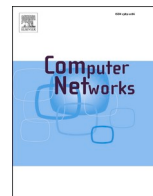




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Special issue on artificial intelligence for future 6 G Systems (AI-for-6 G)

ABSTRACT

The transition from 5 G to sixth-generation (6 G) networks marks a fundamental paradigm shift, from connected systems toward AI-native networking ecosystems in which intelligence is no longer an add-on but the core operational fabric. Large Language Models (LLMs) and generative AI act as cognitive engines for Intent-Based Networking (IBN) and Zero-Touch Service Management (ZSM), while emerging 6 G testbeds validate their promise for ultra-high-speed, sub-millisecond-latency connectivity, immersive applications, and massive IoT deployments.

This Special Issue presents 20 rigorously peer-reviewed contributions spanning network architecture, autonomous resource management, mobility, dynamic slicing, security, and AI-driven operations. State-of-the-art methods including autoencoders, hierarchical Q-learning, Graph Attention Networks, and federated learning, are applied across vehicular networks, AIoT systems, and edge computing. Emerging paradigms, such as explainable AI, multi-agent reinforcement learning, LLM-driven controllers, and agentic AI chart the course toward resilient, self-managing 6 G ecosystems. Collectively, this issue offers researchers, engineers, and industry leaders a rigorous blueprint for the next generation of autonomous, symbiotic communication networks.

1. Introduction

The evolution toward 6 G represents more than an incremental upgrade; it is a redefinition of what a communication network is. Where previous generations optimised human-designed protocols, 6 G embeds AI as a native operational layer, enabling networks that perceive, reason, and act autonomously. By 2030, AI-native 6 G systems are expected to support ultra-reliable low-latency communications, immersive extended reality, massive IoT ecosystems, and mission-critical services at a scale and complexity that render manual management infeasible.

Yet this ambition carries commensurate challenges. Networks must process ultra-high-dimensional, multimodal data streams in real time, maintain adaptability under rapidly shifting channel and traffic conditions, defend against sophisticated threats in federated and distributed environments, and sustain energy efficiency across heterogeneous, densely deployed devices, all while meeting stringent latency guarantees. Scalability, interpretability, and autonomous orchestration are not optional features; they are design imperatives.

This Special Issue addresses these imperatives head-on, bringing together high-quality contributions from academia and industry that advance AI-native 6 G across theory, simulation, and experimental validation. The collected works provide actionable insights for researchers, practitioners, and policymakers shaping the roadmap toward intelligent, self-managing wireless ecosystems.

2. Contents of the special issue

This Special Issue received 53 submissions from researchers across five continents, reflecting the global momentum behind AI-native 6 G research. Following a rigorous peer-review process, where each manuscript was evaluated by at least four domain experts drawn from a pool

of 173 reviewers, 20 papers were accepted, representing a broad and cohesive body of work.

The accepted contributions are organised along seven thematic pillars:

- **AI-enabled physical-layer optimisation.** Papers in this theme advance beamforming, channel estimation, signal detection, and joint spectrum and power control, targeting the ultra-reliable, high-throughput requirements of 6 G physical layers, including THz, ultra-massive MIMO (UM-MIMO), and NOMA-enabled IoT frameworks.
- **Intrusion detection and anomaly detection.** Contributions focus on identifying threats through intelligent anomaly detection, explainable intrusion detection systems, and federated learning-based zero-day attack prevention, addressing the detection challenges of heterogeneous and distributed 6 G environments, including a comprehensive survey of AI-driven anomaly detection for IoT systems enhanced by 6 G capabilities.
- **Trust architectures and federated learning security.** These works harden networks against adversarial threats through zero-trust policy orchestration, Sybil attack mitigation in federated learning, and privacy-preserving mechanisms, ensuring system-level resilience across distributed and non-IID 6 G deployments.
- **AI-based network management, automation, and intent-driven orchestration.** These works address autonomous network operation through agentic AI, LLM-driven controllers, and hierarchical intent decomposition, realising the vision of Zero-Touch Service Management and Intent-Based Networking across business, management, and resource layers.
- **Resource management, routing, offloading, and network optimisation.** Reinforcement learning and cross-layer optimisation techniques are applied to dynamic resource allocation, handover

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decisions, and computation offloading across terrestrial, air-to-ground, and space-ground integrated network environments.

- **Network traffic analytics and QoE prediction.** AI-driven predictive modelling enables proactive service-quality optimisation and real-time traffic analytics, with contributions spanning context-aware mobile traffic forecasting and OTT-MNO collaborative QoE prediction in O-RAN architectures.
- **Vehicular and Internet-of-Vehicles (IoV) networking.** Contributions highlight mobility-aware federated learning, multimodal data fusion, and hierarchical reinforcement learning-based routing for connected and autonomous vehicle ecosystems operating under the stringent latency and scalability demands of 6 G.

Together, these themes offer a comprehensive and coherent map of the AI-native 6 G research landscape, from physical-layer innovation through to autonomous orchestration and trustworthy AI, bridging methodological rigour with real-world experimental validation. As the community moves toward 6 G standardisation and early deployment, we hope this Special Issue serves as both a benchmark of the current state of the art and a catalyst for the next wave of foundational breakthroughs. The rest of this section describes the organisation of this special issue.

2.1. AI-Enabled physical-layer optimisation

Joanna Carolina Manjarres, Douglas O. Cardoso, José Ferreira de Rezende *A Low-Complexity Window-Based Learning Framework for Adaptive 6 G Beam Selection using WiSARD* [1]. In this paper, the authors introduce a weightless neural network framework based on the WiSARD model combined with a window-based learning strategy to tackle the trade-off between contextual richness and real-time adaptability in mmWave beam selection. Evaluated on multimodal LiDAR and GPS data, the proposed approach outperforms DNN baselines while requiring 47% less training data and achieving training speeds 99.78% faster.

Rukhsana Ruby, Usman Aslam, Dian Zhang, Kaishun Wu, Lu Wang *Terahertz Downlink Channel Estimation Using AIoT Systems: OMP Integrated Pruned Deep CNN Method* [2]. This work addresses downlink channel estimation in THz UM-MIMO systems deployed on resource-constrained IoT devices. The authors develop PR-LOMP, a pruned deep convolutional neural network integrated with the orthogonal matching pursuit algorithm, demonstrating that 30% model pruning yields superior estimation performance at significantly reduced computational cost compared to the unpruned DNN-LOMP baseline.

Ayyoub Hussienata, Haitham Al-Obiedollah, Haythem Bany Salameh, Yaser Jararweh *AI-Driven Approach for Enhanced Signal Detection in Future NOMA-Enabled 6 G IoT Networks* [3]. The authors propose a machine learning-based signal detection technique for NOMA-enabled 6 G IoT networks, leveraging a logistic regression classifier combined with cyclic delay diversity to improve detection under low-SNR and low-power conditions. Simulation results confirm that the approach significantly outperforms conventional feature-based multi-user detection methods in energy-constrained IoT scenarios.

Gabriel Pimenta de Freitas Cardoso, Paulo Henrique Portela de Carvalho, Paulo Roberto Lira Gondim *Joint Spectrum Allocation and Power Control for D2D Communication and Sensing in 6 G Networks Using DRL-Based Hyper-Heuristics* [4]. The authors develop a deep reinforcement learning-powered hyper-heuristic strategy for joint spectrum allocation and power control in 6 G systems integrating primary communications, D2D links, and sensing. Rather than relying on fixed rules, the approach learns to select appropriate low-level heuristics dynamically, demonstrating robust adaptation to interference, channel uncertainty, and evolving industrial-environment demands.

2.2. Intrusion detection and anomaly detection

Nasim Nezhadsistani, Mohsen Tajgardan, Mahdi Rabbani, Weijie Niu, Burkhard Stiller. *Design and Evaluation of a Robust and Explainable Intrusion Detection Framework for 5G/B5G Networks* [5]. The authors present a hybrid autoencoder–XGBoost intrusion detection framework enriched with SHAP-based explainability for 5G and B5G networks. The autoencoder simultaneously performs feature extraction and minority class synthesis to address data imbalance, while cross-dataset validation across three benchmarks demonstrates F1-scores between 0.96 and 0.999 and AUC values consistently above 0.97.

Iftikhar Rasheed, Hala Mostafa. *Federated Learning-Based Anomaly Detection for Zero-Day Attack Prevention in 6 G Network Slices* [6]. This contribution proposes a federated learning framework for real-time zero-day attack detection in 6 G network slices, combining hierarchical anomaly detection, adaptive feature extraction, and differential privacy mechanisms. The system achieves a 97.2% detection rate while scaling linearly to 1000 concurrent network slices and maintaining detection latency below 47 ms.

Zeeshan Ali Haider, Asim Zeb, Taj Rahman, Sushil Kumar Singh, Rizwan Akram, Ali Arishi, Inam Ullah. *A Survey on Anomaly Detection in IoT: Techniques, Challenges, and Opportunities with the Integration of 6 G* [7]. This survey offers a comprehensive review of AI-driven anomaly detection techniques for IoT systems, examining how machine learning and deep learning methods can be enhanced through federated learning, edge computing, and blockchain. The authors further analyse how 6 G capabilities, ultra-low latency, massive connectivity, and energy-efficient communication, are poised to overcome the scalability and real-time processing limitations that persist in current deployments.

2.3. Trust architectures and federated learning security

Yulong Fu, Xie Yuanqi, Wei Yi, Bikal Poudel, Jin Cao, Hui Li. *IPO-ZTA: An Intelligent Policy Orchestration Zero Trust Architecture for B5G and 6 G* [8]. The authors put forward IPO-ZTA, a zero-trust security architecture that fuses 6 G Integrated Sensing and Communication capabilities with AI/ML-driven policy orchestration. Two AI components handle predictive security demand estimation and fine-grained dynamic policy adjustment respectively, with a modular 3GPP security capability library ensuring alignment with next-generation standardisation requirements.

Pithani Ashwini, Rashmi Ranjan Rout. *FedSyPo: Detection of Sybil-Poisoning Attack in Federated Learning on Non-IID Data for 6G-based IoT-Edge Networks* [9]. The authors devise FedSyPo, a two-step defence mechanism against Sybil-based poisoning attacks in federated learning environments operating over non-IID IoT data. The scheme assigns cosine-similarity scores to client updates relative to ideal cloud-server features, then applies coefficient-of-variance analysis and k-means clustering to isolate malicious contributions, outperforming existing defences under high malicious-participation rates.

2.4. Network management, automation and intent-driven orchestration

Ilias Chatzistefanidis, Navid Nikaein, Andrea Leone, Ali Maatouk, Leandros Tassioulas, Roberto Morabito, Ioannis Pitsiorlas, Marios Kountouris. *Symbiotic Agents: A Novel Paradigm for Trustworthy AGI-driven Networks* [10]. This paper introduces the concept of symbiotic agents, combining LLMs with real-time optimisation algorithms to enable trustworthy AGI-driven network management. Validated on a live 5 G testbed with vehicle mobility traces, the framework reduces decision errors fivefold relative to standalone LLM agents, while a smaller

language model variant achieves comparable accuracy with a 99.9% reduction in GPU overhead within near-real-time control loops of 82 ms.

Ajay Kattapur, Snigdha Das, Danesh Daroui, Swarup Mohalik, Marin Orlic, Sultan Erta. *DETROIT: Decomposition Techniques for a Hierarchy of 6 G Network Intent Management Functions* [11]. The authors design DETROIT, a hierarchical intent decomposition framework for autonomous 6 G network management. By incorporating QoS algebraic formulations into multiple decomposition algorithms and closing the loop with intent reports and evaluation steps, DETROIT produces decomposed targets within 2% deviation from expectations, capturing the trade-off between meeting SLA targets and optimising network resources across business, management, and resource levels.

Ilias Chatzistefanidis, Navid Nikaein, Andrea Leone, Ali Maatouk, Leandros Tassioulas, Roberto Morabito, Ioannis Pitsiorlas, Marios Kountouris. *AGORAN: An Agentic Open Marketplace for 6 G RAN Automation* [12]. The authors introduce AGORAN, an agentic marketplace for multi-stakeholder 6 G RAN automation, structured around three autonomous AI branches, Legislative, Executive, and Judicial. Deployed on an OpenAirInterface testbed, AGORAN improves composite KPI utility by 57.1% over static approaches while reducing end-to-end resource utilisation by 89.9%, with a fine-tuned 1B-parameter Llama model recovering approximately 80% of GPT-4.1 decision quality.

2.5. Resource management, routing, offloading and network optimisation

Abate Selamawit Chane, Harun Ur Rashid, Kamrul Hasan, Awoke Loret Abiy, Seong Ho Jeong. *Optimizing Handover Decisions with Skipping Mechanisms in 5 G mmWave UDNs using Reinforcement Learning* [13]. This study proposes a deep reinforcement learning framework using the Advantage Actor-Critic algorithm to suppress unnecessary handovers in 5 G mmWave ultra-dense networks. Incorporating a handover skipping strategy, the method limits handover rate growth to 28.74% as user speed increases — compared to 60.7–91.6% for baselines — and restricts throughput degradation to 10% versus drops of up to 57.1% in competing schemes.

Attiq Ur Rehman, Sara Suaiheen, KyungHi Chang. *Adaptive Resource Allocation in 6 G A2G-TN Integrated System: A Cross-Layer Multi-Agent PPO Approach* [14]. This work presents CL-MAPPO, a cross-layer multi-agent proximal policy optimisation framework for resource allocation in air-to-ground and terrestrial network integrated systems. Combining dynamic TDD with centralized training and distributed execution, CL-MAPPO achieves an 18% throughput improvement and 16% interference reduction over conventional MAPPO, with a conditional activation mechanism that limits computational overhead to significant network-state changes only.

Yi Xiao, Xiaolong Xu. *SGICPNOM: A Computation Offloading Mechanism for 6 G Space-Ground Integrated Computing Power Networks* [15]. The authors put forward SGICPNOM, a computation offloading mechanism for space-air-ground integrated networks that jointly optimises latency, energy consumption, and user satisfaction across LEO satellites and cloud data centres. Anchored by a battery-level-driven adaptive weighting strategy and a multi-agent DRL approach with prioritised experience replay, the framework achieves a 22.7% reduction in the weighted latency-energy sum over state-of-the-art baselines, sustaining task success rates above 89%.

2.6. Network traffic analytics and qoe prediction

Andrea Pimpinella, Alessandro E. C. Redondi. *Generative-Aided and Context-Aware Forecasting of Mobile Network Traffic* [16]. Drawing on four years of real-world data from two Italian cities, this paper

establishes a strong correlation between football match schedules and localised traffic surges, and builds a forecasting framework that conditions predictions on advance contextual event information. A lightweight generative augmentation strategy addresses rare traffic pattern scarcity, yielding measurable accuracy gains over traffic-only baselines during peak and busy-hour regimes.

Claudia Carballo González, Ernesto Fontes Pupo, Alessandro Floris, Simone Porcu, Maurizio Murrone, Luigi Atzori. *OTT-MNO Collaboration for a Network-layer ML-based QoE Prediction for Video Streaming over 5 G O-RAN* [17]. The authors design an O-RAN-integrated QoE prediction architecture that establishes structured data-sharing interfaces between Over-The-Top providers and Mobile Network Operators, enabling MNOs to train and update ML-based quality models with application-layer context. Among seven evaluated regressors, Gradient Boosting achieves the strongest performance with $R^2 = 0.906$ and RMSE = 0.259, using network parameters including SINR, CQI, resource blocks, throughput, and device mobility.

2.7. Vehicular and internet-of-vehicles (Iov) networking

Yang Li, Xiaolong Xu, Jian Xu. *AI-Enhanced Hierarchical Routing with Q-learning and Graph Neural Networks for 6G-Enabled Internet of Vehicles* [18]. The authors propose HRQSR, a hierarchical routing framework that pairs a multi-task Graph Attention Network for spatio-temporal link metric prediction with a two-level Q-learning process for intra- and inter-cluster routing decisions in 6 G vehicular networks. Co-simulation experiments on SUMO-OMNeT++ across low, medium, and high traffic densities show HRQSR achieving up to 95% routing success under congestion, outperforming all evaluated baselines in delay and energy efficiency.

Iftikhar Rasheed, Hala Mostafa. *Mobility-Aware Predictive Split Federated Learning for 6 G Vehicular Networks with Ultra-Low Latency Guarantees* [19]. This paper presents MAPSFL, a split federated learning framework tailored to the high-mobility and latency-sensitive demands of 6 G vehicular environments. By integrating predictive mobility modelling with dynamic model splitting and adaptive compression, MAPSFL delivers a 34% reduction in transmission latency and 31% lower CPU utilisation compared to state-of-the-art methods, while maintaining 85% efficiency at a scale of 5000 vehicles under sub-100 ms latency constraints.

Haoyu Tu, Wen Wu, Liang Li, Yongguang Lu, Lin Chen, Xu Chen. *V-FedMM: Dynamic Sample Selection for Efficient Multimodal Federated Learning over Vehicular Networks* [20]. The authors put forth V-FedMM, a vehicular federated learning framework that addresses modality imbalance and heterogeneous vehicle capabilities through a two-stage sample selection mechanism operating at both modality and individual sample levels. Theoretical convergence analysis is complemented by simulation results showing nearly 5% accuracy improvement and 16.8% reduction in computation overhead relative to conventional vehicular FL baselines.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The quality of this Special Issue rests on the rigour and dedication of its reviewers. Each submission was evaluated by at least four domain

experts, whose detailed and timely assessments provided authors with the critical guidance needed to strengthen their work. In total, 173 reviewers contributed to this process, representing a broad spectrum of expertise across the themes covered by this issue.

We are deeply grateful to every member of the reviewing committee for the care they brought to this task. Thorough peer review is the foundation of scientific progress, and their commitment to that standard is reflected throughout the pages that follow.

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