Intelligent Management and Control of Intent-Driven Energy-Saving Policies for 6G Networks

Yao Wang

School of Telecommunications Engineering, Xidian University
Information Systems Technology and Design Pillar, Singapore University of Technology and Design

Homepage: link

CV: link

Thesis: Intelligent Management and Control of Intent-Driven Energy-Saving Policies for 6G Networks

Advisor: Chungang Yang (Xidian University) and Tony Q. S. Quek (Singapore University of Technology and Design)

Brief Biography: Yao Wang is a PhD candidate in the School of Telecommunications Engineering at Xidian University and a visiting PhD student at the Singapore University of Technology and Design. His research focuses on 6G, agentic AI, large-scale agentic networks, LLMs for wireless networking, and network management. He has published over 20 papers in high-impact journals and flagship conferences, including IEEE COMST, ACM UbiComp/ISWC, IEEE TCCN, IEEE CM, IEEE GLOBECOM, and IEEE VTC, with one paper recognized as an ESI Highly Cited Paper. He has authored two books published by Xidian University Press and Springer. He has presented invited talks at IEEE VTC 2025-Fall, IEEE GLOBECOM 2020, and the 2021 Graduate Academic Forum of Guangdong. He cochaired the IDAN Workshop at IEEE IWCMC 2026, served on the TPCs of IEEE VTC 2026-Spring and IEEE ICC 2026, and reviewed for ACM Computing Surveys, IEEE TWC, IEEE TMC, IEEE CM, and IEEE NETWORK.

Research Summary: With the evolution of 6G networks toward end-to-end integration, cross-domain collaboration, and intelligent autonomy, network energy-saving is shifting from single-device or single-resource optimization to system-level management across access, transport, core, and cloud-edge infrastructure. Existing methods mainly operate on low-level device states and configurable parameters, making it difficult to translate energy-saving objectives into executable policies while satisfying performance constraints. Intent-driven network management provides a promising solution by expressing energy-saving requirements as high-level intents and refining them into objectives, constraints, and low-level configurations. However, challenges remain in intent-to-parameter mapping, intent decomposition and optimization, multi-domain policy orchestration, and intent conflict resolution. To address these issues, my doctoral thesis develops a novel framework comprising network-level intent decomposition, energy-aware intent optimization, cross-layer and multi-domain policy orchestration, and intent conflict resolution with closed-loop assurance.

1. INTRODUCTION

As mobile communication systems evolve from 5G toward 6G, network architectures are shifting from centralized, domain-specific deployments toward ubiquitous and cross-domain operation with intelligent autonomy. The deep integration of the radio access network (RAN), transport network (TN), core network (CN), and cloud–edge infrastructure, together with network function softwarization, resource virtualization, and distributed intelligence, continues to increase the number of managed entities and configurable parameters. Meanwhile, dynamic traffic load, radio conditions, and user distributions are transforming network energy-saving from single-device or single-parameter optimization into a system-level management problem spanning multiple resource layers, network domains, and service objectives. IMT-2020 [1] supports enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine-type communications, while IMT-2030 [2] further introduces ubiquitous connectivity, artificial intelligence (AI) and communication, and integrated sensing and communication. These scenarios increase connection density and data processing workloads. As sustainability is an overarching design principle for IMT-2030, energy efficiency (EE) must be considered throughout network planning, deployment, operation, and optimization. Under the "dual-carbon" goals of carbon peaking and carbon neutrality, improving 6G performance while limiting energy consumption growth has become a critical challenge.

Existing energy-saving techniques have progressed from device-component optimization to radio resource and network configuration control [3], [4], [5]. Representative approaches include hardware sleep, carrier shutdown, power control, user association, and resource scheduling. Nevertheless, most existing methods still directly control low-level device states, configurable parameters, or pre-defined actions, resulting in three major limitations:

- **Intent-to-configuration gap:** High-level objectives specify operational scope, performance constraints, and temporal conditions. However, existing approaches still rely on expert knowledge and predefined rules to translate these objectives into network configurations.
- **Lack of end-to-end coordination:** Existing methods optimize individual base stations, the RAN, or a specific domain in isolation. Such can lead to locally optimal decisions and cannot exploit coordinated energy-saving opportunities across 6G infrastructure.
- **Limited adaptability to constraints:** Fixed thresh-

olds, offline models, and static rules cannot adapt to changes in traffic load and network conditions. They also struggle to balance energy consumption against throughput, latency, and quality of experience.

EE management in 6G must therefore move from local control of configurable parameters toward high-level objective-driven, end-to-end intelligent management and control. Intent-based or intent-driven networking (IBN/IDN) allows operators to specify what the network should achieve rather than defining how it should be achieved. Based on the observed network state, an IBN/IDN system can autonomously perform intent respresentation and decomposition, policy generation and orchestration, and conflict resolution and intent assurance. Thereby, high-level energy-saving objectives can be refined into executable network policies. To realize this vision, intent-driven energy-saving policies for 6G should provide the following capabilities:

- **Intent representation and decomposition:** Energy-saving intents should be represented in a structured form and decomposed into objectives, constraints, and actions. This decomposition establishes a mapping between these intents and configurable parameters.
- **Cross-domain policy orchestration:** Coordinated energy-saving policies should be orchestrated across the RAN, TN, CN, and cloud–edge infrastructure, enabling a transition from local, single-domain optimization to global, end-to-end energy-saving.
- **Multi-intent closed-loop assurance:** Energy-saving intents should be coordinated with performance intents related to throughput, latency, and QoE. Policies should then be dynamically adjusted based on intent satisfaction and changes in network conditions.

In summary, intent-driven energy-saving policies for 6G entails three fundamental transitions: from configuration parameter-driven control to high-level intent-driven management, from local single-domain optimization to coordinated end-to-end optimization, and from static rule execution to dynamic closed-loop autonomy. This paradigm provides an intelligent management foundation for the low-carbon operation of future 6G networks.

2. THESIS OVERVIEW

My doctoral thesis presents a systematic investigation of intent-driven energy-saving policies for 6G networks, establishing a technical framework from intent fulfillment to intent assurance. Specifically, it develops a network-level intent decomposition framework, designs an energy-aware intent decomposition and optimization mechanism for RAN scenarios, introduces an LLM-empowered cross-layer and multi-domain policy orchestration paradigm, and proposes an LLM-enhanced cooperative game-theoretic framework for intent conflict resolution.

2.1 Network Intent Decomposition Framework for Telecommunication Networks

In recent years, network sizes have expanded rapidly, while service requirements have become increasingly diverse. On-demand network configurations have intensified the coupling among configurable parameters. A 5G base station may contain up to 1,500 configurable parameters, and this number may reach 2,000 in 6G networks [6]. Their scale and strong interdependence make manual analysis and configuration difficult and error-prone. By allowing operators to specify what the network should achieve, intent-driven network management reduces manual intervention and improves network automation. Although previous studies have investigated full-lifecycle intent management [7] and intent representation [8], the automated analysis of complex network-level intents remains challenging. A unified intent-driven 6G management architecture is therefore needed to connect business requirements with network resources and support intent representation, decomposition, policy generation, configuration execution, and closed-loop assurance.

Network-level intent decomposition (NID) bridges high-level intent refinement and low-level policy generation by transforming abstract intents into objectives, constraints, and actions. However, it is difficult to establish mappings between network-level intents and configurable parameters. Complex intents may also introduce data redundancy and sparsity, thereby increasing network energy consumption. Within the presented architecture, NID represents network-level intents based on 3GPP specifications and converts them into executable operations through modeling, decomposition, validation, and optimization. The underlying infrastructure then generates configurations and executes these. Meanwhile, multiple intents may cause northbound intent conflicts, while resource limitations may lead to southbound resource conflicts among operations. My research therefore investigated NID for 6G mobile communication systems, focusing on its architecture, definition, classification, and implementation. The main contributions were as follows:

- I developed an intent-driven 6G management architecture, while clarifying the role of NID.
- I defined NID and divided it into a design time stage for modeling, decomposition, and validation, and a run-time stage for optimization.
- I constructed a general NID framework comprising a user application layer, an intent decomposition layer, and an infrastructure layer.
- I designed an intelligent NID system and validated its effectiveness against baseline schemes using an energy-saving intent use case.

2.2 Energy-Saving Intent Decomposition and Optimization Mechanism

As next-generation communications evolve, vertical industries impose increasingly diverse service requirements. Future RANs must provide user equipment with higher throughput, lower latency, and assured service quality. Ultra-dense base station deployments introduce numerous configurable parameters. Diverse requirements and on-demand configurations create strong coupling among these parameters. Manual management is inefficient and error-prone, increasing computational overhead and energy consumption. Existing studies examine network architectures and functions and energy-aware attributes [9], but refining high-level intents into configurable parameters remains difficult.

IDN allows operators to specify the desired network state, focusing on what the network should achieve rather than how it should operate. Intent decomposition uses ontology modeling and conflict analysis to map energy-saving intents into quantifiable objectives and operations. Intent optimization then selects the optimal policy under dynamic network states and constraints. Together, these processes enable intelligent, energy-aware RAN management with limited human intervention. However, three challenges remain: (*i*) representing energy-saving intents and their ontologies; (*ii*) mapping network states to energy-saving operations, and (*iii*) selecting optimal policy through AI-based method. Existing studies have not systematically integrated intent modeling, decomposition, and optimization for energy-aware RAN. My research addressed this gap through an energy-saving intent decomposition and optimization mechanism. The main contributions were as follows:

- I proposed a standardized template for representing energy-saving intents.
- I identified the network ontology elements and modeled them using the KAOS language.
- I introduced a SIG-based decomposition scheme that established the *intent–sub-intent–operation* logic.
- I designed a collaborative multi-agent deep Q-network for intent optimization. Simulation results showed improvements in three metrics over baseline schemes.

2.3 LLM-Empowered Cross-Layer and Multi-Domain Intent Orchestration Paradigm

As differentiated services and on-demand deployment grow, IDN is becoming a key paradigm for 6G networks. It reduces manual intervention and supports service customization, automated configuration, and policy execution across the business support system (BSS), operations support system (OSS), and network operation provider (NOP) [10]. However, cross-layer intent management still faces three challenges: (*i*) inconsistent mappings between BSS intents and OSS/NOP capabilities; (*ii*) limited state awareness for online orchestration; and (*iii*) the lack of a unified policy model for full-life cycle management. Moreover, single-domain autonomy across the RAN, TN, and CN produces locally optimal policy, complicates cross-domain conflict resolution, and causes inconsistent policy representations.

Leveraging the reasoning capabilities of LLMs, I developed LAMIO-6G for cross-layer intent management and multi-domain policy orchestration. Aligned with the TMF Autonomous Networks framework [11], it adopts the *business–service–resource* hierarchy and full-life cycle closed-loop automation. At the BSS, a general LLM decomposes intents through LoRA fine-tuning, prompt design, and few-shot learning. At the OSS, domain-specific LLMs perform long–short chain-of-thought reasoning, while a lightweight PPO model selects the optimal policy. The NOP converts this policy into executable commands and returns the results for intent negotiation. The main contributions were as follows:

- I devloped LAMIO-6G across the BSS, OSS, and NOP, using two unified policy and MAPE-K models to generate policies at different abstraction levels.
- I introduced general LLM for intent decomposition via LoRA fine-tuning, prompting, and few-shot learning.
- I designed an intent reasoning and optimization scheme using domain-specific LLMs and a lightweight PPO.
- I evaluated a proof-of-concept of wireless energy-saving. Simulation results demonstrated the feasibility and effectiveness of LAMIO-6G.

2.4 LLM-Enhanced Game-Theoretic Design for Intent Conflict Resolution

As 6G RANs evolve toward autonomous and intent-driven management, network control is shifting from manual configuration to closed-loop decision-making. Operators define high-level intents for energy-saving, throughput, and user QoE, which are translated into parameters such as transmit power, antenna downtilt, and BS switching. These parameters are coupled through energy consumption, throughput, latency, and inter-cell interference, thereby improving one intent may therefore degrade another. Intent utility functions map high-level intents into quantifiable utilities [12], while cooperative game theory (CGT) provides a mathematical basis for intent conflict resolution. The Nash bargaining solution (NBS) offers a rational compromise, weighted NBS (WNBS) supports priority-aware fairness, and Kalai–Smorodinsky bargaining solution (KSBS) provides proportional fairness. However, CGT requires consistent feasible regions, utility vectors, disagreement points, and ideal points, together with the handling of coupled constraints and mixed discrete-continuous variables.

Conventional AI methods are limited by task-specific training and weak generalization. LLMs support structured game modeling and multi-step reasoning [13], [14], but may lack RAN knowledge, generate incorrect symbols or bargaining rules, and provide no closed-loop validation. To address these limitations, I developed LLM-CGT, an LLM-enhanced CGT framework comprising game description, formulation, solving, and evaluation. It standardizes conflict scenarios, constructs CGT models, derives bargaining solutions, and verifies their feasibility. QLoRA fine-tuning, game-theoretic prompts, and retrieval-augmented generation (RAG) further improve reliability.The main contributions were as follows:

- I developed a centralized LLM-enabled RAN controller and formulated intent utility function for energy-saving and performance intents.
- I proposed LLM-CGT and formulated conflicts as a cooperative bargaining game. I derived the WNBS and KSBS for priority-aware and proportional fairness.
- I enhanced the LLM through QLoRA fine-tuning, game-theoretic prompts, and RAG-based game knowledge augmentation to reduce hallucinations.

3. FUTURE WORK

Building on my current work, my future research will advance intelligent EE management for intent-driven 6G networks. I will investigate coordination across domains, resources, and intents, strengthen continuous intent assurance in dynamic environments, and enhance the trustworthy of complex intents. I will also improve LLM reliability and verifiability to jointly optimize network performance and energy consumption under limited resources.

3.1 MoE-Enhanced Intent-Driven Resource Coordination Mechanism

My future research will address heterogeneous agent execution, multi-dimensional resource competition, and diverse intents through scalable, intent-driven coordination. A mixture-of-experts (MoE) architecture will assign network domains, resources, and tasks to specialized agents within a hierarchical monitor-analyze-plan-execute (MAPE) closed-loop. Stackelberg and mean-field games will be explored to reduce the decision complexity of large-scale agents and improve cross-domain energy coordination.

3.2 Intent Assurance and Online Closed-Loop Optimization Mechanism

Dynamic 6G environments will continuously alter service requirements, network states, and resource availability, potentially causing deployed energy-saving policies to deviate from intents. To address this issue, my future work will integrate state monitoring, performance evaluation, intent drift detection, and adaptive policy adjustment into a unified closed-loop. By jointly considering network states, EE metrics, and resource utilization, online evaluation models will extend energy-saving policies from offline optimization to continuous assurance.

3.3 Agentic AI-Based Trustworthy Mechanism for Complex Intents

Although LLMs enhance 6G network management through intent decomposition, policy orchestration, conflict resolution, and intent assurance, complex intents still expose unreliable outputs, inadequate domain constraints, and limited reasoning transparency. My future work will combine domain knowledge augmentation, knowledge graphs, and graph RAG with agentic AI. This integration will improve symbolic consistency, constraint compliance, and interpretability, enabling more reliable intent-driven energy management.

Overall, my future research on intelligent management and control of intent-driven energy-saving policies should focus on multi-domain coordination, online closed-loop assurance, and trustworthy reasoning. Advances in expert collaboration, intent assurance, and reliable agentic reasoning will support automated policy generation, adaptive optimization, and closed-loop control in 6G networks.

Representative Papers:

1. A Survey on Intent-Driven End-to-End 6G Mobile Communication System (IEEE Communications Surveys & Tutorials) with C. Yang, T. Li, Y. Ouyang *et al.*
2. A Survey on Mean-Field Game for Dynamic Management and Control in Space-Air-Ground Network (IEEE Communications Surveys & Tutorials) with C. Yang, T. Li, X. Mi, L. Li, and Z. Han.
3. LLM-Enhanced Game-Theoretic Design for Intent Conflict Resolution in Radio Access Networks (ACM UbiComp/ISWC 2026) with C. Yang, P. Wang, Q. Li, and T. Q. S. Quek.
4. Multi-Intent Conflict Coordination and Resolution in 6G RAN: An LLM-Enhanced Cooperative Game-Theoretic Approach (IEEE Journal on Selected Areas in Communications) with C. Yang, P. Wang, Q. Li, C. Dou, and T. Q. S. Quek.
5. LAMIO-6G: Large AI Model-Empowered Cross-Layer Intent Management and Multi-Domain Policy Orchestration in 6G Terrestrial Networks (IEEE Transactions on Cognitive Communications and Networking) with C. Yang, Q. Li, P. Wang *et al.*
6. A Brief Survey and Implementation on Network-Level Intent Decomposition for Telecommunication Networks (IEEE Communications Magazine) with C. Yang, Y. Yu, Y. Li, D. Li, X. Zhao, and Z. Han.
7. Network Intent Decomposition and Optimization for Energy-Aware Radio Access Network (IEEE Transactions on Vehicular Technology) with Y. Yu, Y. Li, D. Li, X. Zhao, and C. Yang.

REFERENCES

[1] ITU-R. *IMT Vision—Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond.* Recommendation ITU-R M.2083-0. 2015.

[2] ITU-R. *Framework and Overall Objectives of the Future Development of IMT for 2030 and Beyond.* Recommendation ITU-R M.2160-0. 2023.

[3] D. Lopez-Perez, A. De Domenico, N. Piovesan, et al. "A Survey on 5G Radio Access Network Energy Efficiency: Massive MIMO, Lean Carrier Design, Sleep Modes, and Machine Learning." In: *IEEE Communications Surveys & Tutorials* 24.1 (2022), pp. 653–697.

[4] 3GPP. *Study on Network Energy Savings for NR.* 3GPP TR 38.864 V18.1.0. 2023.

[5] ETSI. *Experiential Networked Intelligence (ENI); ENI Use Cases.* ETSI GS ENI 001 V3.2.1. 2023.

[6] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, J. Sjöland, and F. Tufvesson. "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities." In: *Proceedings of the IEEE* 109.7 (2021), pp. 1166–1199.

[7] A. Leivadeas and M. Falkner. "A Survey on Intent-Based Networking." In: *IEEE Communications Surveys & Tutorials* 25.1 (2023), pp. 625–655.

[8] 3GPP. *Management and Orchestration; Intent Driven Management Services for Mobile Networks.* 3GPP TS 28.312 V20.0.1. 2026.

[9] E. Coronado, R. Behravesh, T. Subramanya, et al. "Zero Touch Management: A Survey of Network Automation Solutions for 5G and 6G Networks." In: *IEEE Communications Surveys & Tutorials* 24.4 (2022), pp. 2535–2578.

[10] J. Niemöller, L. Mokrushin, S. K. Mohalik, et al. "Cognitive Processes for Adaptive Intent-Based Networking." In: *Ericsson Technology Review* 2020.11 (2020), pp. 2–11.

[11] A. Boasman-Patel, D. Sun, Y. Wang, et al. *Autonomous Networks: Empowering Digital Transformation for the Telecoms Industry.* TM Forum White Paper, Release 1.0. 2019.

[12] 3GPP. *Management and Orchestration; Intent Driven Management Services for Mobile Networks.* 3GPP TS 28.312 V20.0.1. 2026.

[13] J. Duan, R. Zhang, J. Diffenderfer, et al. "GTBench: Uncovering the Strategic Reasoning Capabilities of LLMs via Game-Theoretic Evaluations." In: *Proceedings of NeurIPS.* Vancouver, Canada, 2024.

[14] M. Chahine, T. H. Wang, H. Zhang, et al. "Large Language Models Can Design Game-Theoretic Objectives for Multi-Agent Planning." In: *Proceedings of the International Conference on Learning Representations.* Vienna, Austria, 2024.