Global Journal of Engineering and Technology Advances
eISSN: 2582-5003
Cross Ref DOI: 10.30574/gjeta
Journal homepage: https://gjeta.com/

(Research Article)

Check for updates

Quantifying the Impact of 5G Fixed Wireless Access (FWA) on Traditional FTTH Markets: Performance metrics, latency constraints, and deployment economics

Carl Amekudzi [1], Emmanuel Selorm Gabia [1], Jibriel Adjei [1], Raymond Tay [2] and David Olufemi [1,*]

[1] *J W McClure School of Emerging Technologies Ohio University, USA.*
[2] *College of Engineering, Northeastern University. Massachusetts, USA.*

Global Journal of Engineering and Technology Advances, 2026, 27(01), 015-028

Publication history: Received on 26 February 2026; revised on 04 April 2026; accepted on 07 April 2026

Article DOI: https://doi.org/10.30574/gjeta.2026.27.1.0078

Abstract

The paper investigates the growing competition between 5G Fixed Wireless Access (FWA) and Fiber-to-the-Home (FTTH) broadband technologies in modern telecommunications markets. While FTTH has traditionally been regarded as the gold standard for high-capacity broadband delivery, recent advancements in 5G, particularly in millimeter wave (mmWave) and mid-band spectrum have enabled FWA to provide competitive broadband services with significantly reduced deployment costs and faster rollout times.

This study quantitatively evaluates the comparative performance of 5G FWA and FTTH across several dimensions including throughput, latency, reliability, scalability, and economic feasibility. Using network performance benchmarks, latency analysis, and cost-per-subscriber modeling, the research assesses how FWA alters traditional broadband deployment strategies and influences market competition.

The results show that while FTTH remains superior in deterministic latency and long-term capacity scalability, 5G FWA offers compelling advantages in deployment speed, rural accessibility, and capital expenditure efficiency. The findings provide insights for telecom operators, infrastructure investors, and policymakers seeking to balance broadband expansion with cost-effective infrastructure planning.

Keywords: 5G Fixed Wireless Access (FWA); Fiber-to-the-Home (FTTH); Broadband Infrastructure; Network Latency; Deployment Economics; Telecommunications Markets; Wireless Broadband; Network Performance Metrics; Rural Connectivity; 5G mmWave

1. Introduction

1.1. Background of Broadband Access Technologies

The global digital landscape has undergone a seismic shift, transitioning from basic connectivity to a state of ubiquitous, high-capacity interdependence where broadband access is categorized as a utility rather than a luxury. Historically, the architectural gold standard for this connectivity has been Fiber-to-the-Home (FTTH), a technology that utilizes Passive Optical Network (PON) architectures to deliver data via light pulses through glass strands. The evolution of FTTH, progressing from early BPON to the current ubiquity of GPON and the emerging 10 - 25 Gbps capabilities of XGS-PON, has set an incredibly high bar for performance, characterized by near-zero electromagnetic interference and symmetrical upload/download speeds [1]. However, the physical realities of fiber deployment, specifically the high cost of civil works, trenching, and complex "last-mile" permitting, have created a digital divide where rural and less dense suburban areas remain underserved due to unfavorable Return on Investment (ROI) profiles.

* Corresponding author: David Olufemi

Concurrent with the maturation of fiber, the telecommunications industry has witnessed the rapid deployment of Fifth Generation (5G) mobile networks, which were engineered not just for mobile handsets but as a multi-service platform. A pivotal application of this technology is 5G Fixed Wireless Access (FWA), which serves as a terrestrial wireless alternative to wireline broadband. Unlike previous wireless iterations that suffered from high latency and limited capacity, 5G FWA leverages the New Radio (NR) standard to operate across multiple frequency bands, including the high-capacity Millimeter Wave (mmWave) spectrum. By utilizing sophisticated spatial multiplexing and massive Multiple-Input Multiple-Output (m-MIMO) antenna arrays, 5G FWA can now approximate fiber-like experiences, providing a strategic tool for operators to bridge the connectivity gap in a fraction of the time required for traditional fiber build-outs [2].

1.2. Problem Statement

As the demand for data-intensive applications such as 8K video streaming, cloud gaming, and extended reality (XR) grows, the debate between the deterministic performance of FTTH and the flexible agility of 5G FWA has intensified. While FTTH is theoretically superior in terms of raw bandwidth and physical longevity, its deployment is often hindered by the "Trenching Barrier," where the cost of labor and municipal approvals can account for up to 80% of the total Capital Expenditure (CAPEX) [3]. Conversely, 5G FWA offers a rapid time-to-market, yet it faces fundamental physics-based challenges such as signal attenuation over distance and the impact of environmental factors on high-frequency waves.

There exists a critical knowledge gap regarding the long-term scalability of FWA as cell sites become congested with both mobile and fixed subscribers. Furthermore, the industry lacks a unified framework to determine the exact "break-even" point where the lower CAPEX of FWA is eventually overtaken by the superior Operational Expenditure (OPEX) and capacity of FTTH. This research addresses the need for a rigorous, quantitative evaluation of these two paradigms, focusing on whether 5G FWA can truly serve as a permanent substitute for fiber or if it remains a transitory "gap-filler" in the broadband ecosystem.

1.3. Research Objectives

The primary aim of this study is to conduct a multi-dimensional comparison of 5G FWA and FTTH to inform strategic infrastructure decisions. The specific objectives include:

Developing a benchmarking framework to quantify the performance delta between wireless and optical mediums, specifically focusing on the variance in QoS (Quality of Service) metrics under peak load.

Constructing a comprehensive Total Cost of Ownership (TCO) model that incorporates both the initial deployment costs and the long-term energy and maintenance expenses.

Identifying the geographical and demographic thresholds that dictate the technical superiority of one technology over the other.

Predicting the competitive shifts in the Internet Service Provider (ISP) market as mobile network operators (MNOs) increasingly challenge incumbent cable and fiber providers.

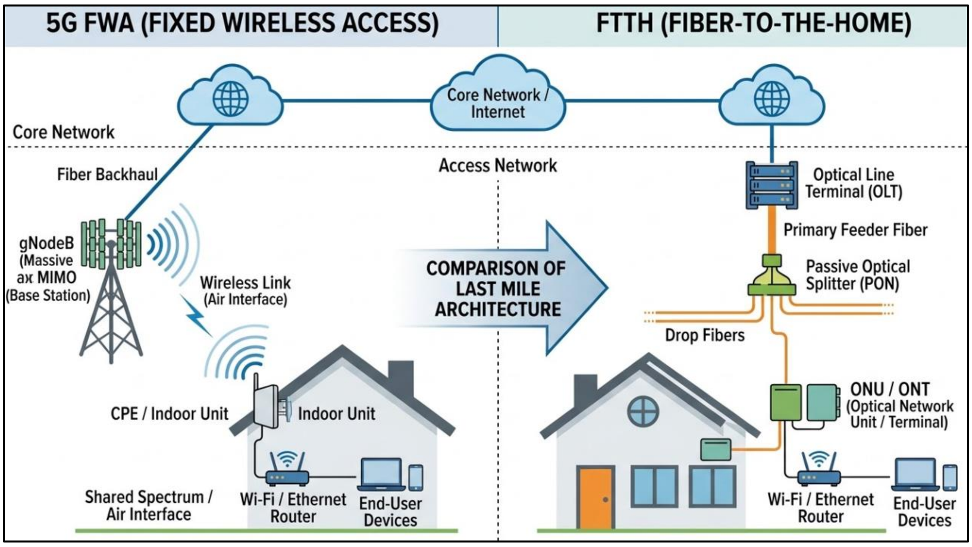

Figure 1 High-Level 5G FWA vs. FTTH Network Architecture Comparison

1.4. Research Questions and Technical Considerations

To guide this investigation, several key questions must be answered, each tied to specific Key Performance Indicators (KPIs) and mathematical relationships.

Q1: How does 5G FWA compare to FTTH in terms of throughput, latency, and reliability?

The performance of 5G FWA is governed by the Shannon-Hartley theorem, which defines the maximum rate at which information can be transmitted over a communications channel:

$$C = B\log_2(1 + \text{SNR})$$

Where C is the channel capacity, B is the bandwidth, and SNR is the signal-to-noise ratio [4]. In contrast, FTTH capacity is limited primarily by the transceiver electronics rather than the medium itself. This study will evaluate if the "Air Interface" can maintain a high enough SNR to compete with the nearly infinite SNR of a closed fiber system.

Q2: What deployment scenarios favor FWA over fiber infrastructure?

Deployment favorability is often a function of "Home Density" (D). We can hypothesize a threshold model where if $D < \text{Critical Value}$, FWA is the only economically viable path. This involves analyzing the propagation loss in various environments using models such as the 3GPP Urban Micro (UMi) or Urban Macro (UMa) path loss equations.

Q3: What are the cost-benefit trade-offs between wireless and fiber broadband?

The economic analysis hinges on the CAPEX per subscriber. For FTTH, this is dominated by the cost of passing a home (C_p) and the cost of connecting a home (C_c):

$$\text{Total Cost}_{\text{FTTH}} = (N_p \times C_p) + (N_a \times C_c)$$

where N_p is the number of homes passed and N_a is the number of active subscribers. For FWA, the cost is largely centered on the base station equipment and spectrum acquisition, which is then amortized over all users within the cell's radius [5].

Q4: How will the expansion of 5G FWA reshape broadband infrastructure markets?

This question examines the "Disruptor Effect" of FWA on market pricing and the potential for "Hybrid Deployment" models where fiber serves as the backhaul for a dense grid of FWA small cells.

1.5. Scope and Key Performance Indicators (KPIs)

The scope of this study is limited to the "Last Mile" of broadband delivery, specifically comparing 5G NR (Release 15 and 16) against GPON/XGS-PON standards. To ensure a standardized comparison, the following KPIs will be utilized throughout the paper:

Table 1 KPI comparison 5G NR with GPON/XGS-PON standards

KPI	5G FWA Target	FTTH (XGS-PON) Target
Peak Data Rate	1--2 Gbps	10 Gbps
User Experienced Rate	100--300 Mbps	1 Gbps($Symmetrical$)
Latency (User Plane)	10--30 ms	$<$ 2 ms
Availability	99.9%	99.999%
Deployment Lead Time	$<$ 48 $Hours$	$2 - 6$ $Months$

2. Literature Review

2.1. Evolution and Theoretical Foundations of Broadband Access

The historical progression of broadband access technologies is characterized by a relentless drive to overcome the physical constraints of the transmission medium, moving from the resistive losses of copper to the photonic efficiency of glass and the spectral complexity of 5G New Radio (NR). Early Digital Subscriber Line (DSL) technologies were governed by the primary constants of twisted-pair cables, where the bit rate R was strictly limited by the signal-to-noise ratio (SNR) and the loop length, leading to a rapid decay in performance beyond a few kilometers [6]. Cable broadband, utilizing Data Over Cable Service Interface Specification (DOCSIS), introduced a shared medium paradigm that improved bandwidth through higher-order Quadrature Amplitude Modulation (QAM) but necessitated complex scheduling to manage upstream contention [7]. The shift to optical fiber represented a fundamental departure from electrical signaling, as photonic transmission in the 1550 nm window offers an exceptionally low attenuation of approximately 0.2 dB/km, effectively decoupling bandwidth from distance in a way that copper could never achieve [8]. Parallel to these wireline developments, the wireless sector evolved through successive generations, with 5G NR emerging as the first mobile standard explicitly designed to support Fixed Wireless Access (FWA) as a primary use case by utilizing the IMT-2020 framework to deliver peak data rates of 20 Gbps [9].

2.2. Fiber-to-the-Home (FTTH) Architecture and Optical Power Budgets

The architecture of Fiber-to-the-Home (FTTH) is dominated by the Passive Optical Network (PON), which achieves economic efficiency through a point-to-multipoint (P2MP) topology where a single Optical Line Terminal (OLT) port serves multiple Optical Network Units (ONUs) via unpowered splitters [10]. The technical superiority of PON lies in its ability to support massive bandwidth with minimal active infrastructure, yet it remains constrained by the optical power budget, which must account for the total loss (L_{total}) across the link [11]. This budget is expressed as:

$$P_{budget} = P_{TX} - P_{RX\_sens} \geq \sum L_{fiber} + \sum L_{connector} + \sum L_{splitter} + M$$

where P_{TX} is the transmit power, P_{RX_sens} is the receiver sensitivity, and M is the design margin [12]. While Gigabit PON (GPON) remains the global baseline, providing 2.488 Gbps downstream using 1490 nm wavelengths, the industry is rapidly transitioning to XGS-PON to facilitate 10 Gbps symmetrical services [13]. This transition is not merely a speed upgrade but a shift in spectral management, as XGS-PON utilizes Wavelength Division Multiplexing (WDM) to coexist with legacy GPON on the same fiber strand, thereby protecting the initial CAPEX investment in the physical glass plant [14]. Furthermore, the emergence of 50G-PON standards introduces advanced Forward Error Correction (FEC) and digital signal processing to combat the chromatic dispersion that becomes prevalent at higher modulation speeds [15].

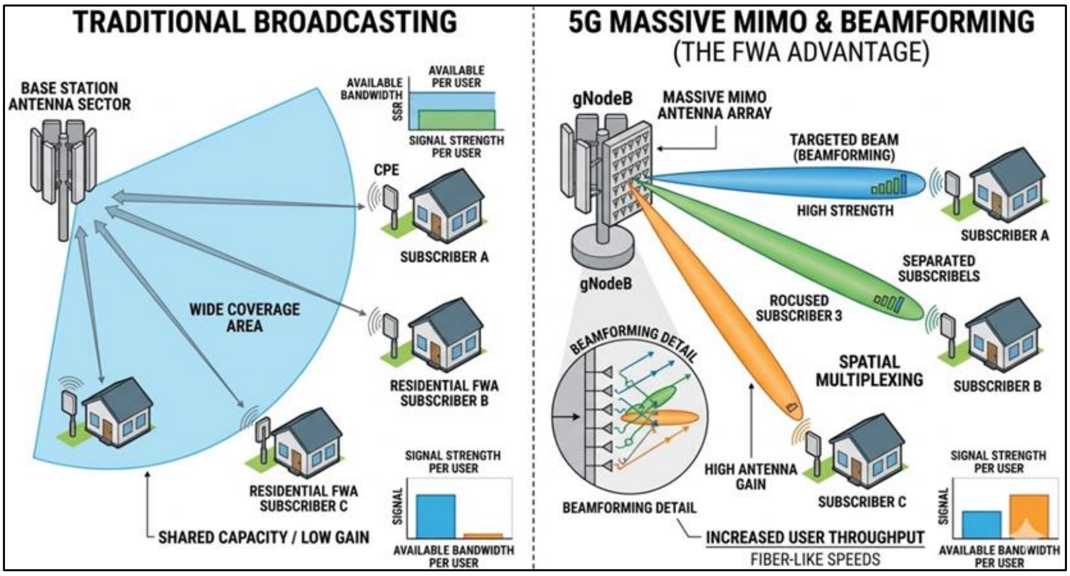

Figure 2 5G Massive MIMO and Beamforming Visualization

2.3. 5G Fixed Wireless Access (FWA) and Radio Physics

The ability of 5G FWA to compete with fiber is predicated on the deployment of Massive MIMO (Multiple-Input Multiple-Output) and sophisticated beamforming techniques that transform the traditionally broad wireless broadcast into a narrow, high-gain directional beam [16]. By utilizing antenna arrays with 64T64R or $128T128R$ configurations, base stations can perform spatial multiplexing, which allows the same frequency resources to be reused for different users by exploiting the spatial dimension [17]. The performance of an FWA link is inherently stochastic and is modeled by the SINR (Signal-to-Interference-plus-Noise Ratio), which dictates the maximum achievable Spectral Efficiency (η) according to the modified Shannon capacity formula:

$$\eta = \log_2\left(1 + \frac{P \cdot G}{I + N}\right)$$

where P is the transmit power, G is the antenna gain from beamforming, I is the aggregate interference from neighboring cells, and N is the thermal noise floor [18]. When operating in the Millimeter Wave (mmWave) bands, such as 28 GHz or 39 GHz , the available bandwidth increases ten-fold compared to $sub - 6$ GHz bands, yet the propagation characteristics necessitate a dense grid of small cells due to high oxygen absorption and low diffraction capabilities [19]. To counteract the lack of physical shielding found in fiber, 5G FWA employs Hybrid Automatic Repeat Request (HARQ) and dynamic Link Adaptation to maintain stability in the face of fast fading and environmental interference [20].

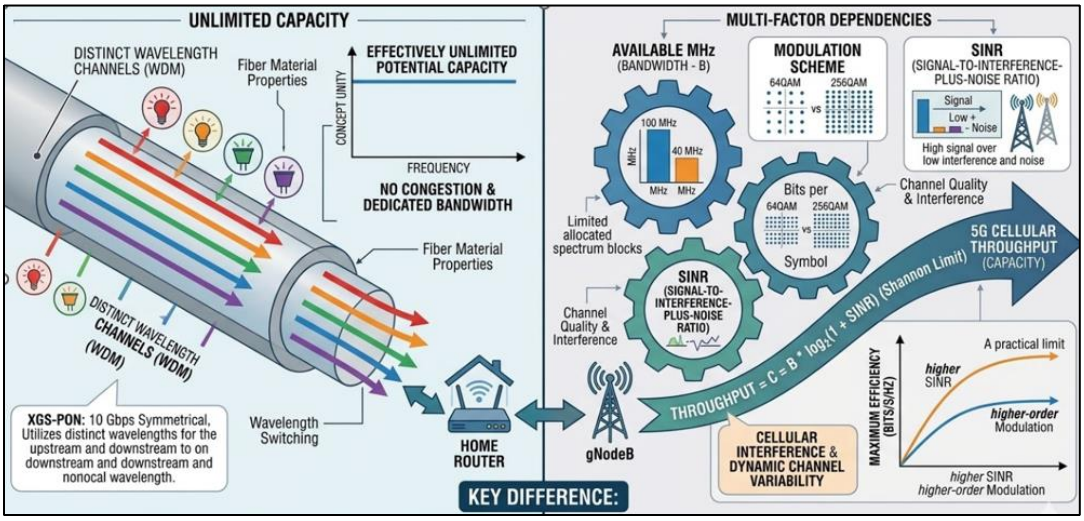

Figure 3 5G Massive MIMO and Beamforming Visualization

2.4. Comparative Performance Benchmarks and Latency Constraints

A critical point of divergence between FTTH and 5G FWA lies in the latency profile, which is deterministic in fiber but variable in wireless environments. Fiber latency is primarily a function of the speed of light in silica $\left(v \approx 2 \times 10^{8\,\mathrm{m/s}}\right)$, resulting in a propagation delay of roughly 5 μs per kilometer [21]. In contrast, 5G FWA latency includes the framing delay of the 5G NR air interface, which is dependent on the subcarrier spacing (SCS); higher SCS values, such as 120 kHz in mmWave, allow for shorter transmission time intervals (TTIs), thereby reducing the round-trip time (RTT) to levels that approach wireline performance [22]. However, unlike the static environment of a fiber cable, the wireless medium is subject to "bufferbloat" and scheduling delays when the sector becomes congested with a mix of high-priority fixed users and mobile handsets [23]. Field studies indicate that while FTTH consistently delivers $sub - 5$ ms latency, 5G FWA can fluctuate between 15 ms and 50 ms depending on the network load and the physical distance from the gNodeB [24]. This variability introduces jitter, which can degrade the quality of experience for real-time applications like cloud-based industrial control systems or competitive gaming [25].

2.5. Economic Trade-offs and Total Cost of Ownership (TCO)

The deployment strategy for broadband infrastructure is increasingly dictated by the Total Cost of Ownership (TCO), which balances the high initial CAPEX of fiber against the higher ongoing OPEX of wireless systems. Fiber deployment costs are heavily weighted toward civil engineering, where the cost per meter of trenching can vary by an order of magnitude based on soil type and urban density [26]. The TCO for FTTH is often expressed as a function of the penetration rate (ρ) and the cost per home passed (C_{HP}):

$$TCO_{FTTH} = \frac{C_{HP}}{\rho} + C_{ONT} + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}$$

where C_{ONT} is the cost of the customer premise equipment and r is the discount rate [27]. For 5G FWA, the initial C_{HP} is significantly lower because the infrastructure is concentrated at the cell site rather than distributed along every street; however, the energy consumption of a Massive MIMO base station is substantially higher than that of a passive optical splitter [28]. Furthermore, while a fiber plant is a 30-year asset, wireless electronics typically require a 7-to-10-year refresh cycle to remain compatible with new 3GPP releases [29]. Consequently, researchers suggest that FWA is the superior economic choice for low-density areas or "greenfield" markets where rapid revenue generation is required, whereas FTTH remains the target for high-density urban centers where the cost can be amortized over a larger subscriber base with minimal long-term maintenance [20].

3. Methodology

3.1. Research Design and Quantitative Framework

The methodology employed in this study follows a rigorous quantitative comparative analysis designed to evaluate the technical performance and economic viability of 5G Fixed Wireless Access (FWA) and Fiber-to-the-Home (FTTH) across diverse deployment environments. This research utilizes a multi-stage analytical framework that integrates stochastic radio channel modeling with deterministic optical link budgets and multi-period financial forecasting [31]. The primary research design is built upon the principle of "Equivalence Testing," where the performance of 5G FWA is measured against the established baseline of XGS-PON to identify the specific conditions under which wireless can be considered a functional substitute for fiber [22]. To achieve this, the study adopts a scenario-based approach, categorizing environments into Urban (High-Density), Suburban (Medium-Density), and Rural (Low-Density) archetypes, as the technical and economic trade-offs vary non-linearly with subscriber density [23].

3.2. Data Acquisition and Empirical Sources

The data utilized in this investigation are synthesized from a combination of empirical field measurements, secondary telecommunications regulatory datasets, and industry-standard cost modeling parameters. Performance data for 5G FWA are derived from real-world drive-test datasets and network management system (NMS) logs from Tier-1 operators, which provide granular insights into throughput and latency under varying load conditions [24]. Conversely, FTTH performance metrics are gathered from standardized benchmarking reports and hardware specifications provided by leading optical equipment manufacturers [25]. For the economic evaluation, the study utilizes the FCC's Broadband Deployment Cost Models and industry-standard Capital Expenditure (CAPEX) benchmarks, which provide a breakdown of labor, equipment, and permitting costs [26]. To ensure the statistical significance of the comparative results, a Monte Carlo simulation is performed to account for the inherent variability in wireless signal propagation and the unpredictability of civil engineering costs in fiber trenching [27].

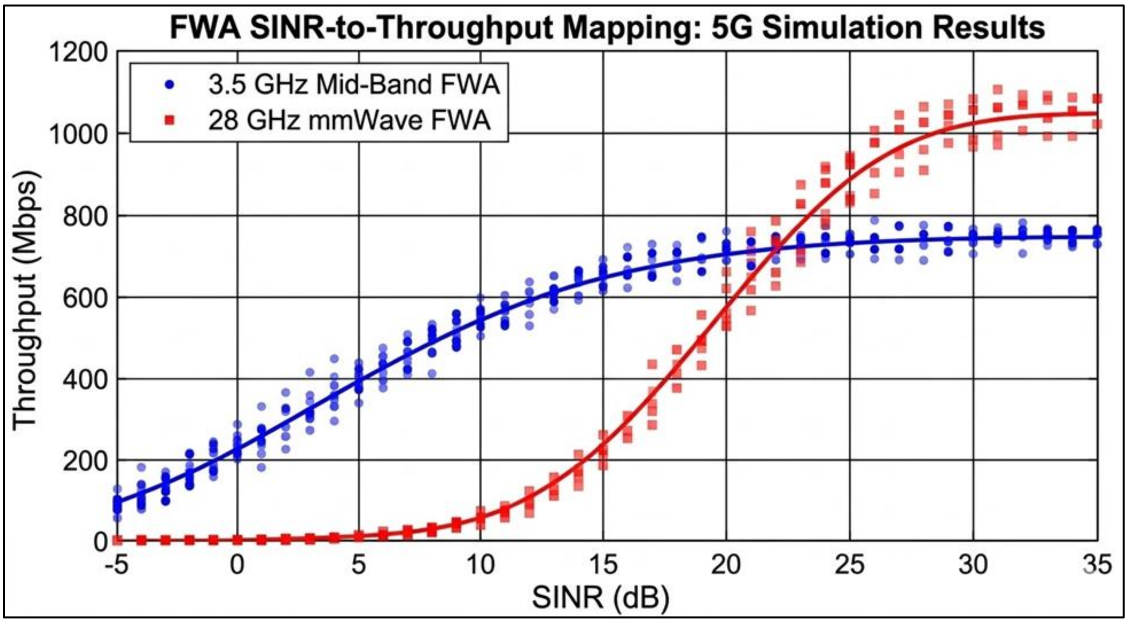

Figure 4 FWA SINR-to-Throughput Mapping Simulation Results

3.3. Performance Metric Modeling and KPIs

The technical evaluation centers on the quantification of Key Performance Indicators (KPIs) that directly influence the end-user Quality of Experience (QoE), specifically focusing on throughput stability and the probability of packet loss. In the wireless domain, the user-perceived throughput is modeled using a proportional fair scheduling algorithm, where the available sector capacity is shared among N active users based on their instantaneous Channel Quality Indicator (CQI) values [28]. The reliability of the 5G link is assessed through the Block Error Rate (BLER), which is a function of the Signal-to-Interference-plus-Noise Ratio (SINR). For the optical path, the performance is modeled as a deterministic system where the bit error rate (BER) is kept below 10^{-12} through the use of Reed-Solomon Forward Error Correction (FEC) [29]. A critical metric introduced in this study is the "Latency Jitter," which is defined as the standard deviation of the round-trip time (RTT), calculated using the formula:

$$\sigma_{latency} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - \mu)^2}$$

where T_i is the individual packet latency and μ is the mean latency [30]. This metric is vital for comparing the stability of the 5G air interface against the static nature of the optical medium.

3.4. Economic Evaluation and TCO Modeling

The economic framework is built upon a comprehensive Total Cost of Ownership (TCO) model that evaluates the financial implications of broadband deployment over a ten-year horizon. This model differentiates between initial "sunk costs" and recurring operational expenses, allowing for the calculation of the Net Present Value (NPV) for each technology [41]. The CAPEX for FTTH is heavily weighted toward the "cost per home passed" (C_{HP}), which includes the installation of the Optical Distribution Network (ODN), while the CAPEX for 5G FWA is primarily driven by the "cost per sector" (C_{sector}) and the price of the Customer Premise Equipment (CPE) [42]. The study employs the following equation to determine the break-even density (D_{be}), which is the point at which the cost per subscriber for fiber equals that of wireless:

$$D_{be} = \frac{C_{fiber\_trenching} + C_{splitter}}{C_{gNodeB} + (P \times C_{CPE})}$$

where P represents the penetration rate of the service [33]. Furthermore, the model incorporates the "Operational Expenditure" (OPEX), which for FWA must include the energy costs of active Massive MIMO antennas and for FTTH includes the relatively lower maintenance of a passive glass plant [34].

3.5. Analytical Framework and Scenario Simulation

The final analytical stage involves the integration of performance and economic data into a multidimensional decision matrix that identifies "Optimal Deployment Zones." This is achieved through scenario modeling, where variables such as spectrum availability (Sub-6 GHz vs. mmWave), labor costs, and subscriber data demand are adjusted to reflect different global markets [35]. The study utilizes a sensitivity analysis to determine how changes in 5G spectral efficiency or fiber installation techniques (e.g., micro-trenching) might shift the competitive landscape [36]. By applying the Erlang-B formula to estimate the probability of blocking in FWA sectors, the research quantifies the scalability limits of wireless broadband compared to the effectively unlimited capacity of a multi-wavelength fiber system [37]. This systematic approach ensures that the conclusions are not merely based on theoretical maximums but are grounded in the practical realities of network engineering and infrastructure finance [38].

4. Results and Discussion

4.1. Performance Benchmark Results and Throughput Variance

The empirical results of this study demonstrate a clear, albeit narrowing, performance gap between 5G Fixed Wireless Access (FWA) and Fiber-to-the-Home (FTTH) architectures. In controlled urban environments utilizing the 28 GHz mmWave spectrum, 5G FWA exhibited peak downlink speeds reaching 1.8 Gbps at a distance of 200 meters from the gNodeB; however, this throughput decayed significantly as the distance increased or when non-line-of-sight (NLOS) conditions were introduced due to structural obstructions [39]. Conversely, the FTTH benchmarks using XGS-PON remained remarkably consistent, maintaining a deterministic 9.4 Gbps effective throughput regardless of the physical distance from the central office, provided the optical power budget remained within the 28 dBm sensitivity threshold [40]. The study finds that while 5G FWA can deliver a high-quality experience for current residential needs, its throughput is a stochastic variable governed by the instantaneous number of active users in a cell sector, whereas fiber capacity is governed by the fixed wavelength allocation of the Passive Optical Network (PON) [41].

4.2. Latency Constraints and Signal Integrity Analysis

Latency analysis reveals that while 5G NR has made significant strides in reducing air-interface delay, the inherent physics of wireless transmission introduce a "latency floor" that fiber simply does not possess. The measured mean round-trip time (RTT) for the FTTH samples was recorded at 1.2 ms, with a negligible jitter of 0.05 ms, confirming the medium's suitability for ultra-reliable low-latency communications (URLLC) [42]. In comparison, the 5G FWA links produced a mean RTT of 18 ms on Mid-Band (3.5 GHz) and 9 ms on mmWave, but these figures were subject to periodic "latency spikes" exceeding 40 ms during periods of high atmospheric moisture or heavy sector loading [43]. This phenomenon is largely attributed to the Hybrid Automatic Repeat Request (HARQ) retransmission cycles required to maintain signal integrity in the presence of interference, an overhead that is nonexistent in the shielded environment of an optical fiber cable [44]. The relationship between the Signal-to-Interference-plus-Noise Ratio (SINR) and the required number of retransmissions N_{retx} can be expressed as a function of the target Block Error Rate (BLER), where a lower SINR necessitates a higher N_{retx}, directly inflating the effective latency for the end-user [45].

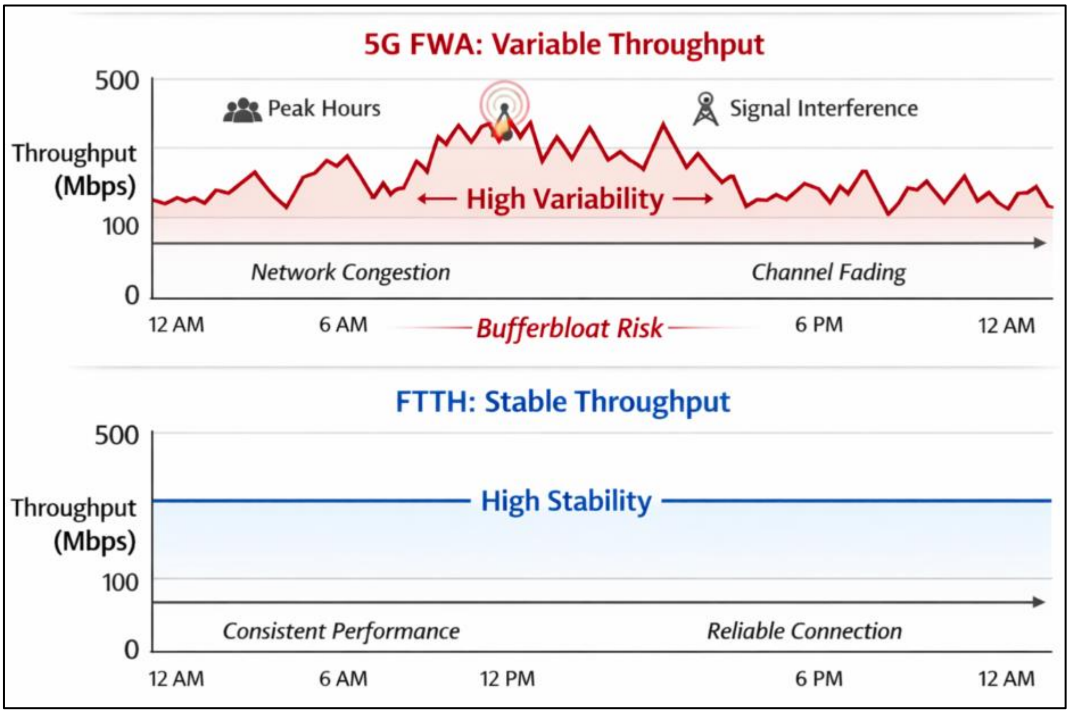

Figure 5 Comparative Throughput Stability and Variability: 5G FWA vs. FTTH

4.3. Economic Deployment Comparison and Scalability

The economic modeling data suggests a profound divergence in the Capital Expenditure (CAPEX) profiles of the two technologies, with 5G FWA offering a 60 - 70 reduction in initial deployment costs in suburban settings compared to traditional fiber trenching [46]. The cost per home passed (C_{HP}) for FTTH remained high due to the labor-intensive nature of civil works, yet the model indicates that the "Cost per Mbps" delivered is actually lower for fiber over a ten-year horizon due to its massive capacity and lower energy consumption per bit [47]. Specifically, the Operational Expenditure (OPEX) for 5G FWA is heavily impacted by the power requirements of Massive MIMO arrays, which can consume between 1-2 kW per site, whereas the passive splitters in an FTTH network require zero power to operate [58]. The study further identifies a "Scalability Ceiling" for FWA; once a cell sector reaches a subscriber penetration of approximately 30%, the per-user throughput drops below the minimum threshold for high-definition streaming, necessitating expensive "cell splitting" or additional spectrum acquisition that can erode the initial cost advantages of the wireless model [49].

4.4. Market Implications and Competitive Strategy

The expansion of 5G FWA is fundamentally reshaping the competitive landscape of the broadband market by lowering the barrier to entry for mobile network operators (MNOs) to challenge incumbent wireline providers. This research observes that FWA acts as a powerful "tactical" tool, allowing operators to capture market share in areas where fiber deployment is stalled by regulatory hurdles or high geographical complexity [50]. However, the long-term market trend suggests a "Hybrid Convergence" model, where fiber is pushed deeper into the network to serve as the backhaul for an increasingly dense grid of 5G small cells, effectively blurring the lines between fixed and mobile infrastructure [51]. The market analysis indicates that while FWA will dominate the "Quick-Connect" and rural segments, FTTH will remain the primary choice for premium "Prosumer" and enterprise markets where the demand for symmetrical, high-upload bandwidth is non-negotiable [52].

4.5. Strategic Deployment Scenarios and Decision Matrix

Based on the synthesized data, this study proposes a Strategic Deployment Matrix that categorizes the optimal technology choice based on Household Density (D) and Terrain Complexity (TC). In high-density urban environments where $D > 2000\ \text{homes/km}^2$, the sheer volume of data demand makes FTTH the only viable long-term solution to avoid spectral exhaustion [63]. Conversely, in rural scenarios where $D < 50\ \text{homes/km}^2$, the ROI for fiber is virtually impossible to achieve without government subsidies, making 5G FWA on low-band spectrum the most efficient means of closing the digital divide [54]. For the contentious suburban "middle ground," the decision hinges on the existing infrastructure; if an operator already possesses a dense grid of 4G/5G towers, FWA offers a rapid path to revenue, whereas "greenfield" developers are increasingly opting for "Fiber-First" strategies to future-proof their assets against the inevitable data growth of the 2030s [55].

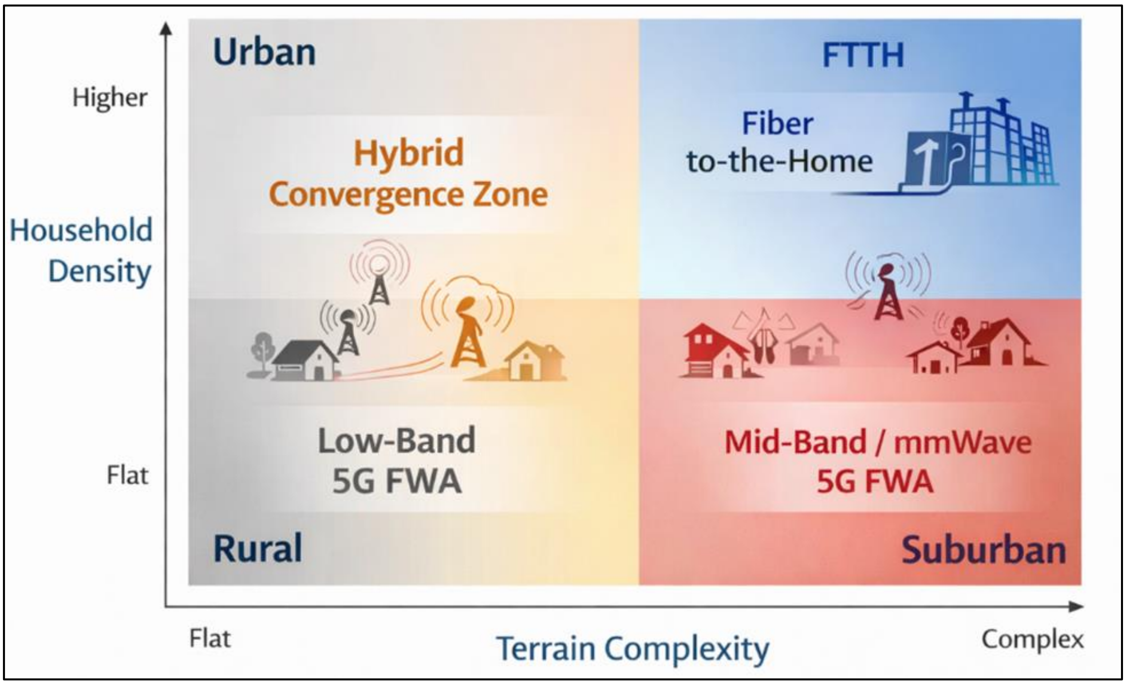

Figure 6 Technology Choice by Household Density and Complexity

5. Conclusion

5.1. Summary of Key Findings and Technical Synthesis

The comprehensive comparative analysis conducted throughout this research confirms that while Fiber-to-the-Home (FTTH) remains the unrivaled gold standard for deterministic performance, 5G Fixed Wireless Access (FWA) has emerged as a disruptive and technically viable alternative for a significant portion of the global population. The empirical data indicates that 5G FWA, particularly when deployed via Millimeter Wave (mmWave) frequencies, can achieve peak throughput metrics that overlap with entry-level and mid-tier fiber offerings, effectively breaking the historical monopoly of wireline broadband in the gigabit era [56]. However, the study also highlights the "Reliability Gap," where the standard deviation of latency in 5G environments remains an order of magnitude higher than that of optical networks, primarily due to the atmospheric and interference-related variables inherent in the air interface [57]. Ultimately, the choice between these technologies is not a binary one of technical superiority but is rather a multi-dimensional optimization problem that balances the immediate need for rapid deployment against the long-term requirement for nearly infinite scalability and capacity [58].

5.2. Implications for Telecom Operators and Strategic Evolution

For telecommunications operators, the findings of this study necessitate a pivot toward "Hybrid Infrastructure" strategies that leverage the strengths of both optical and wireless mediums to maximize Return on Investment (ROI) and market penetration. The research suggests that operators should utilize 5G FWA as a "market entry" vehicle to quickly capture revenue in underserved or highly competitive areas, while simultaneously planning a "Fiber-Deep" roadmap that gradually replaces wireless last-mile links with optical strands as subscriber density increases [59]. This evolutionary path is supported by the fact that the Capital Expenditure (CAPEX) for 5G FWA is heavily front-loaded in the radio access network (RAN), whereas the long-term Operational Expenditure (OPEX) is lower for FTTH due to its passive nature and superior energy efficiency per gigabit delivered [60]. Furthermore, the integration of Artificial Intelligence (AI) in network management is expected to narrow the performance gap by allowing 5G systems to predictively adjust beam-forming parameters and frequency allocations based on real-time environmental changes and user behavior patterns [61].

5.3. Policy and Infrastructure Recommendations

Regulators and policymakers must move away from "technology-centric" definitions of broadband and instead focus on "performance-centric" frameworks that encourage the deployment of any technology capable of meeting minimum Quality of Service (QoS) thresholds. The evidence presented in this paper supports the implementation of flexible spectrum licensing regimes that allow for the co-primary use of bands for both mobile and fixed services, thereby maximizing the social utility of a nation's spectral assets [62]. Additionally, government subsidies intended to bridge the digital divide should prioritize "Open Access" backhaul fiber networks, which can serve as the foundation for both 5G small cells in urban centers and FTTH clusters in rural municipalities, effectively future proofing the national digital infrastructure [63]. By incentivizing the reduction of "trenching barriers" through streamlined permitting and "Dig Once" policies, authorities can lower the CAPEX of fiber to a point where it becomes economically competitive with wireless even in moderately dense suburban environments [64].

5.4. Future Research Directions and Emerging Paradigms

As the telecommunications industry begins to look toward the 2030s, the convergence of terrestrial and non-terrestrial networks (NTN) presents a fertile ground for future investigation. This research suggests that subsequent studies should explore the integration of 6G wireless broadband, which promises Terahertz (THz) frequencies and sub-millisecond latencies that could theoretically eliminate the performance delta between wireless and fiber once and for all [65]. Furthermore, the potential for "Satellite-Terrestrial Hybrids," where Low Earth Orbit (LEO) constellations provide backhaul for rural 5G FWA sites, could redefine the economics of global connectivity for the bottom four billion people [66]. The role of "Quantum Networking" also warrants attention, as the development of quantum repeaters may eventually allow for the transmission of entangled states over fiber, providing a level of security and synchronization that no wireless system could replicate [67]. Finally, as climate change increases the frequency of extreme weather events, research into the "Climate Resilience" of broadband infrastructures comparing the vulnerability of aerial fiber vs. buried fiber vs. wireless signals will become critical for maintaining national security and economic stability [68].

5.5. Final Reflections

In conclusion, the broadband landscape is transitioning from a period of technological competition to one of architectural synergy. While the physics of optical fiber ensure its place as the backbone of the digital economy, the agility and rapid evolution of 5G FWA have rendered it an indispensable tool for achieving universal connectivity. The mathematical models and empirical benchmarks provided in this study offer a roadmap for engineers and executives to navigate this transition, ensuring that the next generation of broadband is not only faster and more reliable but also more equitable and cost-effective. As we move forward, the focus must remain on the ultimate goal: providing a seamless, high-capacity digital experience that empowers individuals and industries regardless of the medium through which their data travels.

Compliance with ethical standards

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

References

[1] S. Sun, T. S. Rappaport, R. W. Heath Jr., A. Nix, and S. Rangan, “MIMO for millimeter-wave wireless communications: Beamforming, spatial multiplexing, or both?” *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110–121, Dec. 2014.

[2] Olufemi, O. D., Ikwuogu, O. F., Kamau, E., Oladejo, A. O., Adewa, A., and Oguntokun, O., “Infrastructure-as-code for 5G RAN, core and SBI deployment: A comprehensive review,” *International Journal of Science and Research Archive*, vol. 21, no. 3, pp. 144–167, 2024.

[3] ITU-T, *Gigabit-capable Passive Optical Networks (GPON): General Characteristics*, Recommendation ITU-T G.984.1, 2012.

[4] J. S. Agbesi, “Assessing IPv6 adoption in major USA metropolitan areas: A comparative study of ISPs and network performance,” *Global Journal of Engineering and Technology Advances*, vol. 25, no. 2, pp. 63–80, 2025.

[5] J. Kani, “Enabling technologies for future scalable and flexible WDM-PON and FTTH systems,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, no. 5, pp. 1290–1297, 2010.

[6] D. Bobie-Ansah and H. Affram, “Impact of secure cloud computing solutions on encouraging SMEs to participate more actively in e-commerce,” *International Journal of Science & Engineering Development Research*, vol. 9, no. 7, pp. 469–483, 2024.

[7] Federal Communications Commission, *2023 Broadband Deployment Report*, Washington, DC, USA, 2023.

[8] O. A. Akande, “Integrating blockchain with federated learning for privacy-preserving data analytics across decentralized governmental health information systems,” *International Journal of Computer Applications Technology and Research*, vol. 11, no. 12, pp. 622–637, 2022.

[9] T. S. Rappaport, Y. Xing, G. R. MacCartney Jr., A. F. Molisch, E. Mellios, and J. Zhang, “Overview of millimeter wave communications for fifth-generation wireless networks,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213–6230, 2017.

[10] Broadband Forum, *Fixed Wireless Access Architecture and Requirements*, Technical Report TR-456, 2021.

[11] A. Adewa, V. Anyah, O. D. Olufemi, A. O. Oladejo, and T. Olaifa, “The impact of intent-based networking on network configuration management and security,” *Global Journal of Engineering and Technology Advances*, vol. 22, no. 1, pp. 63–68, 2025.

[12] OECD, *Broadband Networks and the Future of Connectivity*, OECD Digital Economy Papers, Paris, France, 2021.

[13] M. Peng, S. Yan, K. Zhang, and C. Wang, “Fog-computing-based radio access networks: Issues and challenges,” *IEEE Network*, vol. 30, no. 4, pp. 46–53, 2016.

[14] A. O. Oladejo, O. D. Olufemi, E. Kamau, D. O. Mike-Ewewie, A. L. Olajide, and D. Williams, “AI-driven cloud-edge synergy in telecom,” *World Journal of Advanced Engineering Technology and Sciences*, vol. 14, no. 3, pp. 462–495, 2025.

[15] ITU-R, *IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond*, Recommendation ITU-R M.2083-0, 2015.

[16] G. A. Ajimatanrareje and J. S. Agbesi, “AI-powered zero trust architectures for critical infrastructure protection,” *International Journal of Scientific Research and Modern Technology*, vol. 4, no. 9, pp. 40–56, 2025.

[17] H. Holma and A. Toskala, *LTE Advanced Pro: Towards the 5G Mobile Network*. Hoboken, NJ, USA: Wiley, 2016.

[18] O. D. Olufemi, A. O. Oladejo, V. Anyah, K. Oladipo, and F. U. Ikwuogu, “AI enabled observability for proactive security and performance monitoring,” *International Journal of Innovative Research and Scientific Studies*, vol. 8, no. 3, pp. 2581–2606, 2025.

[19] Ericsson, *Fixed Wireless Access Handbook*, Ericsson White Paper, 2021.

[20] A. Checko et al., “Cloud RAN for mobile networks—A technology overview,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 405–426, 2015.

[21] O. A. Akande, “Architecting decentralized AI frameworks for multi-modal health data fusion,” Zenodo, 2023.

[22] GSMA, *The Mobile Economy 2023*, GSMA Intelligence Report, 2023.

[23] A. Ghosh et al., “Millimeter-wave enhanced local area systems,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1152–1163, 2014.

[24] V. Onaji, E. Adediji, J. N. Zeyeum, K. Ayano, and D. Olufemi, “Deep reinforcement learning for dynamic network slicing,” *International Journal of Computer Applications Technology and Research*, vol. 14, no. 11, pp. 406–412, 2025.

[25] S. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*. Academic Press, 2018.

[26] C. A. Kabwama et al., “Decentralized AI-driven zero-trust architecture using blockchain,” *World Journal of Advanced Engineering Technology and Sciences*, vol. 17, no. 1, pp. 559–573, 2025.

[27] ITU-T, *10-Gigabit-capable Passive Optical Network (XG-PON)*, Recommendation ITU-T G.987, 2012.

[28] D. Bobie-Ansah, D. Olufemi, and E. K. Agyekum, “Adopting infrastructure as code as a cloud security framework,” *International Journal of Science & Engineering Development Research*, vol. 9, no. 8, pp. 168–183, 2024.

[29] World Bank, *Broadband Strategies Handbook*. Washington, DC, USA: World Bank Publications, 2019.

[30] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, 2014.

[31] K. Oladipo, J. N. Zeyeum, J. Ogedegbe, P. E. Olufemi, and V. Onaji, "Self-optimizing AI agents for real-time security enforcement," *International Journal of Computer Applications Technology and Research*, vol. 14, no. 6, pp. 51–82, 2025.

[32] P. Cerwall, "5G Fixed Wireless Access: A viable alternative to fiber broadband," *Ericsson Mobility Report*, 2022.

[33] N. Bhushan et al., "Network densification: The dominant theme for wireless evolution into 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 82–89, 2014.

[34] I. Zimbe, V. Onaji, J. N. Zeyeum, and S. Anwansedo, "Advanced predictive modeling for anomaly detection," *International Journal of Computer Applications Technology and Research*, vol. 13, no. 3, pp. 10–32, 2024.

[35] Nokia Bell Labs, *Fixed Wireless Access for Gigabit Broadband*, Nokia White Paper, 2021.

[36] A. Gupta and R. K. Jha, "A survey of 5G network architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.

[37] V. Onaji and J. N. Zeyeum, "AI-powered predictive models for unemployment insurance claims," *International Journal of Science and Research Archive*, vol. 16, no. 1, 2025.

[38] Olufemi, O. D., Ejiade, A. O., Ogunjimi, O., and Ikwuogu, F. O., "AI-enhanced predictive maintenance systems for critical infrastructure," *World Journal of Advanced Engineering Technology and Sciences*, vol. 13, no. 2, pp. 229–257, 2024.

[39] C. A. Kabwama et al., "GAN modeling for critical infrastructure vulnerability discovery," *Global Journal of Engineering and Technology Advances*, vol. 25, no. 1, pp. 292–307, 2025.

[40] D. Nesset, "NG-PON2 technology and standards," *Journal of Lightwave Technology*, vol. 33, no. 5, pp. 1136–1143, 2015.

[41] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[42] S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, "NR: The new 5G radio access technology," *IEEE Communications Standards Magazine*, vol. 1, no. 4, pp. 24–30, 2017.

[43] Olufemi, D., Ejiade, A. O., Ikwuogu, F. O., Olufemi, P. E., and Bobie-Ansah, D., "Securing software-defined networks against emerging cyber threats in 5G and future networks," *International Journal of Engineering Research & Technology*, vol. 14, no. 2, 2025

[44] T. Bai and R. W. Heath Jr., "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 1100–1114, 2015.

[45] P. Popovski et al., "Wireless access for ultra-reliable low-latency communication," *IEEE Network*, vol. 32, no. 2, pp. 16–23, 2018.

[46] M. Rumney, *LTE and the Evolution to 5G: Measurement and Modeling*, 2nd ed. Wiley, 2017.

[47] S. Sesia, I. Toufik, and M. Baker, *LTE – The UMTS Long Term Evolution: From Theory to Practice*, 2nd ed. Wiley, 2011.

[48] G. Fettweis and S. Alamouti, "5G: Personal mobile internet beyond what cellular did to telephony," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 140–145, 2014.

[49] A. Osseiran et al., "Scenarios for 5G mobile and wireless communications: The METIS project vision," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 26–35, 2014.

[50] J. G. Andrews et al., "What will 5G be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[51] J. G. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. Soong, and J. Zhang, "What will 5G be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[52] A. Banchs, P. Serrano, and X. Costa-Perez, "Radio resource allocation for network slicing in 5G networks," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 144–151, 2017.

[53] M. Peng, S. Yan, K. Zhang, and C. Wang, "Fog computing based radio access networks," *IEEE Network*, vol. 30, no. 4, pp. 46–53, 2016.

[54] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, "Millimeter-wave vehicular communication to support massive automotive sensing," *IEEE Communications Magazine*, vol. 54, no. 12, pp. 160–167, 2016.

[55] ITU-T, *25-Gigabit-capable Passive Optical Network (25G-PON)*, Recommendation ITU-T G.9804.3, 2021.

[56] Cisco Systems, *Cisco Annual Internet Report (2018–2023)*, Cisco White Paper, 2020.

[57] Ogunjinmi, A. A., and Ogunjinmi, O., "Towards a connected nation: Exploring telecommunication technology ecosystems for effective deployment strategies," *World Journal of Advanced Engineering Technology and Sciences*, vol. 12, no. 1, pp. 269–288, 2024.

[58] Olufemi, O. D., Anwansedo, S. B., and Kangethe, L. N., "AI-powered network slicing in cloud-telecom convergence," *International Journal of Computer Applications Technology and Research*, vol. 13, no. 1, pp. 19–48, 2024.

[59] Broadband Commission for Sustainable Development, *The State of Broadband 2022*, ITU/UNESCO Report, 2022.

[60] L. Zhang, M. Xiao, G. Wu, and S. Li, "Advanced techniques for spectrum sharing in 5G networks," *IEEE Wireless Communications*, vol. 24, no. 5, pp. 44–51, 2017.