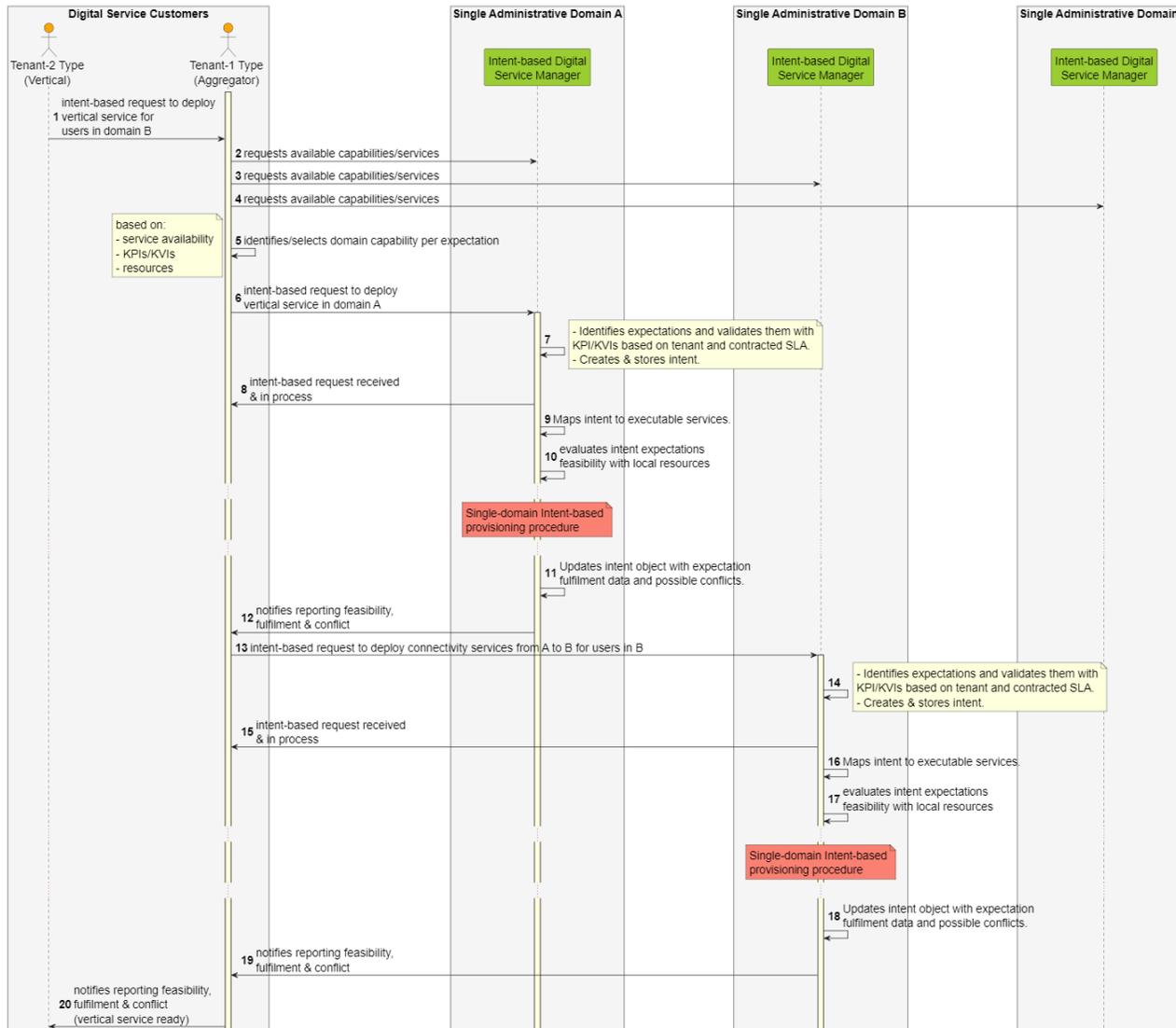
Chapter 4
Intent-based E2E service management automation framework

Intent-based DSP Service Framework

Tenants:
- Tenant-1 type = Aggregator (OTT & Hyperscaler marketplace)
- Tenant-2 type = XASP and vertical accessing DSP w/o aggregator provider
- Tenant-3 type = Vertical accessing DSP w/o aggregator. (Vertical example = Banking)

Application

Digital Service Customers (DSC)

Capabilities & Resources

Digital Service Provider (DSP) (Autonomous Business Management Domain)

Capability Operator (COP) (Autonomous Services Management Domain)

Resource Provider (Autonomous Resource Management Domains)

Tenant-3 type

Vertical (B2B)

Vertical (B2B)

Application Service Provider (B2BC)

Tenant-2 type

Aggregator (OTT, Hyperscaler Marketplace, Telco Consortium) (B2B2X)

Tenant-1 type

Intent-DSC API (Business operations)

Intent-DSP API (Business operations)

Single Administrative Domain (e.g., network operator)

Intent-based Digital Service Manager

Intent-based Digital Service Manager

Single Administrative Domain (e.g., network operator)

Intent-DSP/ Non-intent API (Service operations)

Intent-DSP/ Non-intent API (Service operations)

Service MD (next-gen OSS)

Integration Fabric

Multi-domain integration

Integration Fabric

Service MD (next-gen OSS)

Intent-COP/Non-intent API (Resource operations)

NW MD

CN MD

AI MD

TP MD

Cloud MD

Intent-based DSP Service Management (multi-domain models): Aggregation

- In the aggregation model, a vertical client sends a service request to an aggregator, who becomes responsible for managing intent-based service delivery.

- The aggregator queries multiple **Service Administrative Domains** (SADs) to discover capabilities and determine the best domain(s) to fulfil the intent.

- Once the optimal domains are identified, the aggregator sends specific intent requests to each domain's **digital service manager** (DSM), starting with the one providing the core service.

- Each DSM processes, validates, provisions, and updates the status of the intent based on Service Level Agreement (SLA)-defined KPIs/KVIs and resource availability.

- After all intents are successfully fulfilled across domains, the aggregator notifies the vertical that the service is ready for use.

Intent-based DSP Service Management (multi-domain models): Federation

- In the federation model, the vertical sends the intent directly to a DSM, which processes and maps it to services and checks local feasibility.

- If resources are insufficient locally, the DSM dynamically interacts with peer DSMs in other SADs to request and provision missing capabilities.

- Based on received offers, the DSM selects the best-fit domains and orchestrates federated provisioning of non-local services.

- Once all parts are deployed, the DSM updates the E2E intent and notifies the tenant, who then enables service access for end-users.
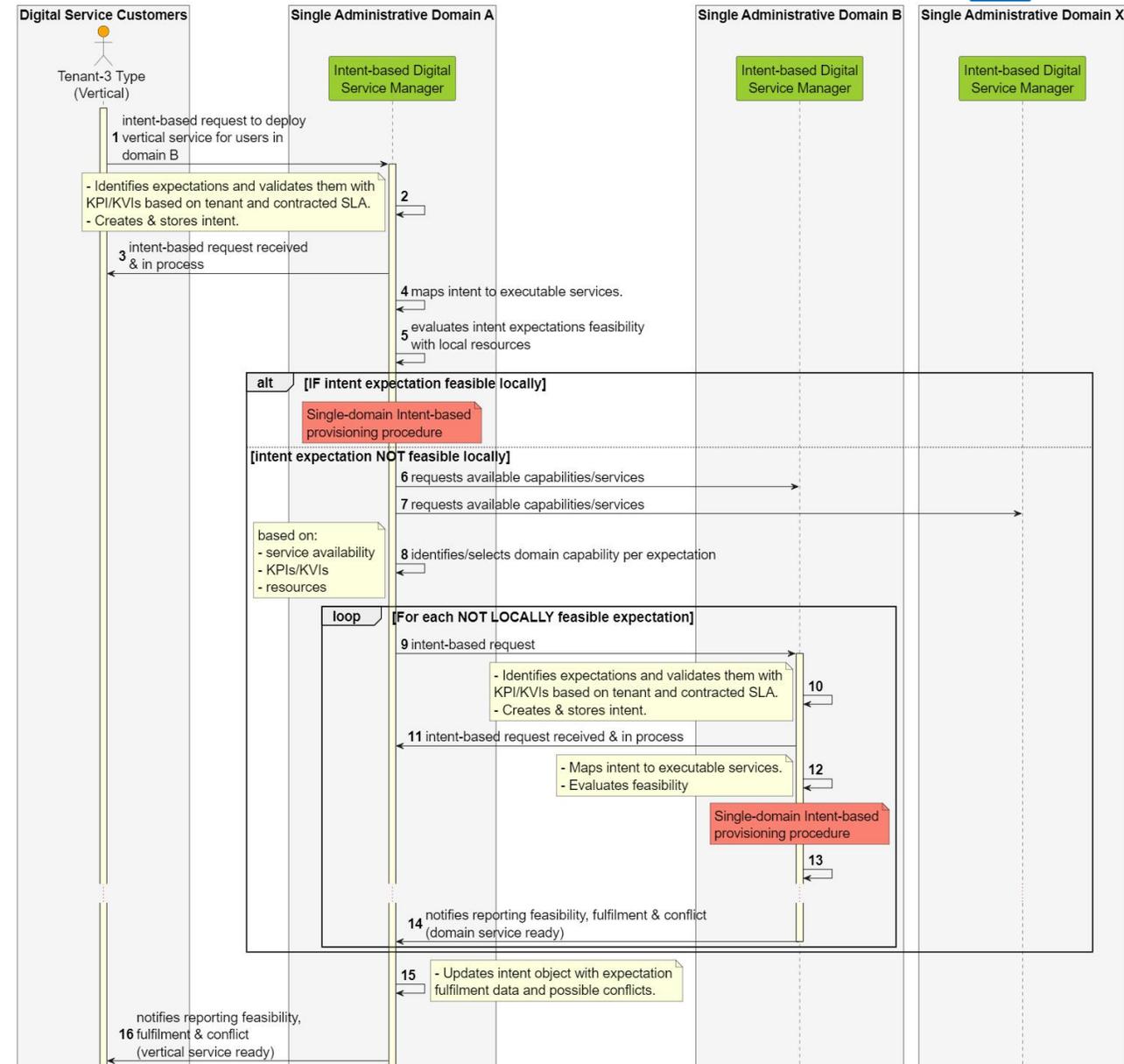
Intent-based DSP Service Management (single-domain) Updated: Negotiation Functionality
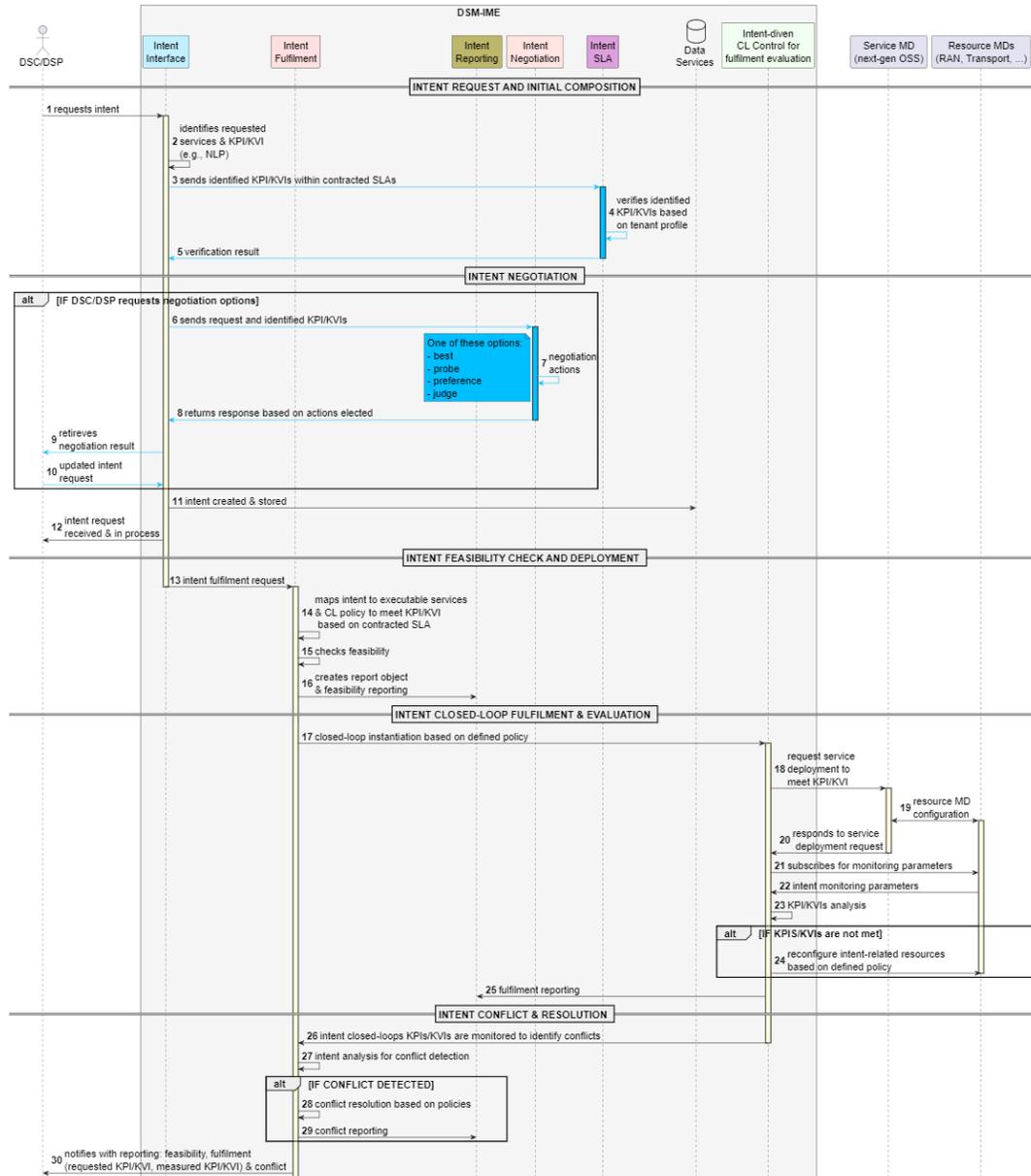
- The DSM-IME (**Intent Management Entity**)has evolved since D2.3 to better support multi-stakeholder scenarios

- While the core workflow remains like the one in D2.3, new steps are highlighted in blue and include added negotiation features:

- After receiving an intent, the system identifies services and verifies KPIs/KVIs based on the tenant's profile.

- If negotiation is requested, the intent negotiation module manages it, enabling agreement between tenant and DSM-IME before provisioning.

- Once finalized, the agreed intent is provisioned through the remaining workflow steps as defined in the original version.

Intent-based interfaces for Intent-based DSP Service Management

Intent Interface

Intent Interpreter	Intent CRUD
Intent Handling Capability Exposure	Intent ADSR
Intent negotiation management	Intent report management

DSC/DSP (Business)
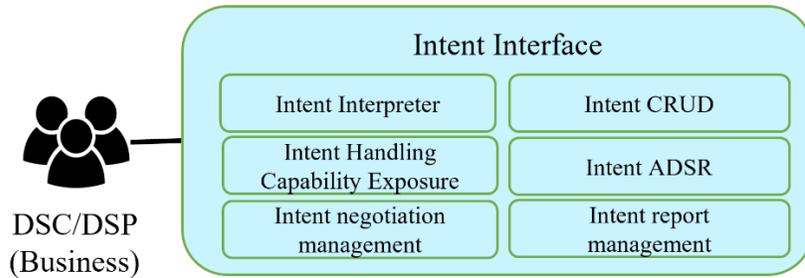
- The vertical intent interface supports the provisioning and assurance of services required by the DSP. But in some situations, a single DSP may be unable to fulfill requests. Thus, extending the interface is required.

- Extending the intent interface requires evaluating whether it would support a federation of DSPs compared with standards. The result is on the right.

- The vertical interface lacks support setting the intent with suspend/resume and negotiating intents. These missing blocks allow multiple DSPs to decompose the intents such that the DPSs fulfill based on their capabilities. Thus, by having these blocks the aggregation or federation models can be achieved.

Intent Functionalities	Supported			Unsupported	
	3GPP	ETSI ZSM	TM Forum	ETSI ZSM	TM Forum
Setting intents	Create intent	Create	SET intent		
	Modify intent	Update			
	Query intent	Read	GET intent		
	Delete intent	Delete	Remove intent		
	Activate intent	Activate			
	Deactivate intent	Deactivate			
	Translate intent				
				Suspend	
				Resume	
Reporting on the intent		Notify/ Report	Report intent		
Negotiating intent				Judge	Judge/ preference
				Feasibility	Probe
				Best	Best/ propose
Handling intent profile		Capability exposure	Capability profiling		

Final Intent-based DSM Functional Architecture

DSM Intent Management Entity (IME)

DSC/DSP (Business)

Intent Interface
- Intent Interpreter
- Intent CRUD*
- Intent Handling Capability Exposure
- Intent ADSR**
- Intent negotiation management
- Intent report management

Intent Fulfilment
- Intent Translation
- Intent Feasibility Check
- Intent CL Governance and Coordination Service
- Intent Conflict Detection/Resolution

Intent Reporting
- Intent Feasibility Check information
- Intent Fulfilment information
- Intent Conflict information

Intent Negotiation
- Intent Judgement and Preferences
- Intent Probing
- Intent Best

Intent SLA
- Service Portfolio (Offering SLA)
- 3P Profiling (Contracted SLA)

Intent-driven Closed-Loop (CL) Control for fulfilment evaluation
- Intent CL Execution
- Intent CL Analytics (KPI & KVI)
- Intent CL Decision
- Intent CL Monitoring
- Intent CL Data Services

Intent Closed-Loop Instances (e.g. for expectation targets)

Data Services

*Create/Retrieve/Update/Delete
**Activate/Deactivate/Suspend/Resume

Service MD (next-gen OSS)

Integration Fabric

Resource MDs (RAN, Transport, Core, App, AI)

Final Intent-based DSM Functional Architecture

- The DSM-IME functional architecture has evolved from previous versions, incorporating new capabilities across all functional blocks.

  - The **Intent Interface** serves as the main user access point, managing lifecycle operations and exposing enhanced features like standby intents and intent interpretation.

  - The **Intent Fulfilment Internals** handle internal processes such as translation, feasibility checks, closed-loop governance, and conflict resolution.

  - The **Intent Reporting** block tracks feasibility, fulfilment status, and conflict resolution data related to each intent.

  - The **Intent Negotiation** module lets tenants to probe, simulate, and request intents with precise expectations before provisioning.

  - The **Intent SLA** block introduces tenant profiling and a 6G service portfolio to support SLA-aware and personalized intent management.

  - The **Intent-Driven Closed Loop (CL) Control** block ensures ongoing fulfilment through monitoring, analytics, decision-making, and execution tailored to each intent instance.

  - The **Data Services** module stores all intent-related data, including SLAs and policies.

- All functional blocks work together with service and resource **Management Domains** (MDs) via a cross-domain interface that enables unified protocol-based communication for E2E **intent-based management** (IBM).

Intent-based Specific Enablers for E2E Services Management

E2E Intent-based Service Fulfilment Management
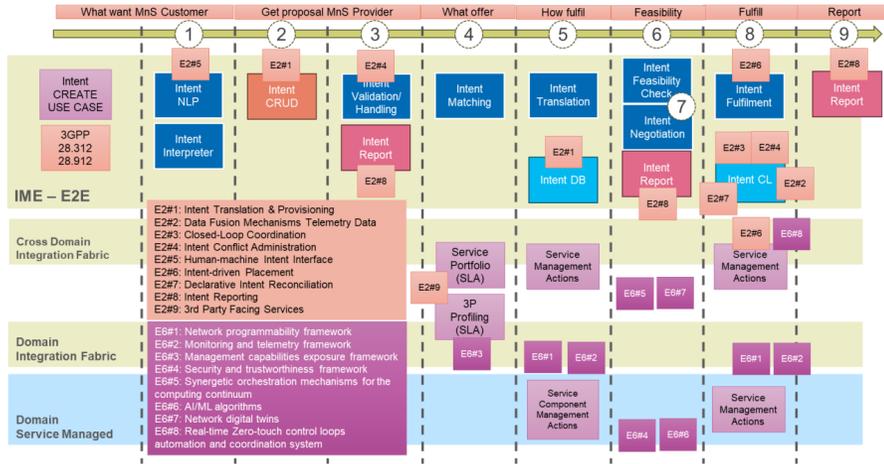
E2E Intent-based Service Evaluation Management
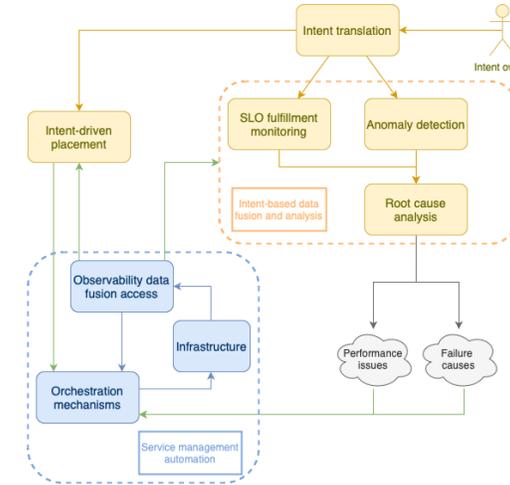
E2E Intent-based Closed Loop Coordination
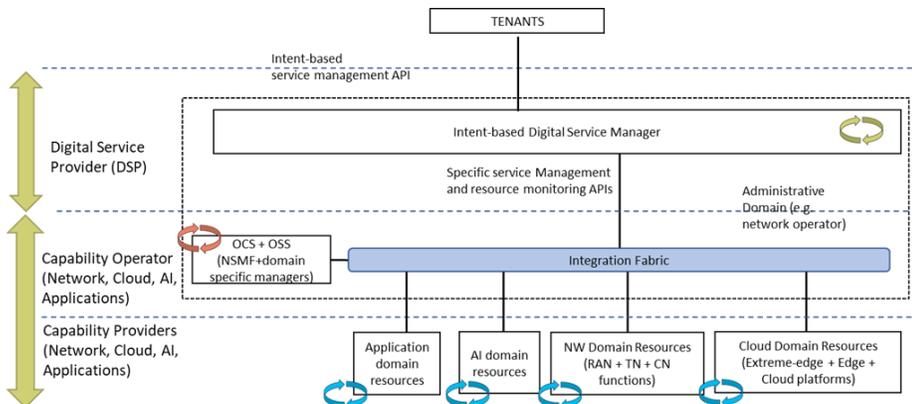
E2E Intent-based Trust Management
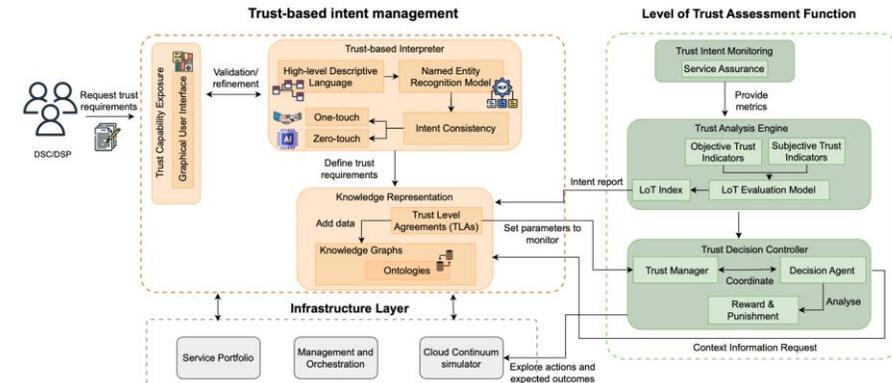
E2E Intent-Based Service Fulfillment Management

E2E service workflow

Discovery			Feasibility		Design & Deployment			Monitoring	Management		
Intent NLP	Intent Interpreter	Intent Validation Handling	Intent Matching	Intent Feasibility Check	Intent Translation	Intent Fulfilment	Intent Negotiation	Intent CL	Intent CRUD	Intent Report	Intent DB
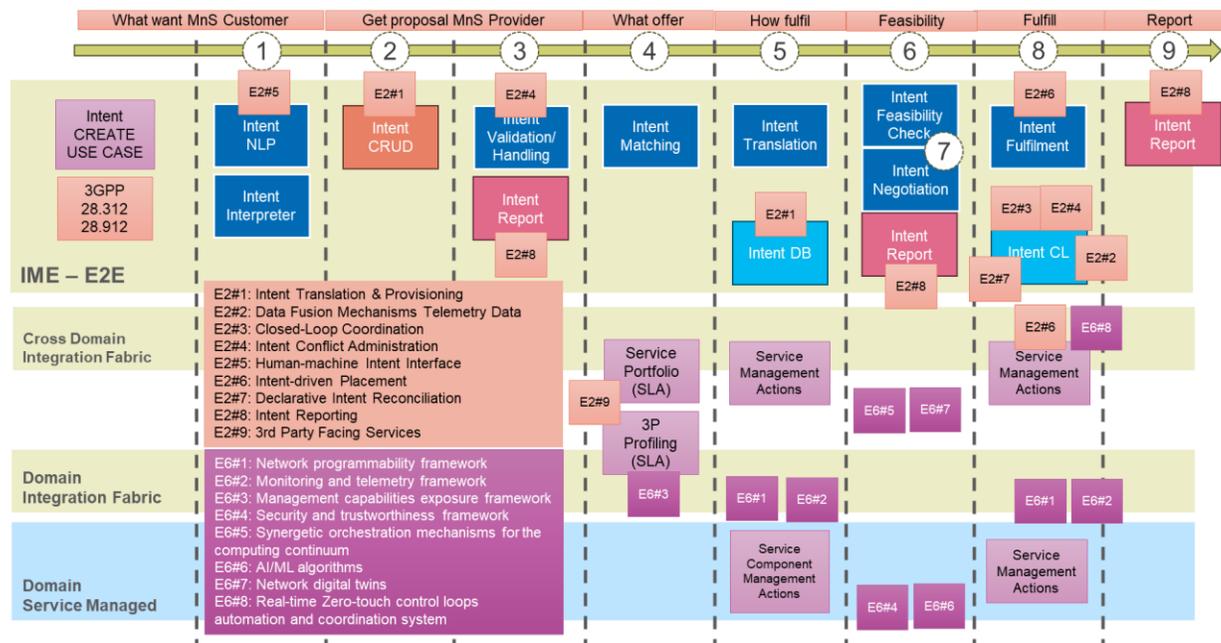
- **Discovery:** DSP identifies and translates customer needs into IBM-IME manipulable intents.

- **Feasibility:** DSP verifies fulfilment of the request using available resources and capabilities, evaluating the service definitions

- **Design-deployment:** DSP uses a dynamic design and deployment process to configure and activate the capabilities across the end-to-end domain

- **Monitoring:** DSP performs detailed monitoring of the service and uses associated policies, ensuring services operate in agreed service levels and trust expectations.

- **Management:** systems that store information about each intent, its lifecycle, and associated actions. A set of interfaces is also needed as a communication channel between the customer and the DSP providing related reports.

E2E Intent-based Service Evaluation Management

- **Continuous Monitoring & Real-Time Evaluation**: Ensures ongoing assessment of intent fulfilment through real-time observability.

- **Intent-to-SLO Translation**: Converts high-level user intents into specific, measurable **Service Level Objectives** (SLOs).

- **Root Cause Analysis (RCA) & Mitigation**: Identifies failures, diagnoses issues, and suggests/takes corrective actions.

- **Dynamic Adaptation**: Adjusts service configurations based on changing network conditions and operational demands.

- **Multi-domain Collaboration**: Supports decision-making across multi-stakeholder setups
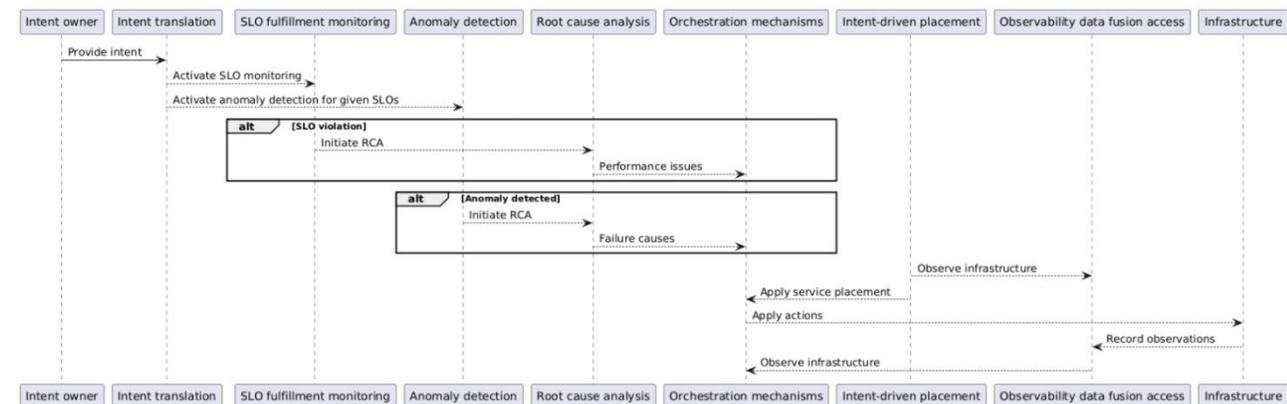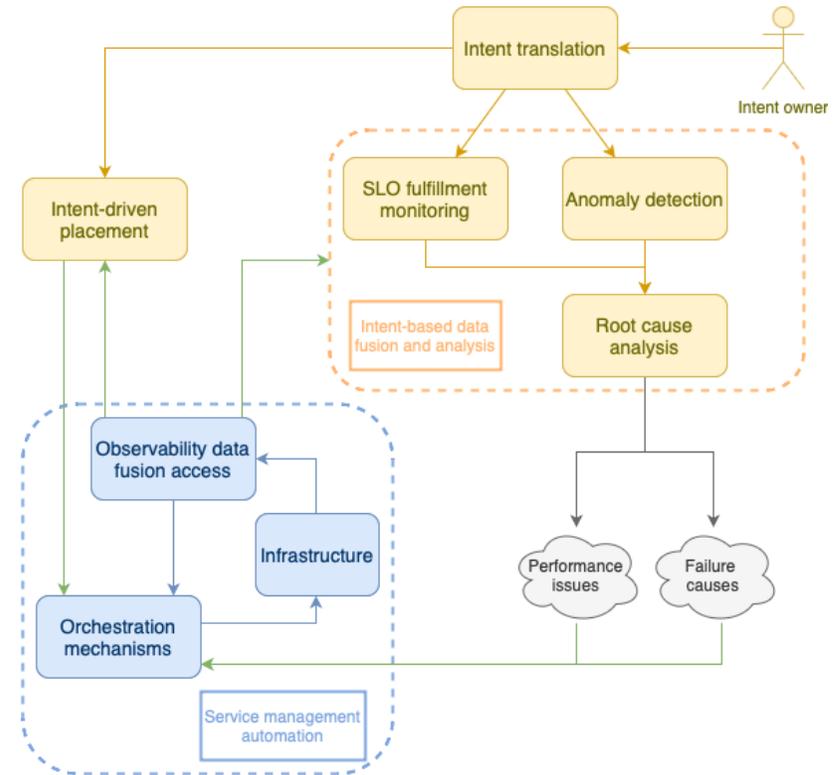
E2E Intent-based Closed Loop Coordination
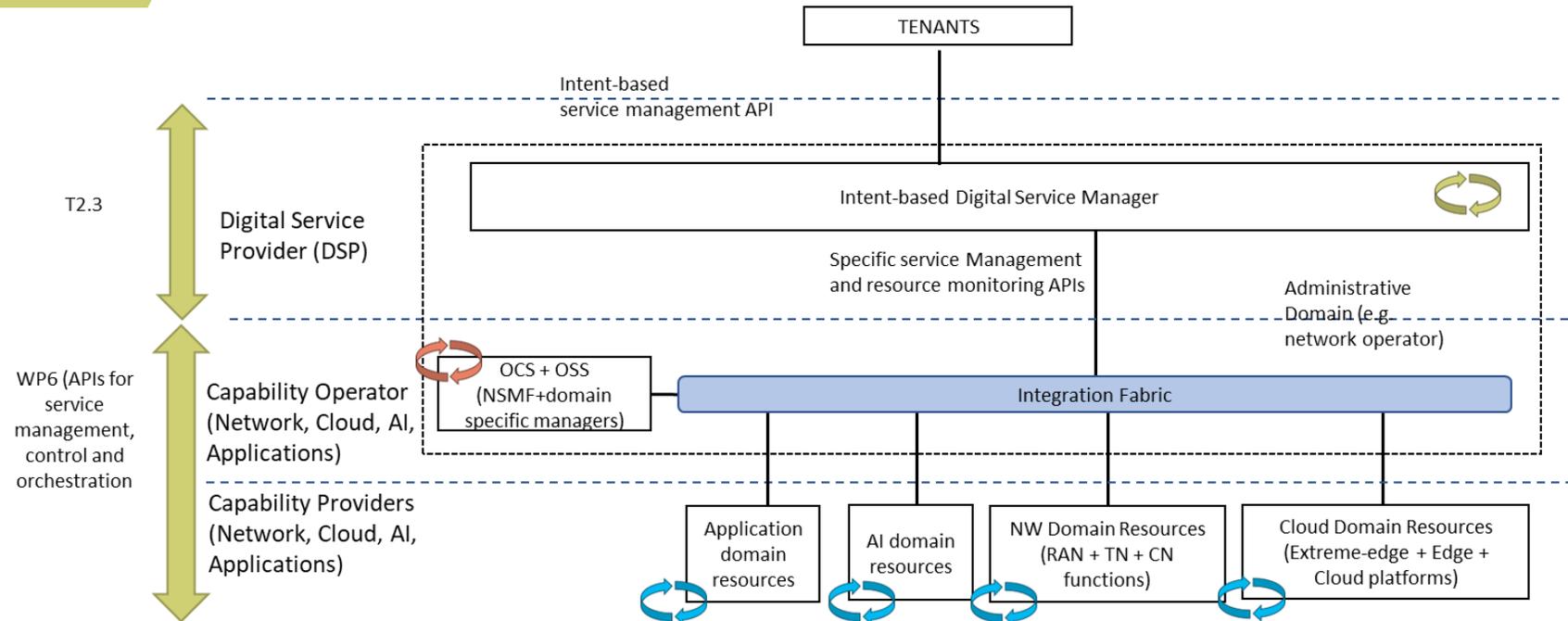
Coexistence of different Closed-Loops in 6G Systems

- **per-layer** (Business, Service, Resource)
- **per-tenant**

Integration Fabric creates **flatness** in the hierarchy of the actors

- DSP and COP access the same **monitoring data** at the same **time**
  - i.e., **Service** and **Business** CLs may react to the **same events**
    - **Risks:** race conditions, conflicting decisions, system instability

Coordination between those loops is **required**

- **Challenge:** CL coordinators at both DSP and COP
  - Coordination between CL Coordinators
  - Multi-layer case studies
    - CL Lifecycle Management
    - Race Conditions
    - Cooperation
    - Conflict Mitigation
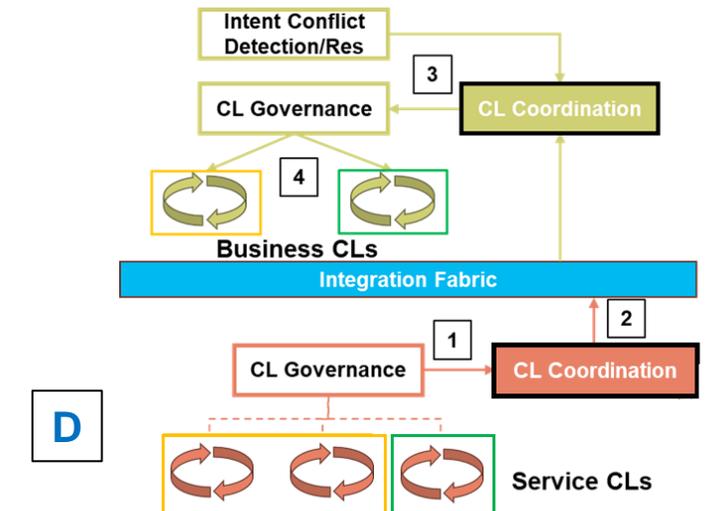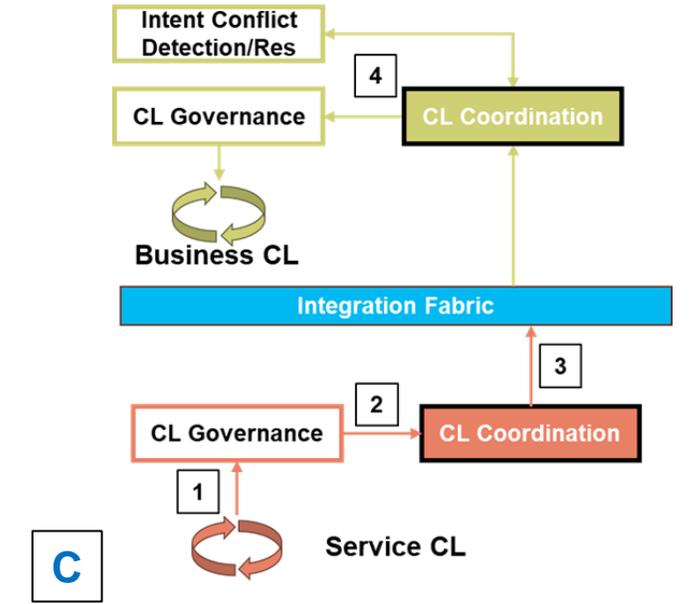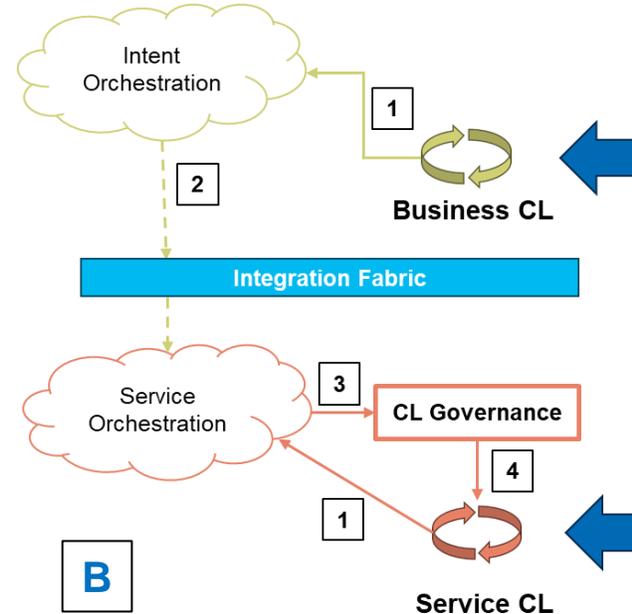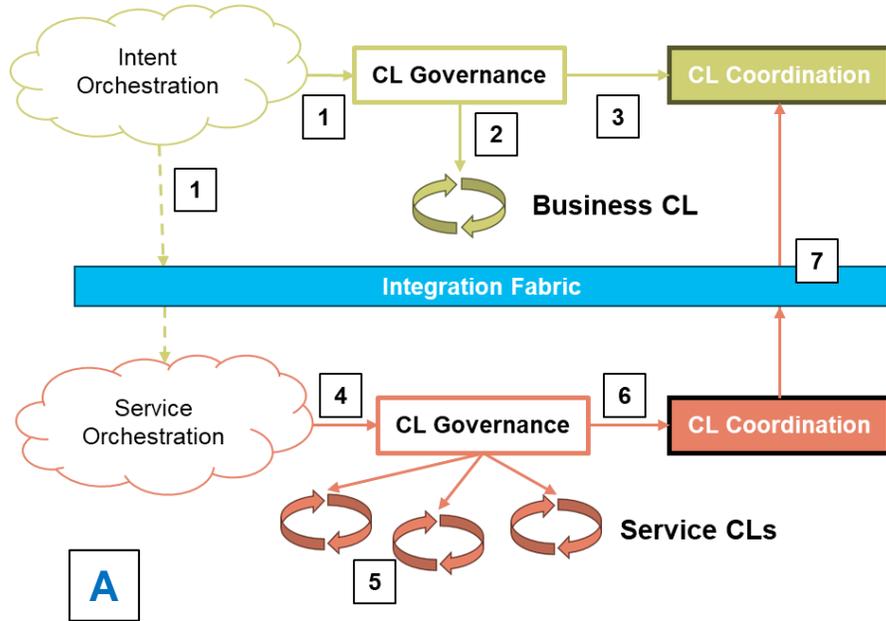
- **Figure A:** CL **lifecycle management** at E2E Service **Orchestration time**
- **Figure B: Race condition** between CLs at DSP and COP layers
- **Figure C: Inter-layer CL Cooperation** through **Escalation** towards DSP CL coordination
- **Figure D: Inter-layer** CL **conflict mitigation** through **Escalation**

E2E Intent-based Closed Loop Coordination (3)

CL Coordination in Multi-DSP Federation scenario

- Intent and CL information is declared and kept consistent in a single source-of-truth among involved DSMs

- The order of intent and CL executions are efficiently organized by the leading DSM and informed to assigned DSMs so that they are aware of their roles in the process

- Any deviation between the operating resources and the declared intent object, CL information, intent delivery pipeline, will trigger an autonomous reconciliation.
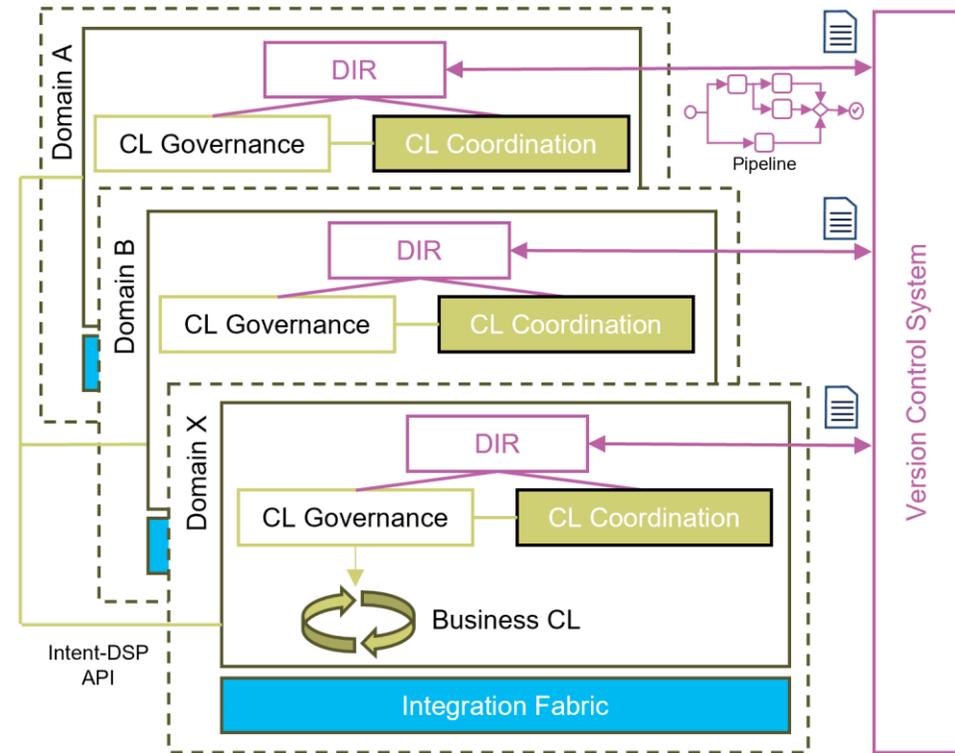
Component interaction for CLs management in the multi-DSP Federation scenario

E2E Intent-based Trust Management

Intent-based Trust Management

- Trust-related requirements using natural language

- High-level language together with an ad-hoc ontology for trust in Computing Continuum

- Incorporates existing ontologies (e.g. [TMFIO24]) to avoid redundancy

- Employs a custom Named Entity Recognition (NER) model

Level of Trust Assessment Function

- Oversees monitoring and decision-making related to trust requirements

- Monitors quantitative parameters (CPU, memory, processes, sensors, disks) to determine the health of network services

- Combines objective monitoring metrics with subjective indicators

- Decision Agent to handle trust lifecycle actions, addressing deviations or violations of trust agreements
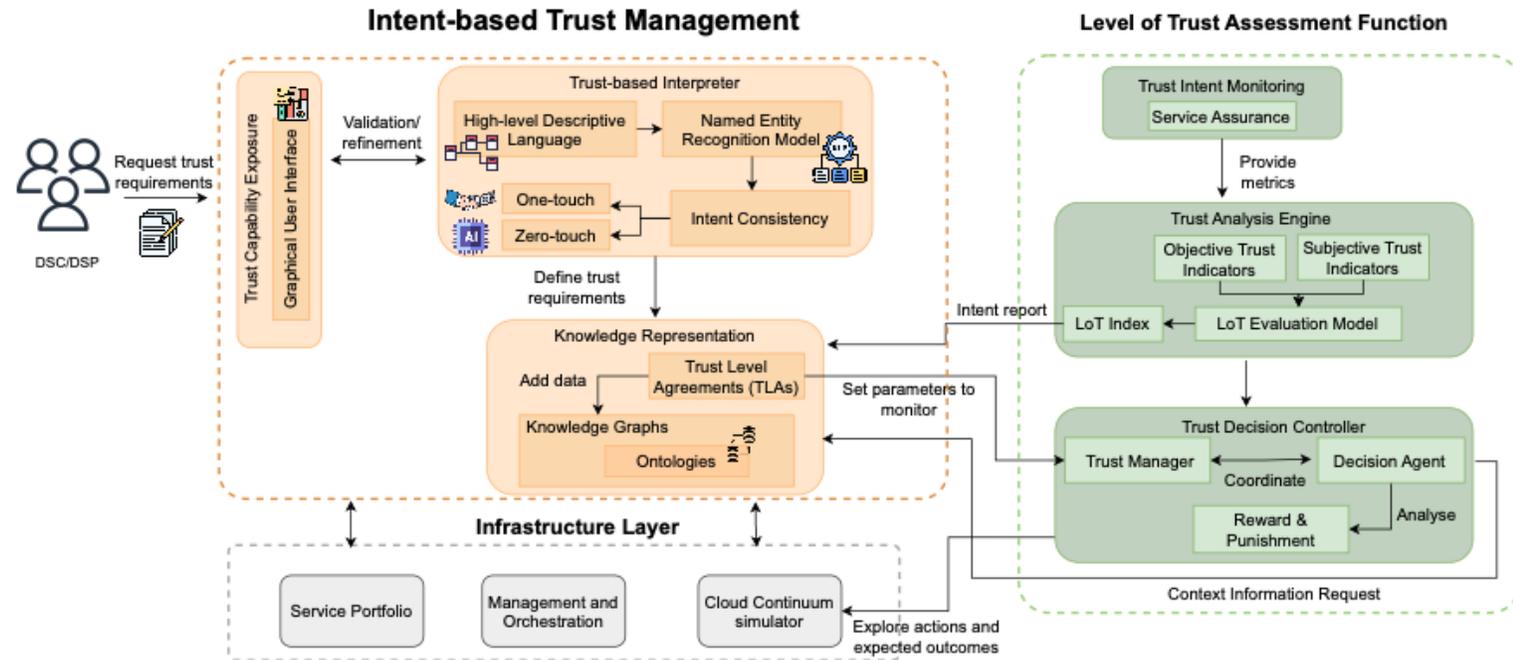
Level of Trust Framework Architecture

Conclusions and recommendations on Intent-based service management automation framework

- The chapter explores how future networks will evolve towards more autonomous and efficient systems through intent-based **management and orchestration** (M&O):

  - Intent-based M&O simplifies service delivery by allowing tenants to express service goals without needing to understand the technical infrastructure.

  - Two key models—aggregation and federation—are presented to enable autonomous interaction across domains, supported by essential DSM functionalities.

  - Use cases illustrate how intent-based systems can be structured for provisioning, evaluation, lifecycle management, and trust integration.

  - Despite advancements, challenges such as intent conflict resolution, security concerns, and standardization gaps remain open for future research.

Chapter 5
Security, Privacy and Resilience

PLS – Context Awareness

- Enhance Secret Key Generation (SKG) for the Physical Layer
  - Identifying different contexts in the channel environment

- Experiments based on an Universal Software Radio Peripheral (USRP)-based hardware demonstrator

- Measurements in different environments
  - Both USRPs stationary with a direct line-of-sight (LOS)
  - Both USRPs stationary without a direct LOS
  - Both USRPs in motion

- ML applied to extract features of signal characteristics
  - Delimiting the contexts

- Context-based identification of SKG parameters
  - Such as frame period for key generation, number of filters, and quantization levels
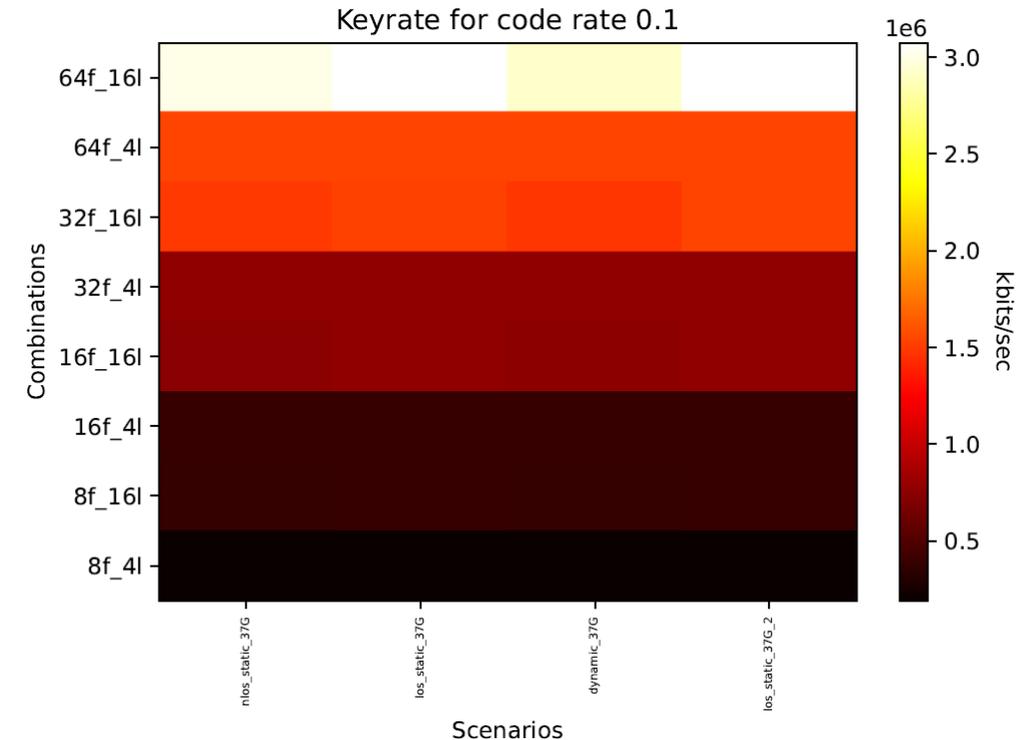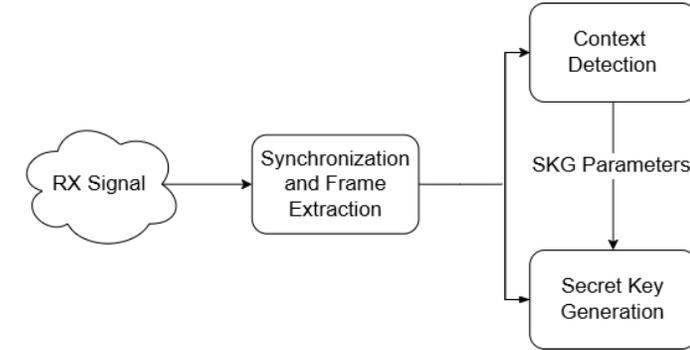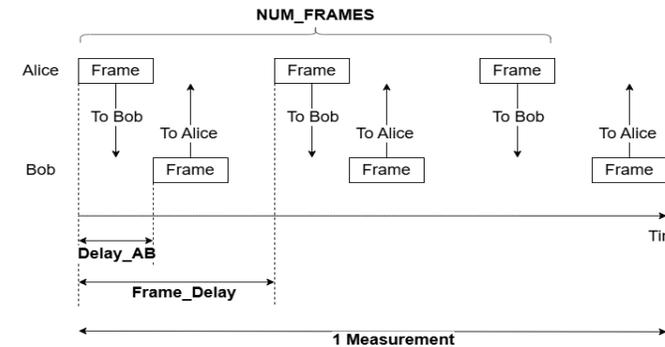
PLS - Physical Anomaly Detection

Placement of anomaly detection in RAN

- Enable efficient security measures through adaptive intrusion detection with AI/ML assisted security agents (SecA).

- Joint optimization of security and resource utilization by dynamically adjusting detection models.

- Consider an exemplified scenario for the deployment of security agents and joint security-QoS optimization applications in the RAN domain.
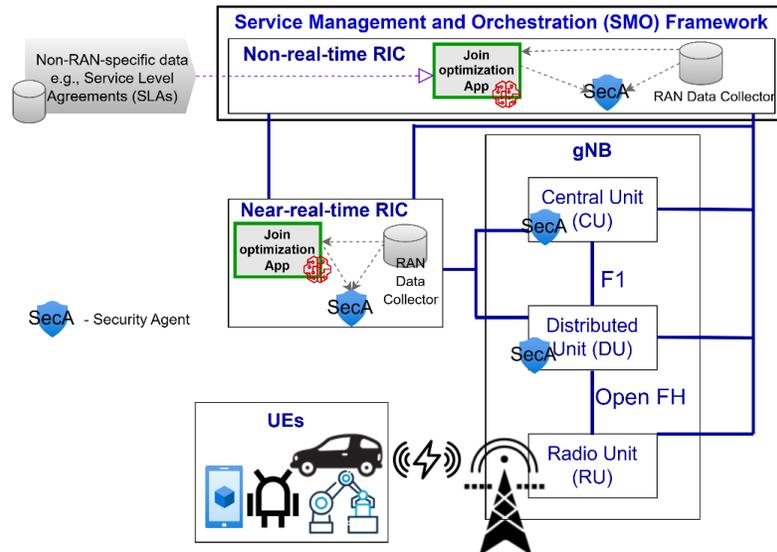
## Digital Twin (DT)-enabled spectrum anomaly detection

- High-fidelity detection of interfering signals (spectrum anomalies) is required for networks serving critical applications, e.g., non-public networks in factories

- A digital twin of the radio environment allows to integrate contextual awareness in the detection process and thereby improve the detection performance

System architecture
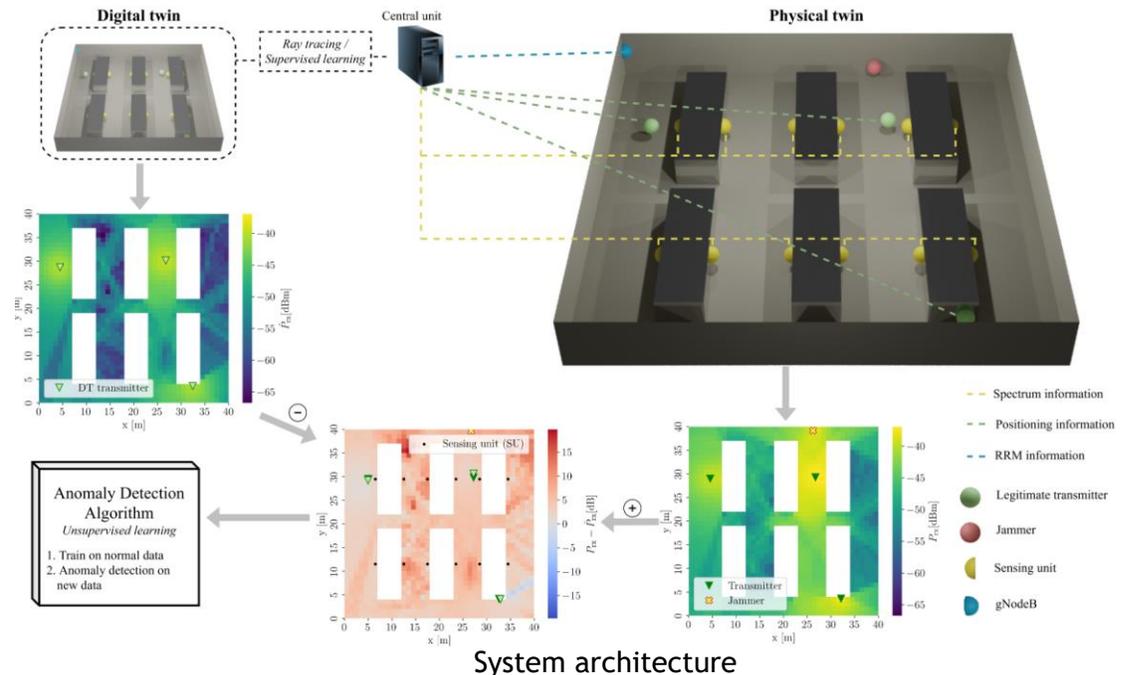
PLS - Physical Layer Deception

- Visual ENcryption for Eavesdropping Negation (VENENA)
  - A graphics-based deceptive encryption
  - As a proof of the Physical Layer Deception (PLD) concept proposed in previous deliverables

- Graphical semantic encoding by tag-image mapping

- Graphical semantic decoding by classification network

- Deceptive encryption with image poisoning network
  - Random falsified message as seed to generate the original image (deceptive message)
  - Poisoning network to generate the poisoned image (true message) and therewith the differential poison mask (key)
  - Power-domain mixing of individually encoded deceptive message and key
  - Successive Interference Cancellation (SIC) required at receiver to decode both the message (exposed) and the key (Physical Layer Security (PLS)-protected)

- Successfully demonstrated feasibility with realistic encoders (rather than only bound-analysis)
  - Very low coding rate, which can be improved by using better knowledge base or better encoding method for practical use
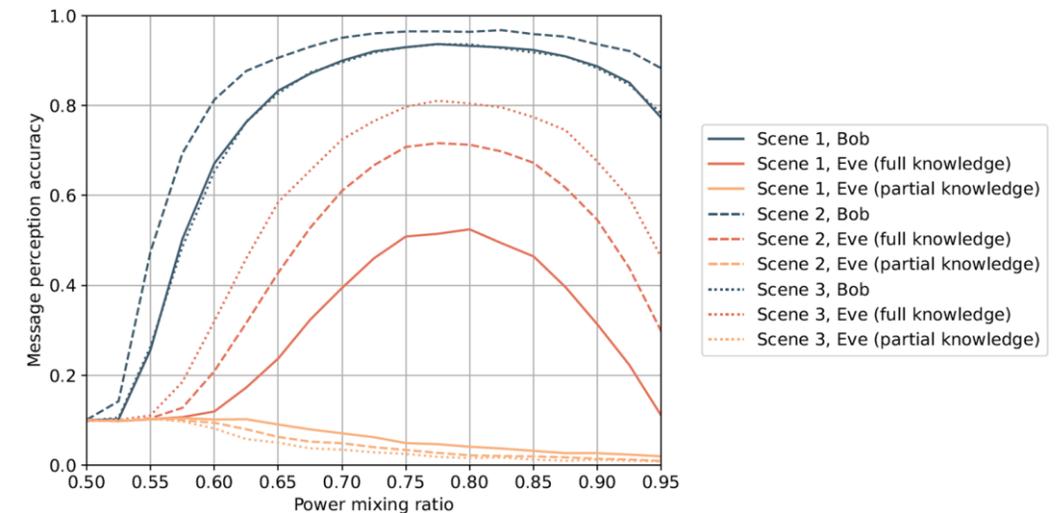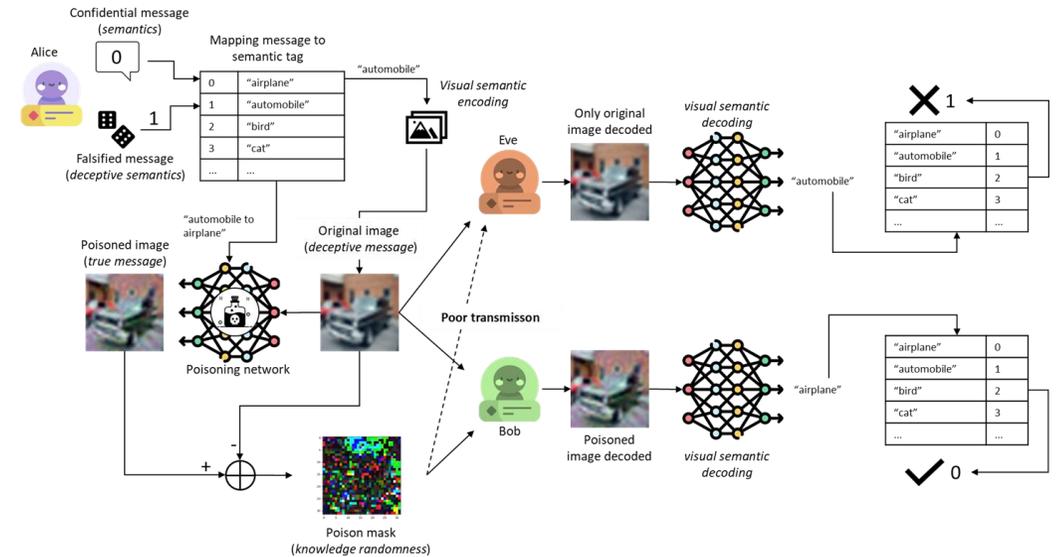
Resilience Simulations

- Availability calculation tool
  - Virtual Network Function (VNF) level
  - Virtualization layer
  - Hosting infrastructure the VNFs
- Simulate scenarios based on the Lower Layer split (LLS) architecture
  - Customizable parameters
  - Considering microservice replicas and VNF redundancy
- Use Reliability Block Diagrams (RBDs)
  - Model and analyze dependencies between components
  - Model interdependencies of VNFs, microservices, and replicas
- Demonstrated in four scenarios
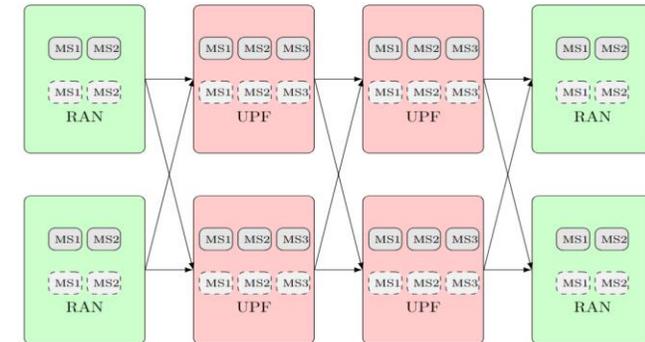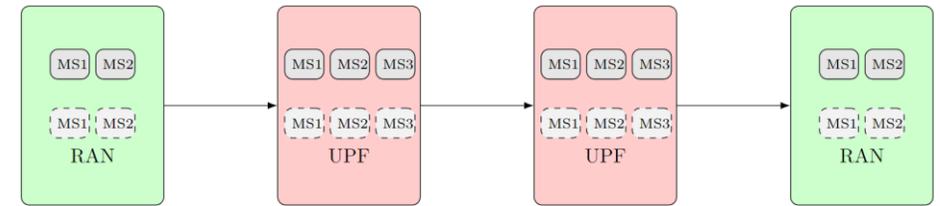

Availability for Each Scenario
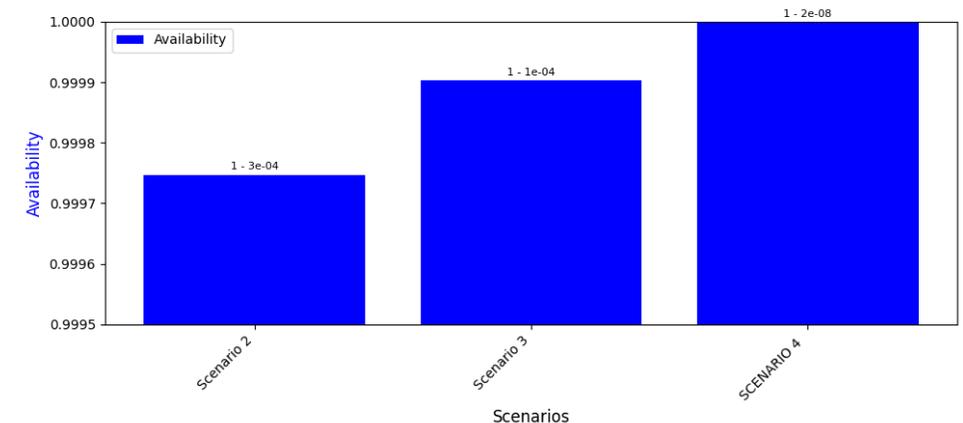
Security & Privacy (S&P) Controls for Threat Mitigation in JCAS

While some of the existing 5G S&P controls can be reused for JCAS, more investigation is required for certain aspects mentioned below:

- Authentication of UE Sensing Unit entities and authorization of network by UE Sensing Units for sensing purpose

- Logging and data provenance related to sensing activities

- Protecting JCAS data in-transit

- Sensing data security in UE and network nodes

- Physical layer security
  - Protection from physical attacks such as ghosting of real objects
  - Protection from sensing jamming

- UE sensing security
  - Security of sensing data at UE
  - Transparency solution at UE

- Data minimization and anonymization techniques at software (SW) and HW level

- Privacy-preserving computation techniques at UE and network for processing sensing data
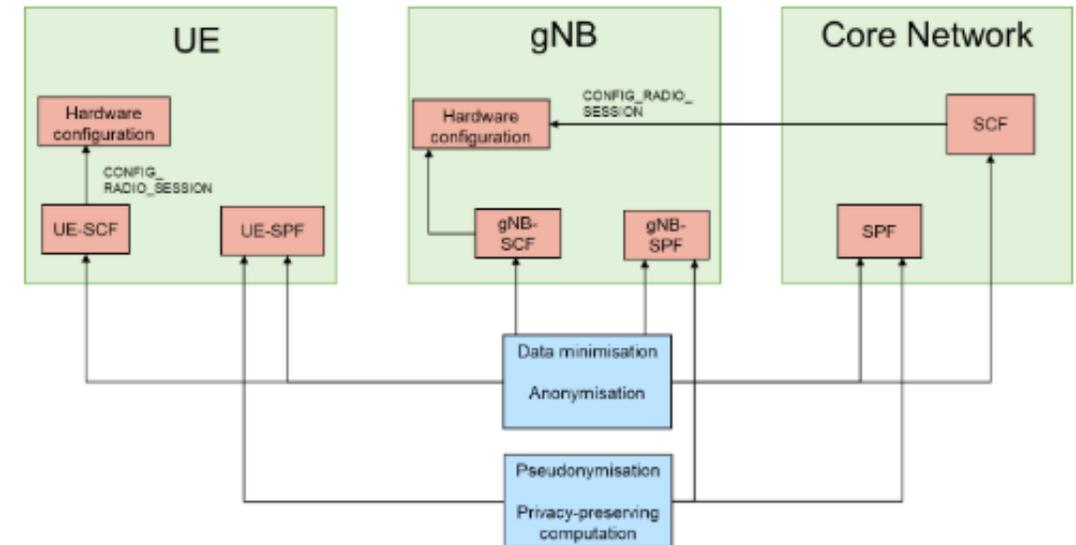

Privacy preserving JCAS framework

Integration Patterns for Trustworthy AI

- Integration patterns
  - Depending on trust assumptions and threat models
  - Not centrally controlled: utilize the controls wherever SPR of AI/ML is needed
- Further evaluation of the developed framework (FASIL: a challenged-based FrAmework for Secure and prIvacy-preserving federated Learning):
  - Allow the usage of any secure aggregation schemes
  - Detection of security attacks against the federated learning (FL) process
    - Security against malicious clients
  - Prevention of information leakage about training data sets
    - Privacy against curious aggregator)
  - Acceptable computation and communication overhead.
- XAI for robustness of AI/ML
  - Making AI/ML based security systems in 6G more robust against bypass attacks.

Evaluation of resistance to the deep leakage from gradients privacy attack

Setup	Attack success metric
Secure Aggregation FL	0.1013
FASIL with 0/10 opened layer	0.1013
FASIL with 1/10 opened layer	0.0975
FASIL with 2/10 opened layer	0.0929
FASIL with 3/10 opened layer	0.0881
FASIL with 4/10 opened layer	0.0844
FASIL with 5/10 opened layer	0.0708
FASIL with 6/10 opened layer	0.0428
FASIL with 7/10 opened layer	0.0213
FASIL with 8/10 opened layer	0.0139
FASIL with 9/10 opened layer	0.0116
FASIL with 10/10 opened layer	0.0014
Plain FL	0.0014

Pairwise Distance for Each Client
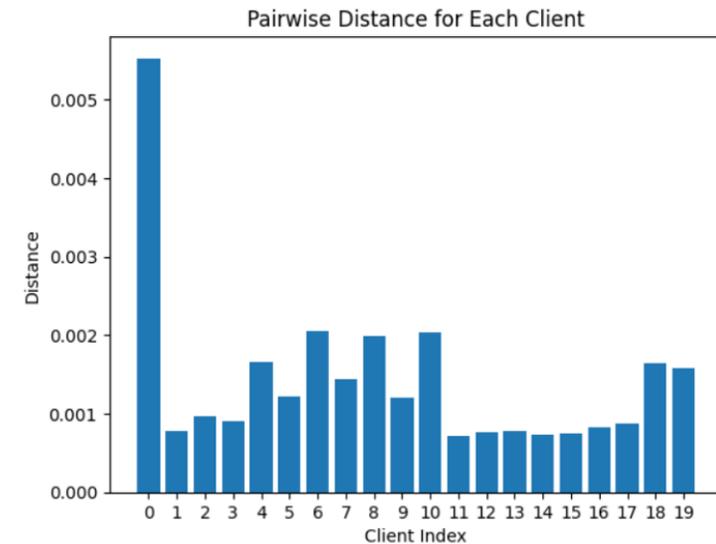
Concrete computation and communication cost and overhead of FASIL

Plain FL		Secure aggregation FL		Proposed protocol	
Comp [s]	Comm [MB]	Comp [s]	Comm [MB]	Comp [s]	Comm [MB]
170.03	6.87	179.35	6.91	182.30	8.09

# Integrating other 6G Enablers from SNS JU projects

- DevSecOps (Development, Security and Operations) practices
  - Privacy modelling and quantification through privacy manifests
  - Continuous privacy evaluation during service updates
  - From project RIGOUROUS [SNS-RIG]

- What-If scenario framework
  - Use Network Digital Twin (NDT) to evaluate and assess the impact of security countermeasures
  - On threats and network performance
  - From project HORSE [SNS-HOR]

- Zero-touch remediation framework
  - Integrating NDT and AI-based decision making
  - Automated security operations
  - From project ACROSS [SNS-ACR]

Notary Service for Transparency

- Evidence for assessing trustworthiness
  - Inspired on the SCITT* architecture being defined by the IETF

- Main components and procedures identified

- Analysis of use cases
  - Vendor-to-operator
  - Intra-operator
  - Inter-domain
  - Network-edge-cloud continuum

- Connection with the LoTAF (Level of Trust Assessment Function) proposal
  - Reliable evidence source(s)

- Analysis of standardization needs

*SCITT: Supply Chain Integrity, Transparency, and Trust
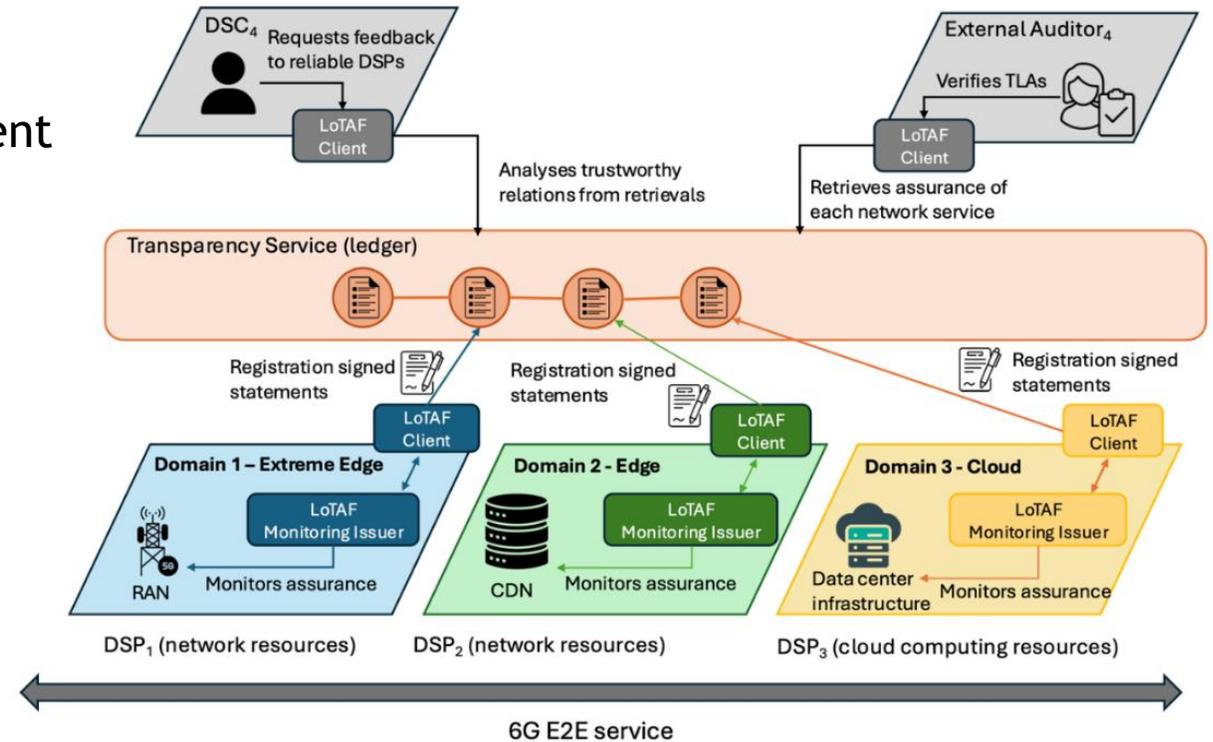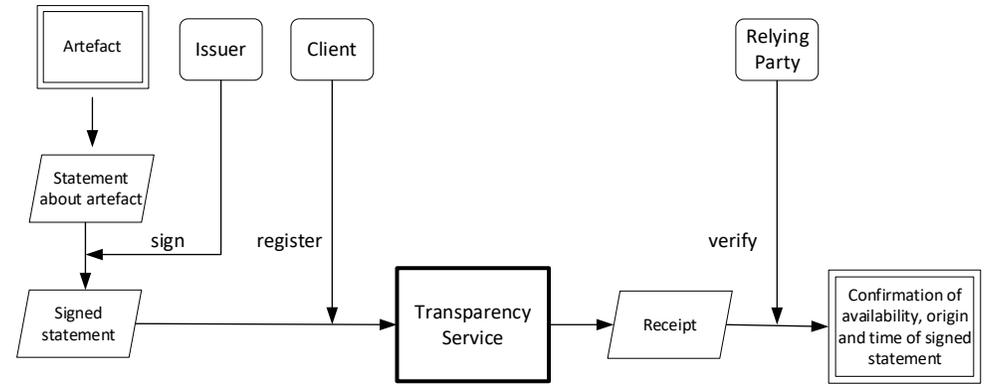
Conclusions and Recommendations on Security, Privacy and Resilience

- Conclude the work focused on the *6G Delta* on Security, Privacy & Resilience (SPR)
  - Specific threats associated with the technology evolution being proposed for 6G
  - And their potential mitigation tools
- Final evaluation of SPR controls and patterns
  - Experimental results focused on Physical Layer Security (PLS)
  - Outcomes on resilience simulations
  - Threat mitigation for privacy and data security in JCAS
  - Integration patterns for trustworthy AI
  - Analyze three significant enablers in development by other SNS projects
- Introduce the proposal for a Trusted Notary Service
  - Reliable source of evidence for assessing trustworthiness
  - Focal point for data related to this assessment procedures, via LoTAF
- Support the discussion for the SPR view of the system blueprint in chapter 6
- Set the ground for SPR considerations on 6G enablers in chapter 8

Chapter 6
Overall 6G system design

Overarching 6G system blueprint

Application enablement platform & Application layers:
- a unified platform for developers and third-party applications to leverage 6G capabilities.
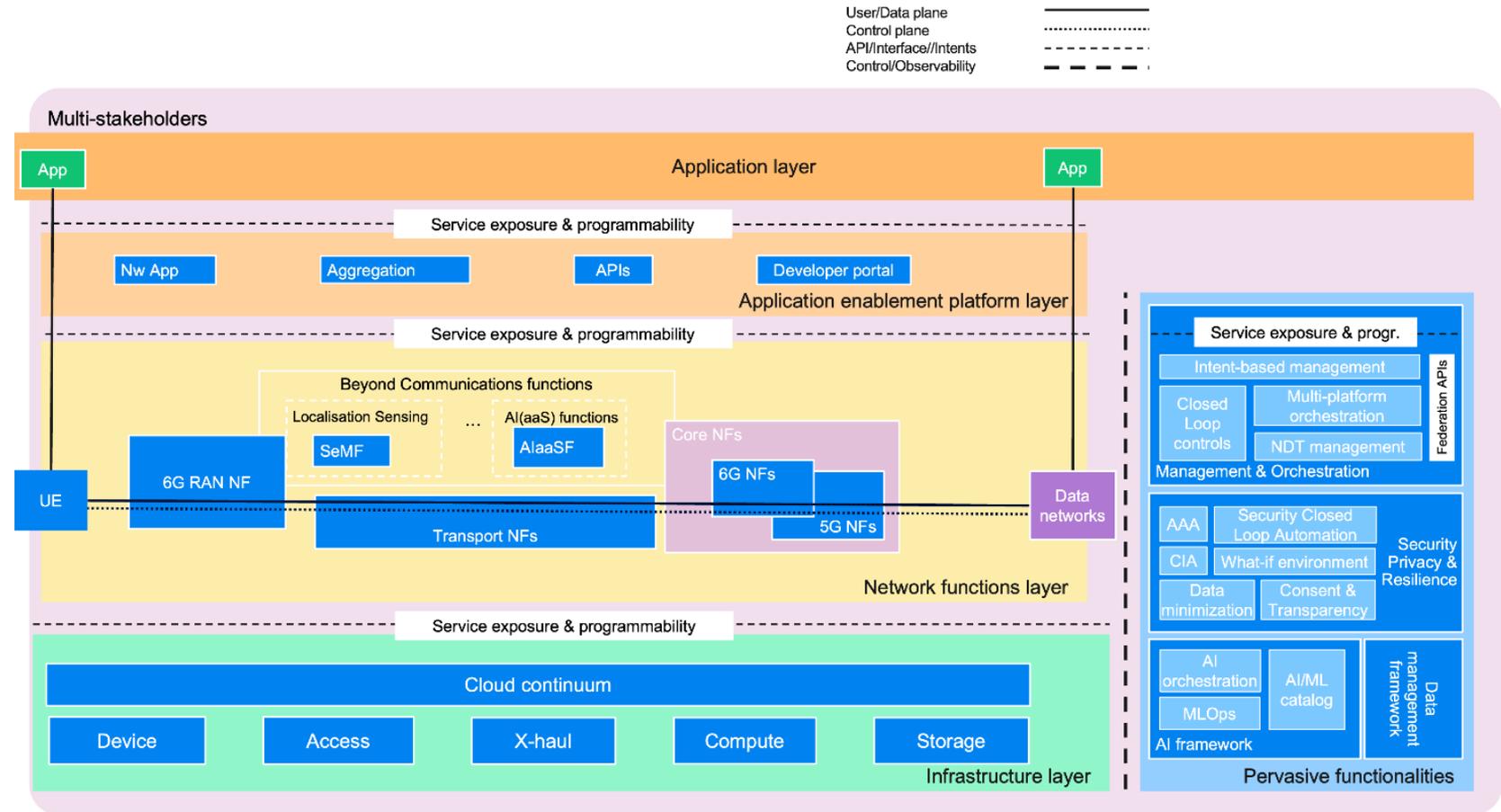
Network functions layer
- a single radio access technology, an extended core, and beyond communications capabilities

Infrastructure layer
- delivering a cloud continuum

Pervasive functionalities
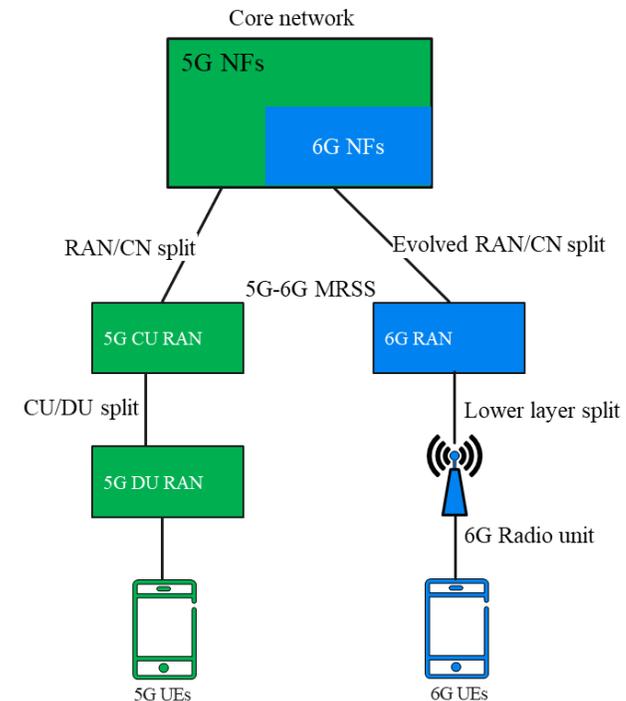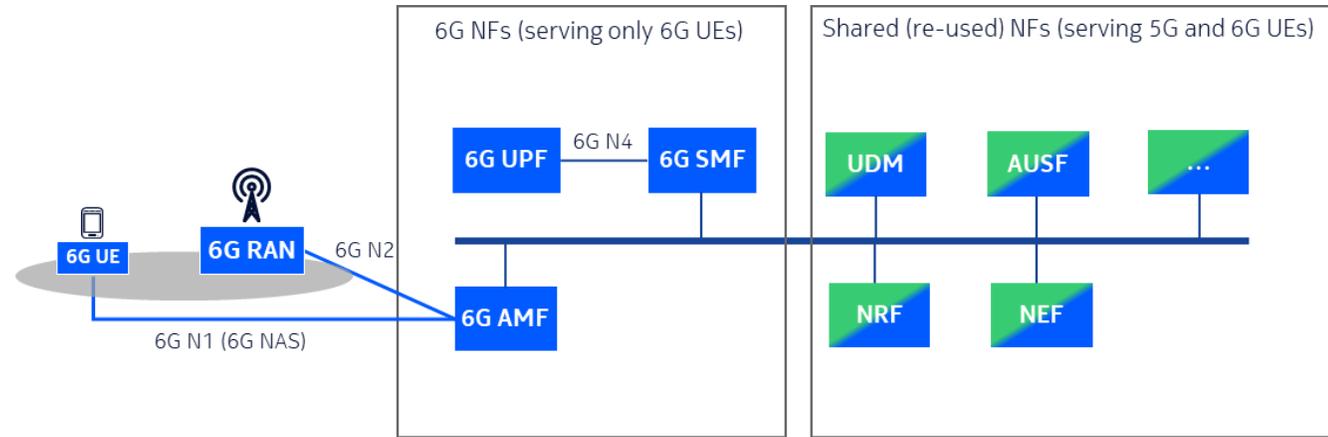- enabling AI/ML, data, security, and automation across all layers

Specific views complement the system blueprint (in the following slides)
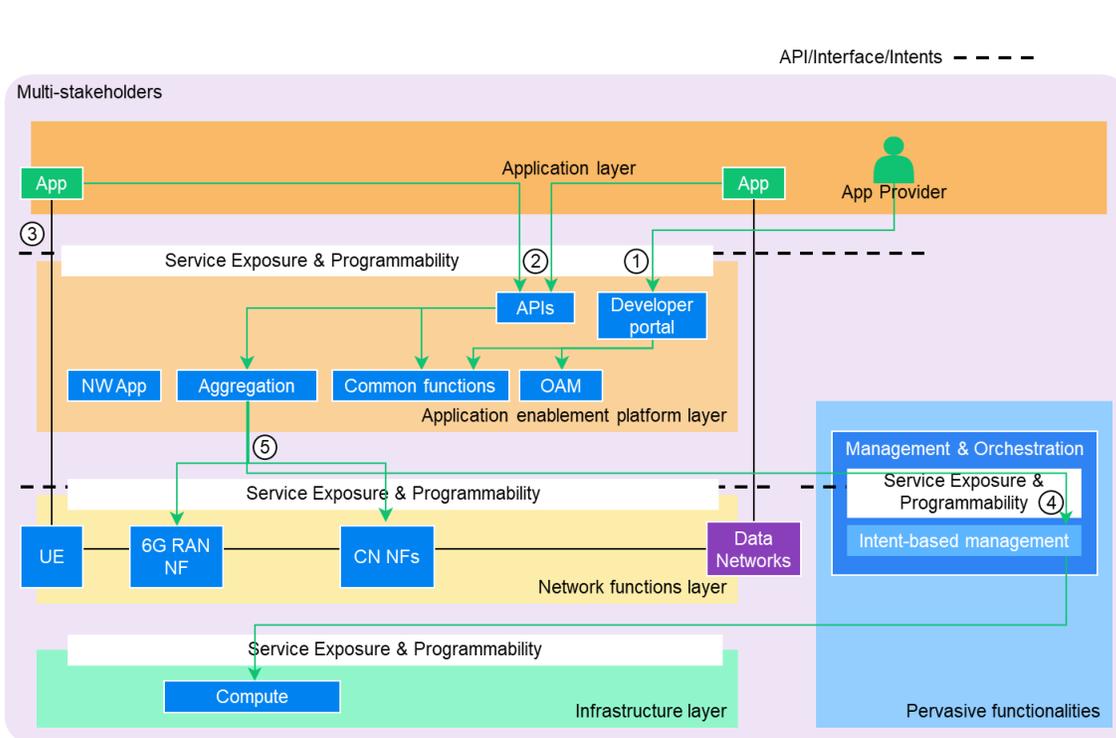
Migration Path view

- Core design in 6G based on evolution of 5G Core with 6G NFs and Shared NFs

- Interworking between 5G and 6G is done by Multi-Radio Spectrum Sharing (MRSS)

- Lower layer split (LLS) in the RAN

AMF: Access and Mobility Management Function
AUSF: Authentication Server Function
CN: Core Network
CU/DU: Centralized Unit / Distributed Unit
NEF: Network Exposure Function
NRF: Network function Repository Function
SMF: Session Management Function
UDM: Unified Data Management
UPF: User Plane Function

6G NFs (serving only 6G UEs)

Shared (re-used) NFs (serving 5G and 6G UEs)

6G UE | 6G RAN | 6G N2

6G UPF — 6G N4 — 6G SMF

UDM | AUSF | ...

NRF | NEF

6G N1 (6G NAS)

6G AMF

Core network

5G NFs

6G NFs

RAN/CN split

Evolved RAN/CN split

5G-6G MRSS

5G CU RAN

6G RAN

CU/DU split

Lower layer split

5G DU RAN

6G Radio unit

5G UEs

6G UEs

System view on new 6G services & exposure framework

Exposure-centric view

- Support various flavors of the service exposure delivery
- Enabling the exposure of new 6G services and network programmability capabilities
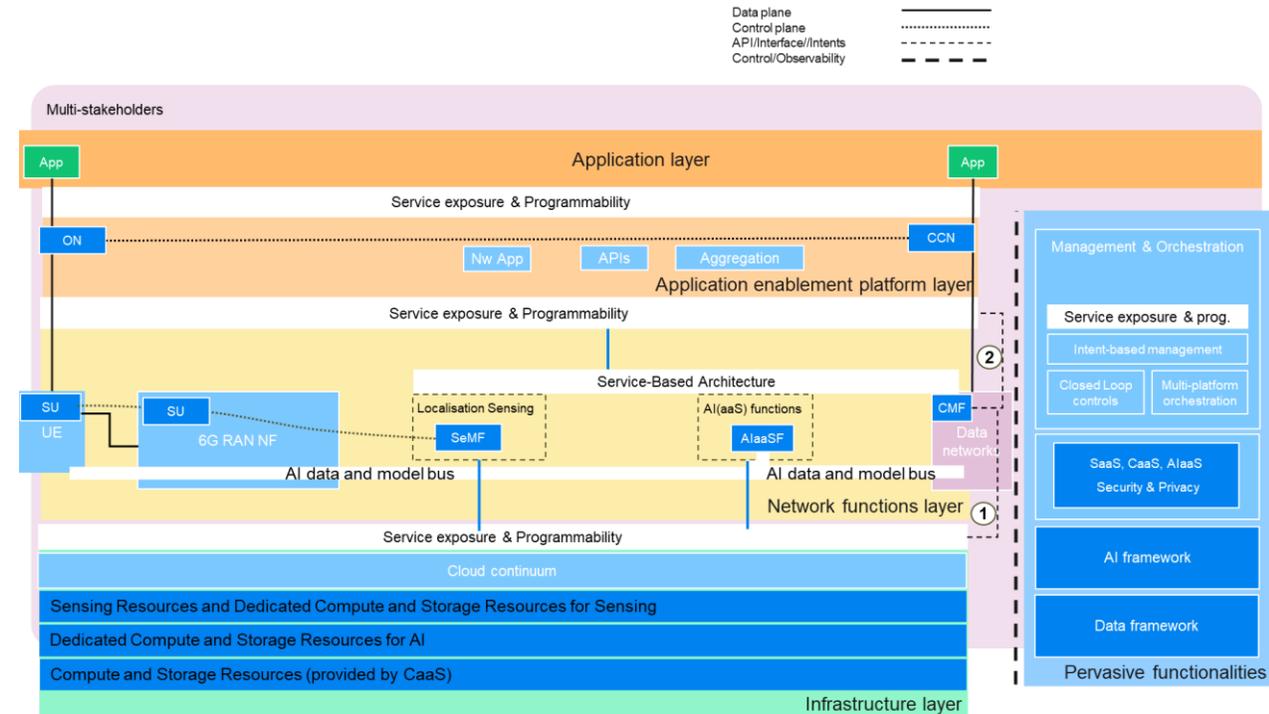
Integrated new services view

- Sensing functions (Sensing Unit -SU, Sensing Management Function -SeMF), AI as a Service (AIaaS)
- Processing offloading functions (Offloading Node -ON, Compute Controlling Node -CNN)
- Compute Management (CMF) – In-network compute resource

System view on radio protocols

- Enablers for Radio Connection Management
  - e.g., mobility management and L2 data recovery mechanisms)
- Integrated new services signalling
  - Sensing, AI, Compute as a Service (SeaaS, AIaaS, and CaaS) signalling
- 6G Transceiver Architecture
- 6G System-on-Chip (SoC)
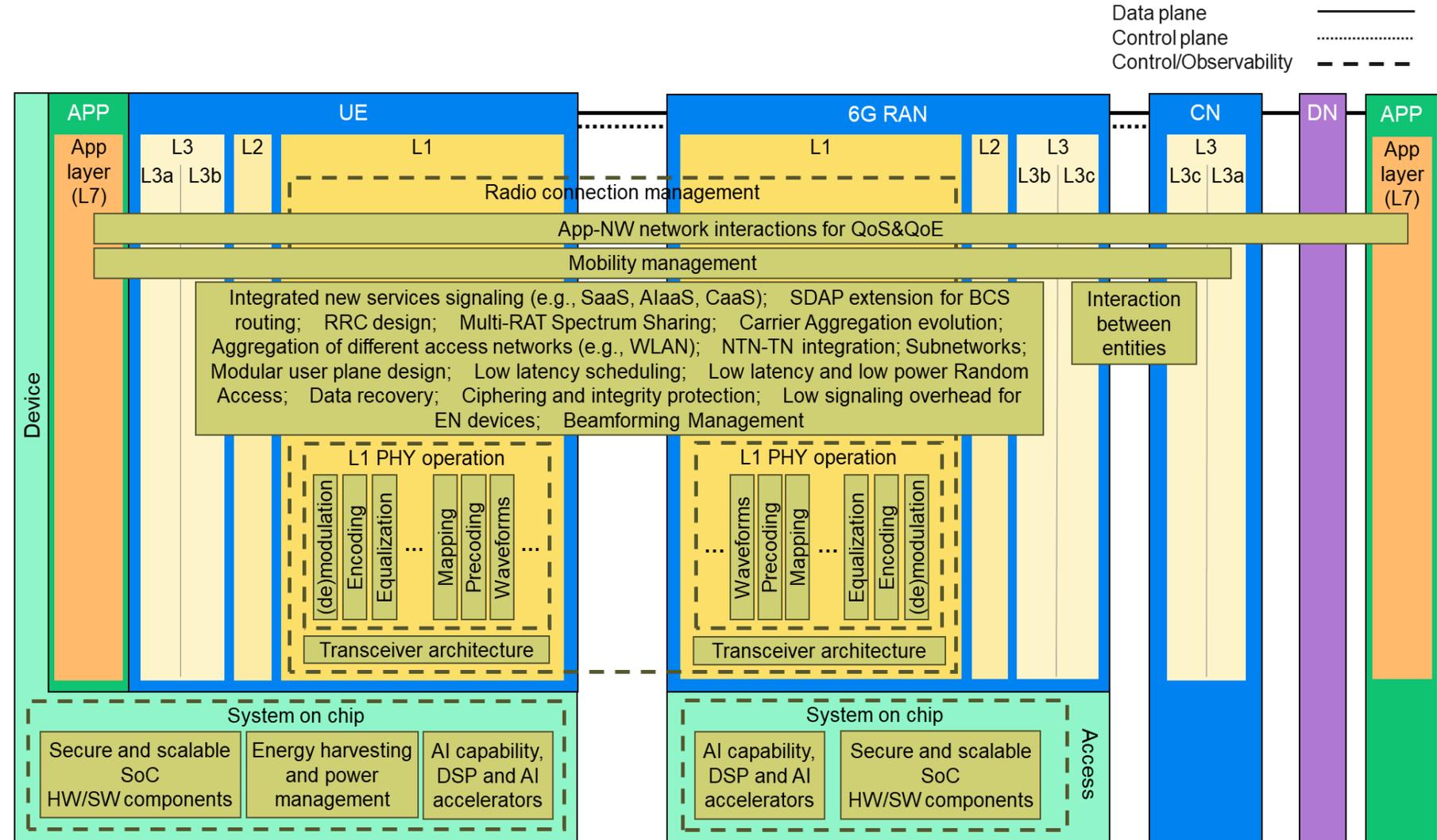
System view on new accesses and flexible topologies

- TN-NTN

- Subnetworks

- Unmanned Aerial Vehicle (UAV)-based Multi-hop Backhaul

- Multi-connectivity
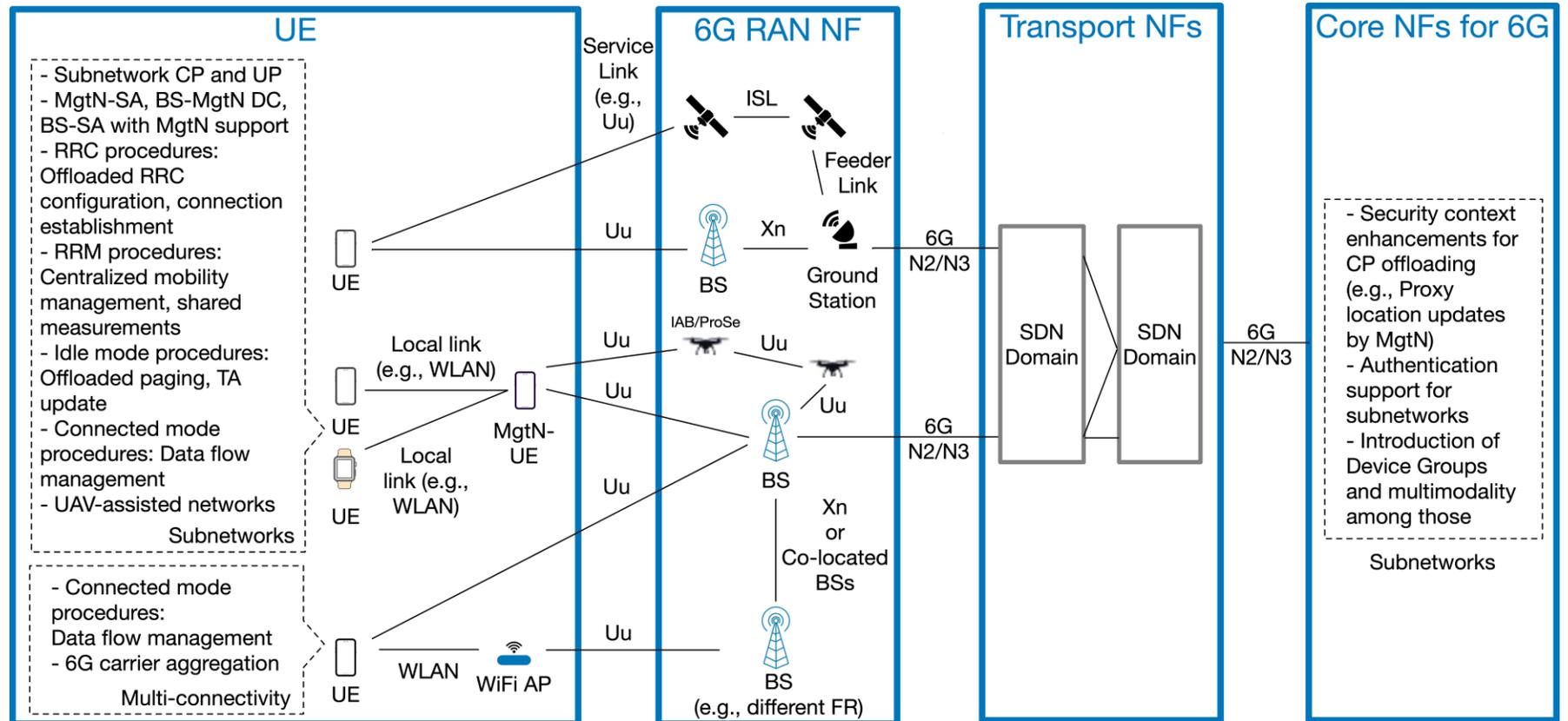
ISL: Inter Satellite Link
SDN: Software Defined Network
WLAN: Wireless LAN

System view on multi-stakeholder support

A single Federation interface supporting various models (peer-to-peer/brokering)

Controllable capability exposures (of services, M&O and federation capabilities)

A same Intent Application Programming Interfaces (APIs) on North Bound Interface (NBI) or East/West Bound Interface (E/WBI) for service requests from a service customers
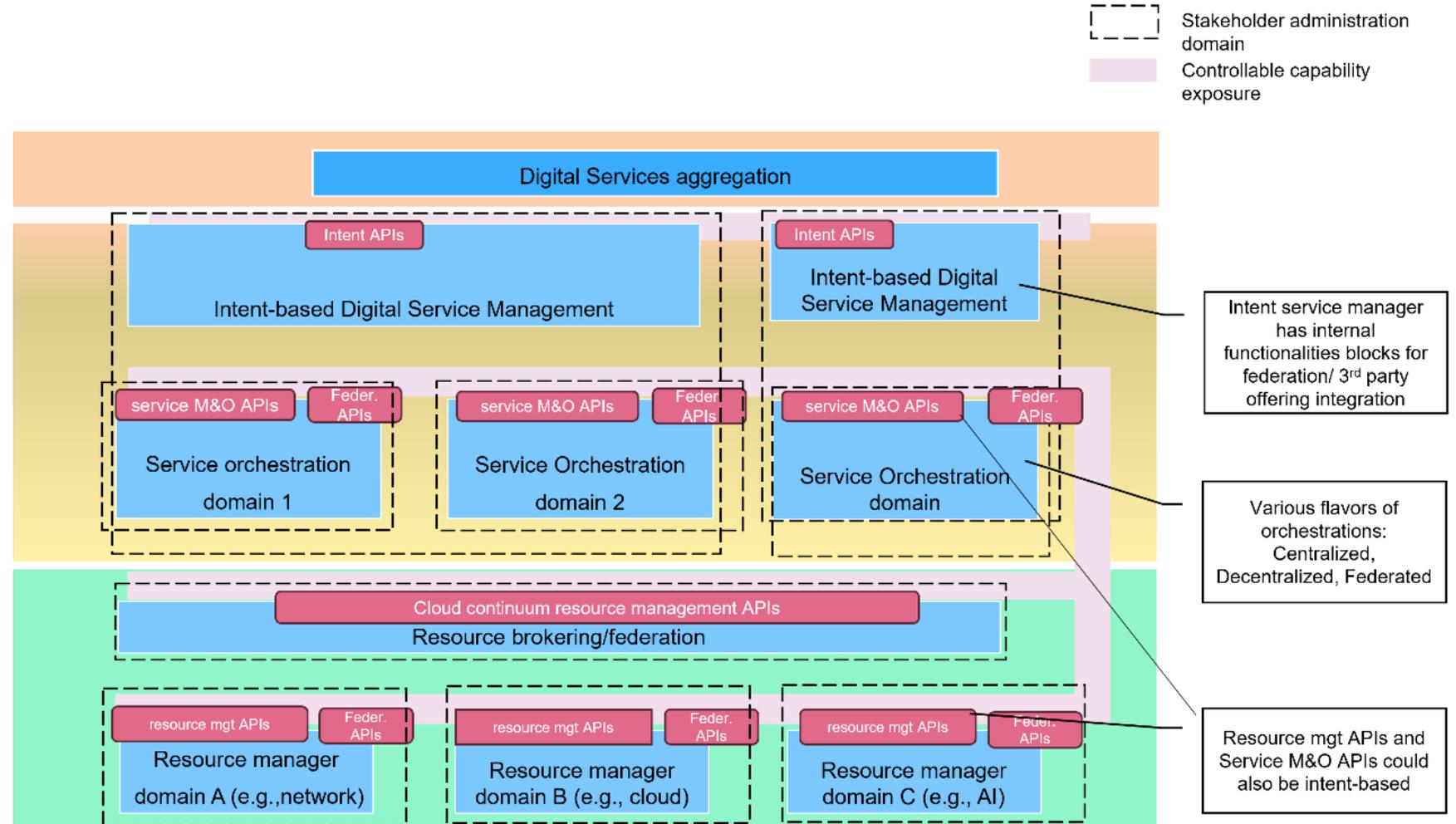
System view on AI/ML and data framework

Each layer contributes to AI/ML processes.

- **AIaasF:** Exposure framework for various consumers, providing customized AI services tailored for the 6G ecosystem.

- **AI Orchestrator:** Manages AI service deployment, execution, and lifecycle.

- **AI/ML Catalogue:** Stores pre-trained AI models, algorithms, and metadata.

- **MLOps Orchestrator:** Manages the end-to-end lifecycle of AI/ML models.

- **Data Framework:** Ensures data collection, processing, and governance, adhering to regulatory requirements.
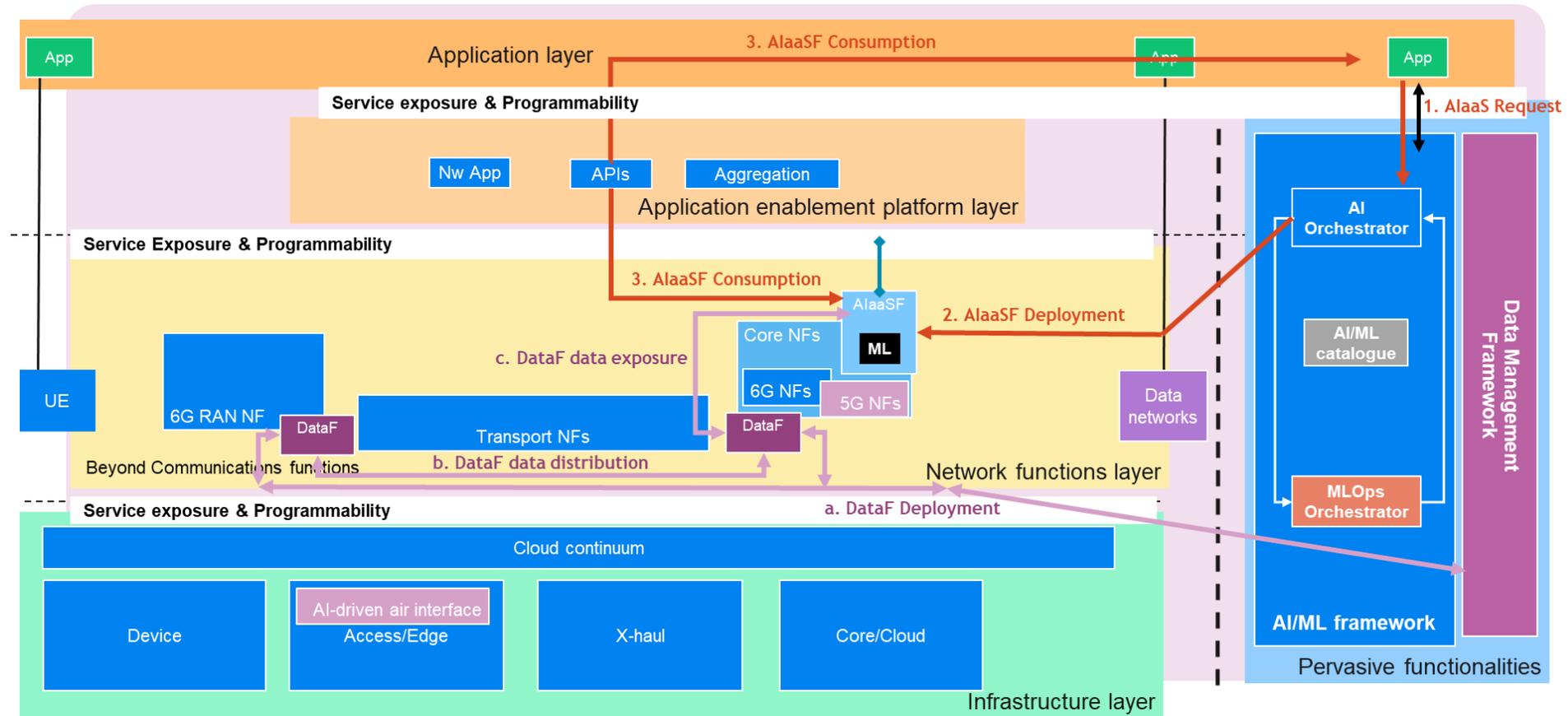
System view on Security, Privacy & Resilience (SPR)

SPR controls featuring confidentiality, integrity, availability, authentication, authorization, privacy and resilience.

Applied across different layers of the 6G system

- **System-level resilience:** Ensuring closed-loop automation for security management.

- **Multi-stakeholder ecosystem:** Addressing security challenges with proper isolation and trust mechanisms.

- **New 6G services:** Securely exposing services and capabilities provided by the 6G platform with strong authentication, authorization, and quantum-safe cryptography.

- **LoTAF and notary services**
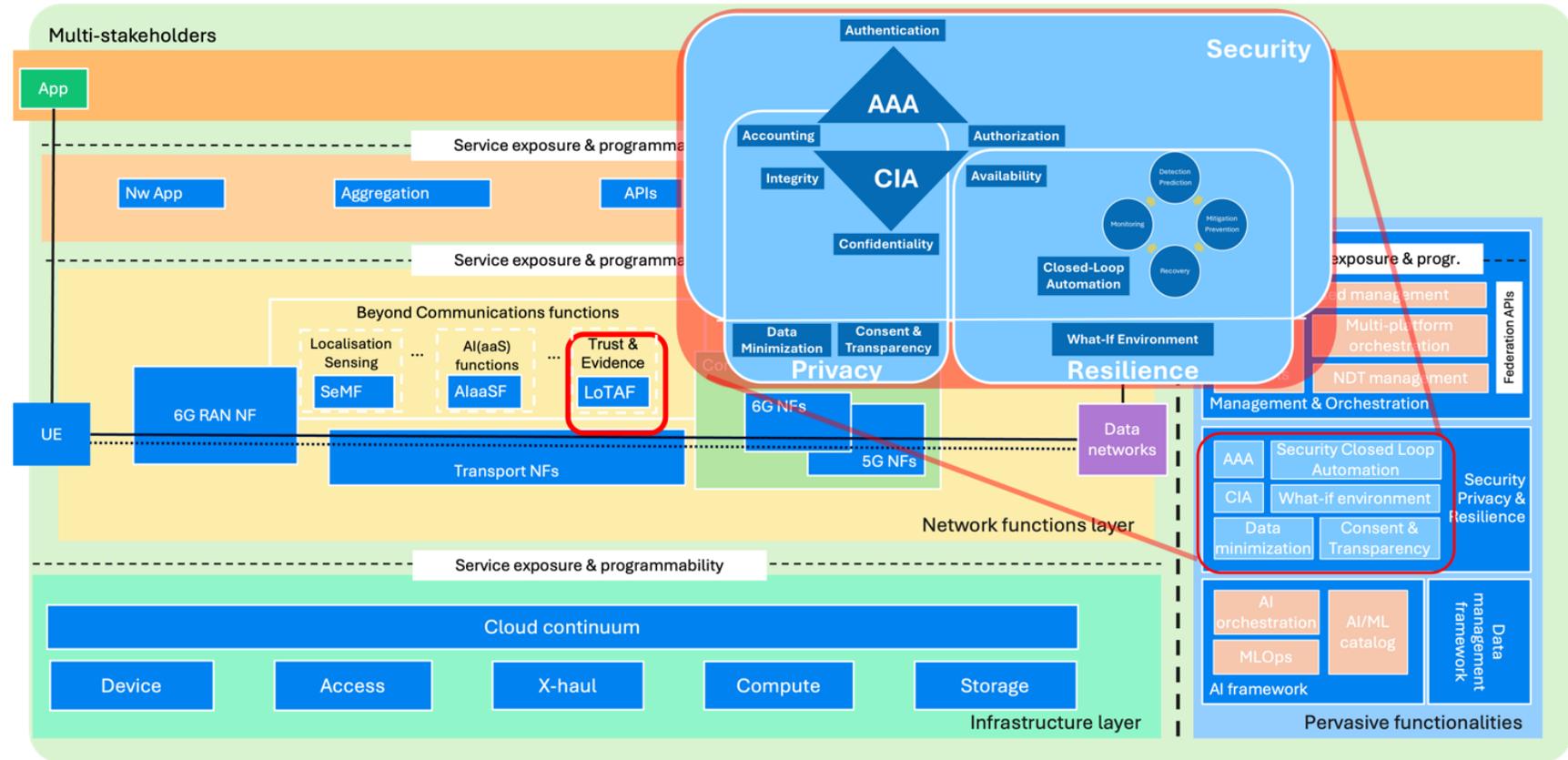
AAA: Authentication, Authorisation and Accounting
CIA: Confidentiality, Integrity and Availability

Enabler selection methodology for industrial cobots use case

- Noisy Knowledge Graph generation
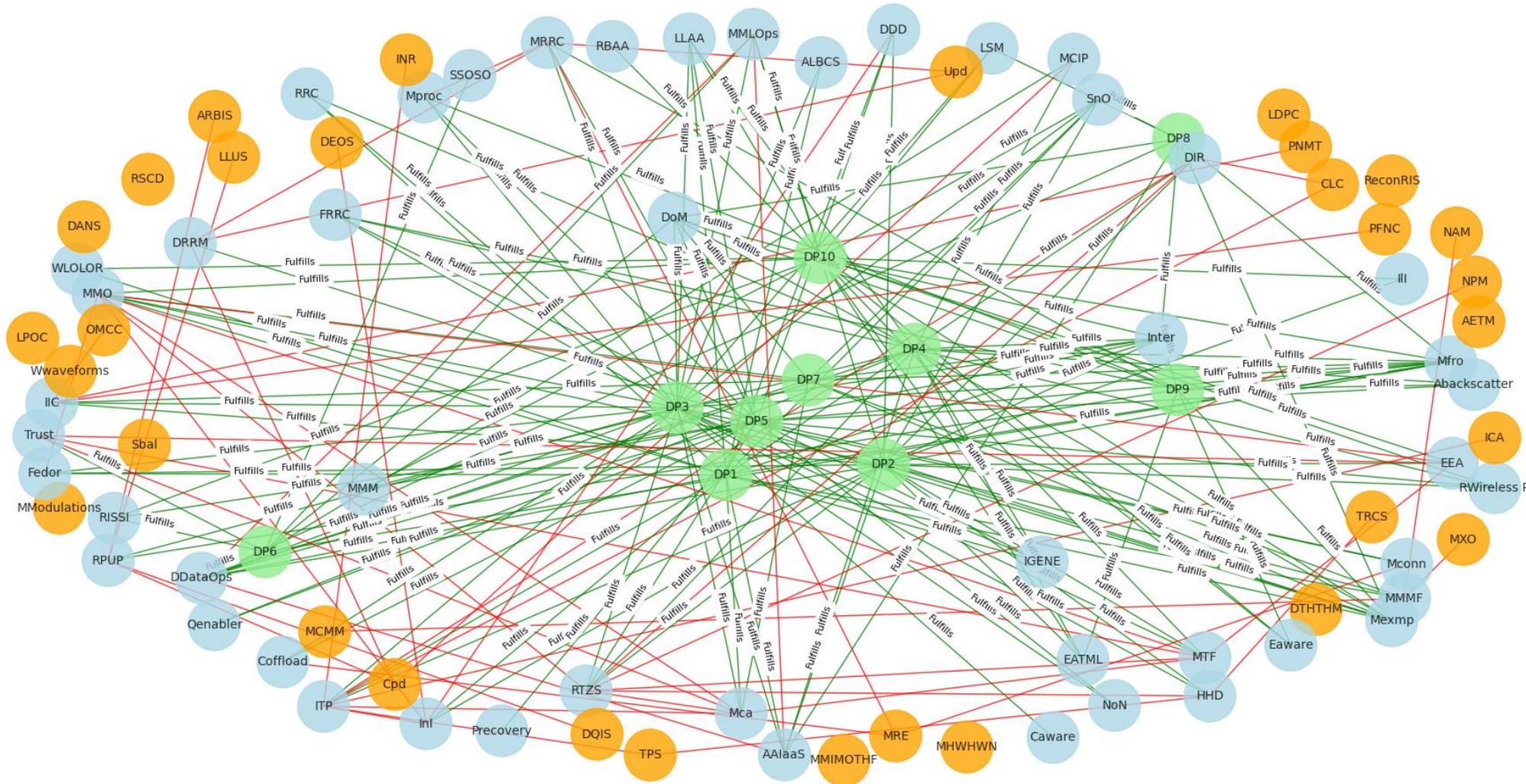
Green bubbles – Design Principles (DP)

Blue Bubbles – Enablers that satisfy at least one DP

Orange Bubbles – Enablers that do not specify any DP

Green edge – Edge between DP and Enablers

Red edge – Edge between enablers and dependent enablers

Node features – KPI data, maturity, importance towards migration

Enabler selection methodology for industrial cobots use case

- Graph pruning

Pruning based on maturity, migration

Pruning based on KPI data

Adjustment based on KVIs and pragmatic considerations
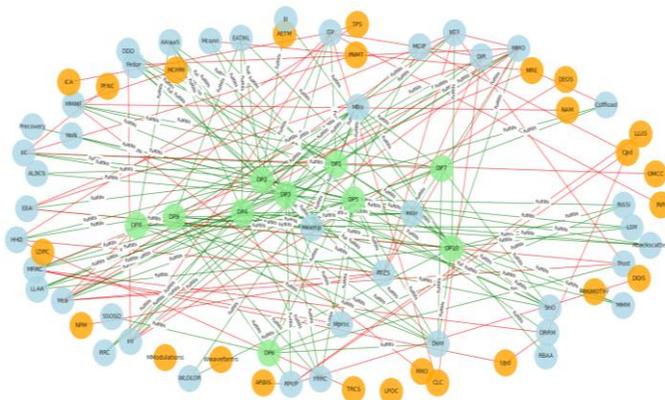
1. All migration-related enablers selected
2. Minimum TRL is 2 for enabler selection
   - Idea is to not penalize research oriented enablers
   - But also to not select enablers which are still very green, unless necessary
3. All dependencies selected
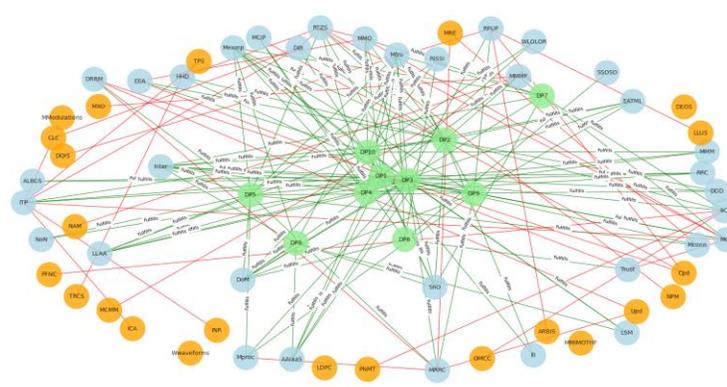
Enablers with a net-positive impact on KPIs

KVI analysis-based selection, followed by Pragmatic consideration to add important enablers missed from this analysis

Enabler selection for industrial cobots use case

- Migration, Maturity and KPI based selected list: Example of categorized enablers*

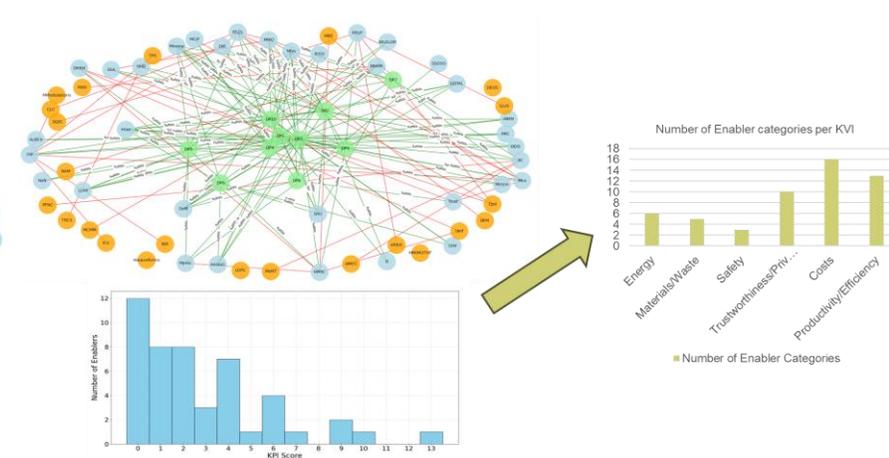| Category	Enabler Name
Intelligent radio interface	• ITx: Intelligent transmitter • IRx: Intelligent receiver • ITRx: Intelligent transmitter and receiver • SpecShare: Spectrum sharing, coexistence
JCAS PHY	• JCSWave: JCAS waveforms and frame structures • JCSRA: JCAS resource allocation
New Devices	• IGENE: Identification of 4 new 6G device classes (RHDRBL, HRLL, EmMTC, EN)
Flexible radio interface and protocol	• FRRC: Flat RRC design • SICMS: Separation of IDLE mode and CONNECTED mode signalling • SDAPBCS: SDAP protocol for beyond communication services • DRRM: Data Recovery and reordering mechanisms • MRRC: Modular RRC design • RPUP: Radio Processing Units for user plane • MCIP: MAC ciphering and integrity protection • RRC: Radio protocols for beyond communication

* For the full list check Annex-C D2.5

Consideration of KVIs and new requirements

Main topic	KVIs	Handprint	Footprint	Sustainability Pillar*	Requirements
Energy	Total energy usage (kWh) in communication dimensions for the cobots Total energy usage (kWh) for data transfer (optimising packets and data vol.)	*Resource efficiency: Functionalities may be provided by machines with less materials, energy, and waste generated*	*Energy is consumed and materials are used to manufacture, deploy, and operate cobots and associated services*	Environmental, Economical	• Energy efficient Network operation • Energy neutral devices • Energy efficient AI/ML training and inference
Materials/Waste	Life expectancy of robots: making better and longer-lasting hardware/software, easily upgradable, modular. Avoid having to replace the entire cobot because of failures in the 6G-related aspects # of virtualised functionalities: Preventing/avoiding material usage for hardware, when these features/capabilities could be virtualised.		*The disposal of machines and devices results in increased electronic waste*	Environmental, Social and Economical	• Modularization • Virtualization • Softwarization • Compute offloading • Resilience • Predictable Low-latency
Safety	# of injuries at work/level of severity of work-related injuries/perception of risk	*Safer work environment leading to less injuries.*		Social and Economical	• Ubiquitous connectivity • Resilience • Explainability
Trustworthiness/Privacy/Security:	# of data leaks/breaches/cyber attacks, with personal information compromised	*Increased autonomy by robots supporting people with disabilities*	*People's privacy may be breached by unauthorized use of robots' and cobots' sensors*	Social and Economical	• Reliability • Trust and Security • Explainability
Costs	# of industries or stakeholders that cannot access cobots for a given reason / # total industries or stakeholders, per domain/vertical and/or per geographical area: Ensuring that the communication and coverage aspects in the infrastructure deployment are not a bottleneck for the implementation of cobots. i.e., it's easy and not expensive to deploy the required communication environment for a proper application of cobots.	*Benefits of robots and cobots might not be distributed evenly among society*	*New business opportunities for old and new businesses from the use of collaborative robots (new markets around robots beyond factory) : Cf. "Accessibility" in "Social benefits"*	Economical and Social	• Low CAPEX • Closed-loop Control • Reliability • Monitoring and Telemetry • Low Energy/Energy neutral • Zero-touch • Service Exposure
Productivity/ Efficiency	Ensure that 6G is reliable and resilient, and so, no downtimes in a given production scenario are due to failures in the communication-related aspects. • downtimes • several production KPIs (distinctive per factory)	*Increased local and global productivity, cost efficiency and enhanced competitiveness from the use of the collaborative robots*		Economical and Social	• Ubiquitous connectivity • Low latency • AI-native • Reliability • Resiliency • Service Exposure • Ensuring SLAs

Mapping of enablers to KVIs*

Category	Enabler Name	Requirements Addressed	KVIs Addressed
Intelligent radio interface	• ITx: Intelligent transmitter • IRx: Intelligent receiver • ITRx: Intelligent transmitter and receiver • SpecShare: Spectrum sharing, coexistence	• AI-native • Reliability to varying channel conditions • Improved data rates and spectral resource efficiency • Reduced costs due to spectrum sharing	• Lower downtimes (**Efficiency**) • Reduced **costs** due to improved coverage, throughput and latency • Improved **Trustworthiness** in network performance
JCAS PHY	• JCSWave: JCAS waveforms and frame structures • JCSRA: JCAS resource allocation	• Reliability to do improved sensing and localization for indoor factory environments	• Lower downtimes (**Efficiency**) • Industry specific production KPIs (**Productivity**)
New Devices	• IGENE: Identification of 4 new 6G device classes (RHDRBL, HRLL, EmMTC, EN)	• Energy efficient and neutral devices	• Reduced **Total energy usage** • Reduced OPEX (**costs**) due to reduced energy requirements
Flexible radio interface and protocol	• FRRC: Flat RRC design • SICMS: Separation of IDLE mode and CONNECTED mode signalling • SDAPBCS: SDAP protocol for beyond communication services • DRRM: Data Recovery and reordering mechanisms • MRRC: Modular RRC design • RPUP: Radio Processing Units for user plane • MCIP: MAC ciphering and integrity protection • RRC: Radio protocols for beyond communication	• Modularization • Energy efficient network operation • Reliability and Resiliency to adverse channel conditions and scenarios • Low latency	• Reduced **Total energy usage** • Lower downtimes (**Efficiency**) • Industry specific production KPIs (**Productivity**)

* For the complete list of mapped enablers check Annex-C D2.5

Final selected enablers for cobot use case

- ITx: Intelligent transmitter
- IRx: Intelligent receiver
- ITRx: Intelligent transmitter and receiver
- SpecShare: Spectrum sharing, coexistence
- JCSWave: JCAS waveforms and frame structures
- JCSRA: JCAS resource allocation
- IGENE: Identification of 4 new 6G device classes (RHDRBL, HRLL, EmMTC, EN)
- FRRC: Flat RRC design
- SICMS: Separation of IDLE mode and CONNECTED mode signalling
- SDAPBCS: SDAP protocol for beyond communication services
- ANIWQM: Application-NW interaction for service differentiation and QoS/QoE management
- E2ESM: E2E service design in modular 6G
- JCSSP: JCAS protocols, signalling and procedures
- CPSP: Compute protocols, signalling and procedures
- MMLOps: Machine Learning Operations
- AMP: Architectural means and protocols
- MTF: Monitoring and telemetry framework
- DDataOps: Data Operations
- Fedor: Federated orchestration system
- AIMLCAS: AI/ML-based control algorithms for sustainability.
- NDTCM: Network digital twin creation mechanisms
- CND: Confidential network deployment
- QSC: Quantum-safe cryptography
- LoTAF: LoTAF
- JCSSec: JCAS security and privacy
- TrustAI: Trustworthy AI
- ITP: Intent Translation and Provisioning
- DRRM: Data Recovery and reordering mechanisms
- MRRC: Modular RRC design
- RPUP: Radio Processing Units for user plane
- MCIP: MAC ciphering and integrity protection
- RRC: Radio protocols for beyond communication
- LSM: lean system and mobility
- Mproc: mobility procedure harmonization
- HHD: Human-machine intent interface design
- NAM: Network autonomy
- MXO: Multi-X orchestration
- MCMM: Multi-cloud management mechanisms
- NPM: Network programmability
- Pcell: Pcell Recovery

- DIR: Declarative Intent Reconciliation
- DDD: Data fusion mechanisms based on telemetry data
- NoN: Network of networks
- ALBCS: Application-layer BCS optimisation
- IIC: Integration and orchestration of extreme edge resources in the computing continuum
- MMMF: Multi-domain/Multi-cloud federation
- Mfro: Migration from 5G to 6G
- DoM: Design of a module
- Inter: Interactions between entities
- Mexmp: Modularisation examples
- SnO: 6G Slicing and orchestration
- AAIaaS: AI-as-a-Service
- Mconn: Multi-connectivity
- LDPC: LDPC channel coding
- LLAA: Low-latency random access
- Wwaveforms: Waveforms
- MModulations: Modulations
- WLOLOR: Wideband array phase noise analysis and role of LO routing
- SSOSO: Secure and scalable SoC architecture tailored to a microkernel-based OS
- MMM: Multi-source energy harvesting and power management
- IlI: Intelligent wake-up
- EATML: Energy-aware tinyML applications
- EEA: Efficient network and service function allocation
- Trust: Trust management
- MMO: Multi-agent system for multi-cluster orchestration
- Mca: Management capabilities exposure
- RTZS: Real-time Zero-touch control loops automation and coordination system
- CLC: Closed Loop Coordination
- ICA: Intent Conflict Administration
- INR: Intent Reporting
- TPS: 3rd party services
- MRE: mobility related enablers
- DQIS: Dynamic adaptation of QoS resources for interactive services
- ARBIS: Ad-Hoc radio bearer and inline signaling
- LLUS: Low latency UL scheduling
- TRCS: Third-Party Resource Control Separation Enabler
- DEOS: Decentralized orchestration system
- PNMT: Programable network monitoring and telemetry
- OMCC: Orchestration mechanisms for the computing continuum
- PFNC: Programmable and flexible network configuration

Conclusions and recommendations on the overall 6G System blueprint

- E2E 6G system architecture completed with specific views of the 6G E2E system and the results of the enabler selection based on KG method.
  - fundamental functionalities and key interfaces of the 6G system, both internally and externally.
- Specific system views of the system blueprint include:
  - radio protocols and flexible topologies,
  - new 6G services and the related exposure framework,
  - multistakeholder aspects in the realization of an E2E 6G system,
  - pervasive functionalities including the AI/ML and data frameworks,
  - pervasive security, privacy and resilience, and migration path from 5G to 6G.
- Implementation of the KG method is only carried out for the Industrial cobots use case
- In future perspectives, selection could be extended to other 6G use cases to cover a large range of KPIs and KVIs.

Chapter 7
Final E2E system-level validation phase

PoC components mapping to the E2E system blueprint

- Application layer components: Intuitive Trigger/User Interface (UI), intelligent components (functionality allocation, swarm planning and management, etc.) real-time video streams, sensor/device status, etc.

- Exposed compute/AI and data resources via the application enablement platform layer

- Advanced 6G functionalities and devices including flexible topologies, 6G-based sensing, AI-native interfaces, energy harvesting devices, adaptive transceiver design and E2E compute offloading mechanisms in E2E extended reality setups.

- Synergetic monitoring and orchestration: Dynamic resource allocation, seamless integration, and continuous trust evaluation via trust evaluation functions.
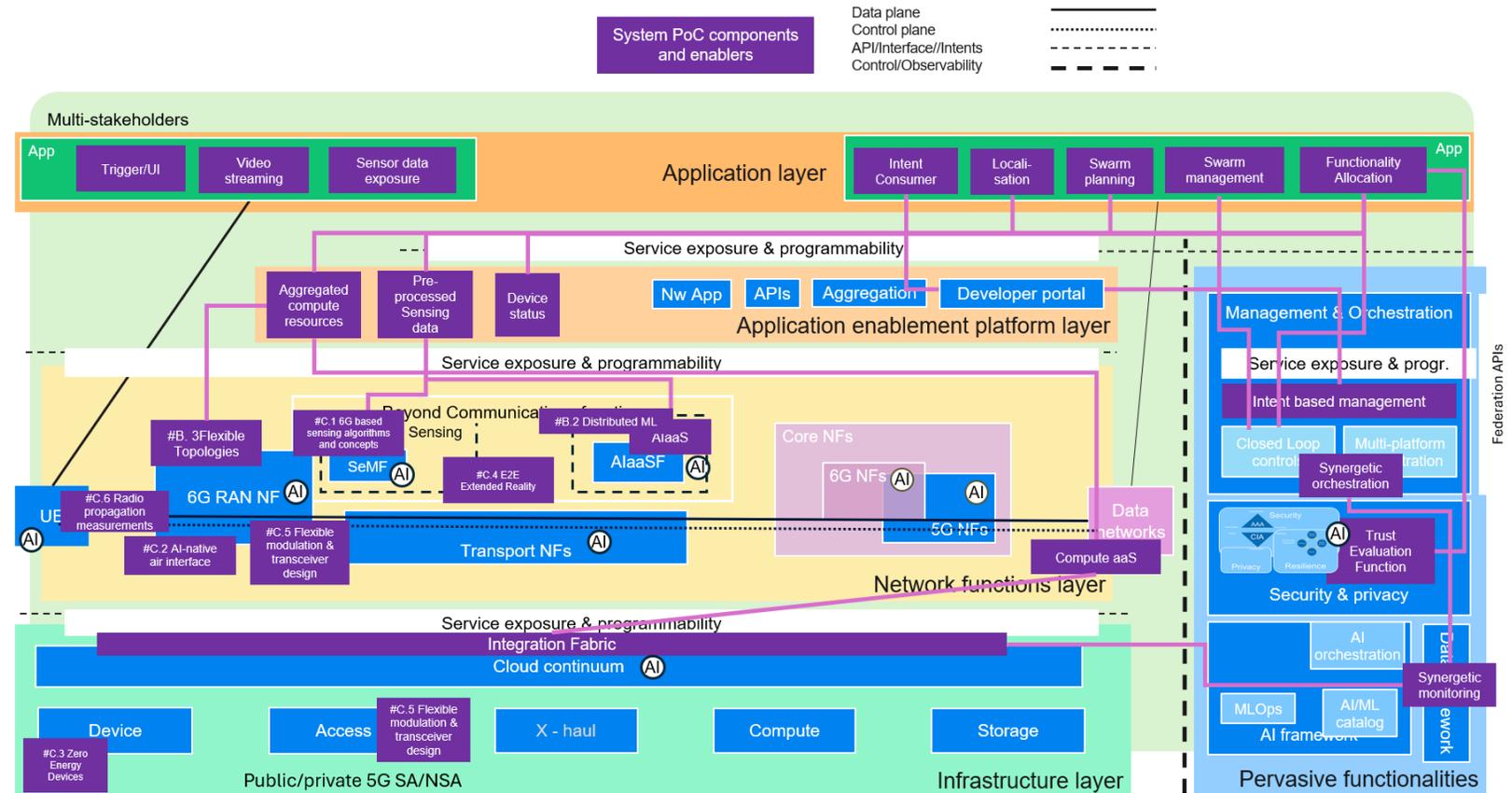
6G Radio & 6G devices Component Proof-of-Concepts (PoCs)

- **PoC #C.1:** Demonstrates real-time 6G sensing algorithms to detect and localize both connected cobots and non-connected human workers, improving safety and efficiency in industrial environments.

- **PoC #C.2(a):** Validates an AI-native air interface using end-to-end learned transmission without Demodulation Reference Signal (DMRS) pilots, showing significant throughput gains and improved spectral efficiency in various mobility scenarios.

- **PoC #C.2(b):** Evaluates ML-based CSI feedback compression in a multi-vendor setup to enhance beamforming accuracy and reduce overhead without sharing proprietary models.

- **PoC #C.3:** Showcases zero-energy backscatter devices integrated into cellular networks for cobot positioning and logistics applications, enabling energy-efficient localization and asset tracking.

- **PoC #C.4:** Implements scalable compute offloading for cobots and VR-controlled robots to reduce power consumption while ensuring real-time sensor data processing for navigation and safety.

- **PoC #C.5:** Develops a dynamically reconfigurable transceiver platform that adapts radio parameters in real time, supporting flexible modulation and waveform selection for diverse 6G use cases.

- **PoC #C.6:** Conducts sub-THz radio propagation measurements in factory settings to build accurate channel models and coverage maps for network planning and performance prediction in industrial environments.
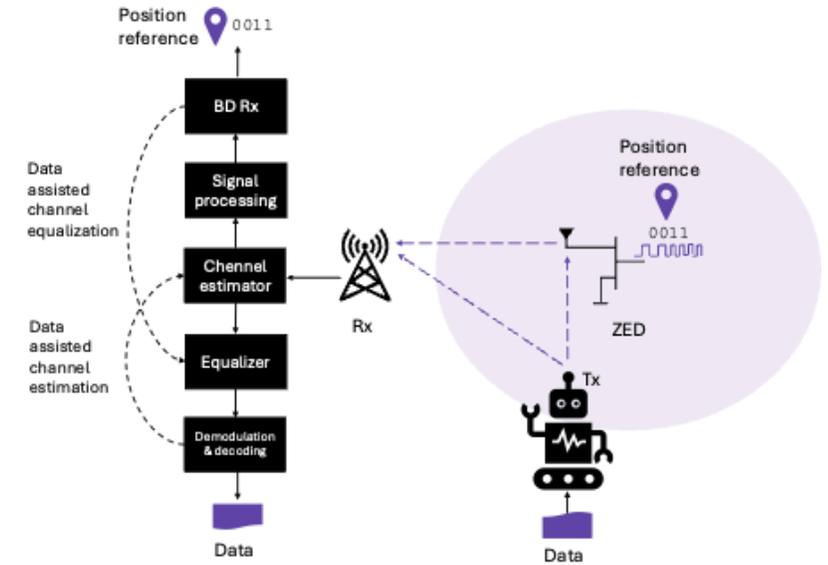
Zero-Energy Device (ZED) assisted cobot positioning
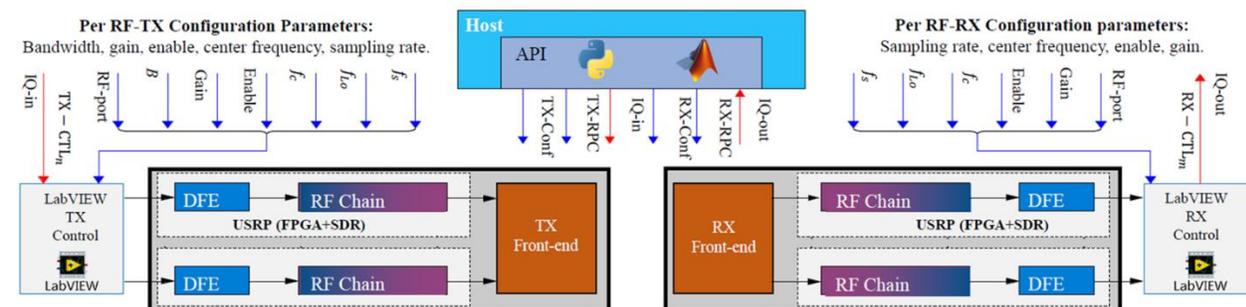
Flexible transceiver system schematic

System PoC design evolution

- System-PoC C introduces energy harvesting-capable proximity-sensing devices in the warehouse inventory management scenario, designed to monitor shelf occupancy with high precision.
- Flexible topology nodes provide communication resources to the energy harvesting devices
- Equipped with energy harvesting capabilities using solar panels, represent a step forward in sustainable and autonomous operation: real-time digital twinning of the warehouse storage areas is updated via the energy harvesting devices for shelf occupancy; this information is then utilised by the evolution of the Functionality Allocation (FA) algorithm
- New APIs leveraging exposure of Application Enablement Platform capabilities, such as Quality-on-Demand (QoD), device status/density, as well as integrating System PoC-B capabilities, such as advanced flexible topologies functionality and compute offloading features
- Integration Fabric adoption as a core enabler in multi-domain resource orchestration scenarios
- Trust Evaluation Function- and Energy-driven Functionality allocation of physical and compute tasks
- Intent-driven orchestration leveraging intent hierarchy, i.e., business intents, as well as intent-based DSM capabilities.
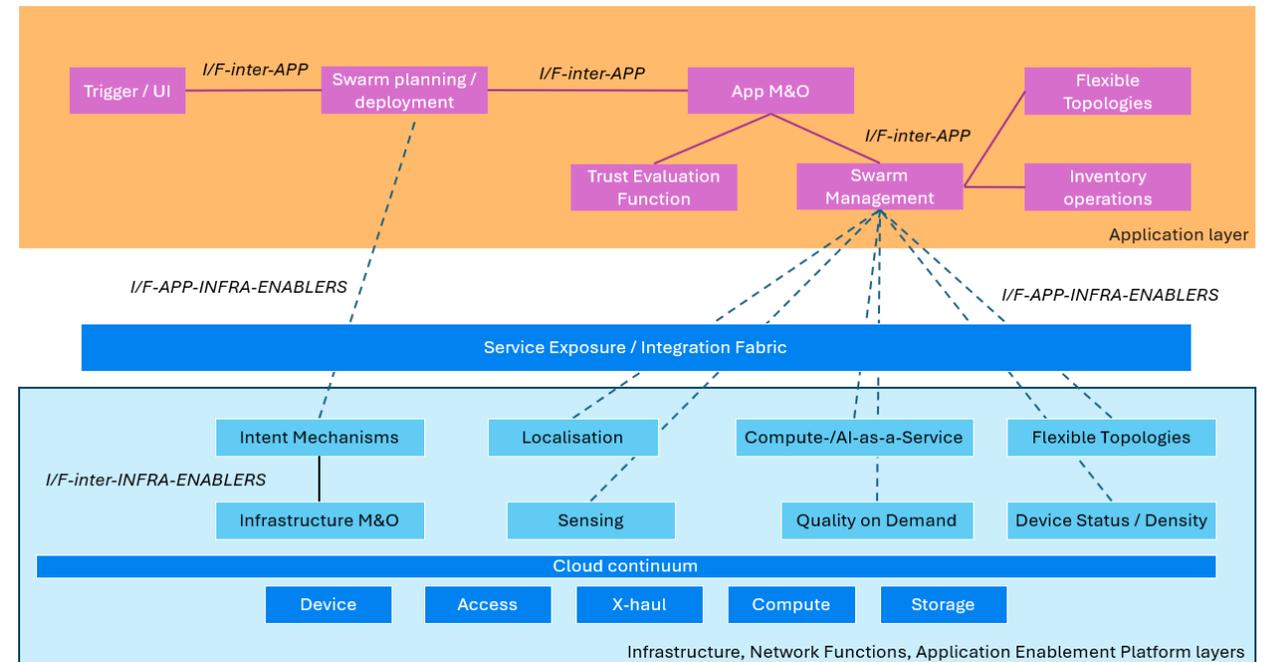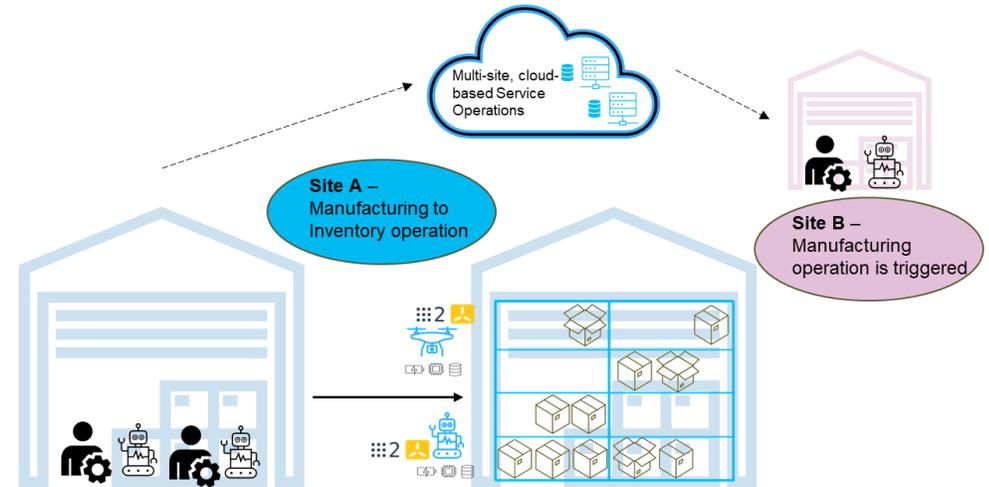
Service migration and scaling

- 6G latency-sensitive service

- Infrastructure
  - Site A – Cloud infrastructure
  - Site B – Local infrastructure
  - Multi-site connectivity

- Multiple objectives
  - E2E service latency
  - Power consumption
  - Compute and network utilization costs
  - Multiple services co-location

- Domains
  - Service Provider
  - Cloud Provider
  - Network Provider
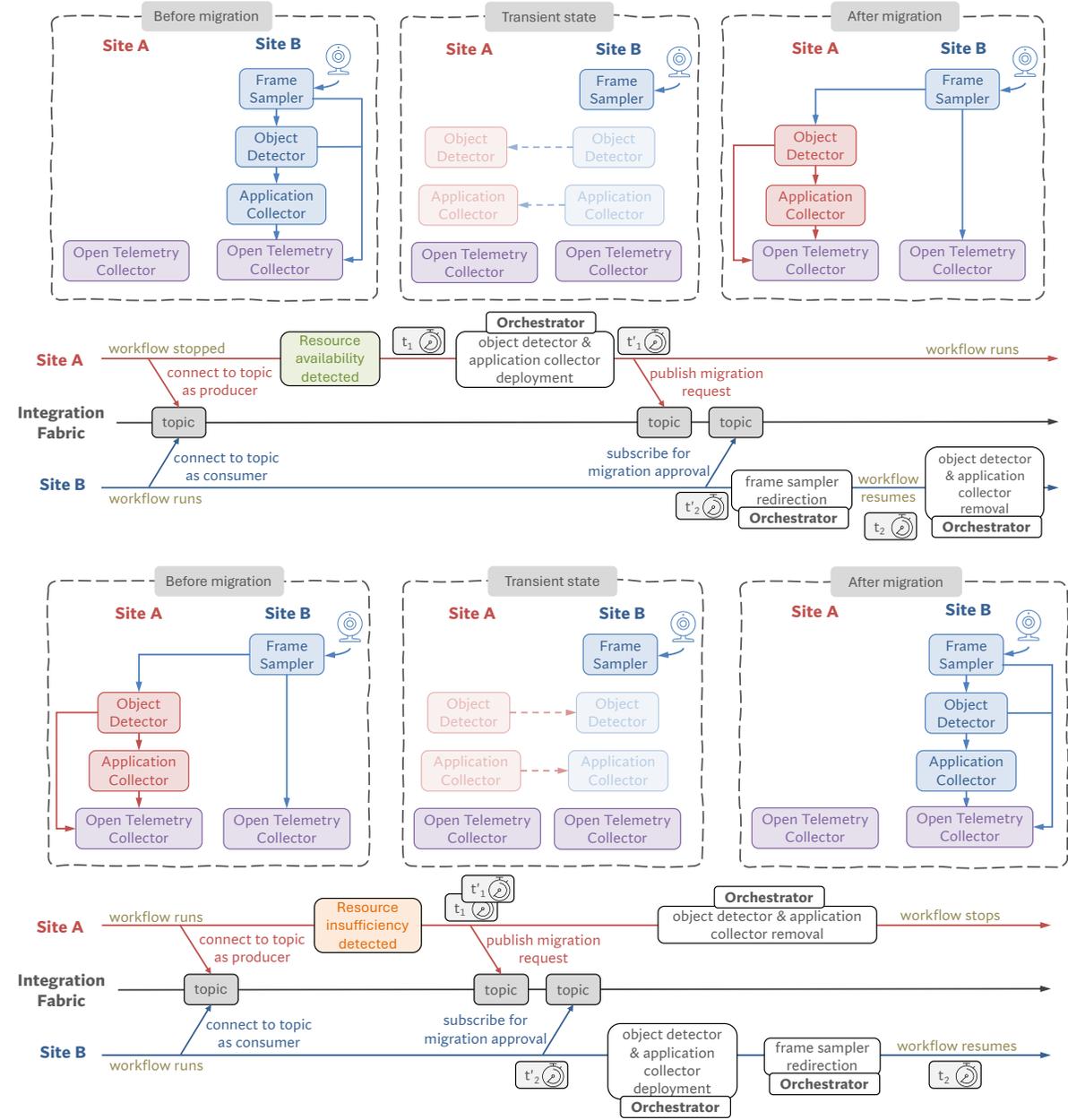
System PoC: Cobot-powered Warehouse Management in the context of multi-site synergetic monitoring and orchestration scenarios

- ## IBM on Transport Resources
  - An intent-based networking (IBN) solution based on the intent-based DSM (detailed in Chapter 4) for configuring the network based on business intent.
  - The implemented solution is based on the "Intent translation and provisioning" enabler described in [HX224-D23].

- ## Management of Transport Domain
  - The SDN controller for managing and controlling the network across the different domains.
  - TeraFlowSDN as the selected solution to deliver an SDN Controller to the multiple sites connectivity.
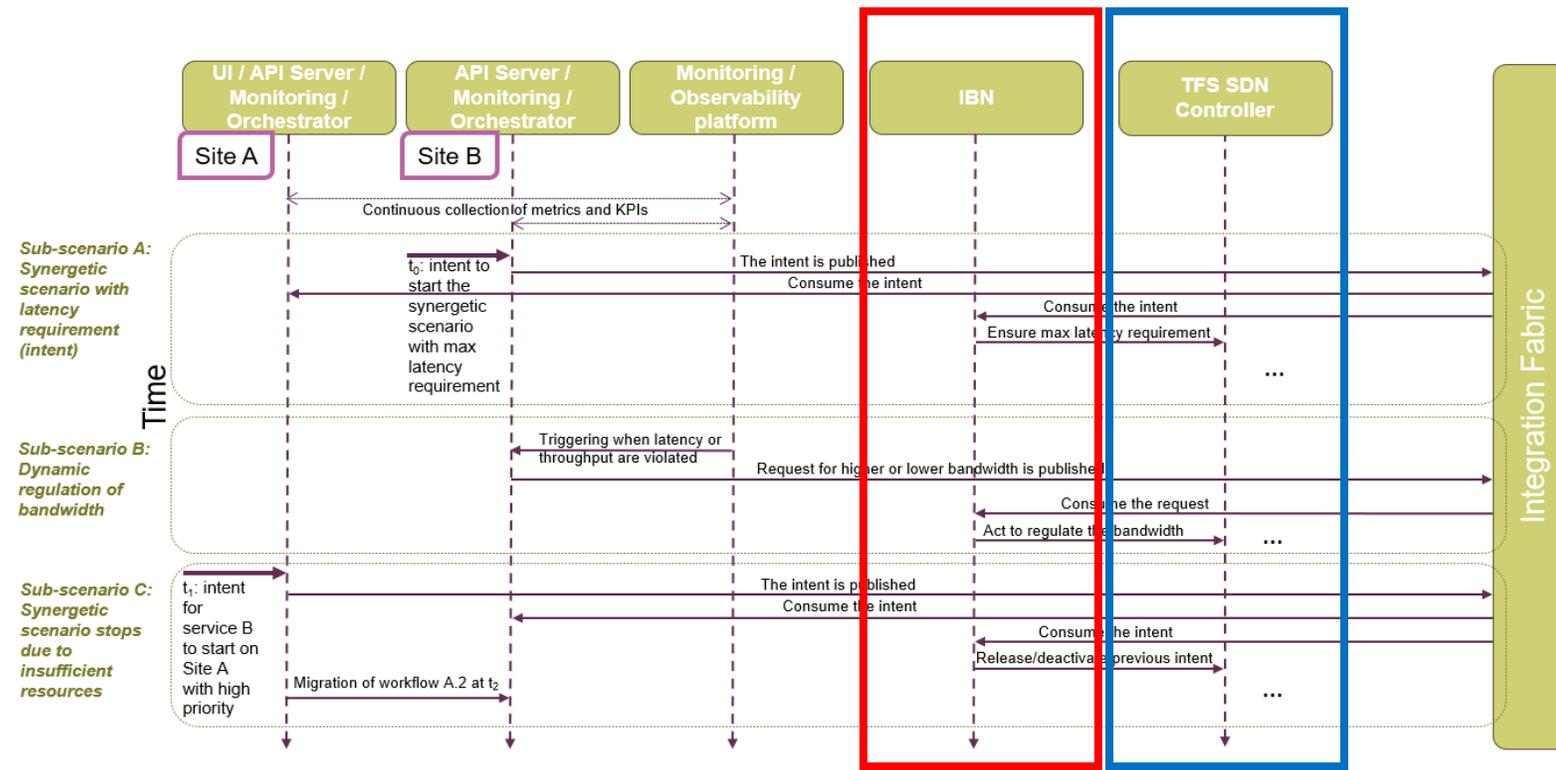
System PoC: Integration Fabric role

- Provides a standardized (e.g., REST-based) interface that abstracts complex underlying system capabilities, enabling easy access to diverse resources and services.

- Seamlessly connects different components at service level in multiple domains and sites, supporting real-time resource allocation and management.

- Facilitates high-level, goal-oriented control that enables and improve intent-driven service management and closed-loop automation.

- Serves as the central integration point for various system enablers, enabling real-world interoperability testing and API refinement.
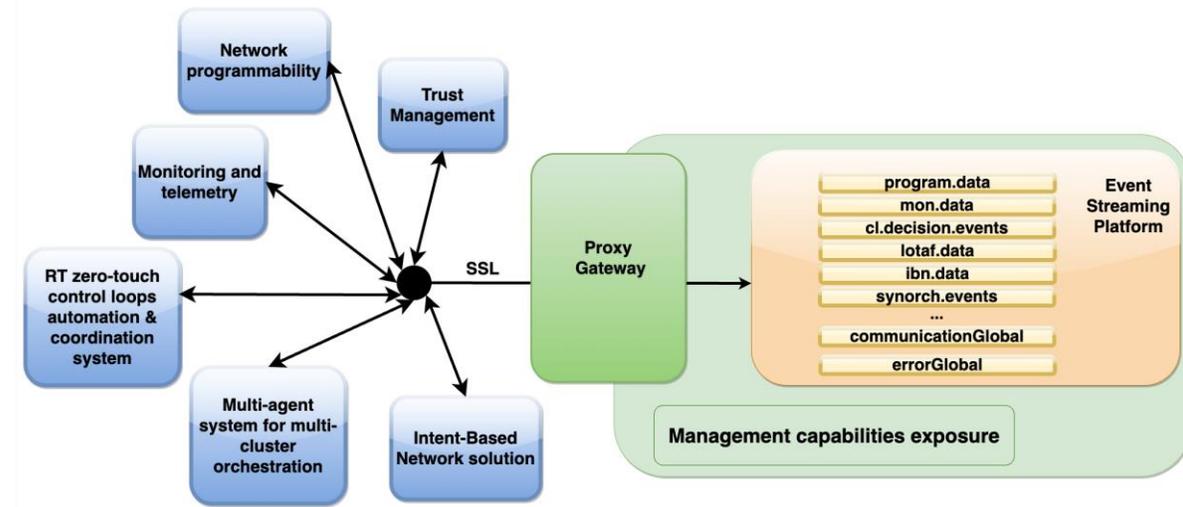
PoC-C Expansion VR Digital Twin

- Expansion of the cobot surveillance use case. Integrating a Virtual Reality (VR) digital twin model of the premises

- In a digital twin the physical environment mirror the digital replica and viceversa (two-way communication).

- The robot provides 3D Laser imaging Detection And Ranging (LiDAR) readings. Providing detailed information of the surrounding environment

- With a VR headset a human user can update the position of the cobot in the digital twin, and in the physical environment.

- D2.6 includes QoS measurements. Detailing the behaviour of uplink (LiDAR) and downlink traffic (joystick commands)
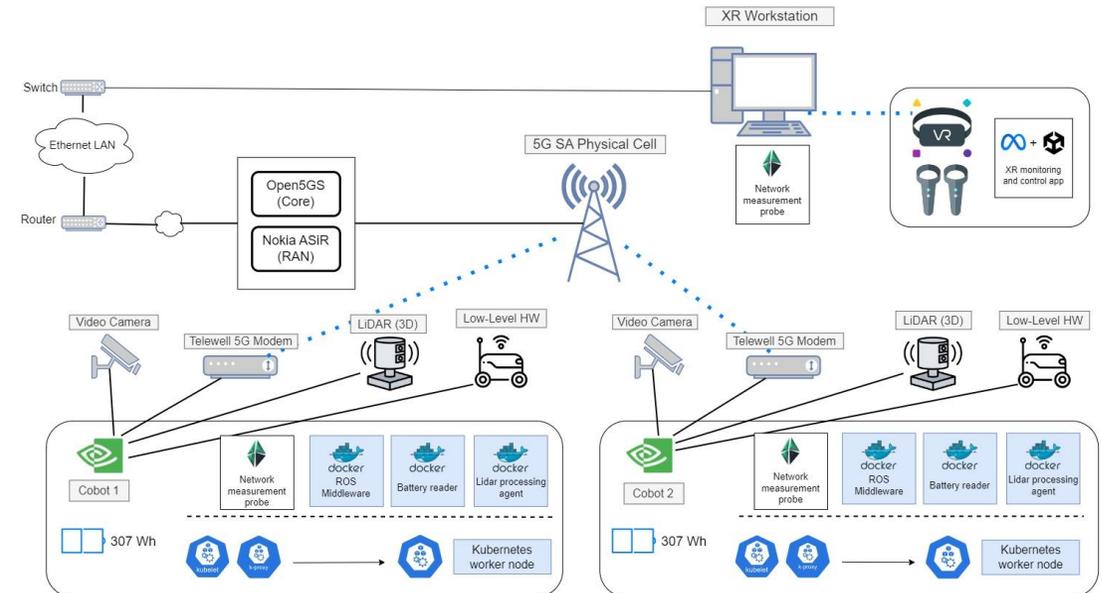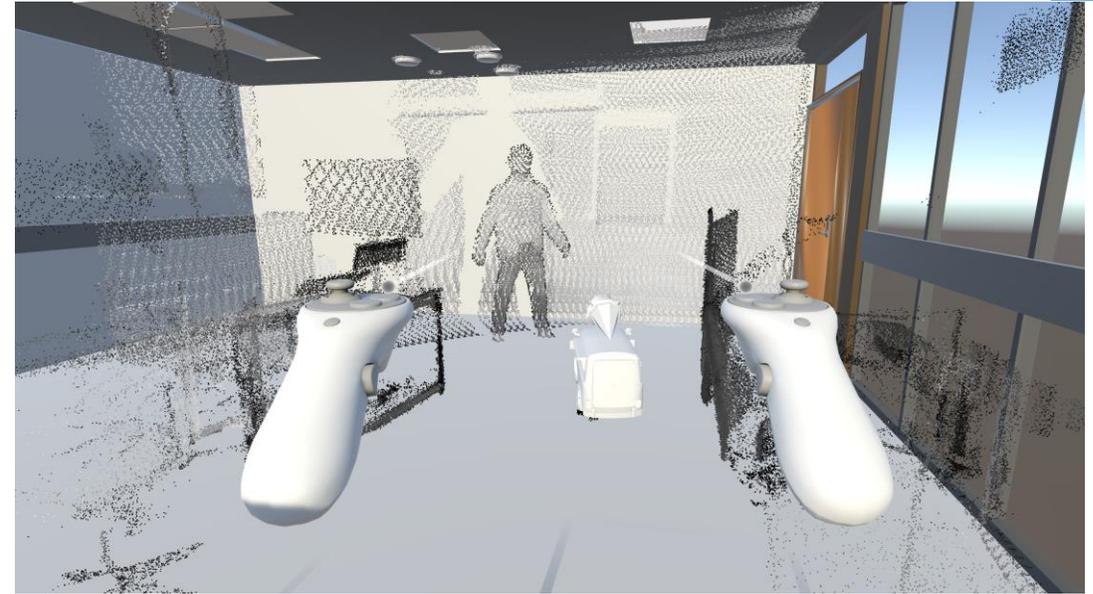
Conclusions towards the E2E system-level validation phase

- The final E2E system-level validation phase design represented a critical milestone, focusing on **experimental-based assessment design** to validate the architecture's robustness and readiness for **future real-world deployment.**

- This phase consolidated the system and component PoC design and implementation specifications, with **system PoC-C aligning with advanced 6G radio and device technologies alongside advanced application features**

- The design and implementation incorporate advanced application features, new devices with energy harvesting capabilities, key enablers such as advanced M&O enablers, the system's integration fabric, the intent-based management framework, AI-powered closed-loop automation, as well as **new APIs leveraging exposure** of Application Enablement Platform layer capabilities, such as QoD and device status/density.

Chapter 8
E2E system design qualitative assessment

Assessment of the 6G system design (1)

- Fulfilled design principles and impact on the sustainability of key system aspects

System blueprint key aspects	Fulfilled main design principles	Economic sustainability	Environmental sustainability	Social sustainability (inclusion & trustworthiness)	Related enablers (examples)
Application enablement platform	1, 2, 7, 8	Reduces integration costs, simplifies communication, offers open-source platform	Aggregating capabilities from different NWs can lead to more efficient use of resources by reducing redundancy	Making 6G capabilities accessible to a wide range of developers and users can potentially promote digital inclusion	App-NW interaction, 3rd party services, application-layer BCS optimization, management capabilities exposure
New services (sensing, compute, AI, etc)	1, 2, 7, 8	Accelerates time-to-market, cost-effective and scalable AI access, optimizes resource utilization	Promotes energy efficiency, resource sharing, algorithm optimization	JCAS helps in optimizing network deployment, potentially extending its coverage to underserved area, improving people safety and social well-being, and environmental monitoring AIaaS supports more personalization and can improve digital inclusion. CaaS can enables the development of applications that promotes inclusion	JCAS protocols, signalling and procedures, compute protocols, signalling and procedures
Flexible access and topologies	3, 4, 5	NTN: Cost-effective deployment, flexible topologies, use of non-terrestrial nodes; Multi-connectivity reduces complexity by simplifying architectural options, leading to faster time-to-market	NTN: reduces the need for terrestrial nodes and their connections, enabling ad-hoc deployment and potentially reducing power consumption; Multi-connectivity allows reusing of existing infrastructure	Achieves a ubiquitous network, extending network access and service coverage to the entire globe, including remote and rural areas; UE-formed subnetworks can extend network coverage, particularly in areas where a direct connection to the base station is not available; Flexible topologies, such as subnetworks, enhance network resilience and security	NTN integration, subnetwork management node, UAV assisted flexible topologies network of network, multi-connectivity, E2E context aware management
PHY layer and radio protocols	9, 5, 10	Spectrum sharing and coexistence: Reduces deployment costs, efficient spectrum use	Adaptable to future technologies and diverse use cases, with a flexible protocol stack operation, modular components, and the integration of new capabilities like JCAS, NTN, and AI-ML.	Resilient and reliable protocols, ensuring network availability and dependability, privacy and security in radio protocol design, ensuring user data protection and fostering trust in the 6G network	RRC design, modular user plane design, data recovery, ciphering and integrity protection, mobility procedure harmonization, low-latency random access, SoC architecture tailored to a microkernel-based OS, multi-source energy harvesting and power management,

Assessment of the 6G system design (2)

System blueprint key aspects	Fulfilled main design principles	Economic sustainability	Environmental sustainability	Social sustainability (inclusion & trustworthiness)	Related enablers (examples)
Multi-stakeholder support	2, 4	Seamless integration of edge, core, and cloud resources, ensuring optimal resource utilization and service delivery	Reduces energy consumption and possibly lowers operating costs, benefiting both network operators and other resource/service providers	Encourages collaboration and reduces barriers to entry for various stakeholders	Multi-domain, multi-cloud federation, federation manager, 3rd party resource control separation,
Pervasive AI/ML frameworks	2, 4, 5, 6	MLOps reduces costs, accelerates time-to-market, improves decision-making, enables scalability, and mitigates risks; offers tools for efficient ML model lifecycle management	By leveraging AI/ML algorithms for network operations, the framework can help in reducing energy consumption in the network	Includes privacy-preserving data collection and training protocols, ensuring trusted distributed AI/ML applications development.	Machine learning operations, energy-aware tinyML applications
Pervasive data framework	2, 4, 5, 6	Reduces operational costs, optimizes data management processes, speeds up insights generation, and fosters collaboration and innovation	Promotes energy efficiency, resource optimization, cloud adoption, data reduction, and enables remote work and collaboration	Promotes responsible data usage by ensuring data quality, and accessibility and containing data privacy-preserving mechanisms	Monitoring and telemetry framework, DataOps, data fusion mechanisms based on telemetry data
Pervasive security, privacy and resilience	5, 6	Reduces cost from security breaches and cyber-attack, minimizing downtime. Provides competitive advantage, attracting customers and partners	Promote energy aware security protocols	Facilitates transparency, accountability, and trustworthy AI/ML, fostering user trust and confidence in the 6G ecosystem; LoTAF helps users assess the trustworthiness of network services; Resilience through closed-loop automation for security management, including what-if scenarios, and NDT environment.	Confidential network deployment, quantum-safe cryptography, level of trust assessment function, JCAS security and privacy, trustworthy AI, trust management, secure and scalable SoC architecture tailored for trustworthy AI/ML
Pervasive M&O	1, 2, 4, 6; 9, 10	Cost-efficient operation, multi-agent systems, decentralized orchestration, resource sharing, reduced operational expenses	Promotes use of edge and extreme-edge resources, reduces data interchange with core networks, minimizes data center size, Reduces resource usage through AI/ML-based control algorithms	Orchestration over the cloud continuum increases network availability and reliability, decreases end-to-end latency, promotes digital inclusion, ensures optimal application deployment, balances latency, energy consumption, and resource availability while ensuring network security	Multi-X orchestration, multi-agent system for multi-cluster orchestration, Real-time Zero-touch control loops automation and coordination system, AI/ML-based control algorithms for sustainability, Network digital twin creation mechanisms, Intent based manager enablers

Assessment on Security Considerations for 6G Enablers

- Bidirectional relationship between Hexa-X-II enablers and SPR controls of chapter 5

Enablers support SPR objectives (Security, Privacy, and Resilience)

WP	ENABLERS
WP2	Data recovery mechanisms; Ciphering & integrity protection; Enhanced Special Cell (SpCell) change with UE initiation; Pcell recovery; Data-driven mobility Intent and TLA management LoTAF; Notary service; Trustworthy AI
WP3	MLOps; DataOps; Intent-based management (Zero Touch) Multi-connectivity JCAS protocols, signalling, and procedures
WP4	Trustworthy radio solutions Security and privacy (jamming attack detection, key generation for encryption, etc.)
WP5	Secure and scalable SoC architecture tailored for trustworthy AI/ML
WP6	3rd-Party resource control separation system; User-centric service provisioning system; Trust management functionalities Secure AI/ML-based control for intent-based management system Real-time zero-touch control loops governance and coordination (for recovery & security); Privacy protection for data analytics system

Enablers rely on SPR controls for their functionality

WP	ENABLERS
WP2	Radio protocols for beyond communication; Data fusion mechanisms based on telemetry data; Intent Conflict Administration; Human-machine intent interface design; Declarative Intent Reconciliation; Intent Reporting; 3rd party services
WP3	AIaaS; Architectural means and protocols 6G Network modularization E2E service design in modular 6G network of networks Exposure and data management, integration and orchestration of extreme edge resources in the computing continuum multi-domain/multi-cloud federation
WP4	RIS-assisted transmission
WP5	RIS system integration; Energy-aware protocols RAN scope dedicated connectionless design Energy-aware tinyML applications
WP6	Multi-agent system for multi-cluster orchestration Decentralised orchestration All the overall functionalities in the smart management framework [HEX225-D65]. Network programmability system

Collectively, it provides a unified framework for enhancing privacy, security, and resilience

Assessment on Intent-based E2E service management automation

<u>Objective 2: Description of the blueprint and system validation of the environmentally, economically and socially sustainable 6G platform</u>

- The IBM framework supports scalable, flexible, and automated service management across single and multi-domain 6G scenarios.

- Aggregation and federation models enable cooperative, trustworthy resource management while preserving stakeholder autonomy.

- Intent-driven trust mechanisms enhance security, resilience, and privacy to meet strict 6G service requirements.

- The framework aligns with 6G goals through closed-loop coordination, adaptive resource allocation, and intelligent conflict resolution.

- The blueprint from D2.2 has been advanced with new IBM capabilities and technological innovations.

<u>Objective 5: Efficient network realization, implementation, and management</u>

- Automation in intent-based management reduces reliance on human intervention and enables dynamic resource allocation based on real-time KPIs.

- Closed-loop coordination and monitoring provide continuous service optimization and support integration with standards like TM Forum, 3GPP, and ETSI ZSM.

- Sustainability is addressed through energy-efficient strategies and adaptable workflows that support both emerging 6G services and legacy systems.

Assessment on standard-related impact

- **Standardization is crucial for 6G platform success, addressing key technical aspects**

Key areas
- Service exposure for diverse applications and devices (traditional and beyond communication)
- Security, privacy, and resilience framework to counter new threats (delta 6G threats)
- Intent-based E2E service management automation for efficient network control
- Radio protocol design and evolution for enhanced communication capabilities
- Leveraging open-source tools for network orchestration, security, AI-driven management, and real-time monitoring

Key Standardization Bodies and contributions
- **3GPP SA5** for Network as a Service (NaaS) and management services exposure; trustworthy AI-based control to enhance the management plane; intent-based management, including intent generic models and solutions
- **3GPP SA2** for evolving the NEF (Network Exposure Function) and potentially the Common API for Policy and Charging (CAPIF) to support the exposure of beyond communication services
- **3GPP SA3** for SPR enablers (Distributed and trustworthy AI, Quantum-safe cryptography, Distributed ledgers, Remote attestation, Context-awareness)
- **ETSI-MEC and ETSI-NFV** for addressing security and privacy threats, mitigation techniques, and the use of Network Data Telemetry (NDT) for threat evaluation
- **ETSI SAI** for understanding risks associated with widespread AI use in networks and developing relevant proofs of concept
- **IETF Security Area** for attestation techniques, quantum-safe technologies, and automated certificate and key management procedures
- **ETSI ZSM** for intent-based management, including intent life-cycle specifications and the use of smart contracts for supporting the governance of intent-driven closed loops
- **TM Forum** for the usability of Intent standardized API, from abstraction definition to implementation possibilities on how to use to translate intent into SLA requirements

Open-Source Tools and Contributions
- **OpenAirInterface:** RAN performance and architecture optimization
- **Kubernetes:** Orchestrating distributed workloads and AI applications
- **Prometheus:** Performance monitoring and observability
- **Apache Kafka:** Secure network exposure through mutual TLS authentication
- **Qujata:** Post-quantum cryptographic evaluations
- **TeraFlowSDN, CockroachDB, OpenConfig:** Network slicing and automation, gNMI telemetry for real-time observability

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