

Optimizing Telecommunications Network Performance: A Comprehensive Review and Analysis

Solomon Nsor-Anabiah,

Telecommunication Engineering Department,

Ghana Communication Technology University, Ghana,

Ruhiya Abubakar,

Electrical/Electronics Engineering Department,

Ghana Communication Technology University, Ghana

Owusu Agyeman Antwi,

Telecommunication Engineering Department,

Ghana Communication Technology University, Ghana

Michael Agyare,

Telecommunication Engineering Department,

Ghana Communication Technology University, Ghana,

Joseph Wumboranaan Nanjo,

Electrical/Electronics Engineering Department,

Sunyani Technical University, Ghana,

Emmanuel Atebawone,

Department of Information Technology Studies,

University of Professional Accra, Ghana.

Abstract- This study presents a comprehensive review and analysis of strategies for optimizing telecommunications network performance in the context of rapidly evolving technological landscapes and increasing user demands. As the proliferation of mobile devices, IoT applications, and high-bandwidth services continues to escalate, network operators face significant challenges in maintaining efficiency, reliability, and quality of service. The research systematically examines various optimization techniques, including traffic management, resource allocation, and quality of service (QoS) enhancements. It highlights the role of Artificial Intelligence (AI) and Machine Learning (ML) in enabling predictive analytics for dynamic network management. The study also explores the impact of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for adaptable and scalable network architectures that are sensitive to fluctuating demands. Furthermore, the study reviewed the significance of big data analytics in user behavior and

traffic patterns for informed decision-making in network planning and optimization. Security considerations are also addressed, emphasizing the need for robust protocols to safeguard network integrity and user privacy amidst growing cyber threats. The findings of this research underscore the necessity for a holistic approach to network optimization that integrates technological advancements with strategic management practices. Additionally, collaboration among key stakeholders is essential for fostering continuous improvement in telecommunications networks.

Keywords- analysis, optimizing network performance, telecommunication networks, measuring and monitoring, traffic, enhancing

I. INTRODUCTION

High network performance is important in telecommunications because it provides reliability, speed, bandwidth, Quality of Service (QoS), scalability and security. Overall, network performance is essential for delivering reliable, high-quality, and secure telecommunications services that meet the needs of users and businesses in today's digital world. Investing in network infrastructure and monitoring network performance are key strategies to ensure optimal service delivery and user satisfaction.

Wireless technology for mobile cellular communication has evolved from the First Generation (1G) in the 1980's to 5G and beyond as we have it today. The telecommunication network 1G was followed by 2G in the 1990s, 3G in the 2000s and 4G in the 2010s [1,2]. Each technology played a critical role within its period of operation leading to the development of the next level till today. For instance, 1G enabled analogue voice communication and mobility, 2G introduced digitized voice communication with text or SMS transmission capabilities and increased efficiency through enhanced multiplexing techniques such as GSM and CDMA. Even though network speeds were of the order of 10 kbit/s, it was the best at the time. 3G came as an improvement over the former, enabling better power consumption, enhanced handover and increased users within the system. Aside ushering in the mobile broadband at rates around a few Mbps, 3G was pivotal in the smartphone revolution. According to [2], the 4G technology brought about the revolution in the internet video sharing. Finally, the coming into being of 5G with speed reaching 2Gbit/s and less than 1ms latency, triggered Internet of Things (IoT) for manufacturing, smart cities, smart grid among others. telecommunications network optimization and highlight key strategies for improving network performance [3].

Optimizing telecommunications network performance is a critical area of research, especially as demand for high-speed internet and reliable communication services continues to grow. While there has been significant progress in this field, there is limited understanding of how to balance QoS requirements with network efficiency, especially in heterogeneous networks. Also, the integration of Machine Learning (ML) and Artificial Intelligence (AI) for predictive maintenance and performance optimization is still in its infancy. Furthermore, the role of edge computing in optimizing network performance is not fully understood, especially regarding latency reduction and bandwidth management. Finally, optimizing network performance often overlooks security implications, leading to vulnerabilities. The main aim of this research is to fill the afore mentioned gaps. The significance of optimizing telecommunications network performance lies in its multifaceted impact on user satisfaction, operational efficiency, scalability and flexibility, security resilience, sustainability via reduced carbon footprint, competitiveness, and adaptability to future technological advancements and challenges.

II. FACTORS AFFECTING TELECOMMUNICATIONS NETWORK PERFORMANCE

A. *Bandwidth: Understanding the role of bandwidth in network performance*

Bandwidth is critical in the determination of performance and efficiency of a telecommunication networks. Bandwidth may be defined as the maximum rate of transferring data across a network, the basic units are bits per second (bps) or megabits per second (Mbps) [4]. A higher bandwidth allows for faster data transmission, enabling users to access online services, stream multimedia

content, and communicate in real-time more effectively. According to [5], bandwidth consumption can be defined as utilizing a network's transmission capacity to transfer data from source to destination within the network, over a particular period of time. It is confirmed that, the total bandwidth harnessed in a network at any given time is smaller than the theoretical maximum rate of data transmission.

Bandwidth can be measured as: $\text{Bandwidth (bps)} = (\text{Total amount of data transferred}) / (\text{Time taken to transfer the data})$. For instance, when 1 GB of data is transferred in 60 seconds, the bandwidth is calculated as: $\text{Bandwidth (bps)} = (1810^9 \text{ bps}) / (60 \text{ s}) = 1.33 * 10^8 \text{ bps}$ or 133 Mbps. Another method for measuring bandwidth is the use of the Speedtest tool, which evaluates the actual rate of data transfer between a server and client. In this case, the download and upload speeds of the network are measured and displayed in Mbps. The following are key points to understand the role of bandwidth in network performance:

1. **Data Transfer Speed:** Bandwidth directly impacts the speed at which data can be transmitted between devices on a network. Higher bandwidth means faster data transfer speeds, reducing latency and improving the overall user experience.
2. **Capacity:** Bandwidth determines the capacity of a network to handle multiple concurrent users and data-intensive applications. Networks with limited bandwidth may experience congestion and slower speeds during peak usage times.
3. **Quality of Service (QoS):** Bandwidth allocation is essential for implementing QoS policies that offer priority to some traffic against others. QoS management ensures that critical applications get sufficient bandwidth to maintain performance levels.
4. **Streaming and Multimedia:** High-bandwidth connections are necessary for streaming high-definition video, audio, and other multimedia content without buffering or interruptions. Insufficient bandwidth can result in degraded video quality and playback issues.
5. **Cloud Services:** Bandwidth is critical for accessing cloud-based services and applications, as data needs to be transferred between local devices and remote servers efficiently. Adequate bandwidth ensures seamless connectivity to cloud resources.
6. **Remote Work and Collaboration:** In today's digital workplace, remote work and collaboration tools rely on sufficient bandwidth for video conferencing, file sharing, and real-time communication. Low bandwidth can hinder productivity and communication effectiveness.
7. **Network Performance Optimization:** Optimizing bandwidth usage through traffic shaping, compression, caching, and other techniques tend to enhance performance of network performance, trigger latency reduction, and improve overall efficiency.
8. **Future Technologies:** Emerging technologies like 5G networks, IoT devices, and AI-driven applications will place increasing demands on bandwidth. Network operators need to continually upgrade infrastructure to support these technologies and deliver optimal performance.

To conclude on this, it must be noted that bandwidth is a critical factor in determining the performance, capacity, and reliability of modern telecommunications networks. Network operators

must carefully manage and allocate bandwidth resources to meet the evolving needs of users and ensure seamless connectivity in an increasingly digital world.

B. Latency: Exploring how real-time applications are impact by latency

Latency means delay in the transmission of data among devices over networks. In the context of real-time applications, such as video conferencing, online gaming, VoIP calls, and live streaming, latency can have a significant impact on user experience and application performance. According to [6], latency, which includes startup delays, rebuffering occurrences, as well as end-to-end delays is one of the critical variables that significantly influence user experience. This assertion was corroborated by research conducted by [7] to understand the end-to-end latency effect on a modern telecommunication network. In another study, [8] concluded that in the realm of modern computing, efficiency and speed are paramount, but these depend on latency as a critical factor for great user experience and system performance. The author indicated that latency, is also known as lag or delay in data transmission, response and processing helps to determine the seamlessness of the functions and interactions among various technologies. To determine the effect of latency on real-time application, some key points have been enumerated as follows:

1. **Communication Delay:** Latency introduces delays in the transmission of data packets, affecting the real-time applications such as VoIP calls and video conferencing. When latency is high, it could lead to audio/video desynchronization, choppy video playback, and communication lags.
2. **Gaming Performance:** In online gaming, latency, also known as ping, directly affects gameplay responsiveness and player interactions. High latency can result in delayed actions, laggy gameplay, and unfair advantages/disadvantages for players with different latency levels.
3. **Streaming Quality:** Latency can impact the quality of live streaming services by causing buffering, stuttering, and delays in content delivery. Viewers may experience interruptions in the stream or lower video/audio quality due to latency issues.
4. **Interactive Applications:** Real-time interactive applications, such as virtual classrooms, remote collaboration tools, and multiplayer games, require low latency to maintain smooth interactions between users. High latency can disrupt real-time collaboration and hinder user engagement.
5. **User Experience:** Latency directly influences the overall user experience of real-time applications. Users expect instant responses and seamless interactions in real-time communication and multimedia services. High latency can frustrate users and lead to a subpar experience.
6. **Network Conditions:** Latency can be influenced by various factors, including network congestion, packet loss, routing inefficiencies, and distance between devices. Optimizing network infrastructure and using low-latency networking technologies can help reduce latency and improve application performance.
7. **Quality of Service (QoS):** The implementation of good QoS techniques offers priority to real-time traffic which can help resolve the impact of latency on critical applications. QoS policies can ensure that real-time applications receive sufficient bandwidth and minimal latency for optimal performance.

8. End-to-End Latency: Real-time applications are sensitive to end-to-end latency, which includes data round time from source to destination and back. Minimizing end-to-end latency through efficient network design, routing optimization, and low-latency protocols is essential for real-time application performance.

In conclusion, latency is critical in network performance, responsiveness, and user experience of real-time applications. Network operators, application developers, and users need to be aware of latency issues and implement strategies to minimize latency for seamless real-time communication and collaboration.

C. Packet Loss and Jitter: Analysis of the effects of jitter and packet loss during data transmission

Jitter and packet loss are common network issues that can impact data transmission in real-time applications. A study to analyze the negative effect of packet loss on video quality was conducted by [9] using dataset containing 11,200 full HD and ultra-HD video sequences encoded to H.264 and H.265 format with packet loss rate (PLR) between 0 and 1%. Analysis of the simulation revealed that the quality of video declined as packet loss rate increases, irrespective of compression parameters. [10] determined that the measurement and analysis of jitter is critical to stable and reliable network connectivity, especially for real-time applications. The researchers contend that addressing the root causes of jitter offers the best opportunity for mobile network operators (MNOs) to optimize network performance, leading to enhanced user experience. Based on the reviews espoused, it can be concluded that packet loss and jitter have enormous impact on data transmission:

1. Packet Loss: This is the failure of network to deliver data packets to the destination. This can lead to gaps in transmitted data, affecting the integrity and completeness of the information being sent. In real-time applications, the loss in packets may lead to missing or corrupted data, leading to audio and video distortions, choppy playback, and communication disruptions. Aside also triggering retransmission requests, causing delays and increasing latency in data transmission, high packet loss rates can degrade overall application performance and QoS in real-time tools such as online gaming and video conferencing.

2. Jitter: Jitter refers to the variation in packet arrival times at the destination, causing irregular delays in data transmission. Jitter can be caused by network congestion, routing changes, or varying latency levels. Jitter can disrupt the smooth flow of data in real-time applications, leading to inconsistent playback, out-of-sync audio/video, and jittery performance. During VoIP calls and video conferencing, jitter can create call quality issues, including voice distortion, echo, and communication delays. Additionally, applications sensitive to timing and synchronization, such as live streaming and interactive games, may experience jitter-induced disruptions in data delivery.

3. Mitigation Strategies: To resolve these challenges, Forward Error Correction (FEC) techniques can be deployed to recover lost packets by providing backup data to packets under transmission, and regenerate packets at the destination. This can help mitigate the effects of jitter through the reconstruction of the original data stream. Also, implementing buffer mechanisms can smooth out variations in packet arrival times caused by jitter, reducing the impact on real-time applications. Finally, prioritizing real-time traffic and ensuring sufficient bandwidth for critical applications can

help minimize the effects of packet loss and jitter on data transmission, resulting in enhanced quality of service (QoS).

Analysis of this section shows that packet loss and jitter can significantly impact data transmission in real-time applications, leading to degraded performance, quality issues, and disruptions in communication. Understanding these network issues and implementing appropriate mitigation strategies are crucial for maintaining a reliable and seamless data transmission experience in real-time scenarios.

D. Throughput: Measuring the overall capacity and efficiency of data transfer

Throughput is a critical metric used to measure the overall capacity and efficiency of data transfer in a network or communication system. High throughput represents large amount of data transmission per second in a network, which offers fulfilment for user requests and overall healthy performance. On the other hand, low throughput means a network is delivering small data amounts per second, which leads to poor network performance caused by high latency rates, jitter and packet loss [11]. Throughput can be defined as the rate at which data is successfully transmitted from a source to a destination over a communication channel or network. It is typically expressed in bits per second (bps), kilobits per second (Kbps), megabits per second (Mbps), or gigabits per second (Gbps). It provides insights into the actual data transfer performance of a network or system, reflecting its capacity to handle and deliver data efficiently. While its measurement helps to assess the effectiveness of network infrastructure, understanding throughput enables network administrators and engineers to optimize network resources, identify bottlenecks, and improve overall data transfer speeds and reliability. Factors affecting throughput are; bandwidth, latency, packet loss, jitter, as well as protocol overhead. The measurement of throughput can be achieved using network performance testing software or by calculation, and can be improved through optimization, hardware upgrade, and implementation of QoS policies [11]. Throughput plays a crucial role in evaluating the performance and efficiency of data transfer in networks. Monitoring and optimizing throughput are essential for ensuring reliable and high-speed data transmission, meeting the demands of modern communication systems and applications.

E. Network Congestion: Addressing the challenges posed by network congestion

Network congestion occurs when the demand for network resources exceeds the available capacity, leading to performance degradation, delays, packet loss, and reduced throughput. Addressing network congestion is crucial to maintaining optimal network performance and ensuring efficient data transfer. A case study conducted with data set from Seoul city proves that rapid urbanization is causing network congestion levels to surge drastically, resulting in a direct impact on the quality the environment, urban life and the economy [12]. To resolve the congestion issues, the authors deployed Traffic Congestion Pattern Analysis and Convolutional Autoencoder to identify network paths that suffer from recurring congestion in performance prediction and mitigation in high traffic networks. Also, a report generated by [13] reveals that new network interconnections, system and dispatch changes, and resource retirement are responsible for the ever-increasing congestion in existing networks. The report further indicated that [13] used existing planning processes such as retirement, reliability, economics, and generation interconnection to remedy the adverse impact on the network transmissions. Internet of Things

(IoT) consists of different computing devices operating on non-standard platforms typically have restricted bandwidth, limited storage capacity, and lower computing power tend to cause serious congestion in a network [14]. The paper concluded that, it is important to design a congestion control mechanism in order to facilitate efficient rates of data transfer within IoT networks. It is worth noting that network traffic management, capacity planning, load balancing, packet prioritization, congestion control algorithm, and monitoring and analysis are key strategies for resolving challenges associated with network congestion.

III. EMERGING TECHNOLOGIES AND NETWORK PERFORMANCE

A. 5G Technology: Assessing the implications of 5G on network performance

The drastic digital transformation currently taking place in society due to the advent of 5G has provided the internet with good things including the prospects of connecting 28 billion devices by 2025. The increased traffic volumes are largely met by the connectivity requirement of 5G, which includes low latency, high data rates, and high reliability. Despite this development, there exist some challenges that affect its application in the manufacturing industry [15]. With the use of the TOPSIS method which ensures robust results, the paper determined that 5G will positively impact on productivity, maintenance, flexibility, but little on network performance. The evolution of 5G technology has significantly introduced a shift in the telecommunication sector, offering unique opportunities and challenges. The new technology offers infrastructure upgrade and a shift in business models. However, the deployment and management of 5G also pose special challenges to mobile network operators (MNOs). According to [16], explored these unique challenges and determine 5G heightens network complexity, increases data volumes, and security and reliability issues. The rest are regulatory and standards compliance as well as the management of spectrum. To overcome these network challenges introduced by 5G, the author recommended Network Management Systems (NMS). The system would provide the needed solution through dynamic slice management, real-time analytics, configuration tools, and dynamic service management. Others are, security policy enforcement and precision time protocol (PTP) management [17]. Emerging technologies such as 5G has a great potential in the area of faster speeds (up to 10 Gbps), lower latency, increased capacity that supports large number of devices, enhanced reliability, and improved coverage. As this technology continues to roll out globally, it is expected to drive innovation and enable new applications that were previously not possible with current network technologies.

B. Internet of Things (IoT): Examining IoT's influence on network performance requirements

The Internet of Things (IoT) refers to the network of interconnected devices that communicate and share data with each other over the internet. As IoT devices continue to proliferate across various industries and applications, they have a significant impact on network performance requirements. A study conducted by [18] came to the conclusion that a typical IoT implementation has negative consequences on mobile network. It is believed that IoT introduces interference in wireless applications, reducing the efficiency and reliability of the network. The paper identified that, with the application of optimization and performance techniques, the challenges created by interference can be mitigated. The authors are clear about the fact that IoT devices create interferences that lead to that hurt the adequate functioning of business processes. The productivity

issues, downtime challenges and customer satisfaction difficulties can be resolved by also deploying network convergence. An assertion was made by [19] to the effect that the adoption of IoT offers many advantages to organizations across the globe, yet it has the ability to also introduce unforeseen risks that needs the special attention of these organizations. To offset these risks and make sure IoT fits into its purposes the paper suggests changes to the organization, its processes and systems, as well as development of its capacity and capabilities. IoT has been identified as a phenomenon with a high negative impact on telecommunications network traffic. The exponential expansion in device connectivity causes significant rise in network traffic. A surge in network traffic may result in network congestion, which negatively affects network performance and user experience [20]. Additionally, connected IoT devices tend to generate and transmit big data in real-time, further straining the network and preventing from handling data flow in a fast-paced manner. Also, the sheer connection of the number of devices and the data generated necessitates higher bandwidth capacity or more operational cost. Overall, the increasing adoption of IoT devices underscores the importance of robust network infrastructure that can meet the evolving performance requirements of these interconnected devices. Network scalability, low latency, reliability, security, bandwidth management, and edge computing are key factors that organizations need to consider when designing and implementing networks to support IoT applications effectively.

C. Cloud Computing: Understanding the impact of cloud-based services on network performance

Cloud computing refers to the delivery of computing services, including storage, processing power, and applications, over the internet. Cloud-based services have revolutionized the way businesses and individuals' access and manage data, applications, and resources. Findings from an investigation conducted by [21] reveals that migrating an application to the cloud improves the performance of the application and reduces the energy consumption of the existing network. [22] opined that the adoption of cloud computing has the capacity to increase network performance through reliability and availability, reduced bandwidth requirements, and reduced network latency. The adoption of cloud computing has significant consequences on network performance due to increased data traffic, reliability and availability issues, bandwidth requirements, and security concerns. The rest are network latency, scalability and flexibility challenges, and hybrid cloud environments. Organizations must prioritize network optimization strategies and invest in technologies that enhance network performance to maximize the benefits of cloud services while minimizing potential challenges.

IV. MEASUREMENT AND MONITORING OF NETWORK PERFORMANCE

A. Metrics for Evaluating Network Performance: Throughput, Response Time, Error Rate

Throughput measures the amount of data that can be transmitted over a network in a given period of time. It is typically measured in bits per second (bps) or packets per second (pps). Higher throughput indicates a more efficient network. Network performance metrics offer a deeper understanding for network infrastructure and the services under operation. The metrics

have the propensity to offer real-time cursory view of the potential outages, challenges, and network errors. [23] has outlined some key network performance metrics capable of determining unexpected network challenges quickly. They include, bandwidth usage, packet loss, retransmission, throughput, and latency. The rest are, network availability, connectivity and jitter. By regularly monitoring these metrics and analyzing performance data, organizations can identify potential issues, optimize network configurations, and ensure reliable and efficient network performance. Response time, also known as latency, measures the time it takes for a request to be sent from a client to a server and for the response to be received back. Lower response time indicates faster network performance and better user experience. Error rate measures the frequency of errors or data loss that occur during data transmission over the network. A low error rate is desirable as it indicates reliable network performance. Other metrics that can be used to evaluate network performance are packet loss, jitter, network availability, bandwidth utilization, and network congestion.

B. Tools and methodologies for monitoring network performance

Network monitoring tools are advanced capabilities produced to ensure that networks function appropriately, while delivering uninterrupted services. [23] has identified some of the best methodologies needed for effective network monitoring. They include; Bandwidth utilization monitoring, Network traffic monitoring, Built-in reporting system, and Dynamic and intelligent network mapping. Other are; Automatic alerting, Remote administration, Flow-based monitoring and reporting, and Intuitive centralized dashboards. The rest are; Wireless network performance metrics monitoring, User experience monitoring, and Automatic recovery. The most appropriate monitoring tool for network device is directly correlated with the variety of factors like network size and complexity. Also, the required features, budget constraints and integration needs are important [24,25]. Some of the essential monitoring tools include, Nagios XI, Datadog, Lansweeper, and StarWinds [26]. There are several tools and methodologies available for monitoring network performance. Some popular tools and methodologies include, Network monitoring software, SNMP (Simple Network Management Protocol), NetFlow and sFlow, Packet analysis, Performance testing tools, Quality of Service (QoS) monitoring, and Synthetic monitoring. By leveraging these tools and methodologies, organizations can effectively monitor network performance, detect issues proactively, and optimize network resources to ensure reliable and efficient operation.

C. Case studies on real-time network performance monitoring

[27] provided a case study where a company called Obkio conducted network performance monitoring using a team of telecommunication experts who are specialized in performance monitoring. The team of experts first identified the network performance metrics and KPIs, they then collected and analyzed these metrics and KPIs. Finally, the analyzed metrics and KPIs were deployed towards the improvement of the performance. Here are a few case studies to show the benefits and importance of real-time performance monitoring of networks:

1. Case Study: Company X improves network performance with SolarWinds Network Performance Monitor (NPM)

Company X, a global technology company, was experiencing network slowdowns and outages that were impacting employee productivity and customer satisfaction. To address these issues, Company X implemented SolarWinds Network Performance Monitor (NPM) to monitor their network infrastructure in real-time. By leveraging NPM's network monitoring capabilities, Company X identified and resolved performance challenges before they impacted user satisfaction [27]. The tool provided visibility into network traffic, device performance, and application behavior, allowing IT teams to quickly troubleshoot and optimize network configurations. Based on this, the company recorded an increased performance in its network, with reduced downtime, faster response times, and improved overall user experience. Real-time network monitoring with SolarWinds NPM helped Company X maintain a reliable and efficient network infrastructure to support their business operations.

2. Case Study: Healthcare provider enhances patient care with real-time network monitoring

A large healthcare provider was facing network performance issues that were affecting the delivery of critical patient care services. Slow application response times, network congestion, and intermittent connectivity problems were impacting the efficiency of healthcare professionals and patient outcomes. To address these challenges, the healthcare provider implemented a comprehensive real-time network monitoring solution that included tools like PRTG Network Monitor and Wireshark [27]. These tools allowed IT teams enhanced network traffic monitoring capabilities, identified bottlenecks, and conducted troubleshooting on performance issues in real-time. By leveraging real-time network monitoring, the healthcare provider was able to ensure reliable access to electronic health records (EHRs), medical imaging systems, and communication platforms for healthcare professionals. The improved network performance resulted in faster diagnosis, treatment, and care coordination, leading to better patient outcomes and enhanced quality of care.

3. Case Study: Retail chain optimizes network performance with NetFlow analysis

A leading retail chain with multiple locations across the country was experiencing network congestion and slow application performance that was impacting customer transactions and store operations. To address these issues, the retail chain implemented NetFlow analysis to monitor network traffic and identify performance bottlenecks. By analyzing NetFlow data using tools like SolarWinds NetFlow Traffic Analyzer, the retail chain was able to pinpoint bandwidth-intensive applications, identify peak traffic times, and optimize network configurations to improve performance. Real-time NetFlow monitoring helped IT teams proactively manage network resources, prioritize critical applications, and ensure seamless customer experiences. As a result of implementing NetFlow analysis for real-time network performance monitoring, the retail chain saw a significant improvement in network performance, with faster transaction processing, reduced downtime, and increased customer satisfaction. The retail chain was able to optimize their network infrastructure to support business growth and deliver exceptional customer service across all store location [27].

V. STRATEGIES FOR OPTIMIZING TELECOMMUNICATIONS NETWORK PERFORMANCE

A. Network Virtualization: Leveraging virtualization for enhanced performance and flexibility

In the fast-paced outlook in the IT infrastructure landscape and its attendant issues, network virtualization provides the best solution. Virtualization of existing networks consist of the creation of integrated virtual networks to enhance flexibility and efficiency of the network. This can be achieved through the maximization of resource utilization, scalability, cost savings, enhanced security, data recovery, application-centric approach, and hybrid integration [28]. Network management challenges have been occasioned by increased variety of network functionality in addition to proprietary devices. The resultant effect is network ossification which in turn reduces the quantum and quality of service provisioning. To mitigate these problems, [29] encourages the deployment of Network Function Virtualization (NFV) as a promising phenomenon which is able to decouple network functions from the existing dedicated hardware and software. Network virtualization is the process of creating virtual networks that are decoupled from physical network hardware, allowing for enhanced performance, flexibility, and efficiency. By leveraging virtualization technologies, organizations can optimize their network infrastructure to meet the growing needs for current workloads and modern applications. Overall, network virtualization offers organizations a flexible, scalable, and cost-effective solution to optimize their network infrastructure and deliver high-performance connectivity for modern applications and services in a more secured environment. By leveraging virtualization technologies, organizations can enhance their network capabilities, improve operational efficiency, and adapt to evolving business requirements in today's dynamic digital landscape [29].

B. Software-Defined Networking (SDN) and Network Function Virtualization (NFV)

Software Defined Networking (SDN) play functions such as load balancing, network maintenance, and adaptive routing are good applications for cloud computing and IoT technologies.

Network Function Virtualization (NFV), offers both commercial and many academic communities' solutions. Additionally, virtualization also reduces storage and electric power use [30]. [31] asserts that the role played by SDN and NFV is instrumental in the 5G network architecture, and are key ingredients to network security and management. These are two key technologies that perform a crucial role part in network virtualization and modernization of network infrastructure. While they are related concepts, they serve distinct purposes and offer unique benefits in optimizing network operations.

Software-Defined Networking (SDN): SDN is an architectural approach that separates the control plane from the data plane in networking devices, allowing for centralized control and programmability of network resources. In an SDN environment, network administrators can dynamically manage and configure network devices through a centralized controller, rather than individually configuring each device. SDN features include:

1. **Centralized Control:** SDN enables centralized management of network devices, allowing administrators to define and enforce network policies from a single point of control. This centralized control simplifies network configuration and enhances network visibility and monitoring.

2. **Programmability:** SDN provides programmable interfaces that allow administrators to automate network provisioning, configuration, and optimization tasks. By leveraging APIs and software-defined protocols, organizations can customize network behavior to meet specific application requirements.

3. **Agility and Flexibility:** SDN architecture promotes agility and flexibility by decoupling network control logic from underlying hardware, making it easier to adapt to changing network conditions and business needs. Organizations can quickly deploy new services, scale network resources, and respond to dynamic traffic patterns.

4. **Improved Performance:** SDN optimizes network performance by dynamically routing traffic based on real-time conditions and application requirements. By implementing intelligent traffic engineering and load balancing algorithms, organizations can enhance network efficiency and reduce latency.

NFV is an approach for virtualizing the functions and services of networks that were originally undertaken by dedicated tools and devices like load balancers, routers and firewalls. Through the virtualization of network functions, organizations can consolidate multiple services onto a common hardware platform, improving resource utilization and scalability. Its main features and benefits include:

1. **Cost Savings:** NFV helps organizations reduce capital and operational expenses by replacing expensive proprietary hardware appliances with virtualized software-based solutions. By running network functions on cloud or standard server infrastructure, guarantees cost savings for companies through hardware consolidation and resource optimization.

2. **Scalability:** NFV enables organizations to scale network functions up or down based on demand, without the need for physical hardware upgrades. By deploying virtualized network functions in a cloud environment, organizations can dynamically allocate resources to meet changing workload requirements.

3. **Service Agility:** NFV promotes service agility by accelerating the deployment of new network services and applications through software-based provisioning. Organizations can quickly launch new services, update configurations, and scale resources without the constraints of traditional hardware-based solutions.

4. **Enhanced Security:** NFV enhances security by isolating virtualized network functions from each other and applying security policies at the software level. Organizations can implement granular access controls, encryption, and threat detection mechanisms to protect against cyber threats and data breaches.

In summary, SDN and NFV are complementary technologies that enable organizations to modernize their network infrastructure, improve operational efficiency, and deliver innovative services to meet the demands of digital transformation. By adopting SDN and NFV principles,

organizations can achieve greater flexibility, scalability, performance, and cost savings in managing their networks and supporting diverse applications and workload.

C. Quality of Service (QoS) implementation for prioritizing critical traffic

Quality of Service is very critical in modern networks, because it is a phenomenon that measures the performance metrics and improves the experience of end-users [32]. IoT devices and 5G applications introduce challenges on networks QoS should be implemented at all times to ensure that the network maintains acceptable levels of QoS at all times. To achieve this, the authors proposed the queuing mechanism topological symmetry to reduce delay, packet loss ratio, and the over-provisioning of resources. QoS is referred to a set of tools used to manage and prioritize network traffic to ensure that critical applications and services receive the necessary bandwidth, latency, and reliability they require. Implementing QoS in a network environment involves configuring network devices to classify, prioritize, and manage traffic based on predefined policies and service level agreements (SLAs) [32]. Here are major key steps for implementing QoS to prioritize critical traffic:

1. **Traffic Classification:** This phenomenon identifies and classifies network traffic according to their needs and importance. This may include voice, video, data, real-time applications, and mission-critical services. Use classification mechanisms such as IP address, port numbers, protocols, or Deep Packet Inspection (DPI) to differentiate between traffic types.
2. **Define QoS Policies:** Establish QoS policies that define the priority levels, bandwidth allocations, latency requirements, and packet loss parameters for each class of traffic. Create service level agreements (SLAs) that outline the performance expectations for critical applications and services.
3. **Traffic Prioritization:** Assign appropriate priority levels to different classes of traffic based on their criticality and requirements. Typically, traffic is classified into multiple queues with different priority levels (e.g., high priority, medium priority, low priority). Use QoS mechanisms such as Differentiated Services Code Point (DSCP), Class of Service (CoS), or Traffic Class to mark packets with the appropriate priority.
4. **Traffic Shaping and Policing:** Traffic shaping helps to control traffic transmission rate and prevents congestion by smoothing out bursts of traffic. Configure traffic policing to enforce traffic limits and ensure that non-critical traffic does not exceed allocated bandwidth, thus protecting critical applications from being starved of resources.
5. **Queue Management:** Configure queuing mechanisms such as First-In-First-Out (FIFO), Priority Queuing, Weighted Fair Queuing (WFQ), or Class-Based Queuing (CBQ) to manage the order in which packets are transmitted based on their priority levels. Implement scheduling algorithms to ensure that high-priority traffic is processed ahead of lower-priority traffic during periods of congestion.
6. **Monitoring and Optimization:** Continuously monitor network performance, QoS metrics, and compliance with SLAs to identify bottlenecks, latency issues, or packet loss. Fine-tune QoS policies and configurations based on real-time network conditions and feedback from users to optimize the prioritization of critical traffic.

By following these steps and leveraging QoS mechanisms, companies are able to prioritize critical traffic, attain consistent performance for essential applications, and enhance the overall quality of service delivered across their network infrastructure.

VI. ANALYSIS

This section analysis the information gleaned from the experimental data collected.

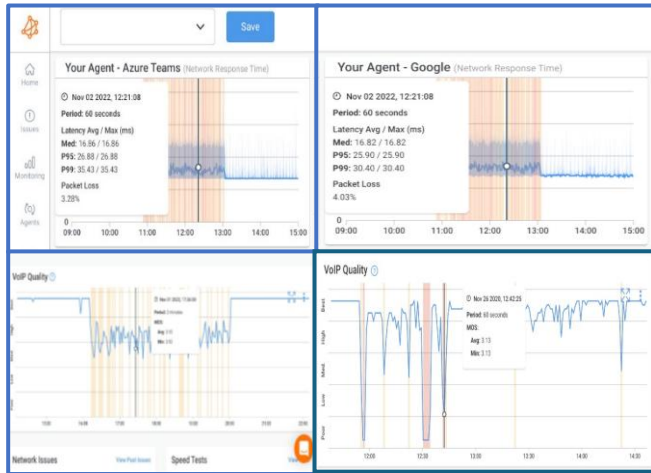


Fig. 1: Monitoring of Latency and MOS
(Adopted from Obkio's Dashboard, 2022)

Fig. 1 depicts the monitoring graphs for latency and MOS using the best tools. The top left is monitoring conducted on Azure teams using “Your Agent” and shows that both the average and maximum latencies read 16.86ms, while the packet loss was 3.28%. Monitoring of the Google network with the same tool shows in the top left that average and maximum latency are the same at 16.82ms, but the packet loss was 4.03%. In the lower left and lower right graphs, the average and minimum MOS are 3.92/3.92 and 3.13/3.13 respectively.

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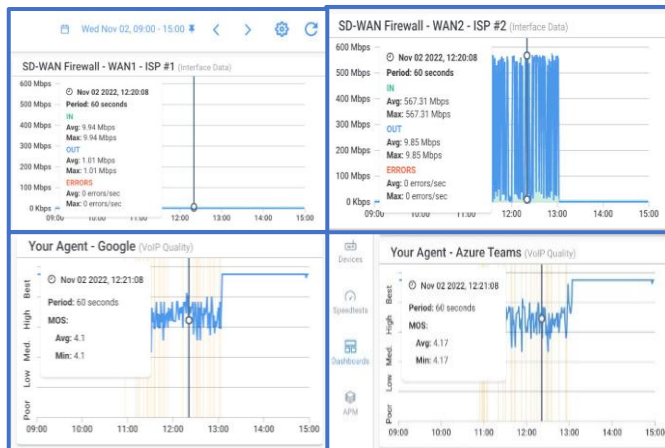


Fig. 2: Monitoring of Latency and MOS
(Adopted from Obkio's Dashboard, 2022)

In Fig. 2, the metrics latency and MOS were monitored over a period of 60secs. On the top left side of Figure shows the use of SD-WAN Firewall to WAN1 on November 2, 2022 at 3:00pm and the results were 9.94Mbps average latency and the same result for the maximum latency for incoming traffic, and 1.01Mbps each for the outgoing traffic. On the same

date at 12:20pm, SD-WAN Firewall was used to monitor WAN2 and it revealed that both the average and maximum latency were 567.31Mbps for inbound traffic and outbound were 9.85Mbps for both average and maximum latency. However, during these two monitoring exercises, no errors were recorded. This is an indication that networks behave differently at different times and should be monitored always to detect any discrepancies. Even in the absence of errors, WAN two had higher latency both at the in incoming and outgoing traffic compared to WA1.

On the other hand, ‘Your Agent’ was used to monitor Google and Azure Teams on the same date and time as depicted on both the bottom left and right of Fig. 2. The Mean Opinion Score (MOS) was monitored in both cases, the left side had 4.1 for both average and minimum records, while

right hand side recorded 4.17 for both average and minimum opinions. This is a clear manifestation of the fact that each network has different opinions generated by users, and it is through monitoring that these can be detected.



Fig. 3: Monitoring of DNS, TCP SSL and Others. (Adopted from Obkio's Dashboard, 2022)

On the upper left of Fig. 3, 'Your Agent' tool was used to monitor Google network on November 2, 2022 at 12:20:14pm, and the outcome indicates that the Domain Name System (DNS) recorded 86.90ms, Transmission Control Protocol (TCP) had 12.00ms, Secure Sockets Layer (SSL) was 261.70ms and the WAIT time for the CPU

was 110.90ms. On the same date, at 12:20:08 pm, the SD-WAN Firewall was used to monitor the utilization of four CPUs with 60 seconds, and results show that, CPU1, CPU2, CPU3 and CPU4 were utilized 10%, 7%, 15% and 13% respectively. Utilization of the CPU measures the amount of traffic on the network, and for the four CPUs the figures were relatively small, indicating the network is very healthy. The bottom left of Fig. 3 measured average and maximum latency as 14.26ms and 14.61ms respectively. The jitter was 2.92ms, while packet loss was 6.03%. On bottom right, both average and maximum latency were 15.11ms, jitter was 3.25 and packet loss 4.27%. These results show a healthy network with efficient performance.

TABLE I: THE IMPACT OF CALL QUALITY ON MEAN OPINION SCORE (MOS)

No.	Call Quality	MOS
1	Best	over 4.34
2	High	4.03-4.34
3	Medium	3.6-4.03
4	Low	3.1-3.6
5	Poor	below 3.1

Table I illustrates the effect of call quality on the average number of opinions (MOS) or commendations from network users. When opinions formed about the network is more 4.34, it means the quality of call is the best. High quality of calls generates 4.03-4.34 MOS, medium quality is 3.6 to 4.03 up to poor call quality represented by MOS below 3.1. Comparing Table 1 with results from Fig. 2 reveals that the call quality of the network monitored is high.

A. Contributions of the Study

Per the results or findings made in section VI of the study, the contributions include:

- 1. Network Architecture Improvements:** Analyzing different network architectures (e.g., SDN, NFV) that can enhance performance, scalability, and flexibility of telecoms networks.
- 2. Traffic Management Techniques:** Discussing algorithms and techniques for effective traffic management, including Quality of Service (QoS) mechanisms, load balancing, and congestion control.
- 3. Performance Metrics:** Identifying key performance indicators (KPIs) used to measure network performance, such as latency, throughput, jitter, and packet loss.
- 4. Data Analytics and AI:** Exploring the role of big data analytics and artificial intelligence in predicting network behavior, identifying bottlenecks, and automating network optimization processes.
- 5. Resource Allocation Strategies:** Examining resource allocation strategies that optimize bandwidth usage and improve overall network efficiency.
- 6. Energy Efficiency:** Discussing methods to reduce energy consumption in telecommunications networks while maintaining performance levels, contributing to sustainability goals.
- 7. Emerging Technologies:** Reviewing the impact of emerging technologies such as 5G, IoT, and edge computing on network performance optimization.
- 8. Security Considerations:** Addressing how optimizing network performance can be balanced with security measures to protect against vulnerabilities and attacks.
- 9. Case Studies and Real-World Applications:** Providing insights from case studies that illustrate successful optimization strategies implemented in various telecommunications settings.

VII. RECOMMENDATIONS FOR TELECOM OPERATORS AND ORGANIZATIONS

This section seeks to offer some recommendations to mobile network operators (MNOs) and organization to help them optimize their networks for efficient performance and customer satisfaction.

A. Best Practices for Maintaining high Network Performance

Maintaining high network performance is essential for ensuring optimal user experience, productivity, and efficiency within an organization. To achieve this, MNOs and organizations should implement regular monitoring and analysis, conduct regular capacity planning, implement network segmentation to divide the network into logical segments or VLANs based on departments, applications, or security requirements. Also, QoS should be implemented along with network optimization and the design of a robust security system including intrusion detection and prevention and firewalls. Finally, redundancy mechanisms such as link aggregation (LACP), failover configurations, redundant power supplies, and backup connections to ensure high availability and minimize downtime, and regular maintenance and updates should be conducted.

B. Investment considerations for network performance optimization

Investing in network performance optimization is a critical ingredient for improving network efficiency, productivity, and high user satisfaction. Some of the key investment considerations for optimizing network performance include, network infrastructure upgrades, bandwidth expansion, network monitoring tools, QoS solutions implementation, and network segmentation technologies. Additionally, investments should be made for network security solutions, redundancy and high availability, and training and skills development.

C. Future trends and challenges in telecommunications network performance

Future trends and challenges in telecommunications network performance are influenced by technological advancements, evolving user demands, and the increasing complexity of network infrastructures. It is recommended that the following key trends and challenges are considered, 5G network rollout, Internet of Things (IoT) expansion, edge computing integration, Virtualization and Software-Defined Networking (SDN), and resolving network security Concerns. In addition, Quality of Experience (QoE) optimization, network automation and AI, as well as sustainability and green networking should be implemented.

VIII. CONCLUSION

This study has provided a comprehensive review and analysis of the various strategies and technologies employed to optimize telecommunications network performance in an increasingly complex and demanding environment. The rapid growth of mobile devices, IoT applications, and high-bandwidth services poses significant challenges for network operators, necessitating innovative solutions to ensure efficiency, reliability, and quality of service. The findings highlight that a multi-faceted approach is essential for effective network optimization. Techniques such as traffic management, resource allocation, and quality of service enhancements are critical in addressing immediate performance issues. However, the integration of advanced technologies like Artificial Intelligence (AI) and Machine Learning (ML) is pivotal for enabling predictive analytics and dynamic network management. These technologies empower operators to anticipate network demands and make informed decisions that enhance overall performance. Moreover, the adoption of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) has emerged as transformative strategies that allow for greater flexibility and scalability in network architectures. These innovations enable operators to respond swiftly to changing conditions and user demands, fostering a more resilient telecommunications infrastructure. The role of big data analytics cannot be overstated, as it provides valuable insights into user behavior and traffic patterns. By leveraging this data, network operators can optimize planning and resource allocation, leading to improved service delivery and customer satisfaction.

Additionally, addressing security concerns remains paramount in the optimization process, as robust protocols are essential to protect network integrity and user privacy in the face of evolving cyber threats. The research contributes to the existing literature by synthesizing current knowledge and identifying best practices, ultimately offering a roadmap for future innovations in

telecommunications network performance enhancement. Recommendations for further research are provided, focusing on emerging technologies and user-centric models to ensure sustainable and efficient telecommunications infrastructures in the digital era. Some areas include:

- Investigate the implications of network slicing for performance optimization in 5G networks, including case studies on its implementation across different industries.
- Examine optimization strategies tailored for rural or underserved areas, considering the unique challenges and resource constraints faced by these networks
- Explore the potential of blockchain technology to enhance security and trust within telecommunications networks, particularly in the context of optimization.
- Investigate how collaboration between telecommunications providers and other industries (e.g., healthcare, transportation) can lead to innovative optimization solutions that benefit multiple sectors.

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