Tutorial #1 - Towards 6G: Intelligent and Secure Intent-based Networking for Autonomous Network Management

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Supported by

6G-INTENSE Project

Intent-driven NaTive AI architecturE supporting Compute-Network abstraction and Sensing at the Deep Edge

Co-funded by the European Union

'6G-INTENSE project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101139266'

Agenda

Part 1: Fundamental Concepts of Intent-based Networking

- **Introduction to IBN**
  - ✓ What is IBN?
  - ✓ What is the difference between IBN and a traditional network?
  - ✓ Why do we need IBN?
  - ✓ What are the enabling technologies for IBN?
  - ✓ What is the main high-level architecture for IBN ?
  - ✓ SDO effort and 6G-INTENSE proposed architecture.
  - ✓ What are the main components of the IBN life cycle?
  - ✓ 6G-INTENSE Proposed Solutions.

What is Intent-based Networking (IBN) ?

- **Intent** is a set of operational goals (that a network should meet) and outcomes (that a network is supposed to deliver) defined in a declarative manner without specifying how to achieve or implement them.

Intent	Not Intent
“For a smart city service, ensure traffic signal control traffic uses dedicated and redundant slices that avoid fate sharing.“ - a desired outcome with a set of constraints and additional guidance without specifying how to precisely achieve this.	**"Configure a given interface with an IP address.“** - device configuration, not intent.
“Maximize network utilization even if it means trading off service levels (such as latency, loss) unless service levels have deteriorated 20% or more from their historical mean." - A desired outcome, with a set of constraints for additional guidance, that does not specify how to achieve this.	**"When interface utilization exceeds a specific threshold, emit an alert.“** - a rule that can help support network automation, but a simple rule is not an intent.

- **Intent-based Networking (IBN)** is a network that can be managed using intent. It is able to
  - Recognize and ingest intent of an operator/user.
  - Configure and adapt itself according to the operator/user intent.
  - Achieve an intended outcome without requiring the operator/user to specify the detailed technical steps for how to achieve the outcome.
- **Intent-based system (IBS)** is a system that allows users to manage a network using intent.
  - Serve as a point of interaction with users/operators and implement the functionality that is necessary to achieve the intended outcomes.
- **Advantages of Operating with Intent:**
  1) Data Abstraction: Users do not need to be concerned with low-level device configuration.
  2) Functional Abstraction (i.e., management and control logic): Users do not need to be concerned with how to achieve a given intent.

The term **“intent”** adopted as an evolved version of the term “policy” which dates back to policy-driven management system.

What is the difference between IBN and a traditional network ?

- **Policy:** is a set of rules that are used to manage and control the state of one or more managed objects. It is associated to Event-Condition-Action (ECA).
- Policies let users define what to do under what circumstances, but they do not specify the desired outcome.
- Policies typically involve a certain degree of abstraction in order to cope with the heterogeneity of networking devices and domains.
- Policy constitutes a lower level of abstraction than intent.

- ***Policy-based systems***
  - ***Expert Systems :*** operate on knowledge bases with rules that are supplied by operators.
    - They are able to make automatic inferences based on those rules but are not able to **"learn"** new rules on their own.
    - Operator defines beforehand the expected behavior of the system to various events and conditions.

- ***Intent-based Systems***
  - ***Learning Systems :*** able to learn without depending on user programming or articulation of rules.
    - Users focus on what they would like the learning system to accomplish but not how to do it.
    - User only declares what the system is supposed to achieve and not how to achieve these goals.

Why we need Intent-based Networking (IBN) ?

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- Policy management was hard and different network shareholders wanted much simpler solutions
  - ✓ End-users with no technical insights.
  - ✓ App developers that are developing network services without complicated network interface experience and know-how.
  - ✓ Operators that are willing to initiate network services in more abstract and robust manner.

OPERATORS

Requires network operation to be cheap and simple to introduce new services.

USERS

Require more diversified, robust and yet cheap services.

GOVERNMENTS

Demand networks with reliable services everywhere.

Increasing complexity of communication networks

Autonomic

- Self-managing and allowing high-level guidance by a central entity, through Intent.
- An autonomic function adapts on its own to a changing environment.

Automatic

- A process that occurs without human intervention, with step-by-step execution of rules.
- It relies on humans defining the sequence of rules, so is not Autonomic.
- An automatic function may need manual adjustments if the environment changes.

Traditional manual configuration of network equipment to provide transport is no longer sustainable.

What we need ?

Simplify the management and configuration of the network through possibly an autonomic and automatic way.

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What are the enabling technologies to IBN ?

- **Software-defined network (SDN)**
  - Decouple control plane from data plane, offering network re-programmability in a fast and automatic fashion.
  - SDN Controller:
    - Has an overview of the network topology and resources availability.
    - Interact with application layer through APIs (NBI) like OpenStack.
    - Interact with infrastructure layer through APIs (SBI) and protocols like OpenFlow/P4.

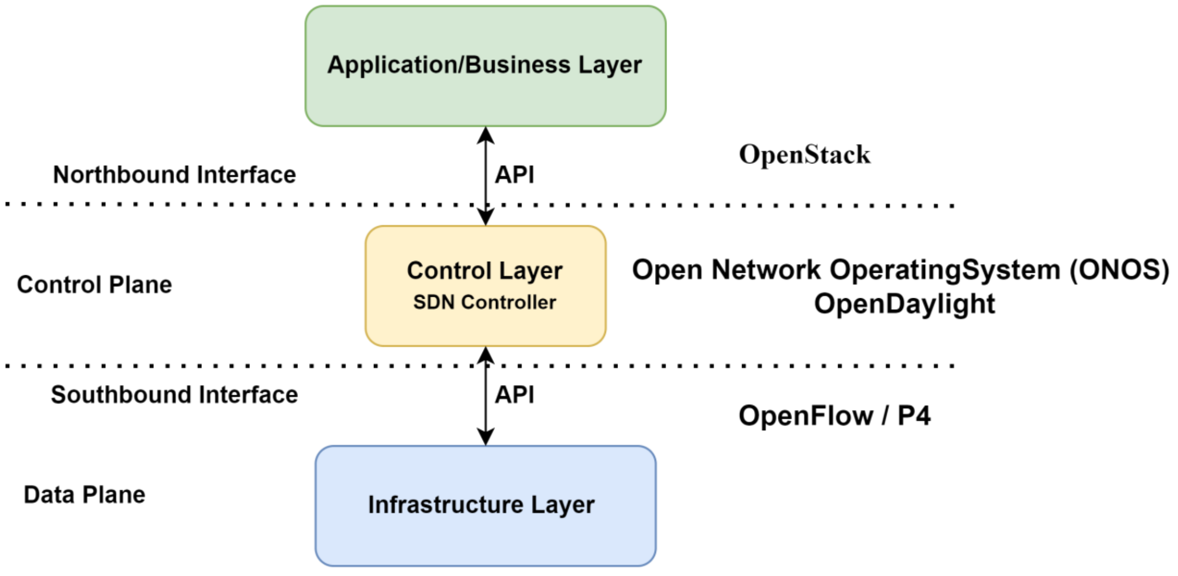
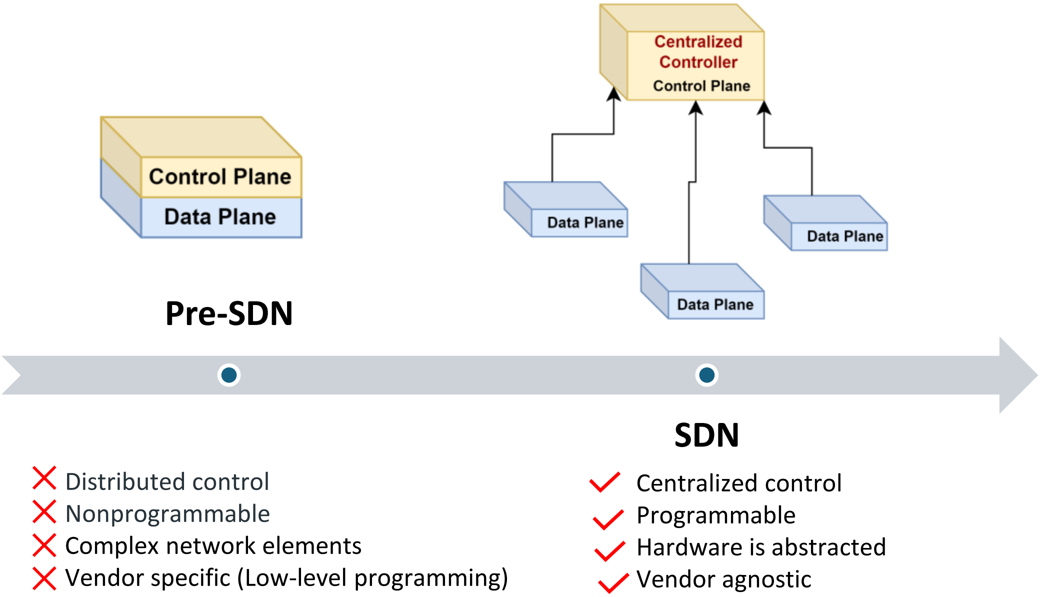


Fig.1 SDN Architecture.



What are the enabling technologies to IBN ?

- **Network Function Virtualization (NFV)**
  - Decouples network functions from dedicated middleboxes (i.e., turns them into software-based virtualized entities).
  - NFV Architecture:
    - **Applications:** Software delivers many forms of network functionality.
    - **Virtual network infrastructure:** The foundation of an NFV infrastructure can be either a platform for managing containers or a hypervisor that abstracts the resources for computation, storage, and networking.
    - **Framework:** To manage the infrastructure and provide network functionality.

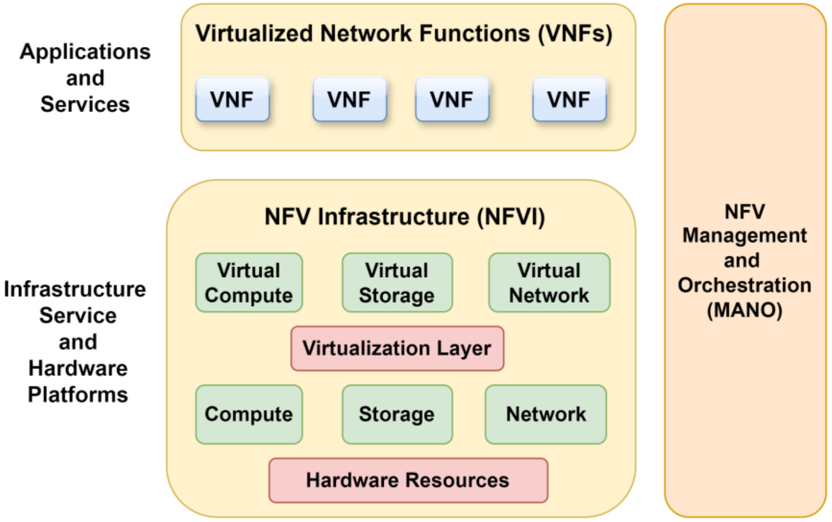
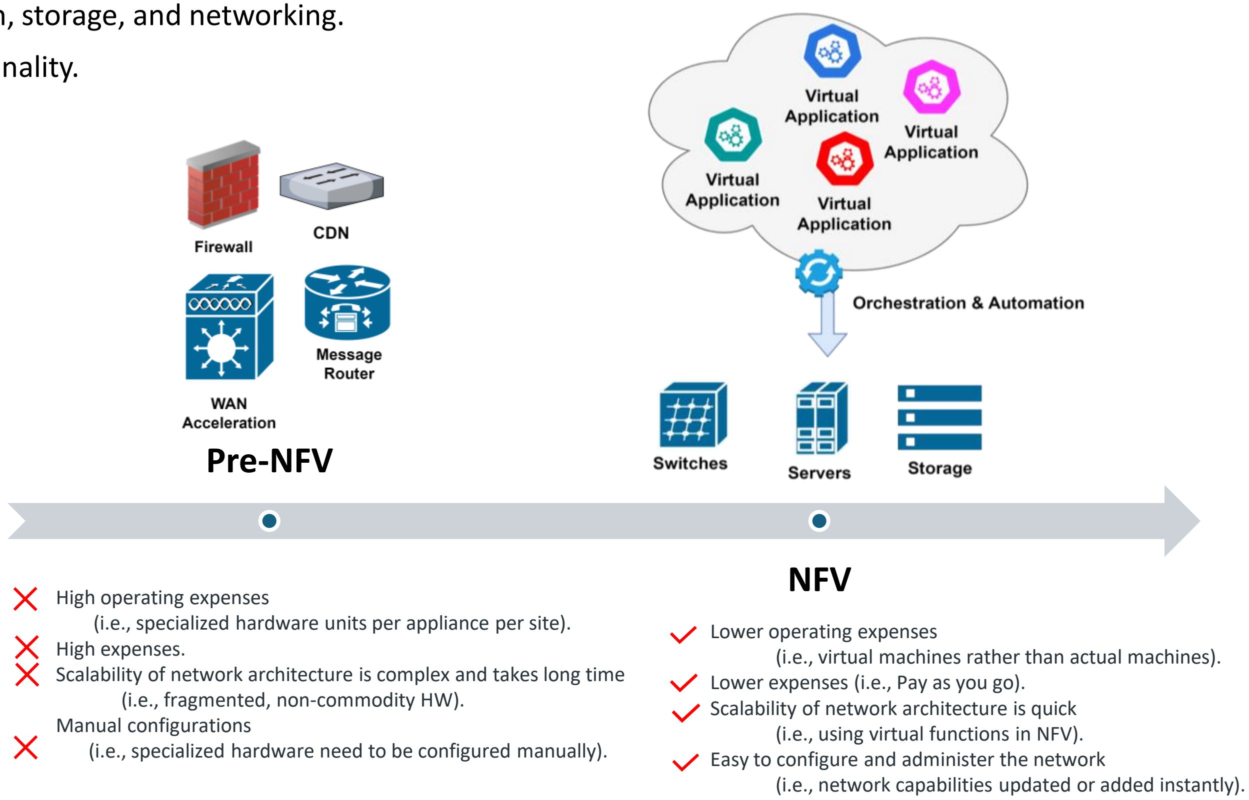


Fig.2 NFV Architecture.



How SDN & NFV enable IBN ?

What's the relationship between SDN & NFV ?

- Two different technologies but complementary to each others.

SDN

- Separate control and data planes.
- Centralized controller.
- Network programmability.

SDN serve NFV by providing programable connectivity between VNFs, which can be managed by the VNFs orchestrator.

NFV serve SDN by implementing its network functions in a software manner on a COTSs servers. It can virtualize the SDN controller to run on cloud.

NFV

- Separate network functions from physical HW.
- Speed up time-to-market new services.

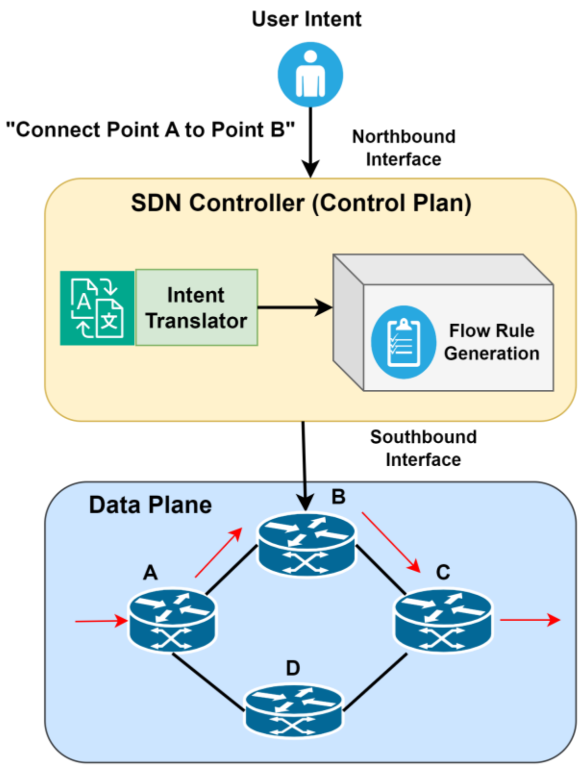


Fig. 3. Example of an IBN-enabled SDN system.

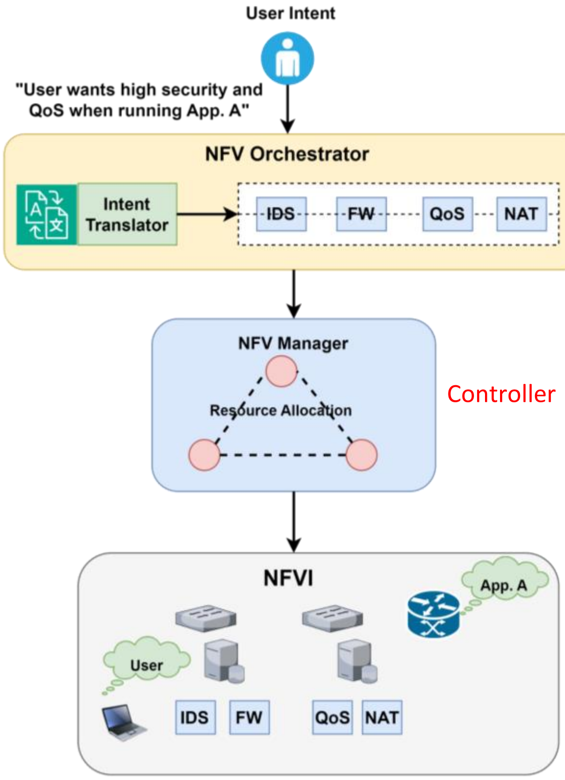


Fig. 4. Example of an IBN-enabled NFV system.

What is the main high-level architecture of IBN ?

- **<u>Business layer</u>**: users express their intents based on KPIs (i.e., SLAs, processes, goals, targets or objectives).
  - Higher-level declarative policy that operates at the level of a network and services.
  - Allowing high-level guidance by a central entity.

- **<u>Intent layer:</u>** It executes the planned sequence of actions after re-evaluate and re-plan after every step.

  - **<u>Knowledge:</u>** handles abstraction of intents.
    - Performs inference from relations between network objects (i.e., physical nodes).

  - **<u>Agent:</u>** an interface to the network objects and performs actions on the network objects after evaluating the intents.
    - Capture the business intent and translate into policies.
    - Utilize ontology-based approach to communicate with users.
    - Communication interface directly to the network objects.

  - **<u>Data:</u>** observes the network objects and used for effective storage.
    - Keep the state of each intent and the relation between network objects.
    - Provides models for the observed data.
    - Provides algorithms for data modeling.
- **<u>Network Layer:</u>** contains the physical nodes.
  - The abstract model of the hardware is stores in this layer and it is responsible to execute actions requested by the agent.
  - Transform the network data into a formal representation so that intent layer can easily work with.

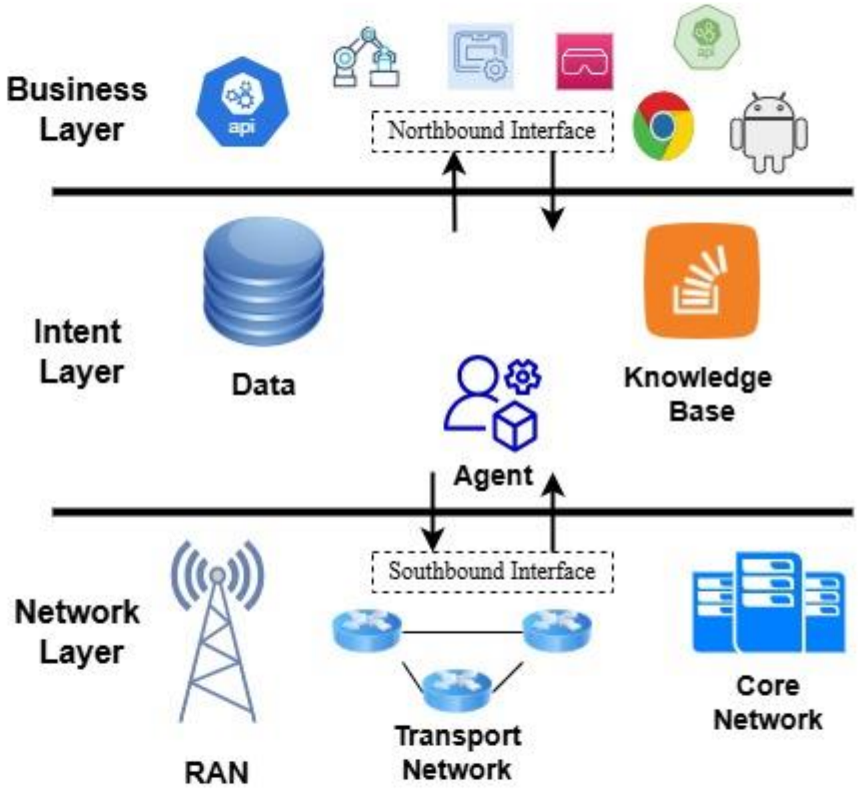


Fig.5 Intent-based Networking Architecture.

KPIs: Key Performance Indicators. **SLAs:** Service Level Agreements.

Standards Developing Organization (SDO) Effort

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➢ TM Forum

- ✓ An autonomous domain is a set of systems or platforms that is capable of intervention using closed control loops.
- ✓ Operational layers are fully decoupled.
- ✓ Intelligence is decentralized and localized within its own domain for fast decision-making.

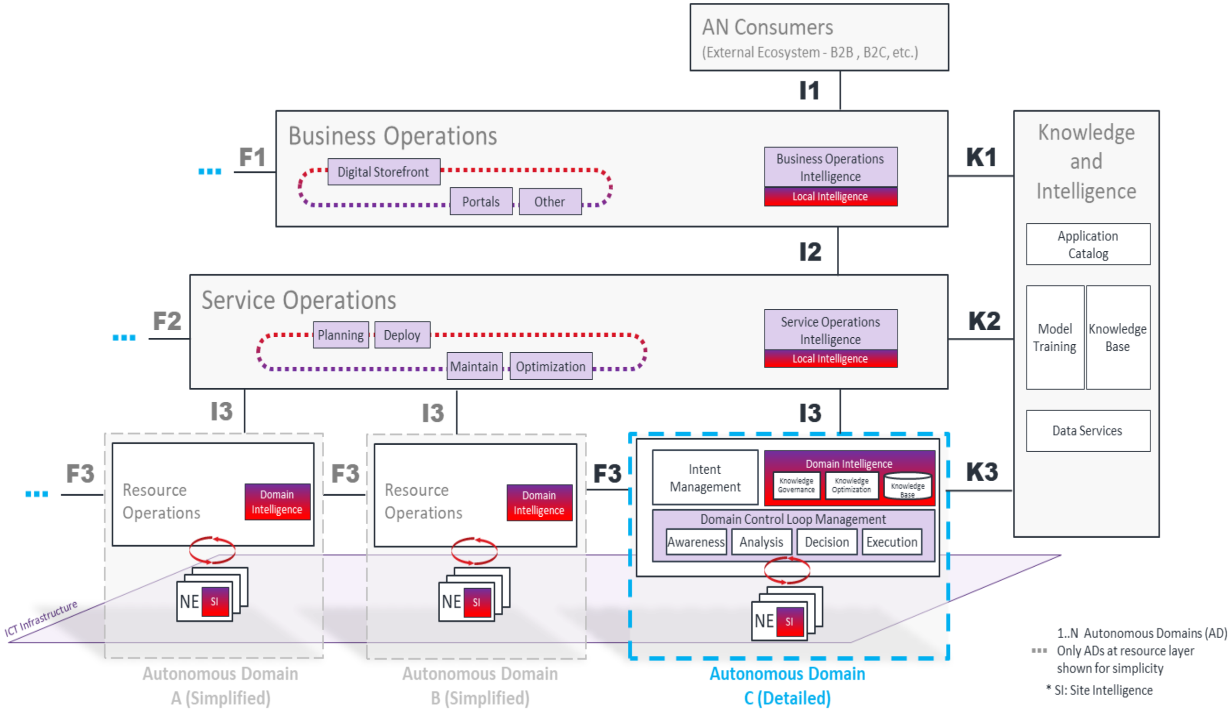

Figure 6: TM Forum Autonomous Networks Reference Architecture.

➢ ETSI ZSM (Zero-touch Network and Service Management)

- ✓ It aims to achieve end-to-end service and network management with minimal or no human intervention by leveraging AI-driven closed-control loop automation, intent-based management, and data-driven decision-making.

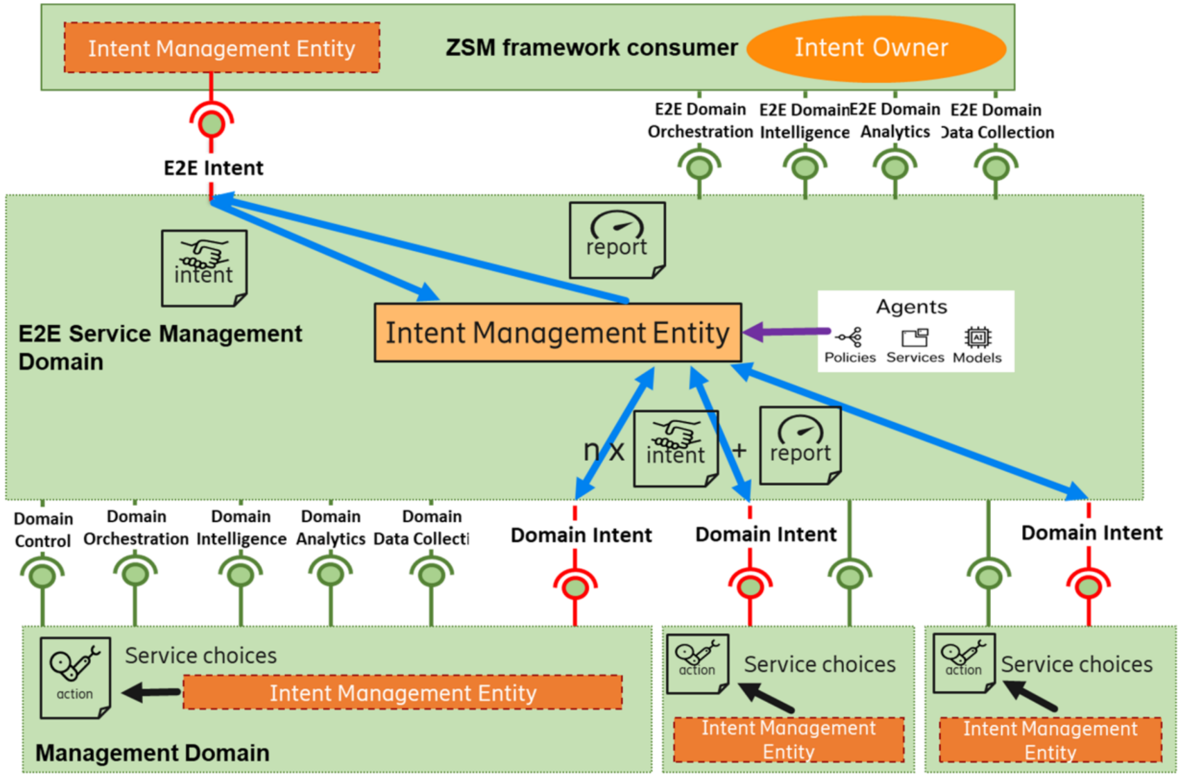

Figure 7: A hierarchy of Intent Management depicted in a simplified ZSM framework architecture diagram.

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6G-INTENSE Proposed Architecture

- A novel Distributed Intent-driven Management and Orchestration (DIMO) framework.
- Three new components for management and orchestration:
  - **t-DMO**: is responsible for handling vertical services and processing service intents from the underlying DMO.
  - **DMO:** operating at the service level, it receives service intent inputs from the t-DMO or directly from verticals.
  - **NCF:** operating at the resource level, it provides an abstraction layer for resource allocation across heterogeneous technological and administrative domains. Given the integration of diverse 6G resource pools, this abstraction is essential for enabling distributed resource management.
- Each operational domain of the 6G-INTENSE architecture operates an intent manager independently of each other, which makes decisions based on intents.
- Native AI empowers the network to interpret and decompose high-level intents using natural language but also equips it with adaptive capabilities to make context-aware decisions through RL/HRL. As a result, the system can autonomously optimize its operations, predict and resolve conflicts, and continually evolve in response to dynamic network environments.

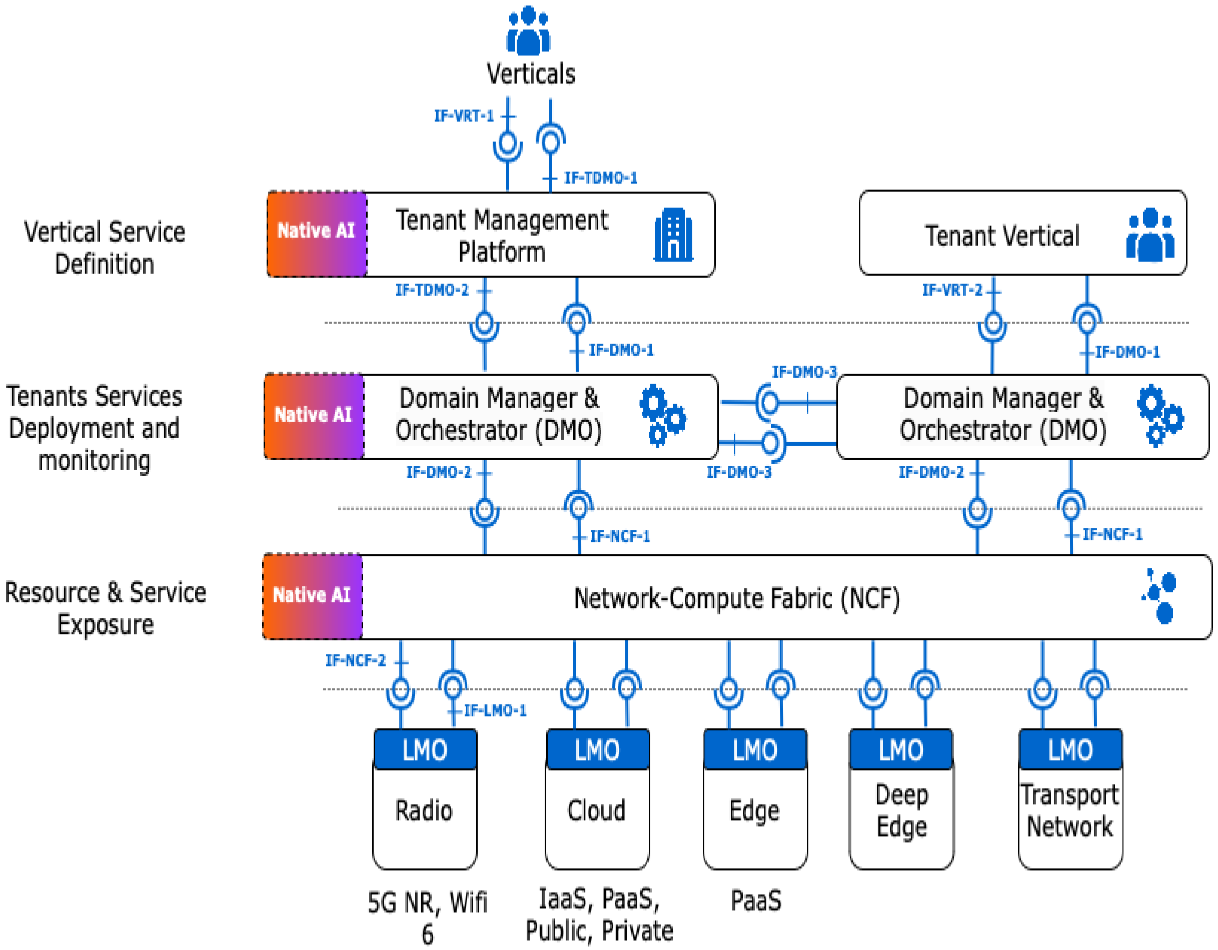

Figure 8. 6G-INTENSE Proposed Architecture.

What are the main component of IBN ?

- IBN provides a **complete life cycle** to the intent, which takes place over five main steps to form a CLA.
  - **Intent profiling:** the users interact with the network to express their intents (i.e., what the user expects as an outcome from the network or service). It can be expressed in different forms such as CLI, API, NLP, drop down menus. In some cases, they collaborate towards expressing a meaningful intent for the network.
  - **Intent translation:** the expressed abstracted intent is translated and converted into network policy and low-level configuration to configure network devices.
  - **Intent resolution**: solves the potential conflict between independently submitted intents.
  - **Intent activation:** activates the network functions and services to provide the intended customized service.
  - **Intent assurance**: indicates the success of the deployed intent in the network throughout its dynamic life cycle.

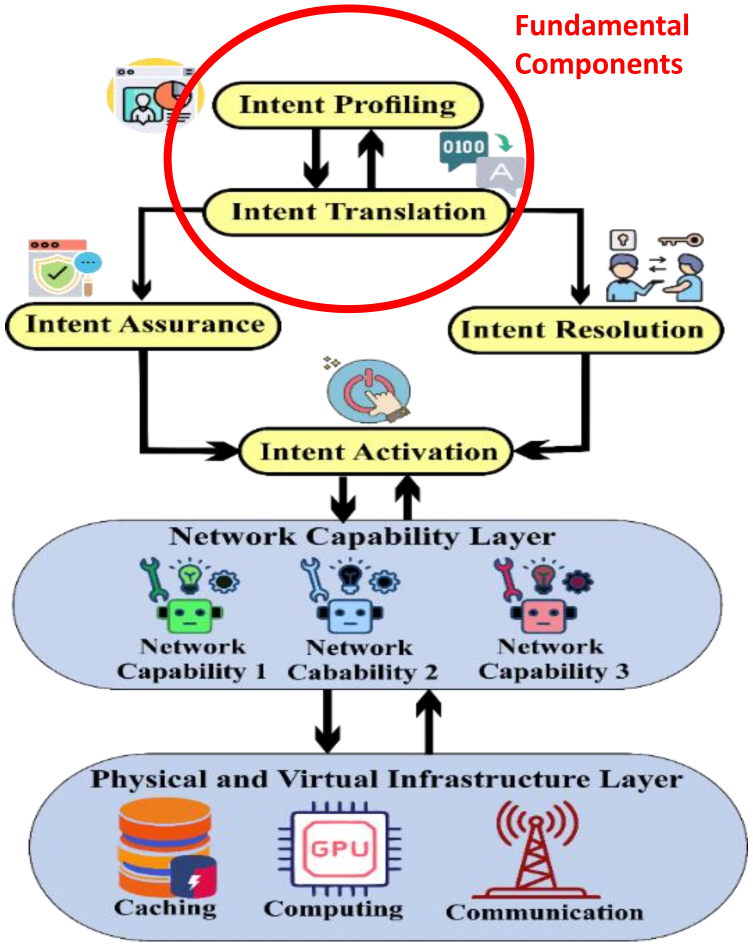

Fig.9 Interaction of the main IBN components.

CLA: closed-loop automation.

Intent Profiling & Translation

What's Objective ?

- Reduce the gap between every type of user, from a simple novice user to a highly experienced network administrator.
- Provide intent language that minimize the gap between human and machine readability.
- Translation of the high-level intent into a low-level network policies (i.e., easily rendered into network configuration languages/scripts (e.g., YANG/NETCONF models).)

- IETF has provided an intent classification

Intent Profiling Classification

- Network Type (i.e., Carrier, Data Center, and Enterprise)
- Intent Scope (i.e., connectivity, application, security, network function)
- Network Scope (i.e., radio access, campus, branch, transport, core, Edge, Cloud, etc.)
- Intent Life-cycle (i.e., persistent and transient)

- According to the type of the intent expression and its scope, different translation mechanisms can be used.
- **How are intents being expressed ?** *1. Template/GUI-Based* *2. NLP* *3. IBN language* *4. API/CLI*
- **How are expressed intents being translated ?** *1. Template/Blueprint* *2. Mapping* *3. Refining* *4. NSD* *5. Policy DB* *6. Graph-based* *7. Inference* *8. Keyword* *9. Machine Learning* *10. Semantics* *11. Feedback Assisted* *12. State Machine*

IETF: Internet Engineering Task Force. **NLP:** Natural Language Processing.

Intent Profiling & Translation

- **Template/GUI-based:** express intent using forms or GUIs (i.e., dropdown selection input) and the selected parameters are then parsed and mapped to a set of network descriptors.
  - ✓ **Pros:** make it easier for users to express their intent.
  - ✓ **Cons:** users can only express their intent within the predefined scope with template/GUI based intent expression.
- **API-based:** users express their intent using CLIs, APIs, or JSON files.
  - ✓ **Pros:** enables users to clearly express their intents and simplifies the complexity of intent translation.
  - ✓ **Cons:** requires users to have expert knowledge.

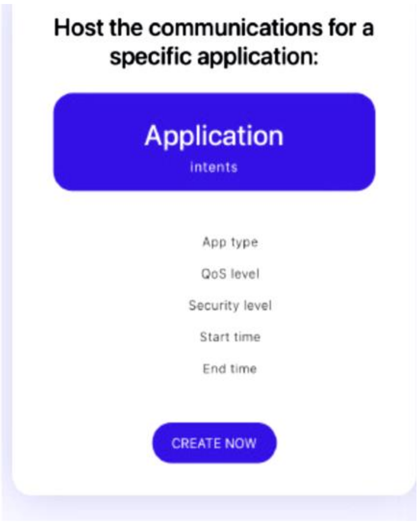

Fig. 2 GUI-based intent expression.

- **IBN Language:** Technical restrictive where, the intent should be readable and abstract the technical details.
  - Flexible enough to be extended and adjusted according to the business intent scenario under consideration.
  - ✓ **Cons:** The users of these languages should be more technical users (i.e., network operators/administrators).
- Nile and NEtworking Modeling (NEMO) language

Example: "Route Alice's traffic to Bob with bandwidth 500 Mbps and latency less than 100 ms, through a firewall and IP encryption,during working hours from 9am to 5pm".

```
define  intent  Routing:
  from    endpoint( 'Alice' )
  to      endpoint( 'Bob' )
  add     middlebox( 'firewall' ),
          middlebox( 'IPSec' )
  with    latency( 'less', '100 ms' ),
          throughput( 'equal', '500Mbps' )
  allow   traffic( 'any' )
  start   hour( '09:00' )
  end     hour( '17:00' )
```

Intent Profiling & Translation: Large Language Models (LLM)

- **ML/NLP-based:** intents using natural human language
  - ✓ **Pros:** make it easier for users to express themselves freely.
  - ✓ **Cons:** present a challenge in implementation due to the diverse range of users, such as application developers, network operators, and end users. These different user roles have varying levels of expertise or experience, different network requirements, and different expression patterns.

- Existing ML methods rely on classifying intents or abstracting key terms from user intents in natural language.
  - ✓ Requires extracting keywords from user intent and querying the network policies corresponding to the keywords from the database through mapping to achieve the intent translation. In practice, the ML models lack labeled datasets.
  - ✓ Handle simple user intents effectively but struggle with vague intents from non-expert users or complex user demands.

Fig.1 Natural language expressed intent.

6G-INTENSE Proposed Intent Profiling & Translation

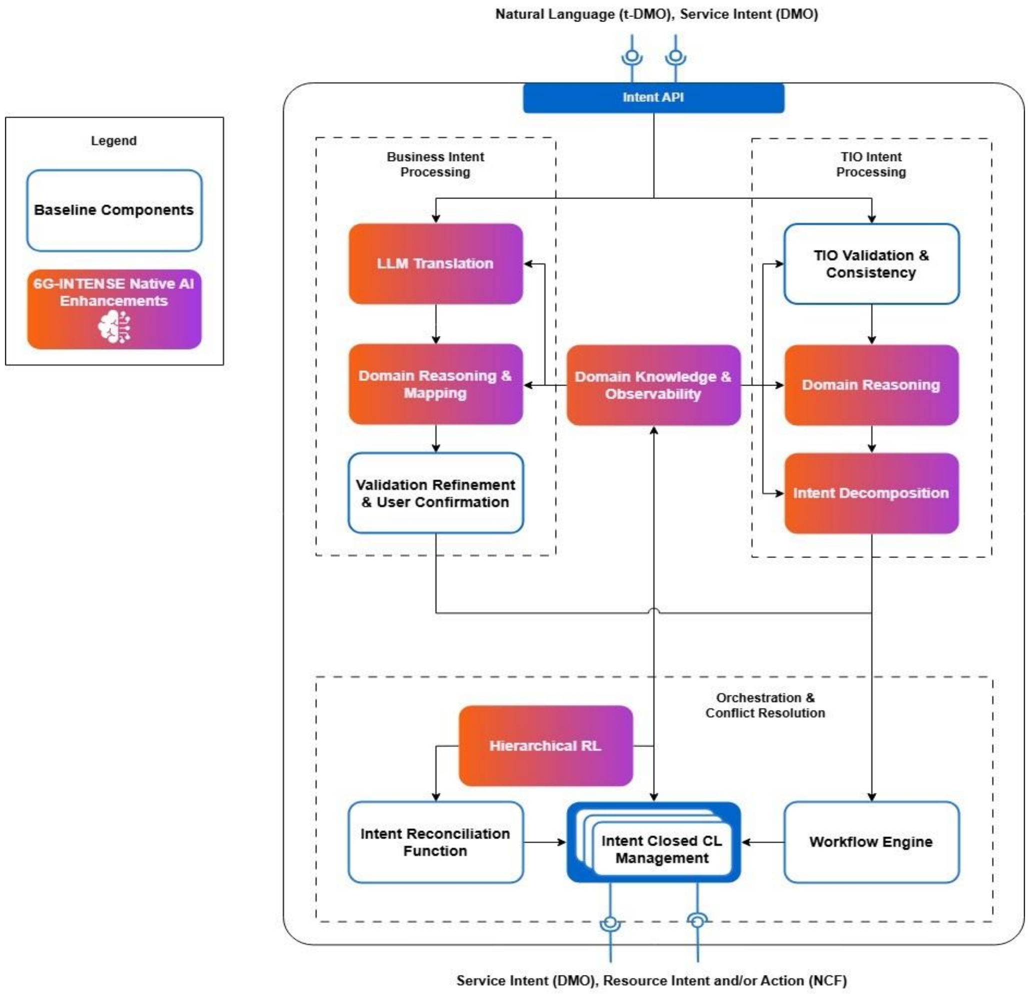

Figure 10. Native AI Integration in Intent handler LCM.

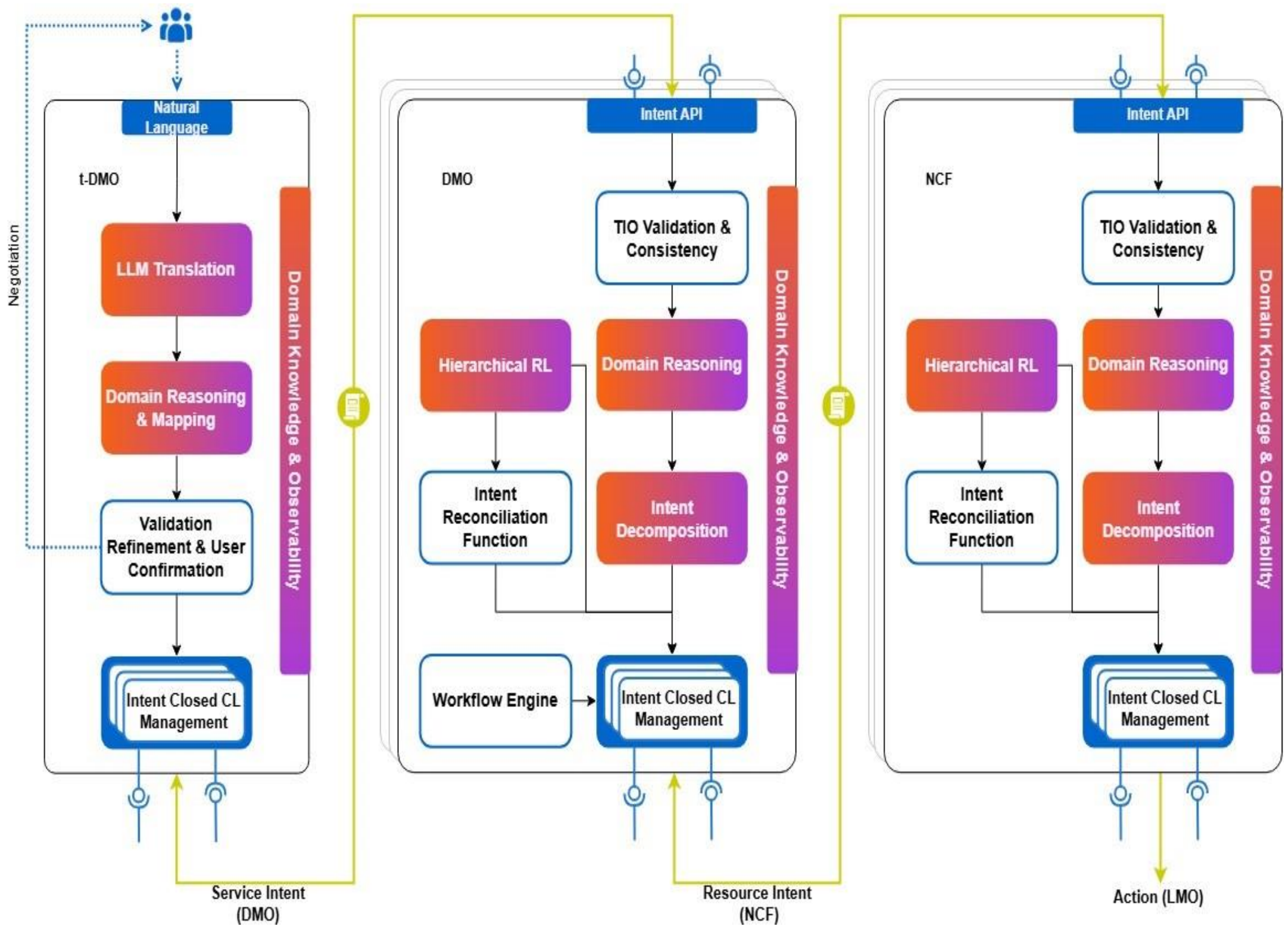

Figure 11. Processing of Intents through Native AI blocks across different levels of the 6G-INTENSE architecture.

RAG-Enabled Intent Reasoning for Application-Network Interaction

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- LLMs have excellent capability in NLP enabling them to comprehend abstract intents without the need for training on a specific dataset.
- We propose a **context-aware AI framework** that utilizes machine reasoning (MR), retrieval augmented generation (RAG) and generative AI technologies to interpret intents from different applications and generate structured network intents.

✓ **Knowledge Database:** chunk the technical documents, embed, and store them in a vector database.

✓ **Intent Refinement:** receives the user application generic intent and interprets it and converts it to a well-defined intent (i.e., intent contains essential information to search the knowledge database).

✓ **Structured Intent Creator:** extracts the relevant information to the well-defined intent from the knowledge database, ranks them based on high similarity, and generates the network structured intent.

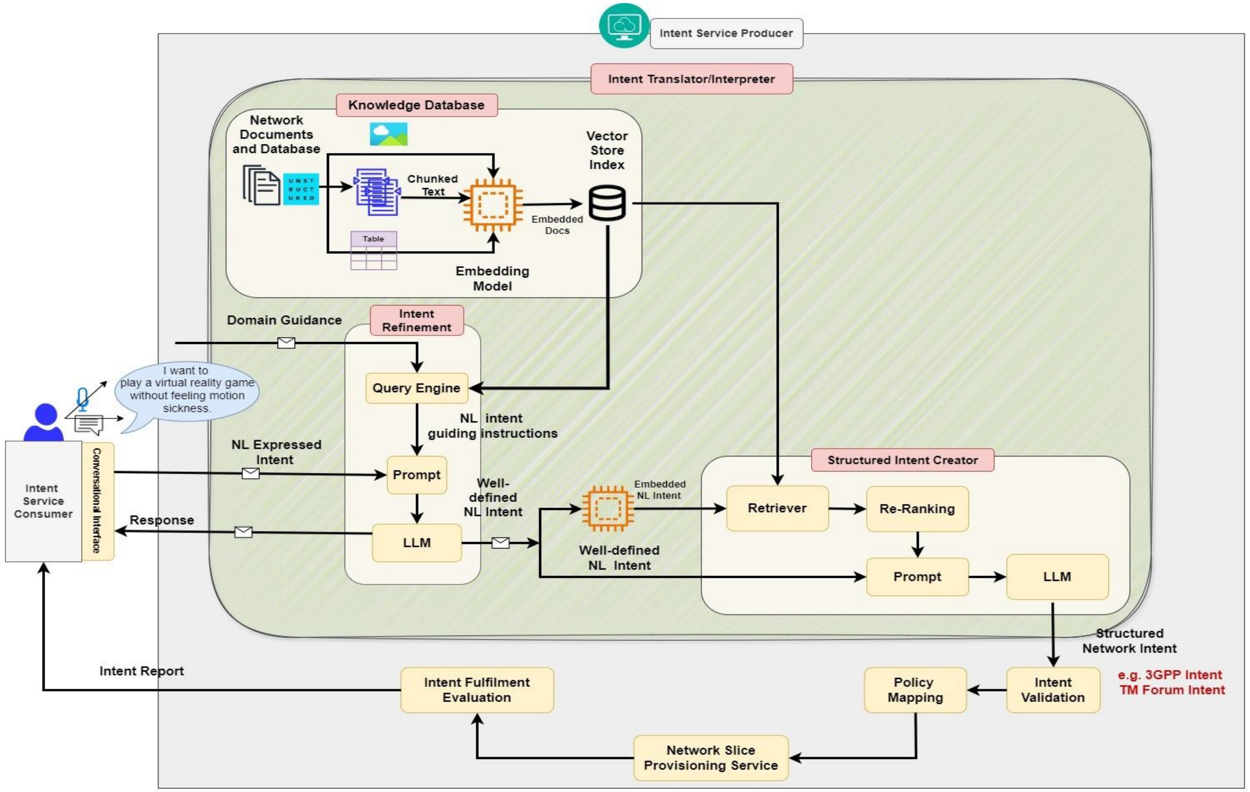

Fig.12 Proposed Intent-RAG Framework.

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Patents : A Functional Model for Translating Natural Language Expressed Intent to Network Structured Intent, Salwa Mostafa, Mohamed K. Abdel-Aziz, Mehdi Bennis.
Magazine Paper (*submitted*) : RAG-Enabled Intent Reasoning for Application-Network Interaction, Salwa Mostafa, Mohamed K. Abdel-Aziz , Mohammed S. Elbamby, Mehdi Bennis.
Video: https://youtu.be/_q7GPy0n5tw

Experimental Results

✓ We evaluate the efficacy of the intent RAG and compare it to LLM and a vanilla RAG framework as a benchmark.

Table I
COMPARISON BETWEEN LLM, VANILLA-RAG, AND INTENT-RAG BASED ON HUMAN EVALUATION

User Intent	4K On Demand Video	I want to play a virtual reality game without feeling motion sickness
Vanilla-RAG Output	Scenario Type: 4K On Demand Video Key Performance Factors: - Data Rate/Throughput (downlink): 30 Mbps - Delay: RTT < 50 ms - Frame Rate: 60 fps - Resolution: $4K(3840 \times 2160)$ - Operation Response Delay: 50 ms - Coverage Quality CSI SINR: -2 dB	Scenario Type: Cloud VR Interactive VR Games, Key Performance Factors/Performance Recommendations: Bandwidth: 100 Mbps (downlink), Packet Loss Rate: $< 0.01\%$ (UDP), Network Delay: < 25 ms, MTP Delay (ms): < 80 ms (good experience), Coverage level CSI RSRP: -107 dBm, Coverage level CSI SINR: 2 dB.
Intent-RAG Output	Scenario Type: 4K On Demand Video, Key Performance Factors: Data Rate/Throughput (downlink): 30 Mbps, Delay: RTT < 100 ms, Packet Loss Rate:10^{-3}, Resolution: 4K, Coverage Level CSI RSRP: -113 dBm, Coverage Quality CSI SINR: -2 dB.	Scenario Type: 3K Cloud VR (Game), Key Performance Factors: Data Rate/Throughput (downlink): 100 Mbps, Delay: RTT < 25 ms, Packet Loss Rate: 10^{-5} (TCP), 10^{-4} (UDP), Resolution: 3K, Coverage Level CSI RSRP: -107 dBm, Coverage Quality CSI SINR: 2 dB.
LLM Output	Scenario Type: 4K On Demand Video Key Performance Factors: 1. Video Quality: The video quality should be at least 3840x2160 pixels to ensure a true 4K experience. 2. Buffering Time: The buffering time should be minimal to provide a seamless viewing experience. 3. Playback Speed: The video should play at a consistent speed without any lag or delays. 4. Audio Quality: The audio quality should be clear and synchronized with the video. 5. User Interface: The user interface should be user-friendly and easy to navigate. 6. Content Selection: The platform should offer a wide variety of 4K content to attract and retain viewers. 7. Device Compatibility: The platform should be compatible with different devices to reach a larger audience. 8. Customer Support: The platform should have a reliable customer support system in place to address any technical issues. 9. Subscription Options: The platform should offer flexible subscription options to cater to different user preferences. 10. Data Usage: The platform should optimize data usage to prevent excessive data consumption for viewers.	Scenario Type: Virtual Reality Gaming Key Performance Factors/Performance Recommendations: 1. Frame Rate: The frame rate of the game should be at least 90 frames per second to ensure smooth and realistic movement in the virtual environment. 2. Latency: The latency, or delay, between the player's actions and the game's response should be minimal to avoid disorientation and motion sickness. 3. Field of View: The field of view should be set to a comfortable level, typically between 90-110 degrees, to avoid a feeling of tunnel vision and motion sickness. 4. Motion Blur: Motion blur should be minimized or turned off completely to reduce the strain on the player's eyes and prevent motion sickness. 5. Head Tracking: The game should have accurate head tracking to ensure that the virtual environment moves in sync with the player's head movements, reducing the risk of motion sickness. 6. Comfort Settings: The game should have options for comfort settings, such as reducing camera movement or adding a virtual nose, to help alleviate motion sickness for players who are more sensitive. 7. Graphics Quality: The graphics quality should be optimized to ensure a smooth and realistic experience without causing lag or stuttering, which can contribute to motion sickness. 8. Audio: The game's audio should be synchronized with the visuals to avoid any discrepancies that can cause disorientation and motion sickness. 9. Breaks: The game should have built-in breaks or prompts for players to take breaks and rest their eyes to prevent eye strain and motion sickness. 10. User Feedback: The game should have a system for users to provide feedback on their experience, allowing developers to make necessary adjustments to reduce the risk of motion sickness.
Ground Truth	Scenario Type: 4K On Demand Video Key Performance Factors: Data Rate/Throughput (downlink): 30 Mbps, Delay: RTT < 100 ms, Packet Loss Rate: 10^{-3}, Resolution: 4K, Coverage Level CSI RSRP:-113 dBm, Coverage Quality CSI SINR:-2 dB.	Scenario Type : 3K Cloud VR (Game), Key Performance Factors: Data Rate/Throughput (downlink): 100 Mbps, Delay:RTT < 25 ms, Packet Loss Rate:10^{-3} (TCP) 10^{-2} (UDP), Resolution: $3K$, Coverage Level CSI RSRP:-107 dBm, Coverage Quality CSI SINR:2 dB

Experimental Results

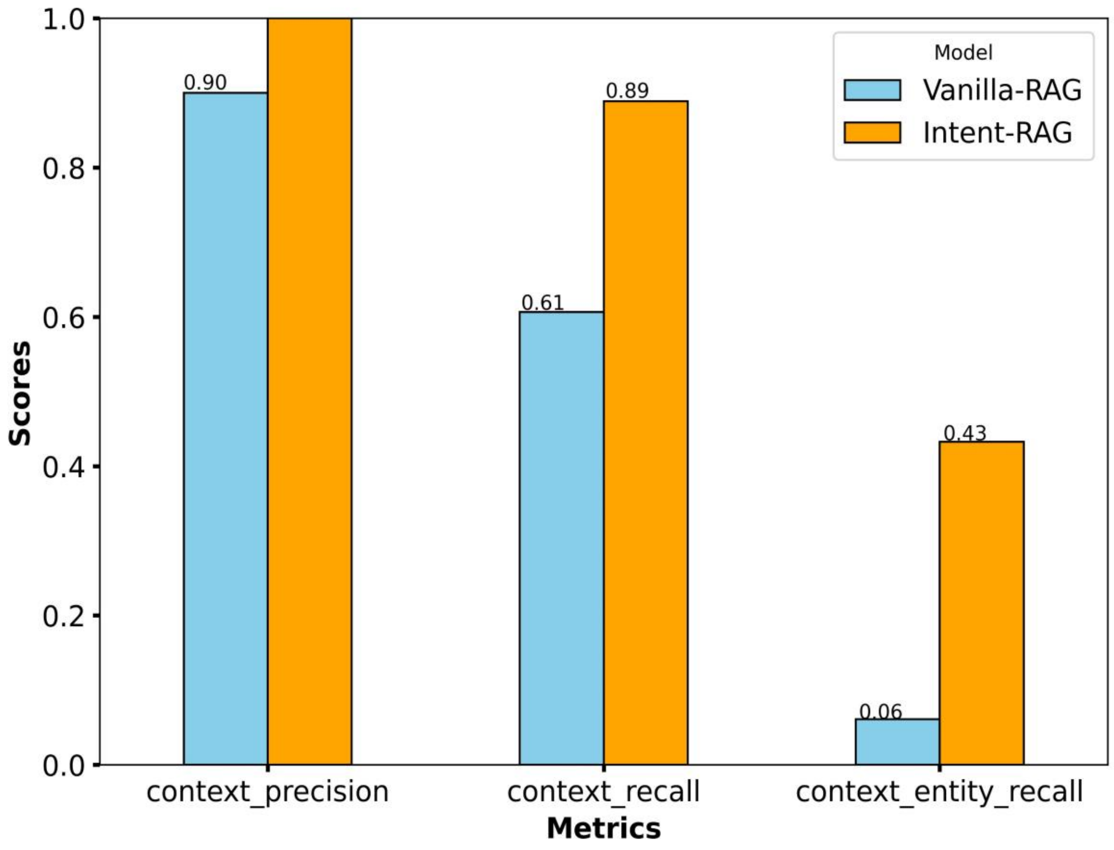

Fig.13 Retrieval part performance of vanilla-RAG and intent-RAG.

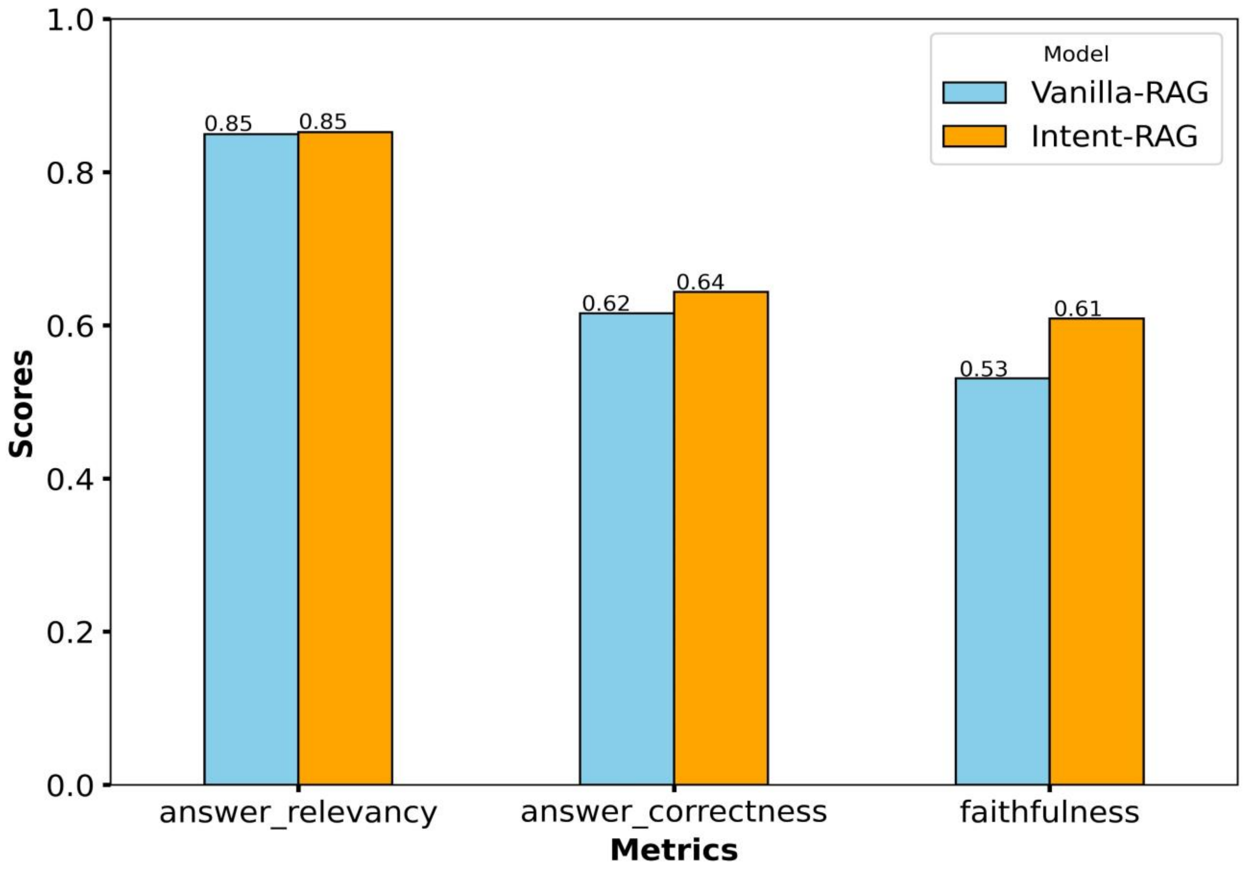

Fig.14 Generative part performance of vanilla-RAG and intent-RAG.

Intent Profiling and Translation Through Emergent Communication

- ✓ ***The objective :***
  - ✓ ***maximize the number of successful associations of intents to network slices.***
- ✓ **The optimization problem can be stated as follows**

$$\max_{\mathbf{Y},\boldsymbol{u}} \sum_{t\in\mathcal{T}} \sum_{n\in\mathcal{N}} x_{t,n}$$

subject to

$$C1: \sum_{m\in\mathcal{M}} y^t_{n,m} = 1, \ \ \forall\, n \in \mathcal{N},\ t \in \mathcal{T}$$

$$C2: x_{t,n} \in \{0,1\}.$$

$$x_{t,n} = \begin{cases} 1 & \text{if } t_n^{\text{comp}} \leq t_{n,req}^{\text{comp}} \text{ and } t_n^{\text{up}} \leq t_{n,req}^{\text{up}}, \\ 0 & \text{otherwise.} \end{cases}$$

$Y^t \triangleq [y^t_{n,m}]$: the $N \times M$ binary association matrix of network slices to IIoT MDs at time slot **t.**

- ✓ We consider the mapping is *successful* if the allocated network slice **m** characteristics can *satisfy the requested QoE*.
- ✓ Note that the uplink and downlink communication messages are not pre-defined and the meaning associated with each message emerges through communication.
- ✓ To solve the above-formulated Dec-POMDP problem, we adopt the multi-agent proximal policy optimization (MAPPO) algorithm.

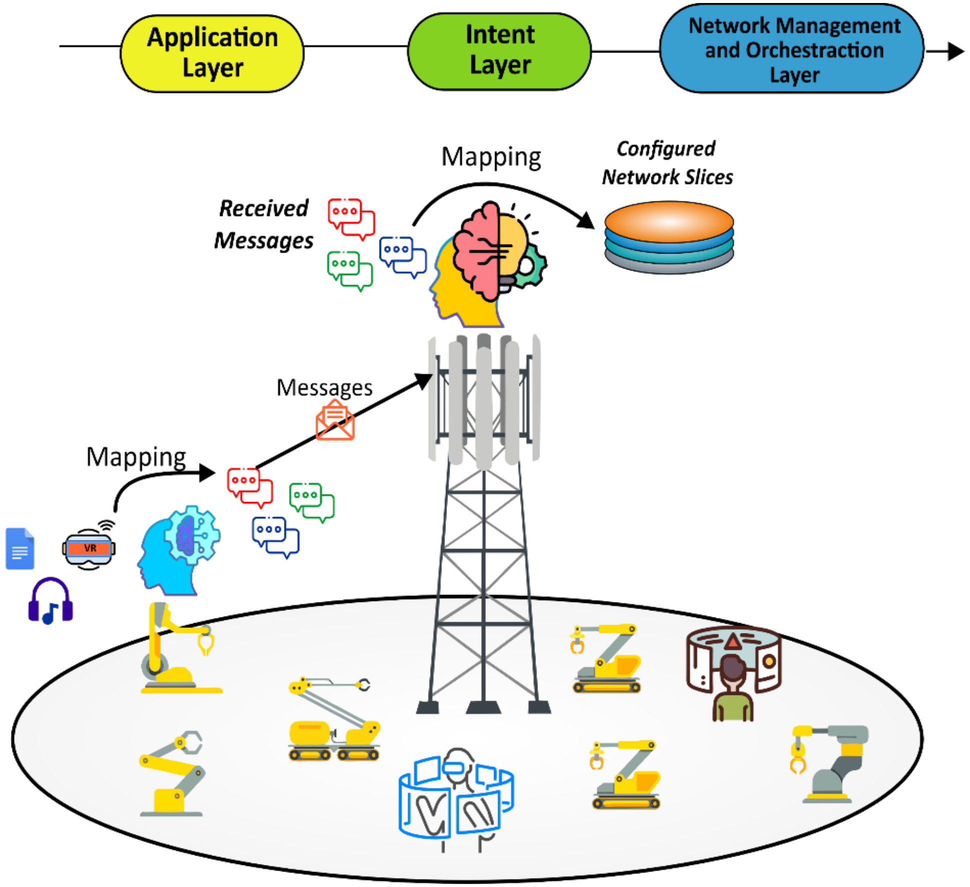

Fig.15 Proposed Framework.

Patents: A Method for Mapping Differentiated Application Requirements to Network Slices , Salwa Mostafa, Mohammed S. Elbamby, Mohamed K. Abdel-Aziz, Mehdi Bennis.
Conference Papers : Intent Profiling and Translation Through Emergent Communication , Salwa Mostafa, Mohammed S. Elbamby, Mohamed K. Abdel-Aziz, Mehdi Bennis, 2024 IEEE International Conference on Communications (ICC 2024),Denver, CO, USA.
Video: https://www.youtube.com/watch?v=Xk4QH9-pTH0&ab_channel=SalwaMostafa

MARL: multi-agent reinforcement learning.

Simulation Results

Fig.16 Normalized successful QoS translations versus the number of episodes.

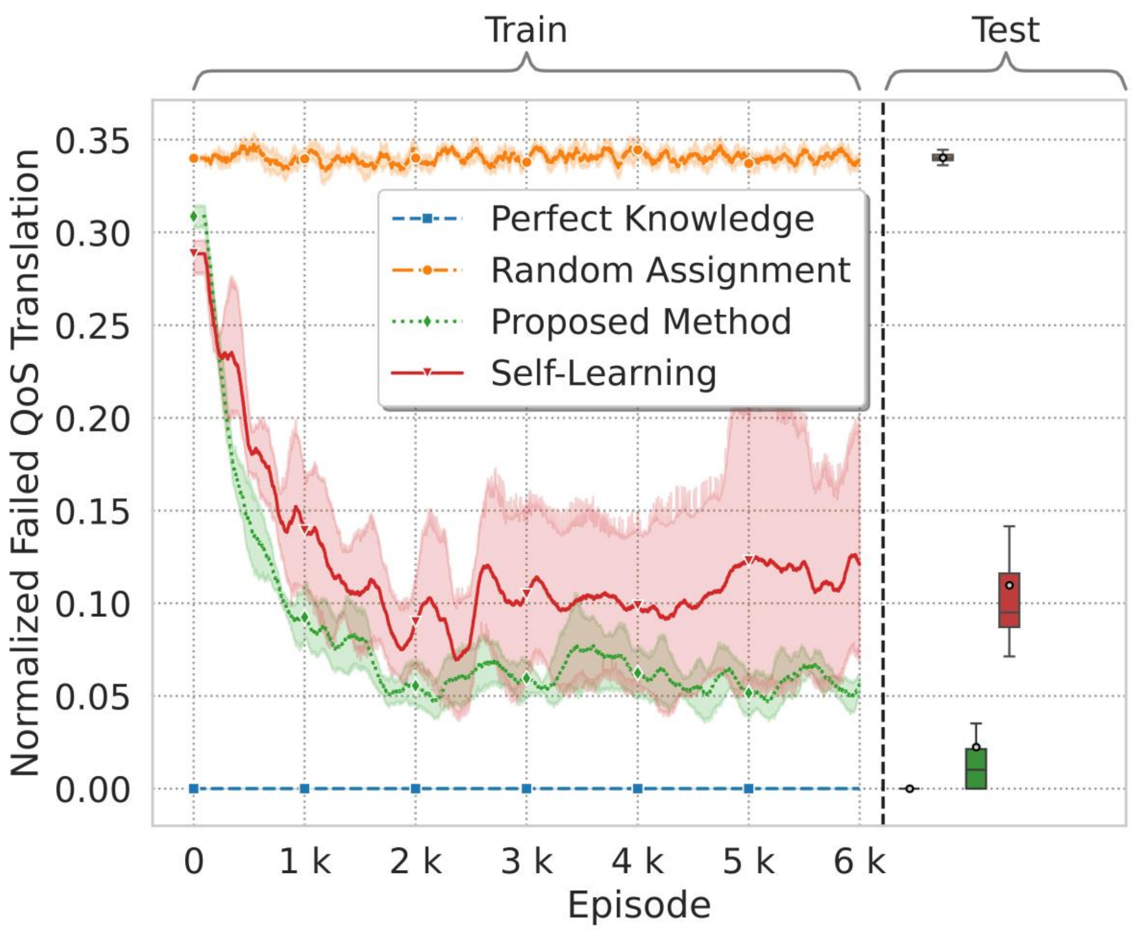

Fig.17 Normalized failed QoS translations versus number of episodes.

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Reference

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Thank You!!!

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Co-funded by the European Union

‘6G-INTENSE project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union’s Horizon Europe research and innovation programme under Grant Agreement No 101139266’