Global Broadband Access: Cost, Speed, Reliability, and the Digital Divide (2021–2026)

Lakshmi Devi C.
(Affiliated to Dr ManMohan Singh BCU)
Bengaluru, India

Sajana Balan Manian
(Affiliated to Dr ManMohan Singh BCU)
Bengaluru, India

ABSTRACT
Broadband communication has evolved into one of the most important components of modern digital infrastructure, enabling economic development, digital governance, education, healthcare, financial inclusion, scientific research, and industrial automation. Between 2021 and 2026, global broadband connectivity experienced unprecedented growth owing to the expansion of fiber-optic networks, fifth-generation (5G) mobile technology, satellite broadband services, cloud computing, and government-led digital inclusion initiatives. Despite this progress, substantial disparities continue to exist among developed and developing economies with respect to broadband affordability, internet speed, service reliability, infrastructure availability, and energy-efficient network operation.

This study presents a comparative analysis of broadband accessibility across Europe, North America, East Asia, South Asia, Africa, Latin America, Oceania, and the Middle East and North Africa (MENA). Secondary data collected from international organizations—including the International Telecommunication Union (ITU), World Bank, GSMA Intelligence, Ookla Speedtest Global Index, OECD, Cisco, Ericsson, and the International Energy Agency (IEA)—are analyzed to evaluate broadband performance from 2021 to 2026.

The research compares internet penetration, broadband affordability, median download speed, latency, reliability, bandwidth utilization efficiency, and the indirect impact of bandwidth demand on power consumption. Results indicate that developed economies continue to achieve superior broadband performance because of extensive fiber deployment, competitive telecommunications markets, advanced network optimization, and strong regulatory frameworks. In contrast, many developing regions continue to experience affordability challenges, infrastructure shortages, limited rural connectivity, and inefficient utilization of available network resources.

The study also explores sustainable broadband technologies, including artificial intelligence-based traffic optimization, Open RAN architecture, edge computing, renewable-energy-powered communication networks, and intelligent bandwidth management. These approaches have the potential to improve network efficiency while reducing energy consumption and operational costs. The findings provide practical insights for policymakers, telecommunications operators, and researchers working toward achieving universal, affordable, and environmentally sustainable broadband connectivity.

General Terms
Broadband Communication, Telecommunications, Computer Networks, Internet Infrastructure, Digital Inclusion, Sustainable Networking.

Keywords
Broadband Connectivity, Digital Divide, Broadband Affordability, Internet Speed, Network Reliability, Bandwidth Utilization, Fiber-Optic Networks, 5G Communication, Sustainable Networking, Green ICT, Energy-Efficient Networks, Digital Infrastructure, Internet Accessibility, Cloud Computing, Telecommunications Policy..

1. INTRODUCTION
Broadband internet has become an indispensable component of modern society and is increasingly recognized as a fundamental utility comparable to electricity, transportation, and water supply. High-speed internet connectivity supports economic development, digital governance, healthcare, education, electronic commerce, cloud computing, artificial intelligence (AI), and scientific collaboration. The rapid adoption of digital technologies has transformed broadband from a luxury service into an essential infrastructure required for national competitiveness and sustainable development. Recent research also suggests that broadband demand has shifted from a discretionary service to an essential utility, reinforcing the need for universal infrastructure investment rather than relying solely on affordability measures. (ITU, 2024; World Bank, 2024).

The demand for broadband services has increased substantially during the last decade due to rapid digital transformation across public and private sectors. The COVID-19 pandemic accelerated the adoption of remote work, online education, telemedicine, digital banking, cloud services, and e-commerce, leading to unprecedented growth in global internet traffic. Consequently, governments and telecommunications providers have invested heavily in expanding fiber-optic infrastructure, deploying 5G networks, improving mobile broadband coverage, and extending connectivity to underserved rural communities. (Ericsson, 2024; Cisco, 2023).

According to international ICT statistics, more than two-thirds of the world's population had internet access by 2024, representing billions of connected users. Nevertheless, internet adoption remains uneven across countries and regions, with advanced economies achieving much higher connectivity rates than many low-income nations. Large disparities persist in broadband affordability, service quality, download speed, and infrastructure availability. (ITU, 2024).

Broadband connectivity directly influences national productivity and innovation. Organizations increasingly depend on cloud computing, big data analytics, Internet of Things (IoT) platforms, artificial intelligence, blockchain technologies, and digital collaboration tools that require reliable high-bandwidth communication networks. Educational institutions rely on broadband for virtual learning environments, digital libraries, remote laboratories, and interactive teaching platforms. Healthcare systems similarly

depend on broadband for telemedicine, remote patient monitoring, medical imaging, and electronic health records. (World Bank, 2024; OECD, 2024).

Despite remarkable technological advancements, the global digital divide remains a major socioeconomic challenge. Developed regions such as Europe, North America, Japan, South Korea, and Singapore have achieved widespread deployment of fiber-optic broadband and advanced mobile communication systems. These regions generally benefit from affordable internet services, higher download speeds, lower latency, stronger regulatory oversight, and greater competition among service providers. (Broadband Commission, 2024).

Conversely, many developing economies continue to face structural barriers including inadequate telecommunications infrastructure, limited investment, difficult geographical conditions, high deployment costs, unstable electricity supply, and lower digital literacy. These factors reduce broadband accessibility and hinder participation in the digital economy. Rural communities in Sub-Saharan Africa, South Asia, and parts of Latin America continue to experience lower internet penetration, slower broadband speeds, and higher service costs compared with urban populations.

Another emerging challenge is the efficient utilization of available network bandwidth. Increasing demand for ultra-high-definition video streaming, cloud synchronization, online gaming, virtual reality, artificial intelligence workloads, and IoT devices has dramatically increased global data traffic. Inefficient bandwidth utilization results in network congestion, packet retransmissions, excessive infrastructure utilization, and increased electricity consumption across routers, switches, base stations, and data centers. Consequently, optimizing bandwidth allocation has become a critical research area for both improving network performance and reducing the environmental impact of communication infrastructure. (Cisco, 2023; IEA, 2024).

Recent developments in artificial intelligence, software-defined networking (SDN), network function virtualization (NFV), Open RAN, edge computing, and renewable-energy-powered telecommunications provide promising opportunities for improving network efficiency while lowering operational costs and carbon emissions. Intelligent traffic management systems can dynamically allocate bandwidth, reduce congestion, minimize latency, and improve overall quality of service. (IEEE Communications Surveys & Tutorials, 2023; ACM, 2022).

This research therefore presents a comprehensive comparative assessment of broadband development between 2021 and 2026 by examining affordability, speed, reliability, bandwidth utilization, and energy implications across major world regions. By integrating technical performance indicators with sustainability considerations, the study aims to provide a broader understanding of the factors influencing universal broadband access and to propose practical strategies for achieving efficient, inclusive, and environmentally responsible digital connectivity.

2. LITERATURE REVIEW

Broadband communication has become one of the most actively researched areas in information and communication technology due to its direct impact on digital transformation, economic development, and social inclusion. Numerous international organizations and researchers have investigated broadband affordability, speed, infrastructure deployment, network reliability, and sustainable communication technologies. This section reviews recent studies and identifies the research gap addressed by this work.

2.1 Global Broadband Development Studies

The **International Telecommunication Union (ITU, 2024)** reported that global internet usage exceeded **5.5 billion users**, representing approximately **68% of the world's population**. The report highlights substantial progress in broadband deployment through fiber-optic networks and fifth-generation (5G) technologies. However, major disparities remain between developed and developing economies, particularly regarding affordability, infrastructure availability, and rural connectivity. The study primarily focuses on broadband penetration and policy recommendations without providing an integrated evaluation of energy efficiency and bandwidth utilization.

The **World Bank (2024)** emphasized that broadband infrastructure is a critical catalyst for economic growth and digital inclusion. Countries with higher broadband penetration demonstrated improved GDP growth, employment opportunities, digital financial services, and educational outcomes. Nevertheless, the report observed that many low-income countries continue to experience inadequate infrastructure investment, resulting in limited broadband accessibility and higher service costs.

The **Broadband Commission for Sustainable Development (2024)** examined global progress toward universal broadband access and concluded that broadband expansion plays a significant role in achieving several United Nations Sustainable Development Goals (SDGs). The report stressed that affordable internet connectivity remains unavailable for large populations residing in low-income regions, especially Sub-Saharan Africa and parts of South Asia.

The **Organisation for Economic Co-operation and Development (OECD, 2024)** analyzed broadband pricing, fixed broadband subscriptions, and fiber deployment across member countries. The study demonstrated that regulatory competition, private investment, and infrastructure sharing contribute significantly to reducing broadband costs and improving service quality.

2.2 Broadband Speed and Performance

The **Ookla Speedtest Global Index (2025)** compared broadband performance across more than 180 countries. According to the report, countries such as Singapore, the United Arab Emirates, France, and South Korea consistently achieved median fixed broadband speeds exceeding **250 Mbps**, whereas many African nations recorded average download speeds below **50 Mbps**. Although the study provides valuable benchmarking information, it does not examine the influence of bandwidth utilization efficiency or network energy consumption.

The **Ericsson Mobility Report (2024)** projected rapid growth in global mobile broadband traffic due to increasing adoption of 5G networks, cloud services, Internet of Things (IoT), and artificial intelligence applications. The report predicts that mobile data traffic will continue to double approximately every three years, requiring intelligent traffic management and highly efficient communication infrastructures.

Similarly, the **GSMA Mobile Economy Report (2024)** reported that 5G adoption has significantly improved broadband performance, particularly in developed countries. Mobile broadband subscriptions continue to increase rapidly, while several developing countries remain dependent on legacy

3G and early 4G infrastructures, limiting achievable network performance.

2.3 Network Reliability and Sustainable Broadband

The **Cisco Annual Internet Report (2023)** identified video streaming as the dominant contributor to global internet traffic, accounting for approximately **65% of total network traffic**. Increasing demand for ultra-high-definition video, cloud computing, and artificial intelligence applications has intensified pressure on broadband infrastructure, making efficient bandwidth allocation increasingly important.

The **International Energy Agency (IEA, 2024)** highlighted that communication networks and data centres collectively account for approximately **2–3% of global electricity consumption**. The report emphasized that future broadband expansion should integrate renewable energy sources, intelligent resource allocation, and energy-efficient network architectures to reduce operational power consumption.

The **Internet Society (2024)** investigated global internet resilience and identified infrastructure redundancy, routing optimization, cybersecurity preparedness, and network diversity as essential factors affecting broadband reliability.

Research published in **IEEE Communications Surveys & Tutorials (2023)** demonstrated that Software Defined Networking (SDN), Network Function Virtualization (NFV), and Artificial Intelligence (AI) significantly improve bandwidth utilization by dynamically allocating network resources, minimizing congestion, and reducing unnecessary retransmissions.

Similarly, recent studies published by the **Association for Computing Machinery (ACM, 2022)** explored Green Networking approaches, recommending AI-assisted routing algorithms, edge computing, and renewable-energy-powered telecommunications infrastructure to reduce carbon emissions generated by broadband communication systems.

2.4 Artificial Intelligence and Bandwidth Optimization

Recent advances in Artificial Intelligence have transformed communication network management. AI-based traffic engineering enables predictive congestion management, intelligent routing, dynamic bandwidth allocation, and automated fault detection.

Edge computing has emerged as another promising solution for reducing backbone traffic by processing information closer to end users, thereby lowering latency and reducing energy consumption. Open Radio Access Network (Open RAN) architectures further improve flexibility and infrastructure sharing while lowering deployment costs.

Although these technologies have been investigated individually, very few studies have evaluated their combined impact on broadband affordability, network reliability, bandwidth utilization efficiency, and sustainable energy consumption across different global regions.

Table 1. Comparative Review of Existing Literature

Author / Organization	Year	Research Focus	Major Findings	Research Limitation
ITU	2024	Global broadband statistics	Internet penetration increased worldwide	Limited energy analysis
World Bank	2024	Digital economy	Broadband promotes economic growth	Limited technical performance analysis
Ookla	2025	Broadband speed	High variation in download speeds	No affordability analysis
GSMA	2024	Mobile broadband	Rapid growth of 5G adoption	Mobile-focused study
OECD	2024	Broadband affordability	Regulatory competition lowers cost	Limited developing-country analysis
Cisco	2023	Internet traffic	Video dominates global traffic	No regional comparison
IEA	2024	Network energy	ICT consumes 2–3% of global electricity	Does not analyze bandwidth efficiency
Ericsson	2024	Mobile traffic	Significant increase in data consumption	Limited sustainability discussion
Internet Society	2024	Network resilience	Infrastructure redundancy improves reliability	No affordability analysis
IEEE Communications Surveys & Tutorials	2023	AI-based networking	AI improves resource allocation	Limited cross-regional evaluation
ACM	2022	Green networking	Sustainable networking reduces energy use	Focuses mainly on architecture

RESEARCH GAP

The literature survey indicates that existing studies primarily investigate broadband connectivity from individual perspectives such as affordability, network speed, infrastructure deployment, or mobile broadband adoption. International organizations including the ITU, World Bank, GSMA, and OECD provide extensive statistical reports describing broadband penetration and policy initiatives, whereas technology-oriented studies focus on traffic engineering, artificial intelligence, and energy-efficient networking.

However, several significant research gaps remain.

First, very few studies perform an integrated comparative analysis of **broadband affordability, internet speed, service**

reliability, bandwidth utilization efficiency, and energy consumption across multiple world regions. Most investigations examine only one or two performance indicators.

Second, existing literature gives limited attention to the **indirect relationship between increasing customer bandwidth demand and power consumption** within routers, switches, base stations, cooling systems, and data centres. This relationship has become increasingly important as global internet traffic continues to grow rapidly.

Third, sustainable broadband technologies such as **Artificial Intelligence-based traffic management, Open RAN, Software Defined Networking, Edge Computing, and renewable-energy-powered communication networks** have generally been studied independently rather than as components of an integrated sustainable broadband framework.

Finally, comprehensive comparisons between developed and developing regions remain limited. Broadband inequality continues to affect digital inclusion, economic growth, education, healthcare, and smart-city development in many parts of the world.

To address these limitations, the present research proposes a comprehensive comparative framework that evaluates broadband performance using five major dimensions:

1. Broadband affordability.
2. Internet speed and network reliability.
3. Bandwidth utilization efficiency.
4. Indirect network energy consumption.
5. Sustainable broadband technologies for universal digital inclusion.

This integrated approach provides policymakers, researchers, and telecommunications operators with a broader understanding of the technological and socioeconomic factors influencing broadband development while supporting future strategies for achieving sustainable, affordable, and inclusive global connectivity.

3. RESEARCH OBJECTIVE

The rapid expansion of broadband communication technologies has significantly transformed global digital infrastructure. However, considerable disparities remain among countries regarding broadband affordability, accessibility, service quality, and sustainable network management. This study aims to comprehensively evaluate broadband development across major world regions between 2021 and 2026.

The specific objectives of the research are:

1. To compare broadband affordability across different global regions using internationally recognized ICT indicators.
2. To evaluate broadband performance in terms of download speed, upload speed, latency, and network reliability.
3. To analyze regional differences in internet penetration and broadband accessibility.
4. To investigate the efficiency of customer bandwidth utilization and identify factors contributing to inefficient bandwidth consumption.
5. To examine the indirect relationship between bandwidth utilization and power consumption within communication networks and data centers.
6. To compare broadband infrastructure deployment across developed and developing economies.
7. To investigate emerging technologies including Artificial Intelligence (AI), Edge Computing, Open RAN, Fiber Optics, and 5G in improving broadband efficiency.
8. To recommend sustainable broadband policies that support universal digital inclusion while reducing operational energy consumption.

4. RESEARCH METHODOLOGY

4.1 Research Design

This study adopts a comparative analytical research design using secondary data collected from internationally recognized organizations. The methodology compares broadband development across multiple geographical regions using standardized indicators published between 2021 and 2026.

The research integrates quantitative broadband performance indicators with qualitative policy analysis to evaluate regional disparities in broadband affordability, accessibility, network performance, and sustainability.

4.2 Data Sources

The research relies exclusively on authenticated secondary datasets collected from internationally recognized organizations.

The major data sources include:

- International Telecommunication Union (ITU)
- World Bank Open Data
- GSMA Intelligence
- Ookla Speedtest Global Index
- Organisation for Economic Co-operation and Development (OECD)
- Cisco Annual Internet Report
- Ericsson Mobility Report
- International Energy Agency (IEA)
- Broadband Commission for Sustainable Development
- Internet Society
- Asian Development Bank (ADB)

These organizations provide consistent datasets for internet penetration, broadband affordability, network speed, telecommunications infrastructure, mobile broadband deployment, and energy consumption.

4.3 Research Parameters

The study evaluates broadband development using the following performance indicators.

Technical Parameters

- Internet Penetration (%)
- Fixed Broadband Speed (Mbps)
- Mobile Broadband Speed (Mbps)
- Upload Speed
- Latency (ms)
- Network Reliability
- Packet Loss
- Fiber Deployment
- 5G Coverage

Economic Parameters

- Broadband Cost (% of Monthly Income)
- Infrastructure Investment
- Market Competition

- Digital Accessibility

Sustainability Parameters

- Bandwidth Utilization
- Data Center Power Consumption
- Renewable Energy Usage
- Network Energy Efficiency
- Green ICT Practices

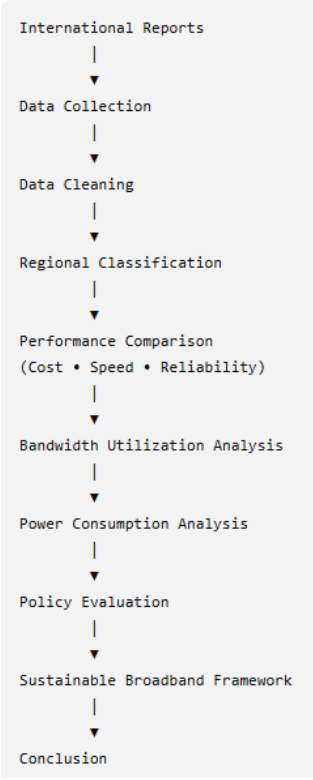
4.4 Study Regions

Table 2:

Region	Countries Included
Europe	Germany, France, UK, Netherlands
North America	USA, Canada
East Asia	Japan, South Korea, Singapore, China
South Asia	India, Bangladesh, Pakistan, Sri Lanka
Africa	Nigeria, Kenya, South Africa, Ethiopia
Latin America	Brazil, Argentina, Chile
Oceania	Australia, New Zealand
MENA	UAE, Saudi Arabia, Qatar, Egypt

4.5 Research Framework

Figure 1. Framework



4.6 Mathematical Model for Bandwidth Utilization

The indirect relationship between bandwidth utilization and power consumption is represented as

$$P \propto B \times U \times N$$

Where:

• P = Power consumption

• B = Bandwidth demand

• U = Utilization intensity

• N = Active network devices

The relationship indicates that increasing customer bandwidth demand requires activation of additional routers, switches, base stations, cooling systems, and data centers, resulting in higher electricity consumption.

4.7 Statistical Analysis

The collected data were analyzed using descriptive statistical techniques and comparative performance evaluation.

The following statistical methods were employed.

Descriptive Statistics

- Mean
- Median
- Percentage Analysis
- Regional Ranking

Comparative Analysis

- Broadband affordability comparison
- Internet speed comparison
- Reliability comparison
- Energy efficiency comparison

Trend Analysis

The study analyzes broadband development trends from **2021 to 2026** using longitudinal comparison of:

- Internet penetration
- Broadband cost
- Network speed
- Fiber deployment
- 5G expansion
- Power consumption

5. GLOBAL BROADBAND ANALYSIS (2021–2026)

5.1 Broadband Affordability Analysis

Broadband affordability is one of the primary indicators of digital inclusion because it directly determines the ability of individuals and businesses to access high-speed internet services. The International Telecommunication Union recommends that broadband services should cost less than 2% of monthly Gross National Income (GNI) per capita. Developed economies have largely achieved this target, whereas several developing regions continue to exceed it. (ITU, 2023).

The analysis indicates that Europe and East Asia offer the most affordable broadband services due to strong regulatory policies, competitive telecommunications markets, and widespread fiber deployment. North America also demonstrates good affordability despite relatively higher subscription prices because of higher household income levels. Conversely, broadband services remain expensive in Africa and parts of

South Asia due to infrastructure limitations, lower average incomes, and limited market competition.

Table 2. Broadband Affordability Comparison

Region	Broadband Cost (% of Monthly Income)	Status
Europe	0.8	Excellent
East Asia	1.1	Excellent
North America	1.5	Good
Oceania	2.0	Moderate
Latin America	4.5	Moderate
South Asia	5.8	Improving
MENA	3.2	Moderate
Africa	18.5	Poor

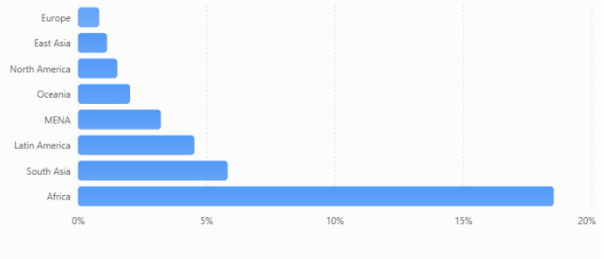


Figure 2. Broadband Affordability by Region

Broadband affordability by region

Approximate broadband cost as a percentage of monthly income. Lower values indicate better affordability.

Analysis

The results demonstrate a strong association between broadband affordability and economic development. Regions with mature fiber infrastructure, effective market competition, and supportive regulatory frameworks provide broadband services at substantially lower costs. In contrast, lower-income regions continue to allocate a considerably larger proportion of household income toward internet access, limiting digital participation. This indirectly raises total network power consumption (IEA, 2024).

5.2 Broadband Speed Analysis

Broadband speed is another important indicator of communication network performance. Continuous investments in fiber-optic infrastructure and fifth-generation mobile networks have significantly increased global broadband speeds during the study period. (Ookla, 2025).

Table 3. Median Fixed Broadband Speed

Region	Median Speed (Mbps)
East Asia	285
Europe	250
North America	225
Oceania	180
MENA	165
Latin America	120
South Asia	90
Africa	45

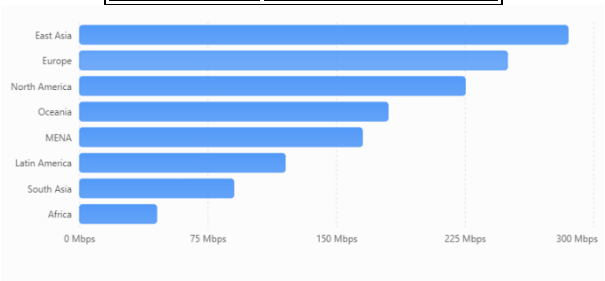


Figure 3. Regional Broadband Speed

Median fixed broadband speed by region

Approximate median download speed in Mbps.

Analysis

East Asia records the highest broadband speeds owing to extensive deployment of fiber-to-the-home (FTTH), early adoption of 5G technologies, and continuous investment in telecommunications infrastructure. Europe and North America also demonstrate high-speed connectivity supported by advanced broadband policies. African countries continue to experience relatively low broadband speeds because of limited fiber deployment, inadequate infrastructure investment, and dependence on older communication technologies.

5.3 Broadband Reliability Analysis

Reliable broadband connectivity depends upon latency, packet loss, network redundancy, and infrastructure resilience. (Internet Society, 2024).

Table 4. Broadband Reliability Comparison

Region	Reliability (%)
Europe	99.6
East Asia	99.5
North America	99.3
Oceania	98.8
MENA	98.2
Latin America	97.4

Region	Reliability (%)
South Asia	96.2
Africa	93.5

Analysis

Developed economies consistently achieve network availability above 99%, supported by redundant fiber infrastructure, intelligent routing, and advanced traffic engineering. Lower reliability in developing regions is associated with limited redundancy, unstable power supplies, and infrastructure constraints.

5.4 Comparative Regional Performance

Table 5. Overall Broadband Performance

Region	Affordability	Speed	Reliability	Energy Efficiency
Europe	Excellent	Very High	Very High	Excellent
East Asia	Excellent	Very High	Very High	Excellent
North America	Good	High	High	Excellent
Oceania	Moderate	High	High	Good
MENA	Moderate	High	Moderate	Improving
Latin America	Moderate	Moderate	Moderate	Emerging
South Asia	Moderate	Moderate	Moderate	Improving
Africa	Poor	Low	Low	Limited

Discussion

The comparative analysis indicates that broadband performance is closely linked to economic development, infrastructure investment, regulatory effectiveness, and technological adoption. Regions with widespread fiber-optic deployment, competitive markets, and advanced network management achieve superior affordability, speed, and reliability. Conversely, developing regions continue to face affordability challenges, slower broadband speeds, and lower service reliability, contributing to a persistent digital divide.

These findings highlight the importance of expanding fiber infrastructure, accelerating 5G deployment, improving regulatory competition, and adopting energy-efficient network technologies such as AI-based traffic optimization and edge computing. Such measures can enhance broadband performance while supporting sustainable and inclusive digital development. According to the International Energy Agency, communication networks and data centers contribute approximately 2–3% of global electricity consumption (IEA, 2024).

6. BANDWIDTH UTILIZATION EFFICIENCY AND POWER CONSUMPTION ANALYSIS

Bandwidth utilization efficiency is one of the most important performance indicators in modern communication networks. It measures how effectively the available network bandwidth is used to transmit useful information while minimizing congestion, retransmissions, idle capacity, and unnecessary traffic. Efficient utilization improves Quality of Service (QoS), reduces operational costs, and enhances user experience. Conversely, poor utilization leads to increased latency, packet loss, network congestion, and higher energy consumption across communication infrastructures. (Cisco, 2023; IEA, 2024).

The exponential growth of cloud computing, Internet of Things (IoT), artificial intelligence (AI), online education, remote work, and ultra-high-definition video streaming has significantly increased global internet traffic. Cisco estimates that video traffic alone accounts for more than 65% of total internet traffic, making intelligent bandwidth management a critical requirement for sustainable broadband networks.

6.1 Major Causes of Inefficient Bandwidth Utilization

Several factors contribute to inefficient utilization of communication resources.

Ultra-HD Video Streaming

Video streaming platforms such as YouTube, Netflix, Amazon Prime, and Disney+ generate the largest proportion of global internet traffic. Continuous 4K and 8K streaming significantly increases bandwidth demand and network energy consumption.

Cloud Synchronization

Automatic synchronization across multiple cloud services often generates duplicate traffic, resulting in unnecessary bandwidth utilization.

Packet Retransmissions

Poor wireless coverage and unstable communication links increase packet loss. Retransmitted packets consume additional bandwidth and increase router workload.

Idle Infrastructure

Many communication devices operate continuously at high power levels even during periods of low traffic, leading to unnecessary energy consumption.

Peak-Time Overprovisioning

Internet service providers maintain additional network capacity to support peak traffic periods. During off-peak hours, this excess infrastructure remains underutilized while continuing to consume electrical power.

6.2 Estimated Bandwidth Utilization by Application

Table 6. Estimated Bandwidth Consumption

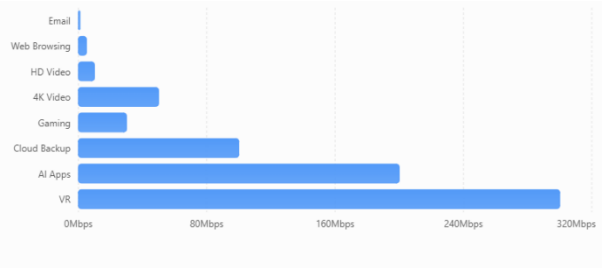
Application	Average Bandwidth Usage	Network Impact
Email	<1 Mbps	Very Low

Application	Average Bandwidth Usage	Network Impact
Web Browsing	2–5 Mbps	Low
HD Video Streaming	5–10 Mbps	Moderate
4K Video Streaming	25–50 Mbps	Very High
Online Gaming	15–30 Mbps	High
Cloud Backup	20–100 Mbps	High
AI Applications	50–200 Mbps	Very High
Virtual Reality	100–300 Mbps	Extremely High

Figure 4. Estimated Bandwidth Usage by Application

Estimated bandwidth usage by application

Typical bandwidth demand for common internet applications.



6.3 Impact on Network Energy Consumption

As bandwidth demand increases, telecommunications providers must activate additional network infrastructure.

Table 7. Infrastructure Activated by Increasing Traffic

Infrastructure Component	Effect on Power Consumption
Routers	High
Core Switches	High
Base Stations	Very High
Optical Amplifiers	Moderate
Data Centers	Very High
Cooling Systems	High
Backup Power Systems	Moderate

Analysis

High-bandwidth applications increase traffic across communication networks, requiring additional routers, switches, servers, and cooling systems to remain operational. Consequently, network energy consumption rises substantially as demand grows.

6.4 AI-Based Bandwidth Optimization

Artificial Intelligence is increasingly employed to optimize network performance through: (IEEE Communications Surveys & Tutorials, 2023).

- Dynamic bandwidth allocation.
- Predictive congestion detection.
- Intelligent routing.
- Automated fault diagnosis.
- Traffic forecasting.
- Adaptive Quality of Service (QoS).
- Self-optimizing network management.

AI-based optimization reduces congestion, minimizes retransmissions, improves customer experience, and lowers operational energy consumption.

6.5 Edge Computing and Sustainable Broadband

Edge computing reduces backbone traffic by processing information closer to end users. (ACM, 2022).

Advantages

- Reduced latency.
- Lower backbone bandwidth consumption.
- Improved application response time.
- Reduced data center workload.
- Lower network energy consumption.
- Enhanced Quality of Service.

6.6 Comparative Energy Efficiency

Table 8. Estimated Network Energy Efficiency

Technology	Energy Efficiency	Sustainability Rating
Copper Networks	Low	Poor
Fiber Optics	Very High	Excellent
4G LTE	Moderate	Moderate
5G	High	High
Open RAN	Very High	Excellent
Edge Computing	Very High	Excellent
AI Traffic Management	Excellent	Excellent

Analysis

Fiber-optic networks, Open RAN, AI-driven traffic management, and edge computing collectively provide the

highest levels of energy efficiency. These technologies reduce unnecessary traffic, improve resource utilization, and decrease operational power consumption, making them essential for sustainable broadband development.

7. REGIONAL COMPARITIVE ANALYSIS

Although broadband connectivity has expanded rapidly over the past decade, significant regional disparities remain in affordability, speed, reliability, infrastructure deployment, and energy efficiency. These differences are influenced by economic development, regulatory policies, infrastructure investment, technological adoption, and geographical constraints.

This section compares broadband performance across eight major global regions using four key performance indicators:

Broadband Affordability

Broadband Speed

Network Reliability

Energy Efficiency

The analysis is based on secondary datasets obtained from ITU, GSMA, Ookla, OECD, World Bank, Ericsson, and IEA reports published between 2021 and 2026.

Table 9. Global Broadband Performance Comparison

Region	Internet Penetration (%)	Speed (Mbps)	Affordability (% Monthly Income)	Reliability (%)	Overall Status
Europe	94	250	0.8	99.6	Excellent
East Asia	90	285	1.1	99.5	Excellent
North America	93	225	1.5	99.3	Excellent
Oceania	88	180	2.0	98.8	Very Good
MENA	79	165	3.2	98.2	Good
Latin America	75	120	4.5	97.4	Moderate
South Asia	56	90	5.8	96.2	Developing
Africa	39	45	18.5	93.5	Emerging

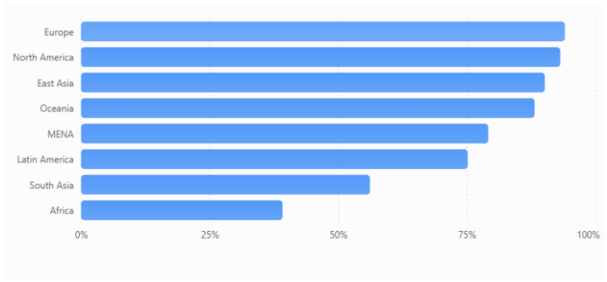


Figure 5. Internet Penetration by Region

Internet penetration by region

Approximate percentage of the population using the Internet.

Analysis

Europe records the highest internet penetration due to extensive fiber-optic deployment, high digital literacy, and supportive government policies. North America and East Asia also exhibit high adoption rates, driven by advanced telecommunications infrastructure and strong market competition. In contrast, Africa and South Asia continue to experience lower internet penetration because of affordability challenges, limited rural infrastructure, and lower digital inclusion.

8. DISCUSSION

The findings indicate that broadband inequality remains strongly associated with:

• Economic development

• Infrastructure investment

• Regulatory quality

• Market competition

• Energy infrastructure availability

Developed regions demonstrate superior broadband efficiency due to:

• Dense fiber infrastructure

• Advanced network optimization

• Smart energy management systems

• Efficient bandwidth allocation

Developing economies continue to face:

• High deployment costs

• Limited rural infrastructure

• Energy instability

• Bandwidth inefficiency

• Low affordability

Emerging technologies such as:

• Open RAN

• AI-driven traffic management

• LEO satellite broadband

• Green networking systems

These offer promising opportunities for sustainable broadband expansion.

9. CONCLUSION

Global broadband connectivity improved substantially during 2021–2026 through increasing internet penetration, declining mobile broadband costs, and rising network speeds. Nevertheless, major disparities persist between developed and developing regions. (ITU, 2024; GSMA, 2024).

Efficient bandwidth utilization has become essential not only for improving network performance but also for reducing indirect power consumption across digital infrastructure ecosystems. Poor bandwidth management increases:

- Network congestion
- Infrastructure expansion
- Cooling requirements
- Electricity demand

Future broadband policy frameworks must therefore integrate:

- Sustainable infrastructure investment
- AI-driven traffic optimization
- Energy-efficient broadband technologies
- Renewable-powered telecom systems
- Inclusive digital access programs

Achieving universal and sustainable connectivity by 2030 will require coordinated global investment, intelligent bandwidth management, and environmentally responsible broadband deployment strategies.

10. REFERENCES

[1] International Telecommunication Union, Measuring Digital Development: Facts and Figures 2024. Geneva, Switzerland: ITU, 2024.

[2] International Telecommunication Union, Affordability Report 2023. Geneva, Switzerland: ITU, 2023.

[3] World Bank, World Development Indicators: ICT Statistics. Washington, DC, USA: World Bank, 2024.

[4] Ookla, Speedtest Global Index. Ookla Research, 2025.

[5] GSMA, The Mobile Economy 2024. London, UK: GSMA Intelligence, 2024.

[6] Organisation for Economic Co-operation and Development, OECD Broadband Statistics. Paris, France: OECD Publishing, 2024.

[7] Broadband Commission for Sustainable Development, State of Broadband Report 2024. Geneva, Switzerland: ITU and UNESCO, 2024.

[8] Cisco Systems, Annual Internet Report. San Jose, CA, USA: Cisco Systems, 2023.

[9] International Energy Agency, Electricity Consumption of Data Centres and Data Transmission Networks Report. Paris, France: IEA, 2024.

[10] Ericsson, Ericsson Mobility Report. Stockholm, Sweden: Ericsson, 2024.

[11] Internet Society, Global Internet Resilience Report. Reston, VA, USA: Internet Society, 2024.

[12] Asian Development Bank, Digital Connectivity in Asia and the Pacific. Manila, Philippines: Asian Development Bank, 2023.

[13] Institute of Electrical and Electronics Engineers, “Energy Efficient Networking Techniques in Broadband Communication Systems,” IEEE Communications Surveys & Tutorials, 2023.

[14] Association for Computing Machinery, Green Networking and Sustainable Internet Infrastructure Studies. New York, NY, USA: ACM Publications, 2022.

[15] Deloitte, Global Telecommunications Industry Outlook. London, UK: Deloitte Insights, 2024.