

Real-Time Monitoring Systems (5G/6G & Beyond): A Technical Review

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Abstract: The evolution of wireless communication networks from 5G to emerging 6G technologies has fundamentally transformed network monitoring and management requirements, necessitating sophisticated real-time monitoring systems capable of operating at microsecond timescales while maintaining comprehensive visibility across distributed network elements. This technical review examines three critical domains in real-time monitoring systems: low-latency distributed tracing with eBPF integration that enables direct kernel-level instrumentation with minimal performance impact, digital twin networks for predictive optimization that create virtual replicas of physical network infrastructure for proactive management, and quantum-secure monitoring frameworks designed to operate effectively in post-quantum cryptographic environments. The convergence of edge computing, cloud-native architectures, and ultra-low latency applications has created unprecedented demands for monitoring solutions that can process massive telemetry data volumes while maintaining microsecond-level precision in event correlation and autonomous network optimization capabilities. These advanced monitoring systems extend beyond traditional network performance metrics to encompass security, quality of service, and autonomous optimization capabilities essential for supporting Industry 4.0, Internet of Things, and mission-critical applications that rely on telecommunications networks as foundational infrastructure.

Keywords: Real-time monitoring systems, eBPF kernel-level telemetry, Digital twin networks, Quantum-secure frameworks, 5G/6G networks.

INTRODUCTION

The evolution of wireless communication networks from 5G to emerging 6G technologies has fundamentally transformed the requirements for network monitoring and management systems. Current 5G networks demand ultra-reliable low-latency communication with stringent end-to-end latency requirements, while 6G networks are expected to achieve even more aggressive latency targets for critical applications (Salh, A. *et al.*, 2021). As networks become increasingly complex, with modern 5G core networks comprising numerous microservices and supporting high-density network slicing architectures, traditional monitoring approaches prove inadequate for meeting the demanding latency, reliability, and scalability requirements of next-generation applications.

Real-time monitoring systems represent a paradigm shift towards proactive, intelligent, and autonomous network management capabilities that can adapt to the dynamic nature of modern telecommunications infrastructure. These systems must process massive volumes of telemetry data across distributed network elements while maintaining microsecond-level precision in event correlation and analysis. The architectural complexity of contemporary 5G networks, characterized by service-based architectures and cloud-native implementations, necessitates monitoring solutions that can seamlessly integrate with containerized environments and provide comprehensive visibility across heterogeneous network functions.

The convergence of edge computing, cloud-native architectures, and ultra-low latency applications has created an unprecedented need for monitoring solutions that can operate at microsecond timescales while maintaining comprehensive visibility across distributed network elements. Global 5G infrastructure investments continue to grow substantially, with projected edge computing deployments expected to reach unprecedented scales in the coming years. The monitoring complexity has increased exponentially as network operators deploy diverse use cases ranging from enhanced mobile broadband to massive machine-type communications and ultra-reliable low-latency communications.

This technical review examines the current state-of-the-art in real-time monitoring systems specifically designed for 5G networks and their evolution towards 6G technologies. The analysis focuses on three critical research domains: low-latency distributed tracing with eBPF integration, achieving minimal instrumentation overhead; digital twin networks for predictive optimization with high accuracy in network state prediction; and quantum-secure monitoring frameworks for post-quantum cryptographic environments supporting advanced key distribution mechanisms over extended fiber optic links.

The significance of these monitoring systems extends beyond traditional network performance metrics to encompass security, quality of service, and autonomous network optimization capabilities.

As telecommunications networks increasingly serve as the foundation for Industry 4.0, Internet of Things, and mission-critical applications, the ability to monitor, analyze, and respond to network conditions in real-time becomes paramount for ensuring service continuity and meeting stringent service level agreements (Rahman, A. U. *et al.*, 2021). Current enterprise 5G deployments require extremely high availability with aggressive mean time to resolution targets, necessitating autonomous monitoring systems capable of processing substantial event volumes while maintaining minimal false positive rates. The economic impact of network downtime for telecommunications operators further emphasizes the critical importance of implementing sophisticated real-time monitoring frameworks that can preemptively identify and mitigate potential service disruptions before they affect end-user experience.

LOW-LATENCY DISTRIBUTED TRACING AND EBPF INTEGRATION

eBPF for Kernel-Level Telemetry in Cloud-Native 5G

Extended Berkeley Packet Filter technology has emerged as a revolutionary approach for implementing kernel-level telemetry in cloud-native 5G environments, demonstrating substantial performance improvements over traditional user-space monitoring solutions (Soldani, D. *et al.*, 2023). Unlike conventional monitoring approaches that rely on user-space applications and introduce considerable overhead, eBPF enables direct kernel-level instrumentation with minimal performance impact, consuming significantly lower system resources while processing high-volume packet streams efficiently. This capability proves particularly crucial in 5G networks where latency budgets are extremely constrained and every processing delay directly affects user experience and application performance across diverse service types.

The implementation of eBPF in cloud-native 5G architectures facilitates comprehensive real-time packet inspection, sophisticated flow analysis, and detailed performance metric collection directly at the kernel level with exceptionally low processing latencies. This approach completely eliminates the context switching overhead associated with traditional monitoring tools and provides unprecedented visibility into complex network behavior patterns. Modern eBPF implementations capture extensive telemetry data, including high-

precision packet timestamps, comprehensive flow characteristics encompassing multiple network parameters, and detailed resource utilization metrics across various system components, enabling network operators to proactively identify and resolve performance bottlenecks before they manifest as service degradations.

Container orchestration platforms benefit substantially from eBPF-based monitoring in 5G environments, demonstrating significantly enhanced anomaly detection capabilities compared to traditional monitoring approaches. The technology enables seamless monitoring of containerized network functions and virtual network functions without requiring any modifications to existing application code or deployment configurations, supporting exceptionally high monitoring densities across large-scale container deployments. This completely non-intrusive monitoring approach maintains the essential agility and scalability characteristics required for cloud-native telecommunications deployments, particularly in highly dynamic scenarios where service functions are frequently instantiated and terminated based on varying demand patterns.

OpenTelemetry-Based Frameworks for End-to-End Service Visibility

OpenTelemetry has established itself as the industry standard for distributed tracing and observability in modern software architectures, with widespread adoption across cloud-native 5G deployments globally. In complex 5G network contexts, OpenTelemetry-based frameworks provide comprehensive end-to-end service visibility across intricate, multi-vendor network infrastructures, processing substantial trace data volumes in large-scale commercial deployments (Aelken, J. *et al.*, 2024). These advanced frameworks enable sophisticated correlation of events and performance metrics across diverse network domains, spanning from radio access networks through core network functions to distributed edge computing resources, with rapid event correlation capabilities for end-to-end service chains spanning multiple interconnected network functions.

The standardized approach offered by OpenTelemetry facilitates seamless interoperability between different monitoring tools and platforms, effectively addressing key technical challenges in multi-vendor 5G deployments where network functions from diverse vendors must

integrate seamlessly while maintaining optimal performance. By implementing consistent instrumentation and standardized telemetry collection mechanisms, network operators achieve unified visibility across heterogeneous network elements while preserving essential vendor flexibility and avoiding restrictive lock-in scenarios that could limit future technology adoption.

Distributed Tracing Architectures

The inherently distributed nature of 5G networks, characterized by complex interdependencies between radio access, transport, and core network

elements, necessitates sophisticated tracing architectures capable of correlating events across multiple network domains with exceptional precision and reliability. Modern distributed tracing systems employ advanced probabilistic sampling techniques, intelligent span aggregation mechanisms, and sophisticated routing algorithms to effectively manage massive telemetry data volumes generated by contemporary 5G networks while maintaining comprehensive end-to-end visibility across complex service chains traversing numerous interconnected network functions distributed across multiple geographic locations.

Table 1: eBPF and OpenTelemetry Integration Framework for Cloud-Native 5G Monitoring (Soldani, D. *et al.*, 2023; Aelken, J. *et al.*, 2024)

| Technology/ Component | Key Characteristics | 5G Network Applications |
|-----------------------------------|---|---|
| eBPF Kernel-Level Telemetry | Direct kernel instrumentation, minimal performance overhead, high-precision packet timestamping | Real-time packet inspection, CNF/VNF monitoring, containerized network function telemetry |
| OpenTelemetry Frameworks | Standardized distributed tracing, multi-vendor interoperability, and adaptive sampling strategies | End-to-end service visibility, cross-domain event correlation, and unified monitoring across heterogeneous elements |
| Distributed Tracing Architectures | Probabilistic sampling, span aggregation, and intelligent routing mechanisms | Multi-domain event correlation, service delivery path reconstruction, root cause analysis |
| Cloud-Native Integration | Non-intrusive monitoring, container orchestration support, and dynamic service scaling | High-density container monitoring, automated anomaly detection, seamless CNF deployment |
| Adaptive Instrumentation | Dynamic sampling rate adjustment, traffic pattern analysis, service level objective optimization | Performance degradation detection, intelligent telemetry collection, and monitoring infrastructure optimization |

DIGITAL TWIN NETWORKS FOR REAL-TIME OPTIMIZATION

Real-Time Network Mirroring for Simulation and Proactive Optimization

Digital twin technology represents a transformative approach to network monitoring and optimization, creating virtual replicas of physical network infrastructure that can be used for simulation, testing, and proactive optimization with exceptional accuracy in network behavior prediction (Rodrigo, M. S. *et al.*, 2023). In 5G networks, digital twins enable real-time mirroring of network behavior, processing substantial telemetry data from extensive network element deployments while maintaining minimal synchronization latencies. These systems allow operators to experiment with configuration changes, predict the impact of network modifications with high confidence levels, and

optimize performance without affecting production traffic carrying significant user data volumes.

The implementation of digital twin networks requires sophisticated data ingestion and synchronization mechanisms to ensure that virtual representations accurately reflect the current state of physical network elements, handling substantial data ingestion rates across distributed network infrastructures. Advanced digital twin systems can process real-time telemetry data from thousands of network components, including base stations, core network functions, and edge computing nodes, updating virtual models with exceptional precision to maintain synchronization between physical and virtual environments. These systems typically consume moderate computing resources while providing comprehensive network state replication across extensive geographic areas.

Commercial digital twin platforms exemplify the practical application of this technology in

telecommunications networks, demonstrating substantial reductions in network optimization time compared to traditional approaches. These systems provide comprehensive network modeling capabilities that enable operators to visualize network behavior across multiple network slices, simulate various traffic scenarios involving large numbers of concurrent users, and implement optimization strategies based on predictive analytics with extended forecast horizons. The platform's ability to integrate real-time monitoring data with sophisticated modeling algorithms demonstrates the potential for digital twins to transform network operations from reactive to proactive management paradigms, significantly reducing mean time to resolution.

Predictive Analytics and Machine Learning Integration

The effectiveness of digital twin networks is significantly enhanced through the integration of machine learning algorithms and predictive analytics capabilities, achieving exceptional prediction accuracies for network performance forecasting across different time horizons (Waseem, M. *et al.*, 2025). These systems can analyze extensive historical performance data, identify complex patterns and trends across multiple network parameters, and predict future network behavior with high confidence levels for extended prediction periods. Advanced machine learning models can forecast traffic patterns with exceptional peak hour prediction accuracy, predict equipment failures well in advance with minimal false positive rates, and recommend optimization

strategies based on current network conditions and projected demand patterns affecting substantial subscriber populations.

Deep learning neural networks, particularly recurrent neural networks and transformer architectures, process comprehensive time-series data from extensive network performance indicators to generate predictive insights. These models can handle substantial input feature dimensions while maintaining efficient training times for models covering entire metropolitan network areas. The integration of anomaly detection algorithms enables the identification of performance deviations with exceptional detection rates and rapid response times for critical network events.

Simulation and Testing Capabilities

Digital twin networks provide comprehensive simulation and testing environments that enable network operators to validate new services, test configuration changes, and evaluate the impact of network modifications before implementation, supporting simulation scales encompassing extensive metropolitan areas with numerous base stations. These capabilities are essential for maintaining service quality and minimizing disruptions in 5G networks, where downtime costs can be substantial and performance degradation can affect large user populations simultaneously. The simulation environments can model complex network topologies with extensive network elements while maintaining real-time simulation speeds with exceptional temporal resolution.

Table 2: AI-Enhanced Digital Twin Framework for Predictive Network Management (Rodrigo, M. S. *et al.*, 2023; Waseem, M. *et al.*, 2025)

| Technology Component | Key Capabilities | Network Applications |
|-------------------------------------|--|--|
| Real-Time Network Mirroring | Virtual replica creation, millisecond-precision synchronization, and comprehensive network state replication | Proactive optimization, configuration testing, and impact prediction without production traffic disruption |
| Predictive Analytics Integration | Machine learning algorithms, pattern recognition, and future behavior prediction with high confidence levels | Traffic forecasting, equipment failure prediction, optimization strategy recommendations |
| Deep Learning Neural Networks | Recurrent neural networks, transformer architectures, and comprehensive time-series data processing | Network performance indicator analysis, anomaly detection, critical event response |
| Simulation and Testing Environment | Complex topology modeling, real-time simulation speeds, and extensive metropolitan area coverage | Service validation, configuration change testing, network modification impact evaluation |
| Reinforcement Learning Optimization | Continuous learning from network behavior, virtual environment optimization, and risk minimization | Network resource allocation, control policy optimization, performance improvement strategies |

QUANTUM-SECURE MONITORING FRAMEWORKS

Post-Quantum Encryption Validation for KPI Streams

The emergence of quantum computing capabilities poses significant challenges to current cryptographic systems, with quantum computers expected to break existing RSA encryption within the next decade, necessitating the development of quantum-secure monitoring frameworks that can operate effectively in post-quantum cryptographic environments (Mehic, M. *et al.*, 2023). These systems must validate the integrity and authenticity of key performance indicator streams processing substantial KPI measurements while maintaining compatibility with post-quantum encryption algorithms such as those standardized by the National Institute of Standards and Technology. Current implementations demonstrate notable computational overhead increases when transitioning from classical to post-quantum cryptographic algorithms, with signature verification times extending significantly for lattice-based schemes compared to traditional approaches.

NIST Post-Quantum Cryptography algorithms, including lattice-based systems such as CRYSTALS-Dilithium with substantially larger signature sizes, hash-based algorithms like SPHINCS+ generating considerably larger signatures, and code-based cryptographic systems, require fundamentally different computational approaches compared to traditional public-key cryptography. Monitoring systems must be adapted to support these new cryptographic primitives while maintaining real-time performance characteristics essential for 5G network operations, where KPI processing latencies must remain minimal to support network slice orchestration and automated service assurance functions.

The implementation of quantum-secure monitoring involves multiple layers of cryptographic protection, including secure key distribution systems capable of generating and distributing substantial numbers of cryptographic keys across distributed network infrastructure, authenticated telemetry collection mechanisms processing high-volume data streams, and tamper-evident data storage mechanisms with integrity verification capabilities supporting extended forensic analysis timeframes. These systems must balance security requirements with performance constraints,

ensuring that cryptographic operations do not introduce excessive latency penalties or computational overhead that could degrade network performance.

Security Architecture and Implementation

Quantum-secure monitoring frameworks require comprehensive security architectures that address threats from both classical and quantum adversaries, implementing defense mechanisms capable of withstanding attacks from advanced quantum computers (European Telecommunications Standards Institute (ETSI)). These architectures incorporate multi-layered defense mechanisms, including quantum key distribution systems operating over extended fiber optic links with substantial key generation rates, post-quantum digital signatures processing high volumes of authentication requests, and quantum-resistant encryption systems supporting data protection for extended classified information retention periods.

The implementation of quantum-secure monitoring systems involves careful consideration of computational requirements, as post-quantum cryptographic algorithms typically require significantly more computational resources compared to classical cryptographic systems, with substantial increases in memory requirements depending on the specific algorithm implementation. Advanced implementations utilize hardware acceleration through dedicated cryptographic processors, parallel processing architectures supporting multiple concurrent cryptographic operations, and optimized algorithm implementations reducing computational latency while maintaining robust security guarantees.

Integration with Existing Infrastructure

The transition to quantum-secure monitoring must be accomplished without disrupting existing network operations or requiring complete infrastructure replacement, with migration strategies designed to maintain high service availability throughout extended transition periods. Hybrid architectures that support both classical and post-quantum cryptographic systems enable gradual migration while maintaining interoperability with legacy systems, supporting concurrent operation of traditional and lattice-based cryptographic algorithms with automatic algorithm selection based on peer capabilities and security policy requirements.

These implementations provide flexibility in cryptographic algorithm selection through configurable security profiles supporting multiple post-quantum algorithm combinations, and enable seamless updates as new post-quantum standards

are developed through automated software distribution mechanisms capable of updating cryptographic libraries across extensive network deployments within scheduled maintenance windows.

Table 3: Post-Quantum Cryptographic Implementation for Network Monitoring Systems (Mehic, M. *et al.*, 2023; European Telecommunications Standards Institute (ETSI))

| Technology Component | Security Capabilities | Network Implementation |
|------------------------------------|---|---|
| Post-Quantum Encryption Validation | NIST PQC algorithms support, lattice-based CRYSTALS-Dilithium, hash-based SPHINCS+ implementation | KPI stream integrity validation, real-time signature verification, network slice orchestration security |
| Quantum Key Distribution Systems | Extended fiber optic link operation, substantial key generation rates, and tamper-evident storage mechanisms | Secure communication channels, automated key rotation, and distributed network infrastructure protection |
| Multi-Layered Defense Architecture | Classical and quantum adversary protection, hardware acceleration support, and parallel processing capabilities | Comprehensive threat mitigation, cryptographic processor integration, and concurrent operation management |
| Hybrid Cryptographic Systems | Classical and post-quantum algorithm support, automatic algorithm selection, configurable security profiles | Legacy system interoperability, gradual migration enablement, seamless infrastructure transition |
| Hardware Security Integration | Dedicated cryptographic processors, tamper-resistant key storage, and automated software distribution | Network element security, maintenance window updates, and extended deployment compatibility |

PATENT LANDSCAPE AND FUTURE INNOVATIONS

Real-Time Latency Heatmaps for Edge Computing

The patent for "Real-Time Latency Heatmaps for Edge Computing" represents a significant innovation in visualizing and optimizing network performance in distributed edge computing environments, demonstrating substantial latency visualization capabilities across extensive edge computing node deployments with high-frequency update capabilities (Sahu, D. *et al.*, 2025). This technology provides intuitive, real-time visualization of latency characteristics across edge computing infrastructure, processing substantial telemetry data volumes while enabling network operators to identify performance bottlenecks and optimize service placement decisions with significant accuracy improvements compared to traditional monitoring approaches.

The implementation of latency heatmaps involves sophisticated data collection and visualization algorithms that can process telemetry data from thousands of edge computing nodes distributed across extensive geographic areas and present actionable insights through intuitive graphical interfaces with minimal rendering latencies. These systems enable network operators to understand

the geographic and topological distribution of latency characteristics with high spatial resolution, facilitating informed decisions about service placement, traffic routing, and resource allocation that can substantially reduce average service latency in urban edge deployments.

Advanced implementations of latency heatmap technology incorporate predictive analytics capabilities that can forecast future latency characteristics based on current trends and planned network modifications with exceptional prediction accuracy for extended forecasting horizons. This predictive capability enables proactive optimization strategies that can prevent performance degradation before it impacts end-users, with early warning systems capable of detecting potential latency increases well in advance. The visualization system supports concurrent monitoring of numerous different service types while maintaining detailed latency representations with fine granularity, enabling operators to identify latency patterns across different application categories and time periods.

O-RAN Intelligent Controller (RIC) for Anomaly Mitigation

The contribution to 3GPP standards for "O-RAN Intelligent Controller (RIC) for Anomaly Mitigation" represents a significant advancement

in autonomous network management capabilities, demonstrating exceptional anomaly detection accuracy rates while maintaining minimal false positive rates across diverse network conditions (Alves, P. V. *et al.*, 2023). This innovation leverages the Open Radio Access Network architecture to implement intelligent anomaly detection and mitigation mechanisms that can respond to network issues rapidly, processing substantial volumes of network performance indicators while maintaining minimal human intervention requirements.

The RIC-based anomaly mitigation system utilizes advanced machine learning algorithms, incorporating sophisticated neural networks to analyze real-time network performance data and identify deviations from normal operating conditions across network elements serving large subscriber populations. When anomalies are detected, the system can automatically implement corrective actions rapidly, such as adjusting resource allocation across numerous radio bearers, modifying traffic routing across extensive network paths, or reconfiguring network parameters spanning multiple base stations to restore optimal performance with high success rates.

Future Innovation Directions

The patent landscape in real-time monitoring systems for 5G/6G networks continues to evolve rapidly, with emerging innovations focusing on artificial intelligence integration, autonomous network optimization, and advanced security mechanisms processing substantial data volumes projected for future network deployments. Future developments are expected to incorporate more sophisticated machine learning algorithms capable of processing extensive network parameters simultaneously, enhanced automation capabilities significantly reducing manual network management tasks, and deeper integration with emerging technologies such as blockchain and distributed ledger systems supporting comprehensive network audit capabilities.

The convergence of 5G networks with other emerging technologies, including extensive Internet of Things deployments, augmented reality applications requiring minimal latency, and autonomous vehicles demanding exceptional reliability, is creating new requirements for monitoring systems that can handle diverse application requirements and service level objectives.

Table 4: Advanced Network Management Patents and Emerging Technologies for Next-Generation Networks (Sahu, D. *et al.*, 2025; Alves, P. V. *et al.*, 2023)

| Innovation/Patent | Key Capabilities | Network Applications |
|---|---|---|
| Real-Time Latency Heatmaps for Edge Computing | Intuitive visualization, sophisticated data collection algorithms, and high spatial resolution geographic mapping | Performance bottleneck identification, service placement optimization, and traffic routing decisions |
| O-RAN Intelligent Controller (RIC) for Anomaly Mitigation | Advanced machine learning algorithms, autonomous anomaly detection, and rapid corrective action implementation | Network performance maintenance, automated resource allocation, and multi-vendor environment interoperability |
| AI-Integrated Monitoring Systems | Sophisticated machine learning algorithms, enhanced automation capabilities, and blockchain integration support | Extensive network parameter processing, manual task reduction, and comprehensive audit trail maintenance |
| Self-Healing Network Technologies | Automatic detection and diagnosis, rapid issue resolution, minimal human intervention requirements | Network performance maintenance, autonomous problem resolution, and continuous service availability |
| Cognitive Networking Capabilities | Experience-based learning, continuous performance optimization, and adaptive response to changing conditions | Dynamic network adaptation, intelligent resource management, and future 6G network support |

CONCLUSION

Real-time monitoring systems for 5G/6G networks represent a transformative paradigm shift toward proactive, intelligent, and autonomous network management capabilities that address the

unprecedented complexity and performance demands of next-generation telecommunications infrastructure. The integration of eBPF technology for kernel-level telemetry, OpenTelemetry frameworks for end-to-end service visibility, and

sophisticated distributed tracing architectures enables network operators to achieve comprehensive monitoring with minimal performance overhead while maintaining microsecond-level precision across cloud-native environments. Digital twin networks enhanced with machine learning algorithms and predictive analytics capabilities provide powerful simulation and testing environments that transform network operations from reactive to proactive management paradigms, enabling operators to experiment with configuration changes and optimize performance without affecting production traffic. Quantum-secure monitoring frameworks incorporating post-quantum cryptographic algorithms ensure long-term security and integrity of network monitoring data in the face of emerging quantum computing threats, while hybrid architectures enable gradual migration without disrupting existing operations. The patent landscape demonstrates continued innovation in areas such as real-time latency heatmaps for edge computing and O-RAN intelligent controllers for anomaly mitigation, indicating a robust future for autonomous network management technologies. These comprehensive monitoring solutions will be essential for realizing the full potential of 6G networks and beyond, where network complexity and performance requirements will continue to increase exponentially, demanding systems capable of processing massive data volumes while maintaining exceptional reliability and security standards for mission-critical applications.

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