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An Operational Reliability Engineering Framework for Sustained High Availability in 5G Core Networks Serving Millions

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Abstract
The rapid global deployment of fifth-generation (5G) mobile networks has introduced unprecedented operational complexity within the 5G core, driven by cloud-native architectures, network function virtualization, software-defined networking, and ultra-low latency service requirements. Ensuring sustained high availability for 5G core networks serving millions of subscribers therefore demands a systematic operational reliability engineering approach that goes beyond traditional fault management and redundancy models. This paper proposes an Operational Reliability Engineering Framework designed to support continuous service availability, resilience, and performance stability in large-scale 5G core environments. The framework integrates reliability engineering principles with real-time observability, predictive analytics, automated fault isolation, and lifecycle-driven resilience planning across both physical and virtual network functions. Key framework components include reliability-centered design, proactive failure mode and effects analysis, service-based architecture dependency mapping, intelligent incident response orchestration, and closed-loop feedback mechanisms for continuous improvement. The proposed framework emphasizes the operationalization of reliability through measurable indicators such as service availability, mean time to detect, mean time to recover, and customer-impact metrics, aligned with strict service level agreements. A layered reliability governance model is introduced to coordinate network operations, DevOps, and vendor ecosystems, ensuring consistent reliability assurance across distributed cloud infrastructures. The framework also addresses scalability challenges, dynamic traffic behavior, and evolving threat landscapes by embedding adaptive capacity planning, stress testing, and fault-injection techniques into routine operations. By providing a structured and actionable reliability model tailored to 5G core networks, this study contributes a practical blueprint for telecom operators seeking to achieve sustained high availability at national and global scale. The framework supports not only technical robustness but also operational decision-making, enabling operators to proactively manage risk, reduce unplanned outages, and maintain service continuity in highly dynamic 5G environments. Overall, the proposed Operational Reliability Engineering Framework offers a comprehensive and scalable approach to sustaining high availability in mission-critical 5G core networks serving millions of users. The framework is intended to be technology-agnostic, interoperable with multivendor ecosystems, and applicable across standalone and non-standalone 5G deployments, supporting long-term network evolution while preserving operational stability, regulatory compliance, service assurance objectives, and continuous alignment with emerging industry standards and best practices worldwide today globally.

Keywords: 5G Core Networks, Operational Reliability Engineering, High Availability, Network Resilience, Cloud-Native Telecom Operations, Service Continuity

1. Introduction

The evolution of fifth-generation (5G) mobile networks represents a fundamental shift in the design, deployment, and operation of telecommunications infrastructures. Unlike previous generations, the 5G core is built around a service-based architecture that decouples network functions, enables dynamic service composition, and supports diverse use cases ranging from enhanced mobile broadband to ultra-reliable low-latency and massive machine-type communications. This transformation has significantly increased operational complexity, as 5G core networks must simultaneously deliver high performance, scalability, flexibility, and near-continuous availability while serving millions of users and mission-critical services (Dako, *et al*., 2019, Nwafor, *et al*., 2019, Oguntegbe, Farounbi & Okafor, 2019).

Central to this evolution is the adoption of cloud-native paradigms that replace monolithic, hardware-bound core networks with virtualized and containerized network functions deployed on distributed cloud infrastructures. Network function virtualization, control and user plane separation, and microservices-based design have enabled rapid service innovation and elastic scaling, but they have also introduced new reliability challenges (Arowogbadamu, Oziri & Seyi-Lande, 2021, Umoren, *et al*., 2021). Failures are no longer limited to physical components; they now emerge from software defects, orchestration errors, dependency misconfigurations, and cascading interactions across complex service chains. As a result, traditional redundancy-focused availability models are insufficient for ensuring sustained high availability in large-scale 5G core environments (Ezeh, *et al*., 2025, Oparah, *et al*., 2025, Sanusi, 2025, Ukasoanya, *et al*., 2025).

Kubernetes and OpenStack have emerged as foundational orchestration platforms supporting this cloud-native transformation. OpenStack provides the virtualization and infrastructure management layer for compute, storage, and networking resources, while Kubernetes orchestrates containerized network functions, managing lifecycle operations such as deployment, scaling, healing, and updates. Together, these platforms enable highly automated and programmable 5G core deployments, but they also shift reliability responsibility from static design-time decisions to continuous, runtime operational control. High availability therefore becomes an operational property that must be actively engineered, monitored, and maintained across heterogeneous and distributed environments (Okafor, *et al*., 2024, Oparah, *et al*., 2024, Uduokhai, *et al*., 2024).

This operational reality motivates the need for a structured reliability engineering framework tailored specifically to 5G core networks. Such a framework must integrate reliability principles with cloud-native orchestration, observability, automation, and analytics, enabling operators to anticipate failures, limit service impact, and rapidly restore functionality at scale. Rather than treating reliability as an outcome of isolated mechanisms, the framework must embed availability assurance into everyday operational processes and orchestration logic (Ahmed, Odejobi & Oshoba, 2021, Dako, *et al*., 2021, Ogunsola & Michael, 2021).

This paper addresses this need by proposing an Operational Reliability Engineering Framework for sustained high availability in 5G core networks serving millions. By aligning reliability engineering practices with Kubernetes- and OpenStack-based orchestration, the framework aims to provide telecom operators with a systematic, scalable, and actionable approach to maintaining service continuity in increasingly complex and dynamic 5G core ecosystems (Akinrinoye, *et al*., 2015, Aminu-Ibrahim, Ogbete & Ambali, 2019).

2.1 Methodology

The study adopts a design-science, mixed-methods methodology to build and evaluate an Operational Reliability Engineering Framework that sustains high availability in large-scale 5G core networks serving millions of subscribers. The approach begins with requirements elicitation from real-world 5G core operational objectives (e.g., “five-nines” service targets), focusing on failure modes typical to cloud-native, multi-vendor cores (control-plane overload, state-store contention, misconfiguration, network-slice isolation failures, and security-triggered service degradation) aligned to 5G technology characteristics and deployment realities (Loung *et al*., 2021; Subedi *et al*., 2021) and known 5G cyber risk surfaces that can directly impact availability (Mohan *et al*., 2022). A conceptual architecture baseline is then specified using scalable secure cloud principles for high-concurrency systems, ensuring tenant isolation, resilient messaging/eventing, and safe-by-design operational controls (Ahmed & Odejobi, 2018; Odejobi & Ahmed, 2018).

Framework construction proceeds in iterative build–evaluate cycles. Reliability engineering artefacts are created for each critical Network Function (NF) and shared platform dependency: (i) a failure taxonomy and dependency graph, (ii) risk prioritization using severity–occurrence–detectability scoring, (iii) fault containment strategies (bulkheads, circuit breakers, graceful degradation), and (iv) recovery patterns mapped to automated runbooks. Because 5G core availability is tightly coupled to elastic capacity decisions, the framework embeds a capacity and scaling subsystem that combines energy-efficient placement and constraint-based resource allocation with predictive scaling models to reduce overload-driven outages while controlling platform saturation (Ahmed & Odejobi, 2018; Ahmed & Odejobi, 2018; Ahmed *et al*., 2019; Ahmed *et al*., 2020). Queueing-theoretic modeling is used to dimension operational bottlenecks that commonly cause availability loss at scale (e.g., incident queues, change backlogs, approval gates, reporting deadlines, and maintenance windows), enabling “high-velocity at scale” governance without creating reliability-harming queues (Akinola *et al*., 2025).

To prevent availability incidents caused by configuration drift and inconsistent enforcement of controls, the framework operationalizes “compliance-as-code” and automated governance pipelines, where policy checks, configuration validation, and deployment guardrails run continuously across environments (Oshoba *et al*., 2023). This is complemented by a resilience-and-recovery evaluation layer that defines recovery objectives, validates rollback and failover behaviors, and tests survivability under injected faults and traffic volatility, consistent with business-critical cloud workload recovery principles (Odejobi *et al*., 2023). Security is treated as a reliability dependency: controls are added to prevent identity/authentication abuse, spoofing, and biased detection behaviors from triggering false positives or lockouts that can cascade into service disruption (Adeniyi *et al*., 2025), while 5G-specific threat scenarios are included in reliability test plans (Mohan *et al*., 2022).

Evaluation is performed using a combination of (a) simulation/analytical modeling, (b) prototype-based experiments in a representative cloud-native environment, and (c) operational scenario walkthroughs. First, analytical validation compares predicted versus observed saturation and delay behaviors for critical queues (e.g., incident triage, change approvals, and deployment throughput) using the queueing models to confirm the framework's capacity governance logic (Akinola *et al*., 2025). Second, controlled experiments execute load tests and fault-injection campaigns across representative 5G core service chains and slice configurations to quantify availability outcomes under failures such as pod/node loss, database latency spikes, misrouted traffic, certificate expiry, and policy misconfiguration, reflecting slicing and multi-service realities (Subedi *et al*., 2021). Third, the predictive scaling subsystem is assessed using back-testing on time-series traffic patterns (diurnal/weekly seasonality, flash crowds), measuring forecast error and the effect on overload incidents and recovery times (Ahmed *et al*., 2020). Finally, the governance and human-in-the-loop operating model is validated through a roles-and-responsibilities mapping and capability assessment to ensure the organization can sustain the framework over time, drawing on structured development and progression mechanisms that support consistent operational maturity (Adenuga *et al*., 2025).

Outcome measures are pre-defined and collected throughout experiments and scenario runs: service availability (per service and per slice), incident rate and recurrence, mean time to detect and recover, change failure rate, rollback success rate, scaling accuracy and timeliness, and policy/compliance drift frequency. The framework is refined until it meets acceptance thresholds (e.g., statistically significant reduction in overload-induced incidents and faster recovery under comparable fault loads), producing the final validated framework specification, runbooks, control gates, and measurement dashboards aligned to scalable secure cloud architectures and reliability-at-scale principles (Ahmed & Odejobi, 2018; Odejobi *et al*., 2023).

Fig 1: Flowchart of the study methodology

2.2 Architecture and Operational Characteristics of 5G Core Networks

This study has examined predictive capacity planning and utilization forecasting models tailored to the increasingly complex reality of multi-regional and multi-vendor mobile core networks. By framing the problem around geographic distribution, vendor heterogeneity, traffic variability, and service evolution, the work has highlighted the limitations of traditional, reactive capacity planning approaches and demonstrated the need for data-driven, predictive methodologies. The analysis of data sources, feature engineering strategies, modeling techniques, architectural frameworks, and operational integration mechanisms provides a comprehensive foundation for understanding how forecasting models can be designed and embedded within modern mobile core network operations (Osuashi Sanni, *et al*., 2023).

From a practical perspective, the contributions of this work have significant implications for mobile network operators. Predictive capacity planning enables operators to transition from static, threshold-based decision making to anticipatory planning that aligns resources with expected demand. By leveraging forecasting outputs, operators can proactively scale network resources, optimize infrastructure utilization, and prioritize investments in regions and network domains exhibiting sustained growth (Rukh, Seyi-Lande & Oziri, 2024, Seyi-Lande & Onaolapo, 2024, Uduokhai, *et al*., 2024). In multi-vendor environments, normalized and harmonized forecasting models support consistent planning across heterogeneous platforms, reducing operational fragmentation and improving transparency in capacity-related decision making. The integration of forecasting insights with network management and orchestration systems further enhances operational efficiency, allowing capacity decisions to be executed in a timely and coordinated manner while maintaining service quality and regulatory compliance (Farounbi, *et al*., 2021, Olatunji, *et al*., 2021, Oparah, *et al*., 2021).

Looking ahead, several avenues for future research emerge from this work. Closed-loop optimization represents a critical next step in the evolution of predictive capacity planning, in which forecast outputs are continuously validated against observed outcomes and used to automatically adjust resource allocation and operational policies. Such closed-loop systems can improve forecast accuracy over time and enable more responsive network behavior under dynamic conditions (Bayeroju, Sanusi & Nwokediegwu, 2023, Seyi-Lande, Arowogbadamu & Oziri, 2023, Umoren, *et al*., 2023). Advances in artificial intelligence and machine learning offer additional opportunities to enhance planning models by incorporating reinforcement learning, adaptive algorithms, and context-aware decision making. AI-driven planning frameworks could analyze complex interactions across regions, vendors, and services to recommend or execute optimal capacity strategies with minimal human intervention (Osuashi Sanni, Atima & Attah, 2022). Figure 2 shows network nodes of the 5G network architecture presented by Subedi, *et al*., 2021.

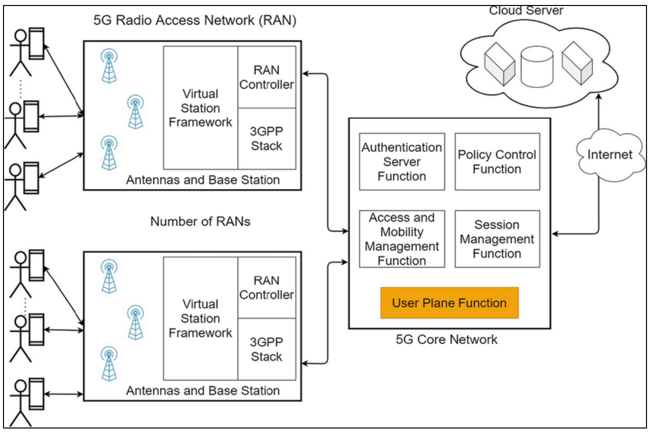

Fig 2: Network nodes of the 5G network architecture (Subedi, *et al*., 2021).

Digital twin applications also present a promising direction for future research. By creating virtual replicas of mobile core networks that mirror real-world behavior, digital twins can support scenario-based forecasting, stress testing, and what-if analysis under controlled conditions. Integrating predictive capacity planning models with digital twin environments would enable operators to evaluate the impact of new services, architectural changes, or traffic surges before implementing them in production networks. Collectively, these research directions point toward a future in which predictive capacity planning evolves into an intelligent, autonomous capability that supports resilient, efficient, and scalable mobile core networks in an increasingly complex and heterogeneous operational landscape (Oguntegbe, Farounbi & Okafor, 2023, Oshoba, Ahmed & Odejobi, 2023, Uduokhai, *et al*., 2023).

2.3 Reliability and Availability Challenges in Large-Scale 5G Core Operations

Reliability and availability challenges in large-scale 5G core operations emerge from the unprecedented scale, architectural complexity, and service diversity that define modern mobile networks serving millions of users. Unlike legacy mobile cores, the 5G core is built on cloud-native principles, distributed microservices, service-based interfaces, and software-defined infrastructure, all of which fundamentally change the nature of operational risk. While these design choices enable flexibility, scalability, and rapid service innovation, they also introduce new failure modes and operational fragilities that must be addressed through a robust reliability engineering framework focused on sustained high availability (Adenuga, *et al*., 2025, Michael & Ogunsola, 2025, Oparah, *et al*., 2025).

One of the most significant challenges lies in the diversity and interaction of failure modes within a highly disaggregated 5G core. Traditional telecom failures were often dominated by hardware faults or monolithic software crashes, typically isolated to specific network elements. In contrast, 5G core failures frequently arise from complex interactions among microservices, containers, orchestration platforms, and underlying cloud infrastructure. A single misconfigured policy function, a delayed state synchronization between control plane services, or a cascading timeout across service-based interfaces can propagate rapidly across the core (Ezeh, *et al*., 2025, Oziri, Seyi-Lande & Arowogbadamu, 2020, Umoren, *et al*., 2025). These failures are often non-deterministic, context-dependent, and difficult to reproduce, complicating root cause analysis and prolonging mean time to repair. Furthermore, the decoupling of control and user plane functions introduces new dependency chains, where partial failures may not result in total outages but instead degrade session establishment, mobility handling, or charging accuracy in subtle yet impactful ways (Dako, Okafor & Osuji, 2021, Ezeh, *et al*., 2021, Ogunsola & Michael, 2021). Figure 3 shows 5G network architecture presented by Mohan, Sugunaraj & Ranganathan, 2022.

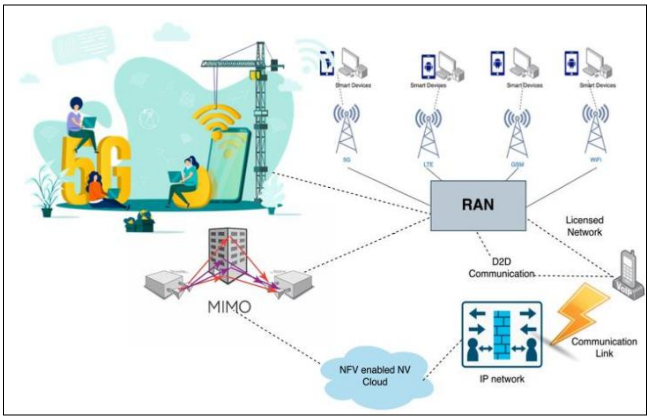

Fig 3: 5G network architecture (Mohan, Sugunaraj & Ranganathan, 2022)

Traffic volatility further compounds reliability challenges in large-scale 5G core environments. The traffic profile of 5G networks is far more dynamic than previous generations due to the coexistence of enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications. Each of these service categories exhibits distinct usage patterns, sensitivity to latency and packet loss, and tolerance for service degradation. Sudden surges driven by live events, viral content, software updates, or large-scale IoT signaling storms can stress control plane capacity far more aggressively than steady-state traffic models predict (Atima, Osuashi Sanni & Attah, 2022, Bayeroju, Sanusi & Nwokediegwu, 2022, Uduokhai, *et al*., 2022). Even when average utilization remains within planned thresholds, bursty signaling behavior can overwhelm session management, authentication, or policy enforcement functions, leading to transient failures that erode perceived availability. Reliability engineering in this context must therefore account not only for peak throughput but also for signaling intensity, concurrency, and state churn (Oguntegbe, Farounbi & Okafor, 2019, Michael & Ogunsola, 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019).

Multivendor dependencies represent another critical reliability and availability risk in large-scale 5G core operations. Most operators deploy cores composed of components sourced from multiple vendors, including network functions, cloud platforms, orchestration systems, and observability tools. While multivendor strategies reduce lock-in and foster innovation, they also introduce integration complexity and ambiguity in failure ownership. Interoperability gaps between vendor implementations of service-based interfaces, differences in error handling semantics, and inconsistent interpretation of standards can result in latent faults that surface only under specific operational conditions (Nwafor, *et al*., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018). During incidents, diagnosing whether a failure originates from a network function, the container runtime, the orchestration layer, or the underlying infrastructure can be time-consuming, especially when visibility across vendor domains is limited.

These challenges are exacerbated by asynchronous software release cycles, where updates from one vendor may inadvertently destabilize interactions with others (Ogunsola & Michael, 2023, Osuji, Okafor & Dako, 2023, Uduokhai, *et al*., 2023). Figure 4 shows a typical example of 5G wireless network architecture presented by Loung, *et al*., 2021.

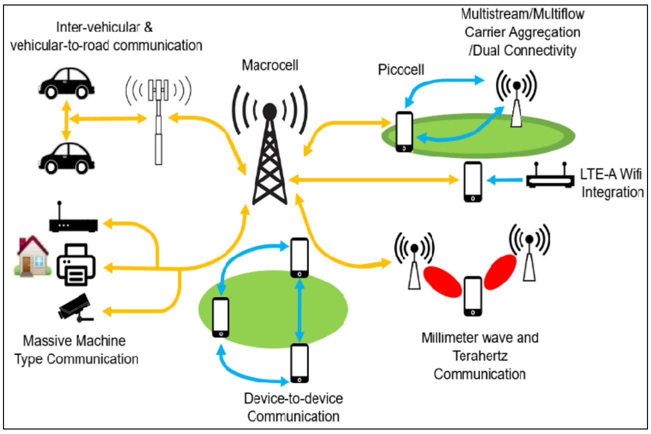

Fig 4: A typical example of 5G wireless network architecture (Loung, *et al*., 2021)

Scalability constraints, both technical and organizational, further influence reliability outcomes in 5G core networks serving millions. From a technical perspective, horizontal scaling of stateless services is relatively straightforward, but many critical core functions still maintain state related to sessions, mobility, and charging. Scaling these stateful components without introducing synchronization bottlenecks, data inconsistency, or excessive signaling overhead remains a nontrivial engineering problem (Nwaigbo, *et al*., 2025, Shah, Oziri & Seyi-Lande, 2025, Umoren, *et al*., 2025). Moreover, control plane scalability is often constrained by database performance, message bus throughput, or inter-service communication latency, all of which can become single points of contention at scale. From an operational standpoint, scaling reliability practices such as configuration management, change control, and incident response across geographically distributed, multi-cloud environments places heavy demands on processes and tooling. Human factors, including skill gaps in cloud-native operations and coordination challenges across teams, can become limiting factors in sustaining high availability (Ogunsola & Michael, 2022, Olatunji, *et al*., 2022, Oparah, *et al*., 2022).

Service continuity risks are particularly acute in 5G core networks due to the expectations placed on the services they support. Many 5G use cases, including industrial automation, public safety, autonomous systems, and enterprise network slicing, require not only high availability but also predictable performance and graceful degradation. Partial outages that might have been acceptable in consumer-centric 4G networks can have severe consequences in these contexts. For example, a control plane failure that prevents new session establishment may not immediately disrupt existing sessions but can still violate service-level agreements for mission-critical applications. Similarly, inconsistent behavior during mobility events can lead to dropped connections or increased latency precisely when reliability is most critical. Ensuring service continuity therefore requires more than binary uptime metrics; it demands fine-grained monitoring of functional correctness, performance stability, and user experience across diverse scenarios (Ahmed, Odejobi & Oshoba, 2020, Nwafor, Ajirotutu & Uduokhai, 2020).

The distributed nature of 5G core deployments introduces additional challenges related to geographic redundancy and fault isolation. While multi-region and multi-availability-zone architectures are designed to improve resilience, they also create complex failure scenarios involving partial network partitions, inconsistent state replication, and asymmetric latency. A failure in one region may trigger traffic re-routing or failover mechanisms that overload another region if capacity planning and admission control are not carefully engineered. Moreover, automated recovery actions initiated by orchestration systems can sometimes exacerbate instability by repeatedly restarting services or reallocating resources without addressing underlying systemic issues. Reliability engineering frameworks must therefore balance automation with safeguards that prevent runaway recovery behaviors (Akinrinoye, *et al*., 2020, Odejobi, Hammed & Ahmed, 2020, Oguntegbe, Farounbi & Okafor, 2020).

Observability limitations remain a persistent barrier to effective reliability management in large-scale 5G cores. The sheer volume of telemetry generated by microservices, containers, and network functions can overwhelm traditional monitoring approaches, leading to delayed or incomplete detection of emerging issues. Correlating metrics, logs, and traces across layers and vendors is essential for understanding failure propagation, yet achieving consistent observability remains challenging in heterogeneous environments. Without high-quality, real-time insight into system behavior, operators are forced to rely on reactive troubleshooting rather than proactive reliability management (Michael & Ogunsola, 2023, Ogunsola & Michael, 2023, Uduokhai, *et al*., 2023).

In sum, reliability and availability challenges in large-scale 5G core operations arise from the interplay of complex failure modes, highly volatile traffic patterns, multivendor dependencies, scalability limits, and stringent service continuity requirements. Addressing these challenges requires an operational reliability engineering framework that goes beyond traditional fault tolerance and redundancy. Such a framework must integrate failure mode analysis, adaptive capacity management, rigorous integration testing, and continuous observability into everyday operations. Only by systematically engineering for reliability at scale can 5G core networks sustain the high availability demanded by millions of users and the critical services that increasingly depend on them (Osuashi Sanni, *et al*., 2024, Wedraogo & Osuashi Sanni, 2024).

2.4 Operational Reliability Engineering Principles for Telecom Networks

Reliability and availability challenges in large-scale 5G core operations emerge from the unprecedented scale, architectural complexity, and service diversity that define modern mobile networks serving millions of users. Unlike legacy mobile cores, the 5G core is built on cloud-native principles, distributed microservices, service-based interfaces, and software-defined infrastructure, all of which fundamentally change the nature of operational risk. While these design choices enable flexibility, scalability, and rapid service innovation, they also introduce new failure modes and operational fragilities that must be addressed through a robust reliability engineering framework focused on sustained high availability (Akinola, *et al*., 2020, Nwafor, Uduokhai & Ajirotutu, 2020, Osuashi Sanni, Ajiga & Atima, 2020).

One of the most significant challenges lies in the diversity and interaction of failure modes within a highly disaggregated 5G core. Traditional telecom failures were often dominated by hardware faults or monolithic software crashes, typically isolated to specific network elements. In contrast, 5G core failures frequently arise from complex interactions among microservices, containers, orchestration platforms, and underlying cloud infrastructure. A single misconfigured policy function, a delayed state synchronization between control plane services, or a cascading timeout across service-based interfaces can propagate rapidly across the core (Akinrinoye, *et al*., 2020, Sanusi, Bayeroju & Nwokediegwu, 2021). These failures are often non-deterministic, context-dependent, and difficult to reproduce, complicating root cause analysis and prolonging mean time to repair. Furthermore, the decoupling of control and user plane functions introduces new dependency chains, where partial failures may not result in total outages but instead degrade session establishment, mobility handling, or charging accuracy in subtle yet impactful ways (Ajayi, *et al*., 2023, Odejobi, Hammed & Ahmed, 2023, Onyelucheya, *et al*., 2023).

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In sum, reliability and availability challenges in large-scale 5G core operations arise from the interplay of complex failure modes, highly volatile traffic patterns, multivendor dependencies, scalability limits, and stringent service continuity requirements. Addressing these challenges requires an operational reliability engineering framework that goes beyond traditional fault tolerance and redundancy. Such a framework must integrate failure mode analysis, adaptive capacity management, rigorous integration testing, and continuous observability into everyday operations. Only by systematically engineering for reliability at scale can 5G core networks sustain the high availability demanded by millions of users and the critical services that increasingly depend on them (Ezeh, *et al*., 2024, Michael & Ogunsola, 2024, Oparah, *et al*., 2024).

2.5 Proposed Operational Reliability Engineering Framework

Reliability and availability challenges in large-scale 5G core operations emerge from the unprecedented scale, architectural complexity, and service diversity that define modern mobile networks serving millions of users. Unlike legacy mobile cores, the 5G core is built on cloud-native principles, distributed microservices, service-based interfaces, and software-defined infrastructure, all of which fundamentally change the nature of operational risk. While these design choices enable flexibility, scalability, and rapid service innovation, they also introduce new failure modes and operational fragilities that must be addressed through a robust reliability engineering framework focused on sustained high availability (Ezeh, *et al*., 2023, Oguntegbe, Farounbi & Okafor, 2023, Odejobi, Hammed & Ahmed, 2023).

One of the most significant challenges lies in the diversity and interaction of failure modes within a highly disaggregated 5G core. Traditional telecom failures were often dominated by hardware faults or monolithic software crashes, typically isolated to specific network elements. In contrast, 5G core failures frequently arise from complex interactions among microservices, containers, orchestration platforms, and underlying cloud infrastructure (Akinrinoye, *et al*., 2024, Seyi-Lande, Arowogbadamu & Oziri, 2024, Uduokhai, *et al*., 2024). A single misconfigured policy function, a delayed state synchronization between control plane services, or a cascading timeout across service-based interfaces can propagate rapidly across the core. These failures are often non-deterministic, context-dependent, and difficult to reproduce, complicating root cause analysis and prolonging mean time to repair. Furthermore, the decoupling of control and user plane functions introduces new dependency chains, where partial failures may not result in total outages but instead degrade session establishment, mobility handling, or charging accuracy in subtle yet impactful ways (Michael & Ogunsola, 2025, Onyelucheya, *et al*., 2025, Oparah, *et al*., 2025).

Traffic volatility further compounds reliability challenges in large-scale 5G core environments. The traffic profile of 5G networks is far more dynamic than previous generations due to the coexistence of enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications. Each of these service categories exhibits distinct usage patterns, sensitivity to latency and packet loss, and tolerance for service degradation. Sudden surges driven by live events, viral content, software updates, or large-scale IoT signaling storms can stress control plane capacity far more aggressively than steady-state traffic models predict (Onyelucheya, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Uduokhai, *et al*., 2023). Even when average utilization remains within planned thresholds, bursty signaling behavior can overwhelm session management, authentication, or policy enforcement functions, leading to transient failures that erode perceived availability. Reliability engineering in this context must therefore account not only for peak throughput but also for signaling intensity, concurrency, and state churn (Okafor, *et al*., 2021, Oshoba, Hammed & Odejobi, 2021, Umoren, *et al*., 2021).

Multivendor dependencies represent another critical reliability and availability risk in large-scale 5G core operations. Most operators deploy cores composed of components sourced from multiple vendors, including network functions, cloud platforms, orchestration systems, and observability tools. While multivendor strategies reduce lock-in and foster innovation, they also introduce integration complexity and ambiguity in failure ownership (Ogbete & Aminu-Ibrahim, 2024). Interoperability gaps between vendor implementations of service-based interfaces, differences in error handling semantics, and inconsistent interpretation of standards can result in latent faults that surface only under specific operational conditions. During incidents, diagnosing whether a failure originates from a network function, the container runtime, the orchestration layer, or the underlying infrastructure can be time-consuming, especially when visibility across vendor domains is limited. These challenges are exacerbated by asynchronous software release cycles, where updates from one vendor may inadvertently destabilize interactions with others (Olatunji, *et al*., 2023, Oparah, *et al*., 2023, Uduokhai, *et al*., 2023).

Scalability constraints, both technical and organizational, further influence reliability outcomes in 5G core networks serving millions. From a technical perspective, horizontal scaling of stateless services is relatively straightforward, but many critical core functions still maintain state related to sessions, mobility, and charging. Scaling these stateful components without introducing synchronization bottlenecks, data inconsistency, or excessive signaling overhead remains a nontrivial engineering problem (Attah &

Osuashi Sanni, 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Uduokhai, *et al*., 2023). Moreover, control plane scalability is often constrained by database performance, message bus throughput, or inter-service communication latency, all of which can become single points of contention at scale. From an operational standpoint, scaling reliability practices such as configuration management, change control, and incident response across geographically distributed, multi-cloud environments places heavy demands on processes and tooling. Human factors, including skill gaps in cloud-native operations and coordination challenges across teams, can become limiting factors in sustaining high availability (Ezeh, *et al*., 2025, Michael & Ogunsola, 2025, Sanusi, 2025, Oziri, Arowogbadamu & Seyi-Lande, 2025).

Service continuity risks are particularly acute in 5G core networks due to the expectations placed on the services they support. Many 5G use cases, including industrial automation, public safety, autonomous systems, and enterprise network slicing, require not only high availability but also predictable performance and graceful degradation. Partial outages that might have been acceptable in consumer-centric 4G networks can have severe consequences in these contexts. For example, a control plane failure that prevents new session establishment may not immediately disrupt existing sessions but can still violate service-level agreements for mission-critical applications (Akinrinoye, *et al*., 2025, Ezeh, *et al*., 2025, Nwafor, *et al*., 2025, Ukamaka, *et al*., 2025). Similarly, inconsistent behavior during mobility events can lead to dropped connections or increased latency precisely when reliability is most critical. Ensuring service continuity therefore requires more than binary uptime metrics; it demands fine-grained monitoring of functional correctness, performance stability, and user experience across diverse scenarios (Ajayi, *et al*., 2025, Okafor, *et al*., 2025, Ukamaka, *et al*., 2025).

The distributed nature of 5G core deployments introduces additional challenges related to geographic redundancy and fault isolation. While multi-region and multi-availability-zone architectures are designed to improve resilience, they also create complex failure scenarios involving partial network partitions, inconsistent state replication, and asymmetric latency. A failure in one region may trigger traffic re-routing or failover mechanisms that overload another region if capacity planning and admission control are not carefully engineered (Osuashi Sanni, *et al*., 2022, Seyi-Lande, Arowogbadamu & Oziri, 2022, Uduokhai, *et al*., 2022). Moreover, automated recovery actions initiated by orchestration systems can sometimes exacerbate instability by repeatedly restarting services or reallocating resources without addressing underlying systemic issues. Reliability engineering frameworks must therefore balance automation with safeguards that prevent runaway recovery behaviors (Osuashi Sanni, Ajiga & Atima, 2020, Oshoba, Hammed & Odejobi, 2020, Oziri, *et al*., 2020).

Observability limitations remain a persistent barrier to effective reliability management in large-scale 5G cores. The sheer volume of telemetry generated by microservices, containers, and network functions can overwhelm traditional monitoring approaches, leading to delayed or incomplete detection of emerging issues. Correlating metrics, logs, and traces across layers and vendors is essential for understanding failure propagation, yet achieving consistent observability remains challenging in heterogeneous environments. Without high-quality, real-time insight into system behavior, operators are forced to rely on reactive troubleshooting rather than proactive reliability management (Ogunsola & Michael, 2021, Osuashi Sanni & Atima, 2021, Umoren, *et al*., 2021).

In sum, reliability and availability challenges in large-scale 5G core operations arise from the interplay of complex failure modes, highly volatile traffic patterns, multivendor dependencies, scalability limits, and stringent service continuity requirements. Addressing these challenges requires an operational reliability engineering framework that goes beyond traditional fault tolerance and redundancy. Such a framework must integrate failure mode analysis, adaptive capacity management, rigorous integration testing, and continuous observability into everyday operations. Only by systematically engineering for reliability at scale can 5G core networks sustain the high availability demanded by millions of users and the critical services that increasingly depend on them (Odejobi & Ahmed, 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

2.6 Implementation Strategy and Operational Integration

Implementing an operational reliability engineering framework for sustained high availability in 5G core networks serving millions requires a deliberate strategy that bridges architectural intent with day-to-day operational realities. Unlike theoretical reliability models, the effectiveness of such a framework is ultimately determined by how seamlessly it integrates into live network environments, organizational workflows, and continuous delivery pipelines. The implementation strategy must therefore balance rigor with practicality, ensuring that reliability principles are embedded into automation, analytics, DevOps practices, and lifecycle management processes without introducing excessive operational overhead or slowing innovation (Ahmed & Odejobi, 2018, Nwafor, *et al*., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

A foundational consideration in deploying the framework is the alignment of reliability objectives with existing network architectures and operational maturity. Large-scale 5G cores are typically deployed across hybrid or multi-cloud environments, combining private data centers, public cloud infrastructure, and edge locations. The framework must be adaptable to this heterogeneity, supporting consistent reliability practices across diverse platforms while respecting local constraints (Arowogbadamu, Oziri & Seyi-Lande, 2022, Fatimetu, *et al*., 2022, Umoren, *et al*., 2022). This often begins with a clear definition of availability targets, service-level objectives, and error budgets for critical control plane and user plane functions. These targets provide a quantitative anchor for implementation decisions, guiding trade-offs between redundancy, performance optimization, and cost. Without such alignment, reliability initiatives risk becoming fragmented or purely reactive (Akinrinoye, *et al*., 2019, Nwafor, *et al*., 2019, Sanusi, Bayeroju & Nwokediegwu, 2019).

Automation plays a central role in operationalizing reliability engineering at scale. Manual processes that may suffice in smaller environments become untenable when managing hundreds of microservices, thousands of containers, and millions of concurrent sessions. The framework should therefore prioritize automation across fault detection, recovery, scaling, and configuration management (Akinrinoye, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Umoren, *et al*., 2023). Automated health checks, self-healing mechanisms, and policy-driven scaling actions enable rapid response to failures and traffic surges, reducing mean time to detect and mean time to restore. However, automation must be implemented judiciously, with safeguards to prevent cascading actions that amplify instability. For example, automated restarts or re-scheduling of network functions should be informed by dependency awareness and historical context, ensuring that recovery actions address root causes rather than symptoms (Aransi, *et al*., 2019, Nwafor, *et al*., 2019, Oguntegbe, Farounbi & Okafor, 2019, Umoren, *et al*., 2019).

Advanced analytics is another critical pillar of effective implementation. High availability in 5G core networks cannot be achieved through static thresholds and reactive alarms alone. The framework must incorporate analytics capable of interpreting large volumes of telemetry data, identifying early warning signals, and predicting potential reliability risks. This includes anomaly detection on control plane signaling rates, correlation analysis across service-based interfaces, and trend analysis of resource utilization patterns (Seyi-Lande, Arowogbadamu & Oziri, 2021, Uduokhai, *et al*., 2021). By integrating predictive analytics into operational workflows, operators can shift from reactive firefighting to proactive reliability management, addressing emerging issues before they impact users. Importantly, analytics outputs must be actionable, translating complex insights into clear operational guidance rather than overwhelming teams with raw data (Oziri, *et al*., 2022, Rukh, Seyi-Lande & Oziri, 2022, Umoren, *et al*., 2022).

DevOps integration is essential to sustaining reliability in environments characterized by frequent software updates and continuous feature evolution. In large-scale 5G cores, reliability incidents are often triggered not by hardware failures but by configuration errors, software regressions, or unintended interactions introduced during updates. An effective reliability engineering framework embeds reliability checks throughout the development and deployment lifecycle. This includes automated testing for failure scenarios, validation of backward compatibility, and controlled rollout strategies such as canary deployments and blue-green releases. By integrating reliability considerations into DevOps pipelines, operators can detect and mitigate risks earlier, reducing the likelihood that changes introduced in development environments will destabilize production networks (Adeniyi, Odejobi & Taiwo, 2025, Sanusi, Chinwendu & Kehinde, 2025, Uduokhai, *et al*., 2025).

Organizational integration is as important as technical integration in the implementation strategy. Reliability engineering requires close collaboration between network operations, software development, cloud infrastructure teams, and vendors. The framework should define clear roles, responsibilities, and escalation paths to ensure coordinated responses during incidents. Shared reliability metrics and dashboards help align teams around common objectives, fostering a culture where reliability is viewed as a collective responsibility rather than the sole domain of operations. Training and skill development are also critical, as teams must be proficient in cloud-native technologies, observability tools, and automation platforms to effectively implement and sustain the framework (Ahmed & Odejobi, 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

Lifecycle management considerations ensure that the reliability framework remains effective as the network evolves. 5G core networks are not static systems; they continuously expand in scale, functionality, and geographic reach. The implementation strategy must therefore include mechanisms for periodic review and adaptation of reliability practices. This involves reassessing failure modes as new services are introduced, updating automation logic to reflect architectural changes, and refining analytics models based on operational experience. Regular post-incident reviews and reliability audits provide structured feedback loops, enabling continuous improvement and preventing the recurrence of systemic issues (Ezeh, *et al*., 2024, Uduokhai, *et al*., 2024, Umoren, *et al*., 2024).

Integration with vendor ecosystems is another practical dimension of implementation. Given the multivendor nature of most 5G cores, the framework must accommodate diverse tooling, interfaces, and support models. Standardized observability interfaces, common incident taxonomies, and shared testing environments can help bridge gaps between vendor components. Contractual and governance arrangements should also support reliability objectives, encouraging vendors to provide transparency into failure behaviors and timely updates that align with the operator's reliability roadmap. Effective integration reduces friction during incident resolution and enhances overall system resilience (Nwafor, Uduokhai & Ajirotutu, 2020, Sanusi, Bayeroju & Nwokediegwu, 2020).

Change management processes must be adapted to support reliability goals without stifling agility. Traditional telecom change control models, characterized by lengthy approval cycles, are often incompatible with the pace of cloud-native 5G environments. The framework should promote risk-based change classification, where low-risk, well-tested changes are deployed rapidly, while high-impact changes receive additional scrutiny. Automation and analytics can support this approach by providing objective risk assessments based on historical data and real-time system state. This balance enables continuous improvement while protecting service availability (Osuashi Sanni & Adumaza, 2023, Oziri, *et al*., 2023, Umoren, *et al*., 2023).

Finally, the success of the implementation strategy depends on the ability to measure and demonstrate value. Reliability engineering initiatives must be supported by clear metrics that reflect both technical performance and business outcomes. Reductions in outage frequency, faster recovery times, improved customer experience, and more efficient resource utilization provide tangible evidence of impact. These metrics not only justify continued investment but also guide prioritization as the network grows and new challenges emerge (Adenuga, *et al*., 2025, Baalah, *et al*., 2025, Sanusi, 2025, Uduokhai, *et al*., 2025).

In essence, implementing an operational reliability engineering framework for sustained high availability in 5G core networks serving millions is a multifaceted endeavor that intertwines technology, process, and people. By grounding the strategy in automation, advanced analytics, DevOps integration, and adaptive lifecycle management, operators can translate reliability principles into practical, scalable operations. The result is not merely a more resilient network, but an operational model capable of supporting the long-term demands of next-generation services and the critical digital ecosystems that depend on them (Ogbete, Aminu-Ibrahim & Ambali, 2020, Seyi-Lande, Arowogbadamu & Oziri, 2020).

2.7 Evaluation Metrics and Performance Assurance

Evaluation metrics and performance assurance are central to validating the effectiveness of an operational reliability engineering framework designed to sustain high availability in 5G core networks serving millions of users. In environments characterized by cloud-native architectures, distributed control planes, and highly dynamic traffic patterns, reliability cannot be inferred from design intent alone. It must be continuously measured, analyzed, and refined through a coherent set of indicators, monitoring strategies, service-level alignment mechanisms, and feedback loops that support ongoing improvement. Without such a disciplined evaluation approach, reliability engineering risks becoming aspirational rather than operationally impactful (Asere, *et al*., 2025, Nwafor, *et al*., 2018, Seyi-Lande, Arowogbadamu & Oziri, 2018).

The definition of key reliability indicators forms the foundation of performance assurance in large-scale 5G core operations. Traditional telecom metrics such as node uptime or link availability are insufficient to capture the nuanced behavior of service-based, microservice-driven cores. Instead, reliability indicators must reflect both system-level resilience and service-level experience. Commonly used measures include service availability percentages for critical control plane functions, mean time between failures, mean time to detect, and mean time to restore (Ahmed, Odejobi & Oshoba, 2019, Nwafor, *et al*., 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019). However, these indicators must be contextualized within the operational realities of 5G, where partial failures and performance degradation can be as damaging as complete outages. As a result, additional indicators such as session success rates, mobility continuity ratios, signaling latency distributions, and policy enforcement consistency become essential for a holistic assessment of reliability (Oziri, *et al*., 2023, Rukh, Oziri & Seyi-Lande, 2023, Umoren, *et al*., 2023).

Equally important is the differentiation between leading and lagging indicators of reliability. Lagging indicators, such as outage duration or incident counts, provide valuable historical insight but do little to prevent future failures. Leading indicators, by contrast, offer early warning of emerging risks. Examples include rising error rates on service-based interfaces, increased variance in control plane response times, or growing discrepancies between requested and allocated resources. By incorporating both types of indicators into the evaluation framework, operators can balance accountability for past performance with proactive risk management aimed at sustaining high availability (Osuashi Sanni, Ajiga & Atima, 2020, Seyi-Lande, Arowogbadamu & Oziri, 2020).

Monitoring strategies must be designed to support these indicators across the full stack of the 5G core. This requires comprehensive observability spanning network functions, cloud infrastructure, orchestration platforms, and inter-service communication. Metrics collection alone is insufficient; logs, traces, and contextual metadata are equally critical for understanding failure propagation and performance anomalies. Given the scale of modern 5G cores, monitoring systems must be capable of handling high data volumes without introducing significant overhead or blind spots. Sampling strategies, adaptive telemetry, and intelligent aggregation are often necessary to maintain visibility while controlling costs and complexity (Bayeroju, Sanusi & Nwokediegwu, 2021, Osuji, Okafor & Dako, 2021, Uduokhai, *et al*., 2021).

Real-time monitoring plays a particularly important role in performance assurance. High availability depends not only on detecting failures quickly but also on distinguishing between transient fluctuations and meaningful degradation. Alerting mechanisms should therefore be informed by dynamic baselines and service-level context rather than static thresholds. For example, a brief spike in signaling latency during a planned traffic surge may be acceptable, whereas the same spike under normal conditions could indicate an impending failure. Context-aware monitoring reduces false positives, minimizes alert fatigue, and enables operators to focus on issues that genuinely threaten reliability (Michael & Ogunsola, 2022, Uduokhai, *et al*., 2022, Umoren, *et al*., 2022).

Service-level alignment is another critical dimension of evaluation in reliability engineering frameworks. Technical metrics must be translated into service-level objectives that reflect business priorities and user expectations. In 5G core networks supporting diverse services, a single availability target is rarely sufficient. Enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications each impose different reliability requirements, and enterprise network slices may have bespoke service-level agreements (Michael & Ogunsola, 2019, Seyi-Lande, Arowogbadamu & Oziri, 2019, Umoren, *et al*., 2019). The evaluation framework must therefore support differentiated metrics and targets aligned with the criticality of each service category. This alignment ensures that reliability efforts are prioritized where they deliver the greatest value, rather than being uniformly applied in ways that dilute impact (Oguntegbe, Farounbi & Okafor, 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Uduokhai, *et al*., 2023).

Error budgets provide a practical mechanism for aligning reliability metrics with operational decision-making. By defining acceptable levels of unreliability for specific services, error budgets create a structured way to balance innovation and stability. When error budgets are being consumed rapidly, the framework can trigger corrective actions such as freezing nonessential changes or reallocating resources to improve resilience. Conversely, when reliability performance exceeds targets, teams may be empowered to accelerate feature delivery or optimize costs. This dynamic use of metrics transforms performance assurance from a passive reporting exercise into an active management tool (Akinrinoye, *et al*., 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020).

Continuous improvement mechanisms are essential for ensuring that evaluation metrics remain relevant and effective over time. 5G core networks evolve rapidly, with new services, architectural changes, and traffic patterns continually reshaping the reliability landscape. Metrics that were meaningful during initial deployment may lose relevance as the network scales or diversifies. The reliability engineering framework must therefore include regular review cycles in which indicators, thresholds, and monitoring strategies are reassessed based on operational experience. Post-incident reviews play a central role in this process, providing structured opportunities to analyze failures, validate assumptions, and identify gaps in observability or response (Bayeroju, Sanusi & Nwokediegwu, 2023, Umoren, *et al*., 2021).

Data-driven learning is a hallmark of mature performance assurance practices. By systematically analyzing incident data, near-misses, and performance trends, operators can refine predictive models and improve early detection of reliability risks. Machine learning techniques can enhance this process by identifying patterns that are not immediately apparent through manual analysis, such as subtle correlations between configuration changes and subsequent performance degradation. However, these techniques must be grounded in high-quality data and domain expertise to avoid spurious conclusions. Human oversight remains essential to interpret analytical outputs and translate them into actionable improvements (Aminu-Ibrahim, Ogbete & Iwuanyanwu, 2020).

Governance and accountability mechanisms further reinforce continuous improvement. Clear ownership of reliability metrics ensures that issues are addressed promptly and consistently. Cross-functional review forums, where operations, development, and vendor teams jointly examine performance data, help break down silos and promote shared responsibility for availability outcomes. Transparency in reporting, including the communication of reliability performance to senior leadership and key customers, also strengthens commitment to sustained improvement (Bayeroju, Sanusi & Nwokediegwu, 2022, Umoren, *et al*., 2021).

Ultimately, evaluation metrics and performance assurance are not merely tools for measuring reliability; they are integral components of the reliability engineering framework itself. By defining meaningful indicators, implementing intelligent monitoring strategies, aligning metrics with service-level priorities, and embedding continuous improvement mechanisms into daily operations, 5G core operators can move beyond reactive assurance toward a proactive, adaptive model of reliability management. In doing so, they create the conditions necessary to sustain high availability at scale, ensuring that 5G core networks can reliably support millions of users and the increasingly critical services that depend on them (Sanusi, Bayeroju & Nwokediegwu, 2020, Umoren, *et al*., 2021).

2.8 Conclusion and Future Research Directions

This work has articulated an operational reliability engineering framework tailored to the realities of large-scale 5G core networks serving millions of users, where sustained high availability is no longer a desirable attribute but a fundamental operational requirement. By grounding reliability engineering in the practical conditions of cloud-native architectures, distributed control planes, and heterogeneous service demands, the framework advances beyond traditional telecom resilience models that were largely hardware-centric and reactive. Its central contribution lies in reframing reliability as a continuous, system-wide discipline that integrates failure mode awareness, adaptive capacity management, automation, analytics, DevOps alignment, and performance assurance into a coherent operational approach.

A key contribution of the framework is its holistic treatment of reliability challenges across the full lifecycle of 5G core operations. Rather than isolating reliability to fault tolerance mechanisms or redundancy planning, the framework emphasizes the interdependence of architectural design, operational processes, and human decision-making. It recognizes that high availability failures in 5G cores are often the result of complex interactions between microservices, orchestration systems, traffic volatility, and multivendor dependencies. By systematically addressing these interactions through structured implementation strategies, advanced observability, and service-aligned evaluation metrics, the framework provides a practical blueprint for managing reliability at scale in real-world deployments.

From an operational perspective, the framework has significant implications for how 5G core networks are designed, managed, and evolved. It encourages operators to shift from reactive incident response to proactive reliability management, supported by automation and predictive analytics. This shift reduces mean time to detect and restore, limits the blast radius of failures, and improves service continuity for both consumer and enterprise use cases. The integration of reliability objectives into DevOps pipelines further aligns innovation with stability, enabling frequent software updates without compromising availability. Importantly, the framework also highlights the organizational dimension of reliability, underscoring the need for cross-functional collaboration, shared accountability, and continuous skill development in cloud-native operations.

The framework also has implications for performance assurance and service-level governance. By advocating differentiated reliability metrics aligned with diverse 5G service categories, it supports more nuanced and effective management of service-level objectives and agreements. This alignment ensures that reliability investments are directed toward the most critical services, including ultra-reliable and low-latency applications, while maintaining overall network efficiency. The use of error budgets and continuous feedback loops transforms reliability metrics from static reporting tools into dynamic levers for operational decision-making, fostering a culture of continuous improvement.

Looking ahead, there are substantial opportunities to extend and refine the proposed framework as networks evolve toward future generations. One promising direction is the deeper integration of artificial intelligence and machine learning into reliability engineering practices. While the framework already recognizes the value of predictive analytics, future research can explore more advanced closed-loop optimization techniques, where AI-driven systems autonomously adjust configurations, resource allocations, and recovery strategies based on real-time conditions and learned behaviors. Such capabilities could further reduce human intervention and improve responsiveness in ultra-large-scale environments.

Another important avenue for future research lies in the convergence of reliability engineering with digital twin technologies. High-fidelity digital twins of 5G core networks could enable operators to simulate failure scenarios, traffic surges, and configuration changes in virtual environments before applying them to live systems. Integrating digital twins with the reliability framework would enhance risk assessment, support more informed change management, and accelerate learning from rare but high-impact failure modes. This approach becomes increasingly relevant as networks grow in complexity and support mission-critical services.

The extension of the framework to future network generations, including early concepts for 6G, presents additional research opportunities. Future networks are expected to be even more software-driven, distributed, and service-centric, with tighter integration between communication, computing, and sensing. These trends will likely amplify existing reliability challenges while introducing new ones related to extreme scale, ultra-low latency, and pervasive intelligence. Adapting the framework to such environments will require rethinking reliability indicators, observability mechanisms, and governance models to account for new architectural paradigms and usage scenarios.

Finally, future work should also examine the regulatory and societal dimensions of reliability in next-generation networks. As mobile cores increasingly underpin critical national infrastructure, healthcare, transportation, and public safety systems, expectations for availability and resilience will continue to rise. Research into how reliability engineering frameworks can support regulatory compliance, transparency, and trust will be essential for aligning technical solutions with broader societal needs.

In conclusion, the operational reliability engineering framework presented in this work provides a robust foundation for sustaining high availability in large-scale 5G core networks serving millions. By integrating technical, operational, and organizational perspectives, it offers both immediate practical value and a platform for ongoing innovation. As networks continue to evolve, extending and refining this framework through advanced analytics, digital twins, and alignment with future network generations will be critical to ensuring that reliability remains a defining strength of mobile core infrastructures in an increasingly connected world.

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