The Evolution of Semantic-Aware Networking: Recent Progress in Theory, Standardization, and Prototyping

Yong Xiao

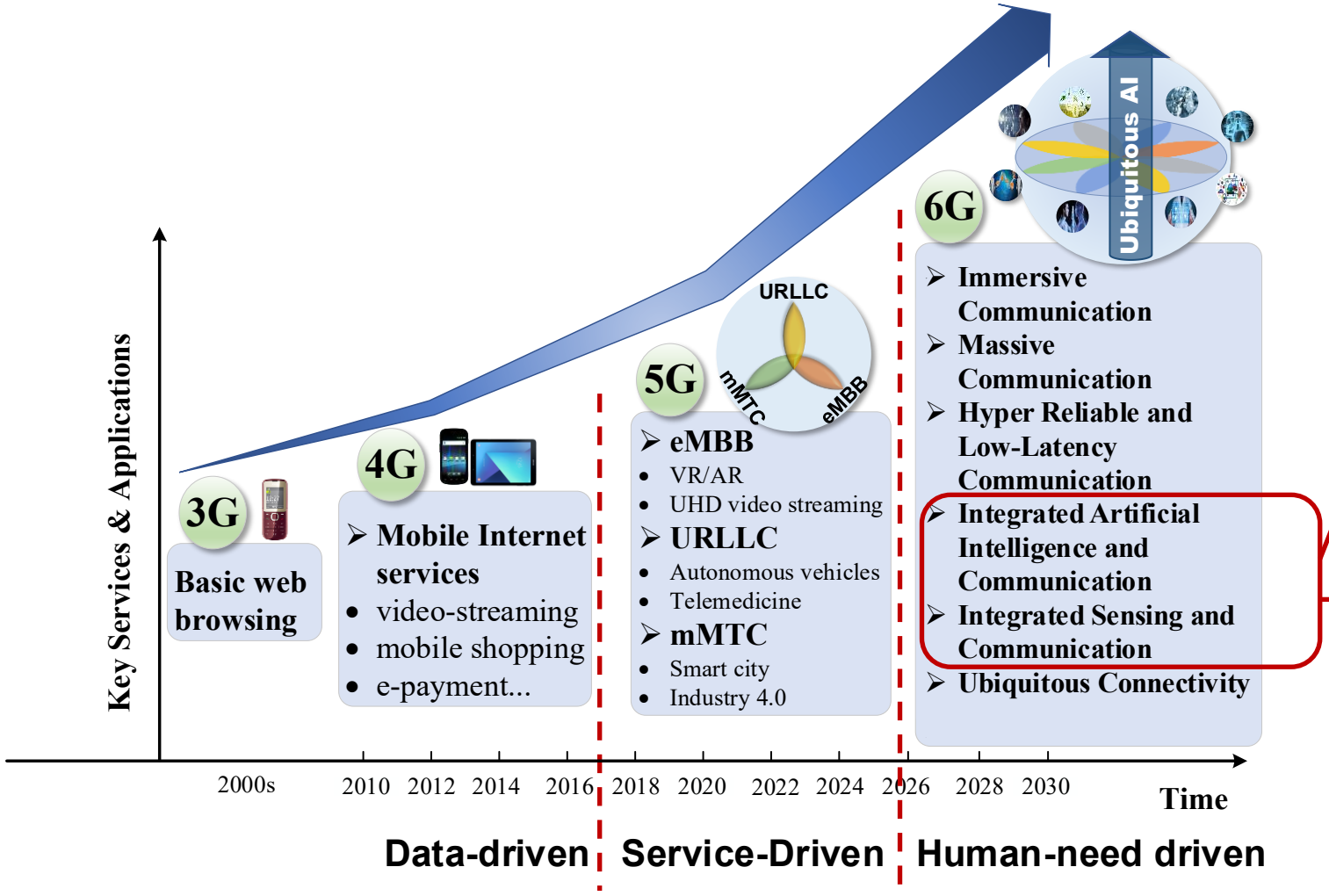
School of Electronic Information and Communications

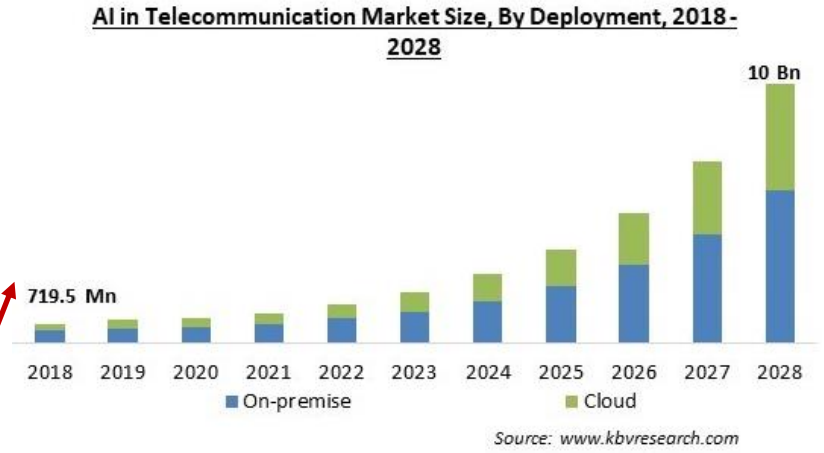
Huazhong University of Science and Technology

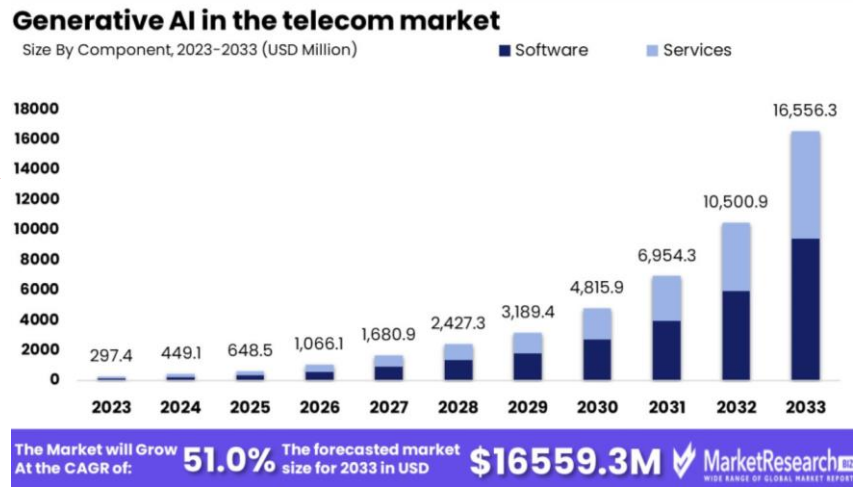
Email: yongxiao@hust.edu.cn
Website： https://sites.google.com/site/xyong2007/

July 10, 2026@AI for Good Summit'26

Mobile Network Evolution: From Service-Driven to Human-Need Driven & AI Native



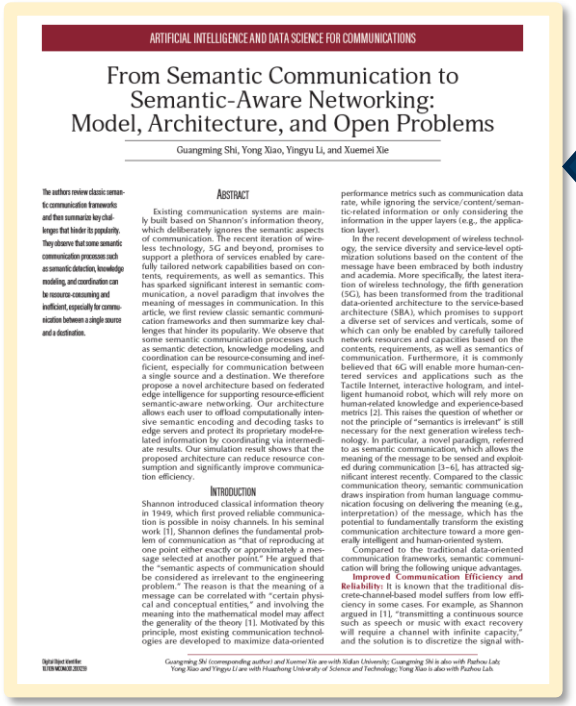




* ITU 《Framework and overall objectives of the future development of IMT for 2030 and beyond》

The Paradigm Shift – Breaking the Shannon Bottleneck

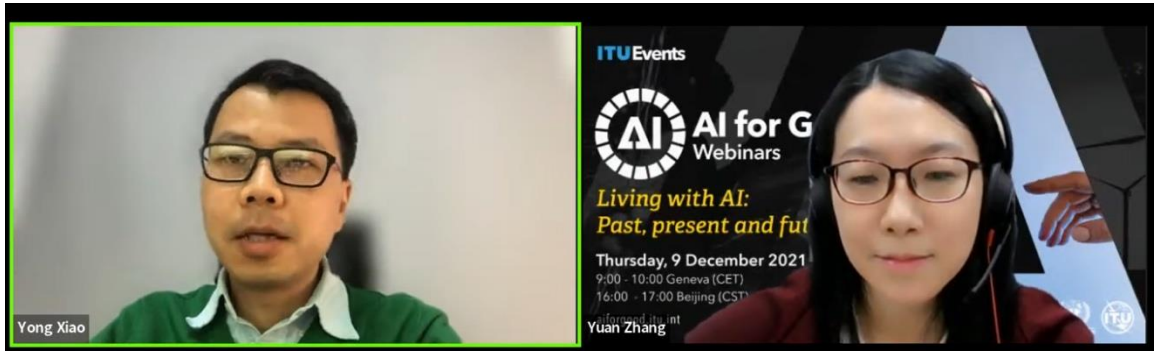
- **The Limitation:** Traditional communications are constrained by Shannon's capacity limits, treating all data bits equally without recognizing human need relevance and downstream utility.
- **The Pioneer Publication (IEEE CM'21):** The very first work to introduce the concept of SAN, shifting the paradigm from isolated point-to-point semantic com. to a comprehensive system-wide networking architecture in which routing, resource allocation, and orchestration are directly driven by the semantic intent of the users.


ARTIFICIAL INTELLIGENCE AND DATA SCIENCE FOR COMMUNICATIONS

From Semantic Communication to Semantic-Aware Networking: Model, Architecture, and Open Problems

Guangming Shi, Yong Xiao, Yingyu Li, and Xuemei Xie

The very first work to introduce the concept of SAN and formally establish it as the future trajectory for 6G networking architecture.



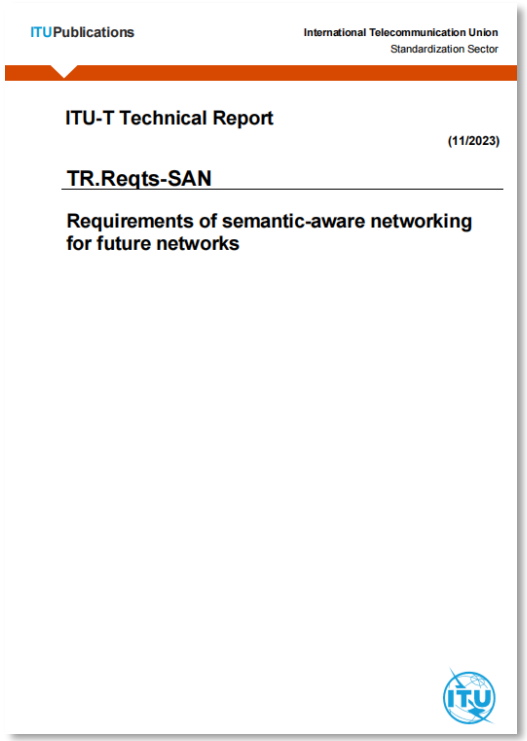
Invited speaker at AI for Good Global Webinar, December 2021

Invited talk "Semantic-aware Networking: Model, Architecture, and Open Problems" at AI for Good Webinar, April 2022

*G Shi, **Y Xiao**, et al., "**From Semantic Communication to Semantic-Aware Networking: Model, Architecture, and Open Problems**, " *IEEE Communications Magazine*, vol. 59, no. 8, Aug. 2021.

Background of Semantic-Aware Networking (SAN)

- **To break the "semantic gap", we have initiated the very first ITU-T Technical Report TR.Reqts-SAN "Requirements of semantic-aware networking in future networks" in Jul. 2022, which was published in Nov. 2023.**
- **ITU-T Recommendation ITU-T Y.RA-SAN: "Requirements and reference architecture of semantic-aware networking in future networks" has also been initiated in Nov. 2023.**
- **The Ultimate Goal:** Fulfilling the promise of human-intention-oriented, semantic-native networks in 6G and beyond.


ITUPublications

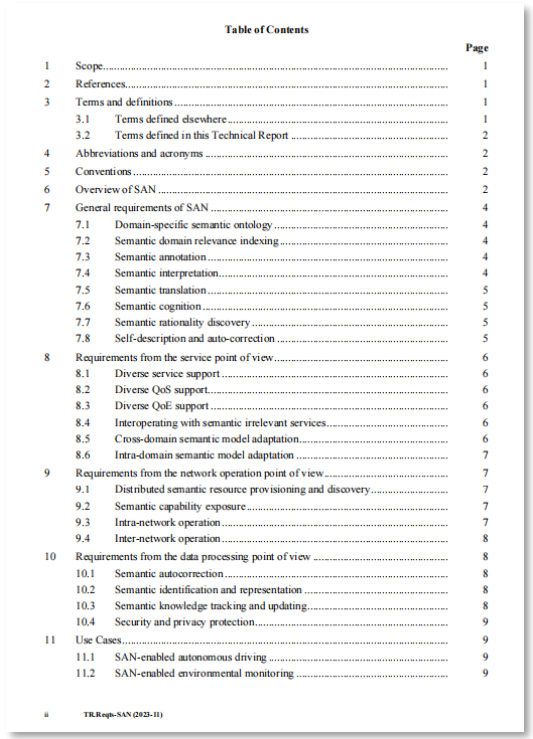
International Telecommunication Union
Standardization Sector

ITU-T Technical Report

(11/2023)

TR.Reqts-SAN

Requirements of semantic-aware networking for future networks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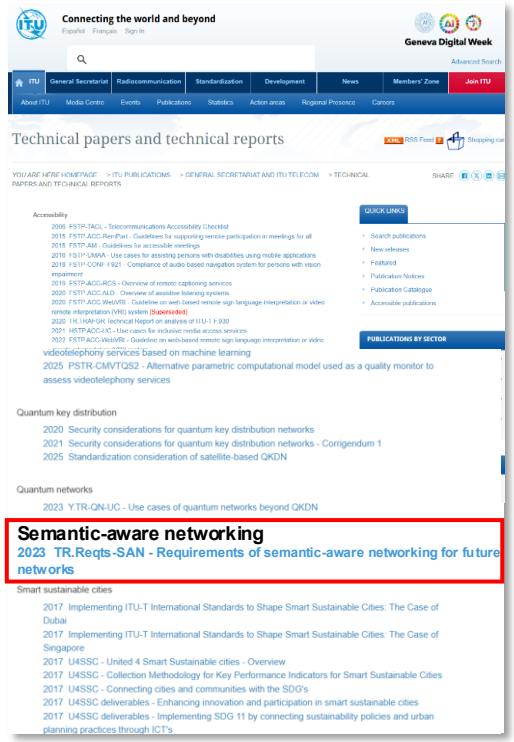


Lead/participated in **10+ technical reports and industrial whitepapers** about SAN

Vice-chair of IEEE P3427 standard on "**Semantic Information Agents**"

80+ invited talks about SAN in major 6G conferences

*G Shi and **Y Xiao**, "An Introduction to Semantic Communication and Semantic-Aware Networking Standardization for 6G," *ACM GetMobile*, vol. 28, no. 3, September 2024.

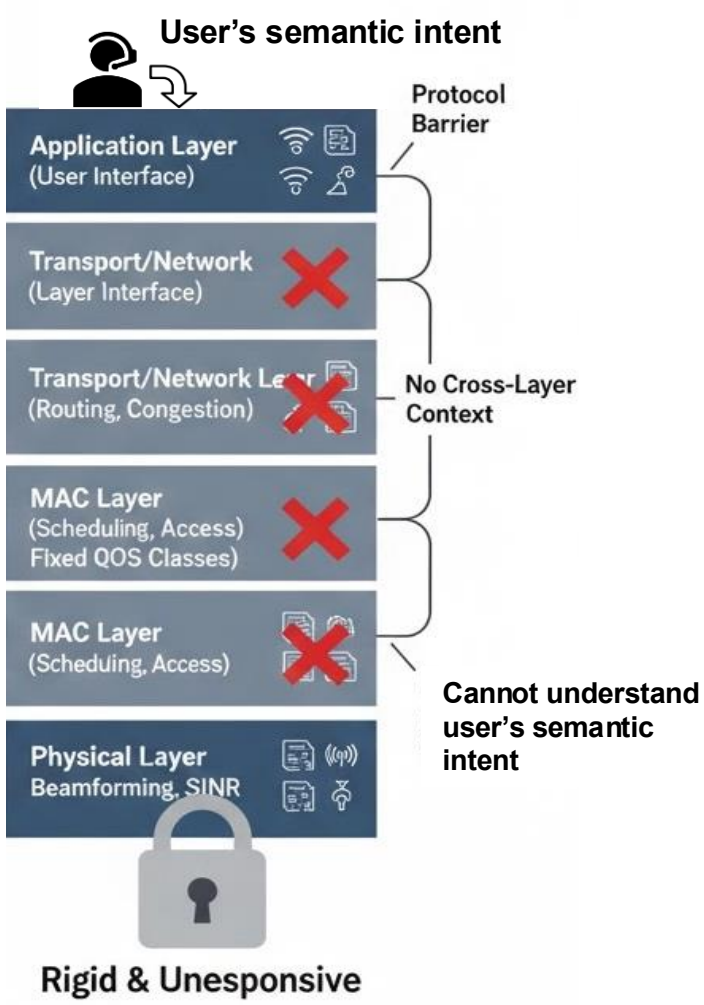
Motivation of Semantic-Aware Networking (SAN)

The "Blind" Pipe Paradigm of Traditional Networking
Traditionally, networks are designed to transport bits reliably and efficiently, regardless of what those bits represent.

The "Semantic Gap" between the User's Demand and Network Orchestration:

- **Layer Isolation:** The Physical and MAC layers optimize for technical metrics (SINR, Throughput, Latency) without knowing why the data is being sent.
- **Context Blindness:** A packet for a critical remote surgery is treated with the same logic as a background software update if they fall into the same QoS class.

The Result: Inefficient resource allocation where the network over-provisions for simple tasks and under-performs for complex, intent-heavy services.



*Y Xiao, et al., "Imitation Learning-based Implicit Semantic-aware Communication Networks: Multi-layer Representation and Collaborative Reasoning," *IEEE J Sel. Areas Com.* (JSAC), vol. 41, no. 3, pp. 639-658, Mar. 2023.
*Y Xiao, et al., "Reasoning over the Air: A Reasoning-based Implicit Semantic Communication Framework," *IEEE Trans. Wireless Com.* (TWC), vol. 23, no. 4, pp. 3839-3855, April 2024.

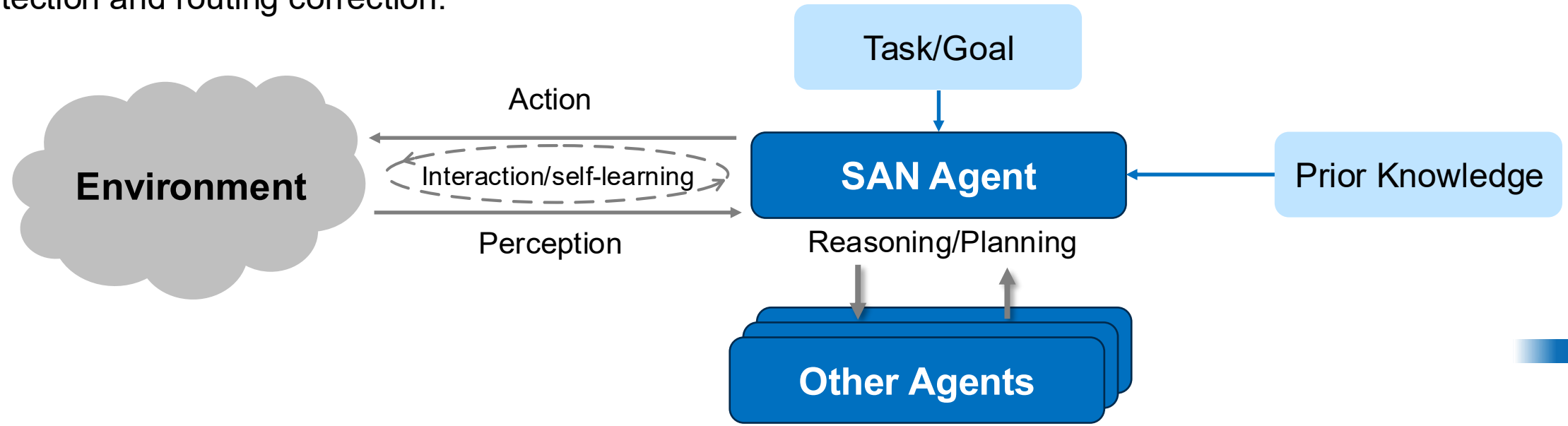
Overview of Semantic-Aware Networking (SAN)

- **ITU-T Definition of SAN:** Networking that exploits machine- and human-shared semantics to assist the learning, communication, and interpretation of the intended meaning.
- **The Core Mechanism:** Adopting machine- and human-shared semantic ontology and syntax to represent, annotate, analyze, reason, and interpret data and services within the network.
- **The "AI in Net" Paradigm:** SAN is not merely applying AI as a tool, nor is it just building pipelines for AI data. It is the native convergence of human-oriented learning and network content delivery.

Paradigm	Focus	Relationship	Ultimate Goal
AI4Net	Network Optimization	AI acts as an external **tool** to optimize legacy network protocols.	Maximize traditional QoS metrics (throughput, latency).
Net4AI	Distributed AI Support	Network acts as a **pipeline** to transport raw AI data and models.	Accelerate remote machine learning training and inference.
SAN (AI in Net)	Human-Oriented Interopretation and Delivery	**"AI in Net"**: AI and networking are natively fused to understand users' intent.	Deliver task-relevant semantics and intent-driven QoE.

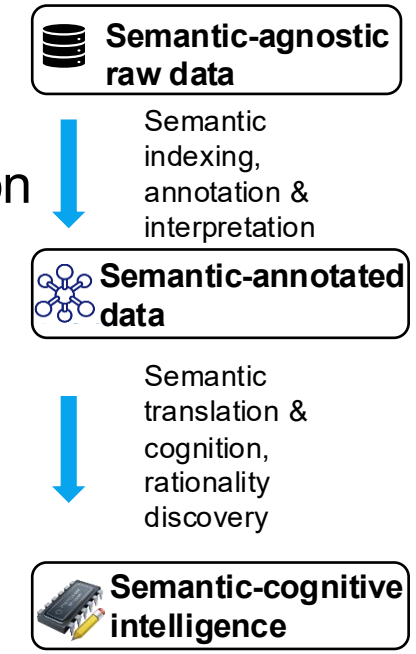
Key Capabilities Enabled by SAN

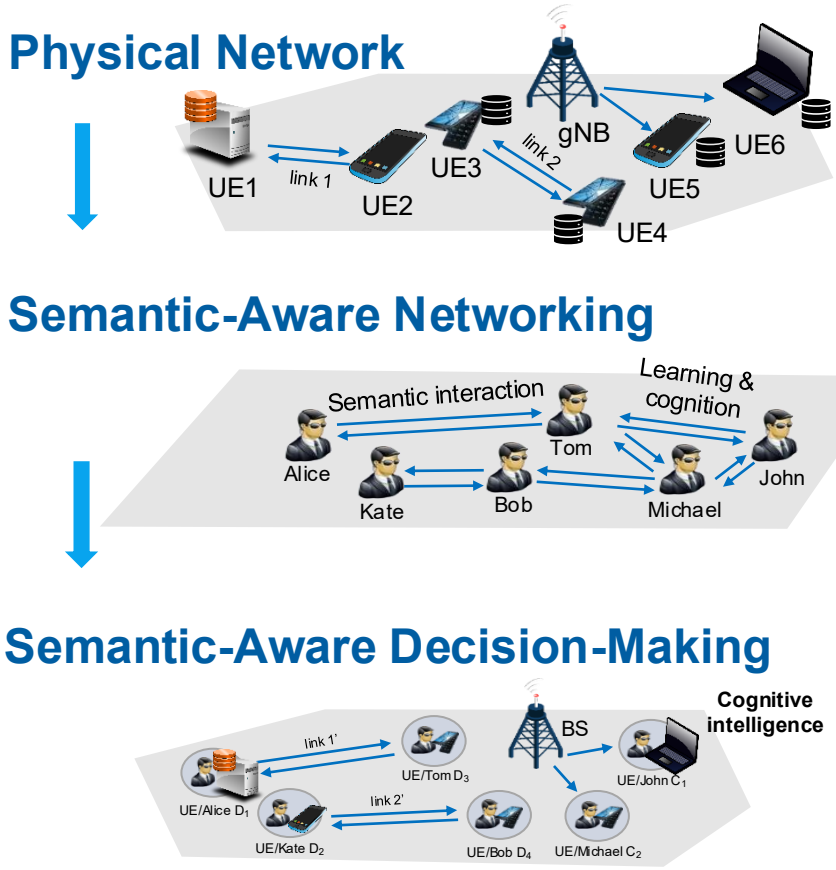
Cost-Effective Data Processing: Automatic discovery, classification, and semantic annotation of user/device data.
Enhanced Interoperability: Converting diverse data and services into shared semantic domains to break silos across networks.
Self-Learning & Inferencing: Utilizing annotated data to automatically train machine learning models and infer logical relations across network protocols.
Self-Evolving & Adapting: Identifying unknown semantics and inferring relationships with existing knowledge bases.
Network Abnormality & Disaster Recovery: Identifying unusual semantic traffic patterns for automated fault detection and routing correction.



General System Requirements for SAN

Semantic Domain & Indexing: Establishing domain-specific semantic ontologies and relevance indexing.
Annotation & Interpretation: Creating standardized frameworks for semantic annotation and semantic interpretation across network nodes.
Translation & Cognition: Ensuring accurate semantic translation between domains and enabling network-level semantic cognition.
Rationality Discovery: Implementing self-description and auto-correction to maintain logical consistency in data flows.

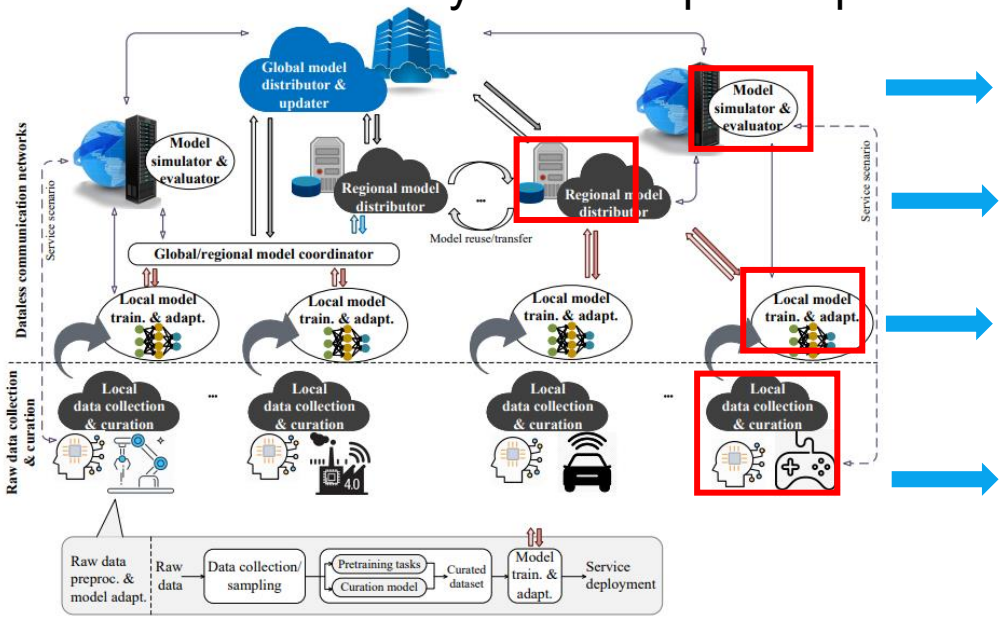




From Requirements to Theory – iSAN for Imitation-based Reasoning

Implicit Semantic-Aware Networking (iSAN) Framework: How the ITU-T requirements drove theoretical evolution from explicit data analysis to implicit semantic discovery.

- **The Challenge:** Traditional network AI solutions rely heavily on predefined data features and rules, resulting in high overhead and struggles to adapt when contextual or hidden information changes or is missing.
- **The Breakthrough:** Introducing iSAN architecture that mimics human cognitive reasoning to uncover hidden, contextual relationships (implicit semantics) by leveraging network-side reasoning and accumulated knowledge.
- **Network-Level Impact:** iSAN drastically reduces communication and computational overhead and enables the network to accurately infer complex implicit user intents, even in dynamic or unseen environments.



Global/regional model simulation and evaluation

Global/regional model distribution

Local model training, sharing, and adaptation

Local data collection & curation

*__Y Xiao__, et al., "Imitation Learning-based Implicit Semantic-aware Communication Networks: Multi-layer Representation and Collaborative Reasoning," *IEEE J Sel. Areas Com.* (JSAC), vol. 41, no. 3, pp. 639-658, Mar. 2023.

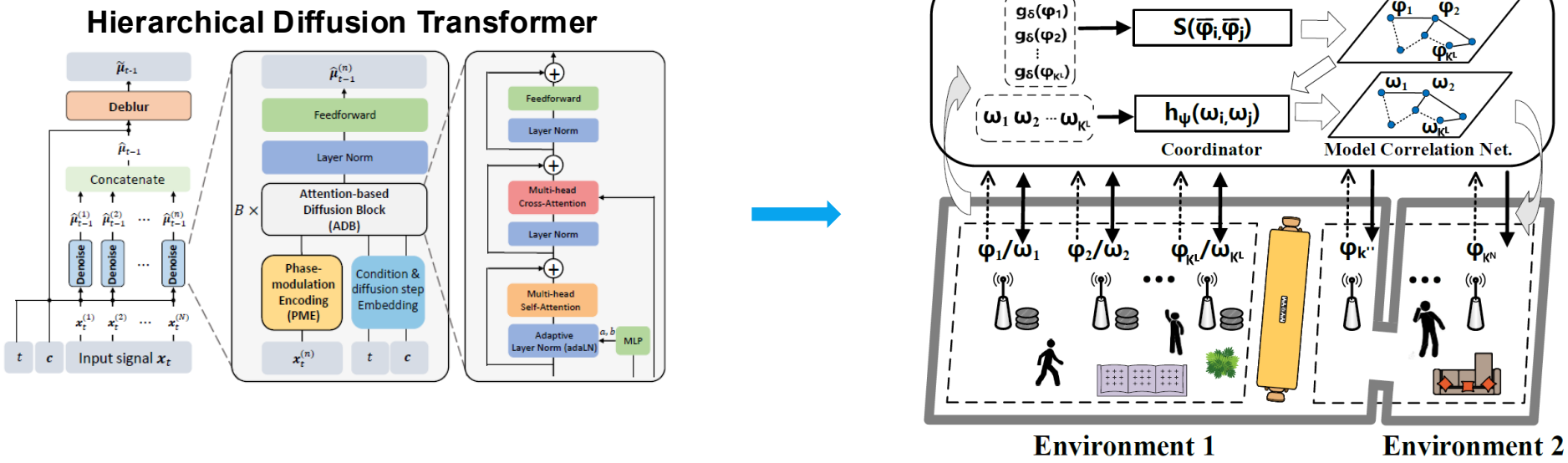
*__Y Xiao__, et al., "Reasoning over the Air: A Reasoning-based Implicit Semantic Communication Framework," *IEEE Trans. Wireless Com.* (TWC), vol. 23, no. 4, April 2024.

*Y Liao, S Tu, __Y Xiao__, et al., "Implicit Semantic-aware Communication Based on Hypergraph Reasoning," to appear in *IEEE Trans. Com.* (TCom), 2026.

Physical-Layer Semantics – SANSee for Integrated Sensing & Com. (ISAC)

SANSee: Physical-Layer Semantics for ISAC in 6G and Beyond

- **The Challenge:** RF signals in Integrated Sensing and Communication (ISAC) are highly location-specific, making "one-size-fits-all" global models unreliable and local training too costly.
- **The SANSee Breakthrough:** Extending semantics to the physical layer (pSAN) to capture underlying semantic similarity (e.g., spatial layouts, gesture profiles) across different RF environments.
- **Zero-Shot Semantic Knowledge Transfer:** SANSee enables models trained in a few locations to seamlessly transfer to entirely new locations without requiring any locally labeled data or local retraining — delivering highly scalable, self-adapting network intelligence for 6G.



*H Zhu, **Y Xiao**, et al., "SANSee: A Physical-Layer Semantic-aware Networking Framework for Distributed Wireless Sensing," *IEEE Trans. Mobile Computing (TMC)*, vol. 24, no. 3, pp. 1636-1653, March 2025.

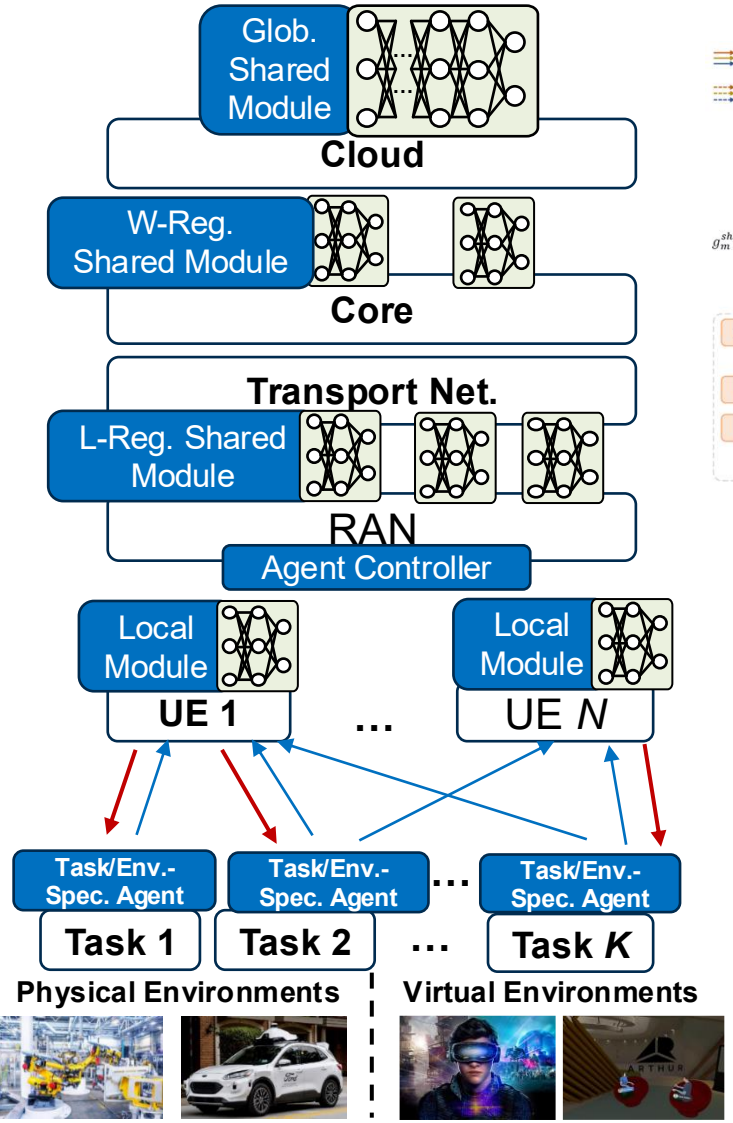
*H Zhu, **Y Xiao**, et al., "Physical-Layer Semantic-Aware Network for Zero-Shot Wireless Sensing," IEEE ICNP Workshop, Reykjavik, Iceland, October 2023.

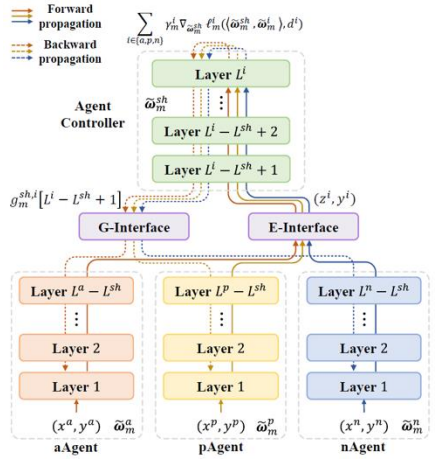
Fulfilling Network Autonomy – SANet for Agent AI-Native Network

The Challenge: As AI evolves from passive models to autonomous, goal-oriented Agentic AI, a severe "**semantic gap**" emerges between high-level Agent AI intents and rigid, bottom-layer network resource allocation.

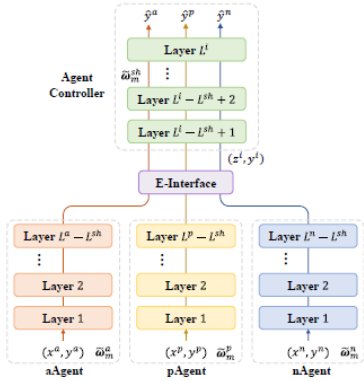
The SANet Breakthrough: SANet establishes a true Agent AI-native networking architecture. It fundamentally redefines cross-layer optimization by embedding semantic-awareness directly into autonomous network agents. Instead of rigid symbol compression, SANet empowers these agents to collaboratively extract task-specific features, reason about application intents, and dynamically negotiate network operations across layers.

Network-Level Impact: SANet achieves AI-native cross-layer optimization. It shifts network management from maximizing traditional bandwidth to optimizing real-time semantic utility and Agentic AI task performance. This directly fulfills the ITU-T visions for autonomous semantic resource provisioning, self-learning, and self-evolving.





Training with Static-weighting Algorithm



Inference

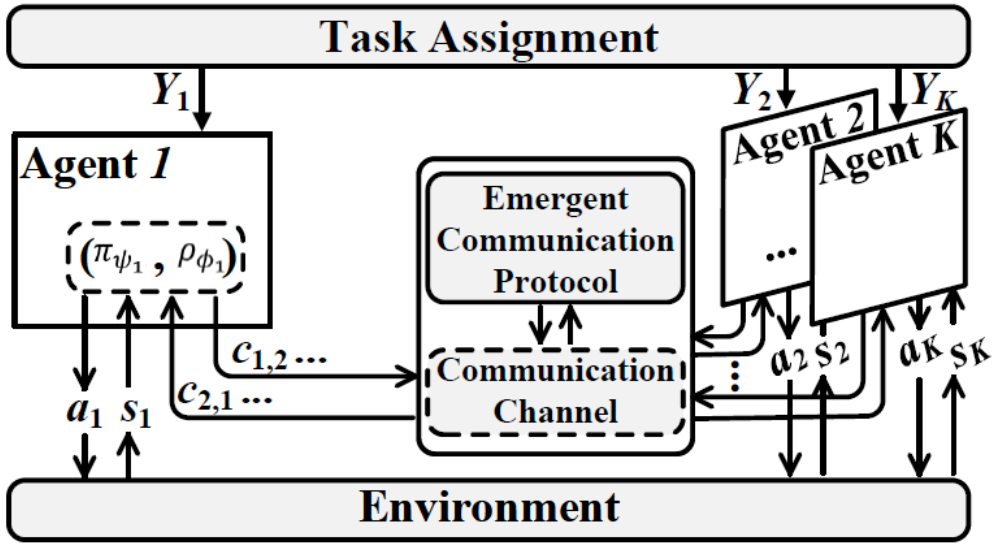
*Y Xiao, et al., "Towards Agentic AI Networking in 6G: A Generative Foundation Model-as-Agent Approach," IEEE Communications Magazine, vol. 63, no. 9, Sep. 2025.

*Y Xiao, et al., "SANet: A Semantic-aware Agentic AI Networking Framework for Cross-layer Optimization in 6G," to appear in *IEEE Trans. Mobile Computing (TMC)*, 2026.

*Y Xiao, et al., "SANNet: A Semantic-Aware Agentic AI Networking Framework for Multi-Agent Cross-Layer Coordination," IEEE GLOBECOM, Taipei, China, December 2025.

The Next Frontier – SANEmerg for Swarm Intelligence in 6G and beyond

The Challenge: In the 6G era, massive multi-agent networking systems (swarm intelligence) must collaborate seamlessly in highly dynamic environments. As environmental or task conditions change, manually predefined protocols inevitably suffer from performance drift and degraded efficiency.
The Breakthrough: The SANEmerg framework pioneers emergent communication for swarm intelligence. Instead of relying on human-designed rules, SANEmerg empowers AI agents to autonomously learn, generate, and evolve their own shared semantic language from scratch to solve complex tasks. By integrating self-evolving mechanisms, the network continuously monitors performance thresholds and triggers autonomous fine-tuning, allowing the swarm to adapt to unseen scenarios without centralized pre-coordination.
Network-Level Impact: This paradigm creates truly self-sustaining, resilient swarm intelligence.



The workflow of the SANEmerg

① **Semantic Task/Goal Cognition**

② **Agent selection and communication emergence**

③ **Task execution and decision-making**

*Y Xiao, et al., "Generalization Bounds of Emergent Communications for Agentic AI Networking," IEEE ISIT Workshop, Guangzhou, China, June 2026.
*Y Xiao, et al., "SANEmerg: An Emergent Communication Framework for Semantic-Aware Agentic AI Networking," IEEE/IFIP WiOpt Workshop, Columbus, OH, USA, June 2026.

Prototyping & Real-World Implementation

- **Successful Network Deployment:** The SANet prototype platform developed in our previous research has been successfully deployed on the China Telecom platform.
- **Global Debut at MWC 2025:** SANet platform has been officially released on June 19, 2025, at the Mobile World Congress (MWC) Shanghai;
- **The Impact:** This successfully transitions SAN from theoretical frameworks and standardization into a live, operational ecosystem.

MWC25
CONNECT. CONVERGE. CREATE.

Leaders from China Telecom, Peng Cheng Lab, and BUPT attended the ceremony

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CHINA TELECOM | CTRI

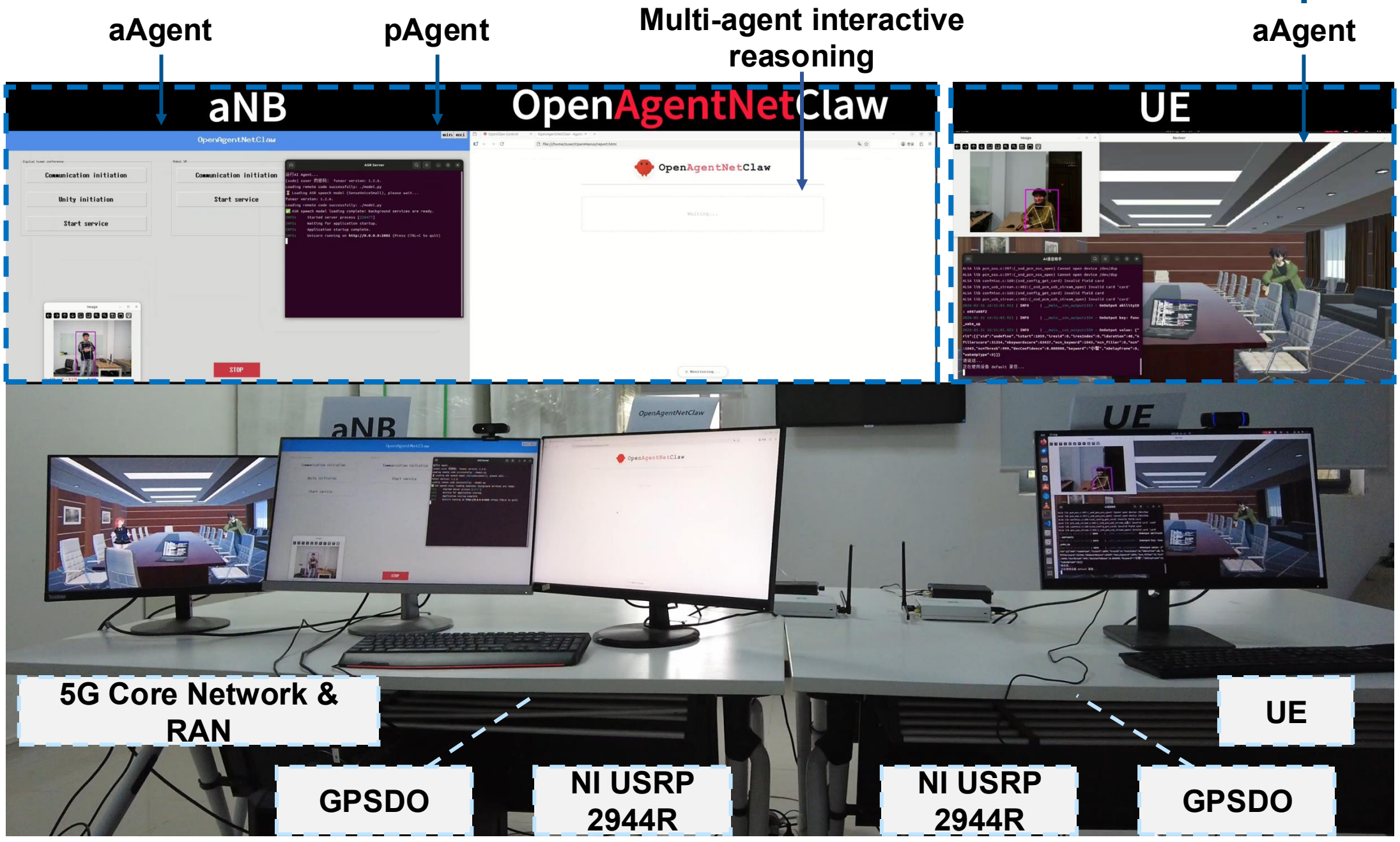
应用证明

应用开始时间	2025 年 5 月 8 日		结束时间	至今	
应用次数	长期使用	产生直接经济效益	无	节省经费	
应用内容	意图驱动的端网云智能体通信网络试验				
起到的作用及达到的效果	华中科技大学，联合鹏城国家实验室、中国电信股份有限公司研究院，基于中国电信云网融合大科创装置，开展了业界首个“意图驱动的端网云智能体通信网络试验”，解决了 AI Agent 应用爆发带来的通算资源与用户个性化需求高复杂度匹配问题。 项目组在突破端侧个性化通信意图感知、分布式智能决策等关键技术的基础上，成功研发意图驱动的端网云智能体通信网络原型系统，并在中国电信云网融合大科创装置开展了端到端试验，大装置的智算资源、组网能力和定制网能力在试验中起到了关键作用。 试验场景包括 VR 沉浸式会议、工业控制以及 AI 手机直播三大场景，在终端智能体主动识别用户通信意图后，可驱动云网智能体完成通信与计算资源的自主编排，证明了跨物理层、网络层和应用层智能体的多维协同的可行性和有效性，自适应实现了智能化资源调度和精准化场景响应，具有本领域国内领先示范水平，为意图智能体组网及协同通信提供了原创性的技术方案。				
单位签章	中国电信股份有限公司 广东研究院				

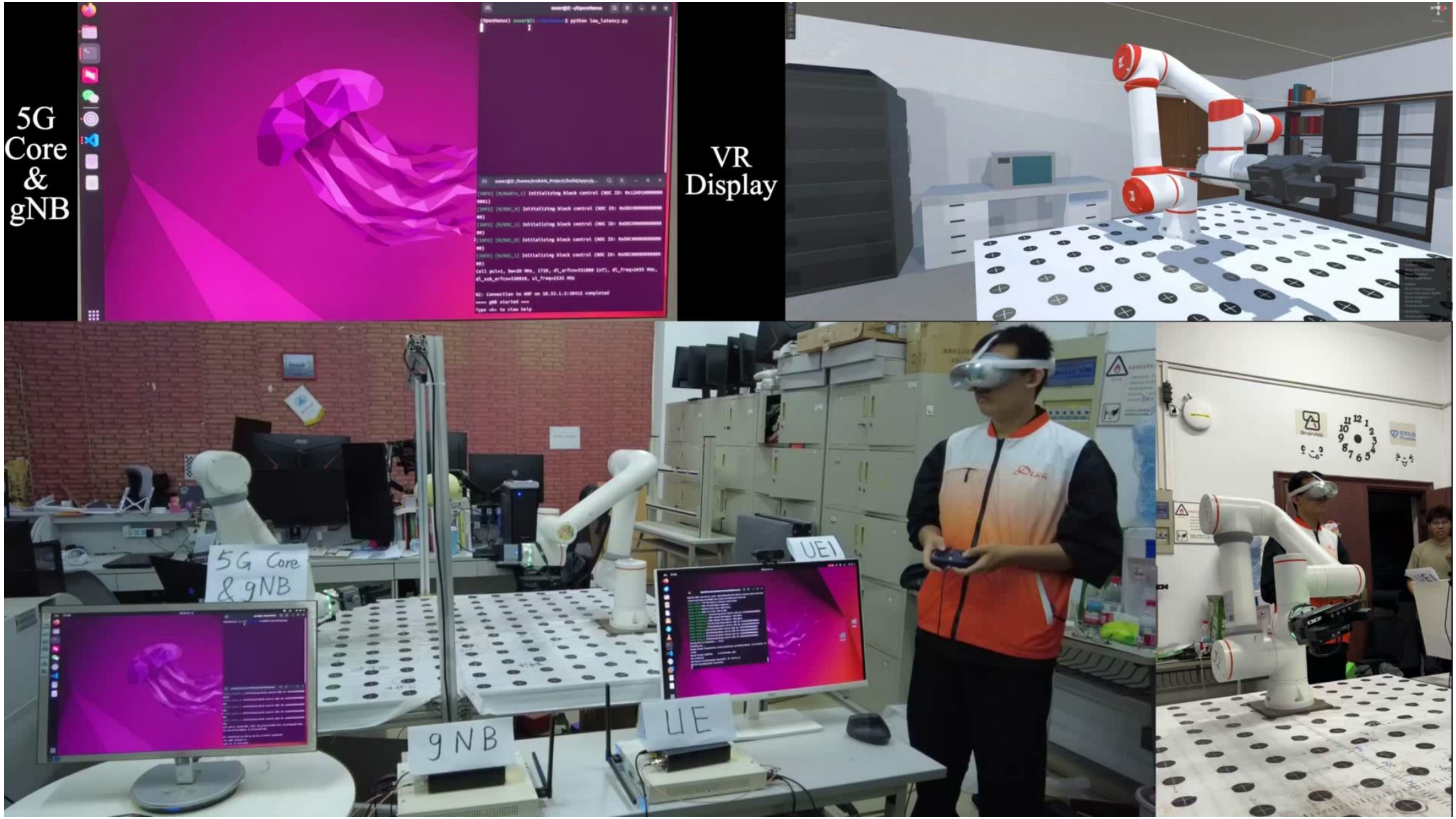
Official Technology Application Certification issued by China Telecom

This is an original, foundational technical solution for intent-driven agentic AI networking and collaborative communication.

SANet Demo 1: User intent-driven metaverse with SAN-based auto-optimization



SANet Demo 2: Digital-Twin-Based Industrial Automation based on SAN



Conclusion & Open Problems

- **Summary:** SAN is no longer just a theoretical concept; it is a standardized, prototyped necessity for the 6G era.
- **The Infrastructure of Tomorrow:** Semantic-aware networks form the true foundation for an AI-native ecosystem.
- **Some Open Problems:**
  - *Semantic Security and Trust:* Defending against adversarial attacks such as semantic poisoning or hallucination exploitation for SAN while preserving strict user privacy.
  - *Heterogeneous Interoperability:* Achieving scalable, zero-shot semantic translation and knowledge alignment between non-cooperative, multi-vendor Agentic AI systems and legacy network infrastructures.
  - *Explainability of Emergent Protocols:* Ensuring that autonomous, self-evolving machine-to-machine languages remain interpretable, controllable, and manageable by human operators.
- **Call to Action:** Continued collaboration across academia, industry, and standards bodies (ITU, IEEE, 3GPP) to refine semantic security frameworks and emergent agentic protocols for fully autonomous, intent-driven networking systems in 6G and beyond.

Thank you!
Q&A

Contact Information:
Yong Xiao
Huazhong University of Science and Technology
Email: yongxiao@hust.edu.cn
Website: https://sites.google.com/site/xyong2007/