

Review

Toward Network-Managed 5G Fixed Wireless Access: Technologies, Challenges, and Future Directions

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Abstract

The increasing digitalization of industrial ecosystems under the Industrial Revolution 4.0 has intensified the demand for fast, reliable, and inclusive broadband connectivity. The expansion of 5G technology led by data-driven services addresses the growing demand for high-capacity, low-latency communication through Fixed Wireless Access (FWA) as a cost-effective broadband solution. FWA is a wireless broadband access technology that provides high-speed connectivity to fixed locations using 5G New Radio (NR) infrastructure instead of physical fiber networks, while reducing deployment time and infrastructure investment. This review examines the technical challenges, economic business implications, and comparative performance of 5G FWA relative to other broadband technologies. It also examines the implementation of Enhanced Telecom Operations Map (eTOM) in several telecommunication network functions. The analysis indicates that successful 5G FWA implementation requires not only technical optimization, but also the adaption of standardized, scalable, and AI-driven network management practices. Emphasis is placed on the role of the eTOM as a structured framework for aligning technical, operational, and organizational processes in FWA deployment. This review highlights how eTOM can support readiness assessment, process harmonization, and lifecycle management to ensure consistent and efficient service delivery. This study provides a comprehensive reference for researchers and industry stakeholders in developing sustainable and future-ready 5G FWA networks.

Keywords: 5G; 5G NR; fixed wireless access; eTOM; network management

1. Introduction

Providing digital infrastructure is an urgent need to support the acceleration of digital transformation. The presence of 5G technology is designed to accommodate the surge in data growth and connectivity needs of modern society, including the implementation of the Internet of Things (IoT) with billions of interconnected devices, as well as various future technological innovations. This is in line with the direction of the Industrial Revolution 4.0, which will form the foundation of intelligent systems and human-critical networks, by leveraging high data value, device density, instant communication, low-latency network performance and massive connectivity [1,2]. The emergence of 5G opens up strategic opportunities to accelerate digital transformation, one of which is through the implementation of 5G Fixed Wireless Access (FWA), which provides an alternative high-speed connectivity service without having to rely on complex fiber optic cable infrastructure [3]. Fixed broadband infrastructure, particularly fiber-to-the-home (FTTH), still faces challenges in the form



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of high investment costs (CAPEX), long implementation times, and limited feasibility in rural or underserved areas [4,5]. The International Telecommunication Union (ITU) emphasizes that universal broadband access is an important factor in supporting sustainable development goals, so innovative access solutions are needed [4].

Early broadband access technologies evolved through multiple wireless networking paradigms prior to the emergence of modern 5G Fixed Wireless Access (FWA). Wireless local area networking technologies such as Wi-Fi (IEEE 802.11) were initially developed to provide flexible wireless connectivity in indoor environments and have since become one of the most widely adopted access technologies supporting residential, enterprise, and public network connectivity [6]. To extend broadband connectivity over larger geographical areas, wireless metropolitan access technologies such as WiMAX (IEEE 802.16) were introduced to provide high-speed wireless access networks capable of supporting both fixed and mobile users over several kilometers [7]. In addition to radio-frequency wireless technologies, optical wireless communication systems such as Free Space Optical (FSO) communication have been investigated as high-capacity communication solutions that utilize the optical spectrum to support high data rates while complementing RF-based wireless networks where spectrum resources are limited [8]. The complementary characteristics of wireless and optical communication technologies have therefore motivated hybrid broadband access architectures aimed at improving network scalability, capacity, and coverage in next-generation access infrastructures [7]. The continued evolution of these technologies has ultimately led to modern Fixed Wireless Access paradigms, where wireless communication links are used to provide last-mile broadband connectivity, particularly in areas where deploying wired infrastructure such as DSL, cable, or optical fiber is economically challenging [9].

In this context, 5G Fixed Wireless Access (FWA) has emerged as a promising alternative to fiber networks, offering near-fiber performance, lower costs, and faster deployment times. Fifth-generation New Radio (NR) technologies such as Massive MIMO, millimeter-wave (mmWave) spectrum, network slicing, and ultra-reliable low-latency communications (URLLCs) enable FWA to deliver high data rates, low latency, and service flexibility [10–14]. Fifth-generation FWA connections are expected to reach around 280 million by 2029, or nearly 85 percent of total FWA connections. Ericsson reports that, by the end of 2023, FWA data traffic reached 19 percent of total global mobile data traffic and is projected to grow more than five-fold to nearly 159 EB by 2029, equivalent to 30 percent of total mobile data traffic. In the Asia-Pacific (APAC), the number of FWA connections is expected to triple, bringing FWA's global contribution to over 45 percent by 2029 [12].

Research on 5G Fixed Wireless Access (FWA) has become a crucial area of study due to its potential to provide high-speed broadband connectivity to underserved urban and rural areas. This technology offers an efficient solution to bridge the digital divide and meet the growing demand for data-intensive services, such as high-quality video streaming, cloud computing services, the Internet of Things (IoT), and automation-based industrial applications. With these capabilities, FWA plays a strategic role in promoting digital inclusivity, expanding equitable access to information, and accelerating the transformation towards a digital society and knowledge-based economy in the 5G era [15–17]. From a technical perspective, FWA utilizes sub-6 GHz and millimeter wave (mmWave) frequency bands to deliver multi-gigabit speeds in line-of-sight (LoS) conditions, and uses adaptive beamforming algorithms and edge computing to extend coverage in non-line-of-sight (NLoS) conditions [11,14,18–20]. By implementing dynamic spectrum allocation and artificial intelligence (AI)-based radio planning, the 5G FWA system can achieve gigabit-class performance even under complex interference conditions [21]. Other research also shows that antenna optimization and the implementation of a Self-Organizing Network (SON)

system enables FWA broadband services to have consistent quality and be equivalent to fixed-grade broadband [22].

A number of techno-economic studies show that 5G FWA is cost-competitive against fiber, especially in suburban and semi-urban areas [23–25]. However, the development of 5G FWA technology faces several challenges. From a technical perspective, frequency spectrum scarcity and selection are crucial factors in determining network performance, service coverage, and implementation feasibility, as well as directly impacting service implementation costs and potential revenue for service operators [26–28]. The issue of frequency spectrum limitations is also an issue. The mmWave band offers high capacity but has limited signal coverage meaning that its transmission distance is relatively short and highly sensitive to physical obstructions. In contrast, the sub-6 GHz band provides a greater signal coverage range, enabling transmission over longer distances, although it is often congested and subject to strict regulatory constraints [14,16].

From an economic perspective, operators face uncertainty regarding return on investment (ROI), high costs of customer premises equipment (CPE), and the risk of market adoption leading to customer crises (churn) [15,29,30]. From an organizational perspective, FWA implementation must be integrated with existing Operational Support Systems (OSSs) and Business Support Systems (BSSs), and comply with national regulations [31,32]. To overcome these multifaceted challenges, telecommunications operators must adopt a well-defined competitive strategy supported by a robust business process framework that effectively aligns technological implementation with overarching business goals [33].

Although an increasing number of studies have investigated 5G Fixed Wireless Access (FWA) with emphasis on physical-layer technologies, radio network planning, and performance enhancement, most contributions treat technical, economic, and operational dimensions as isolated topics [11,18,34,35]. Integrated surveys that jointly examine system architecture, deployment strategies, performance characteristics, techno-economic considerations, and standardized network management practices remain scarce. Furthermore, the application of established business process frameworks, such as the Enhanced Telecom Operations Map (eTOM), to structure the operational lifecycle of 5G FWA networks, has not received attention in current research. To bridge this gap, this paper provides an integrated review of 5G FWA encompassing technical foundations, deployment aspects, key challenges, and further proposes an eTOM-based network management framework to structure network operations and service lifecycle management. By combining engineering-oriented analysis with standard business process modeling, this study provides a holistic perspective that goes beyond conventional performance-centric reviews.

The deployment and evolution of 5G Fixed Wireless Access (FWA) must account for heterogeneous levels of technical and organizational readiness among Mobile Network Operators (MNOs). Differences in infrastructure capability, spectrum holdings, and investment strategies directly affect the feasibility, scale, and sustainability of 5G FWA implementations. In response to these challenges, the integration of techno-economic modeling with the eTOM business process framework is expected to enable the development of a Network Management Framework for 5G FWA that is not only technically and economically efficient, but also capable of supporting accelerated digital inclusion and reducing the digital divide between urban and rural areas. The purpose of this review is to critically examine the technical challenges, economic business implications, and comparative performance of 5G FWA relative to other broadband technologies. By synthesizing recent empirical and theoretical studies, this review aims to fill identified knowledge gaps and offer actionable insights for stakeholders involved in broadband policy, deployment, and research. This paper presents an integrated review related to 5G Fixed Wireless Access. The study's primary focus covers four key dimensions:

1. Technology and infrastructure perspective;
2. Deployment technique and performance evaluation;
3. Challenges in technical, regulatory and economic business approaches;
4. Future direction and network management framework.

The remainder of this paper is organized as follows. Section 2 provides an overview of the technology, infrastructure and evolution of 5G Fixed Wireless Access (FWA), including system architecture, comparison with alternative broadband solutions, and key enabling technologies. Section 3 presents a comprehensive analysis of deployment strategies and performance evaluations reported in recent studies, covering various network scenarios. Section 4 discusses the main opportunities and challenges of real-world applications of 5G FWA in supporting digital inclusion and its development, especially related to technical challenges, spectrum regulatory challenges, and economic-business challenges. Section 5 discusses the future development of 5G FWA related to telecommunications technology automation and network management frameworks containing autonomous and AI-based network operations as well as the evolution toward sixth generation (6G) wireless systems is expected to further enhance the role of Fixed Wireless Access (FWA) as a key broadband delivery mechanism. Finally, Section 6 concludes the paper by summarizing the main findings and providing strategic insights for researchers, policymakers, and industry stakeholders involved in 5G FWA broadband deployment.

2. Technology and Infrastructure Perspective

Fixed Wireless Access (FWA) has evolved from early 4G LTE-based fixed broadband solutions into a key use case of 5G New Radio (NR) networks, enabling high-speed, low-latency connectivity comparable to fiber broadband. Between 2020 and 2025, several operators initiated commercial deployments of 5G FWA, leveraging enhanced radio capacity, beamforming, and wider bandwidths to deliver speeds exceeding 1 Gbps [21,22,36–38]. The transition from 4G LTE FWA to 5G NR is characterized by the adoption of millimeter-wave (mmWave) bands, massive multiple-input–multiple-output (MIMO), and advanced network management through SDN and NFV [39–41].

2.1. Fifth-Generation FWA System Architecture

The architecture of 5G Fixed Wireless Access (FWA) systems represents an evolution of traditional broadband delivery models, integrating the flexibility of wireless access with the performance characteristics of fixed networks. The overall FWA system architecture consists of three primary components: the core network, the radio access network (RAN), and customer premises equipment (CPE) [21,42,43]. Fifth-Generation Fixed Wireless Access (FWA) leverages the standardized 5G system architecture defined by 3GPP, rather than introducing a new architectural framework. The system consists of the 5G Core (5GC), the radio access network (gNodeB), and the Customer Premises Equipment (CPE), which operates as stationary User Equipment (UE) connected via the standard 5G NR interface. From an architectural perspective, no additional network functions or interfaces are introduced specifically for FWA deployment. The main distinction lies in the deployment model, where wireless access replaces fiber-based last-mile connectivity to deliver fixed broadband services. Figure 1 illustrates this deployment-level view, adapted from GSMA TS.64, showing how the FWA device integrates residential gateway functionality while remaining fully aligned with the standardized 3GPP 5G framework [44].

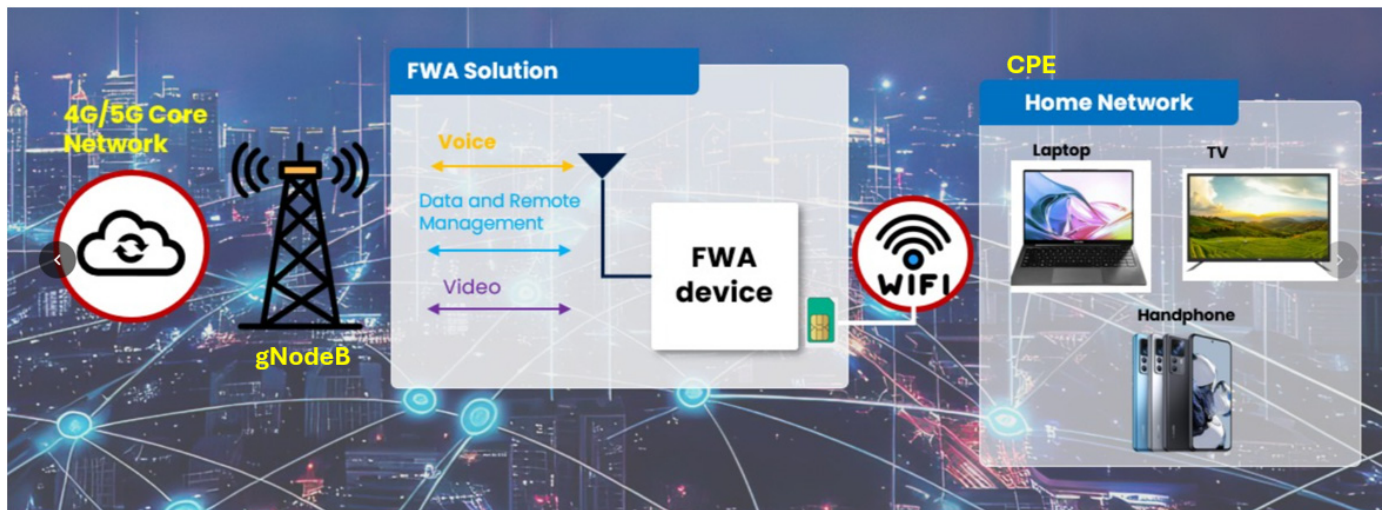


Figure 1. Fifth-Generation Fixed Wireless Access (FWA) leverages the standardized 5G system architecture defined by 3GPP. Adapted from [44].

Topyan et al. [30] propose two alternative architectural designs and outline the potential components associated with each. Both alternatives referred to as Alternative A and Alternative C offer a rapid, cost-efficient, and relatively simple approach for market entry. These models assume that the underlying infrastructure is already owned by the same organization. Several other papers also discuss the 5G FWA architecture, using 5G Core and 5G NR as wireless components that will be connected to the CPE on the customer side. The customer network can take the form of a microsite, macro site, or small cell [21,45,46]. Ndikumana et al. [47] introduce a 5G FWA architecture powered by renewable energy and based on Open RAN technology to serve Low-Density and Rural Areas (LDRA) through a three-level closed-loop framework. The Open RAN approach represents an emerging 5G RAN architecture that enables the deployment of Open Central Units and Open Distributed Units within a virtualized environment.

At the end of the customer, the FWA CPE functions as a fixed endpoint connecting to the 5G base station and providing local connectivity via Wi-Fi 6/6E or Ethernet interfaces [42]. The deployment architecture may follow either a non-standalone (NSA) configuration, leveraging existing 4G EPC for control signaling, or a standalone (SA) configuration that fully utilizes the 5G core capabilities for optimized latency and QoS management [45,48]. Advanced features such as integrated access and backhaul (IAB) have been introduced to enhance deployment efficiency, enabling small cells to use 5G radio links as both access and backhaul channels, thus minimizing the need for wired infrastructure. Moreover, network slicing and edge computing integration within the 5G FWA architecture allow operators to deliver differentiated service tiers and reduce latency for time-sensitive applications. Consequently, 5G FWA not only serves as a cost-effective broadband solution but also as a foundational enabler for digital transformation and fixed-mobile convergence strategies across residential and enterprise markets [49].

2.2. Comparison with Alternative Broadband Solution

Broadband connectivity can be delivered through multiple access technologies, each with distinct architectural principles, transmission media, and performance characteristics. Besides 5G Fixed Wireless Access (FWA), other major broadband technologies include Digital Subscriber Line (DSL), satellite-based broadband, Hybrid Fiber-Coaxial (HFC), and fiber-based solutions such as Fiber-to-the-Home (FTTH) and Gigabit Passive Optical Network (GPON). Each of these technologies represents a different evolutionary stage in broadband development ranging from legacy copper and coaxial systems to high-

capacity optical and next-generation wireless architectures. As illustrated in Figure 2, these technologies exhibit substantial differences in achievable data rates, latency, and scalability, forming a performance spectrum that extends from sub-100 Mbps to multi-gigabit and even tens-of-gigabit speeds [36,45,50,51].

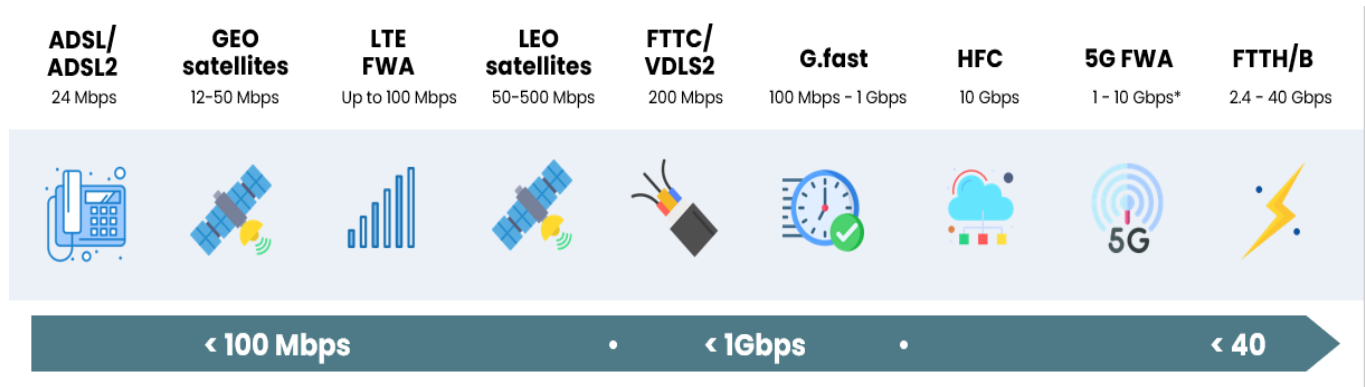


Figure 2. Fixed broadband technologies and average download speeds. Adapted from [37]. (*) means that The data rate represents theoretical peak performance of 5G FWA and may vary depending on spectrum, network deployment, and environmental conditions.

Legacy broadband systems such as Asymmetric Digital Subscriber Line (ADSL/ADSL2) typically deliver downstream rates up to 24 Mbps, constrained by copper loop attenuation and distance limitations [51]. Satellite-based broadband, particularly those relying on geostationary (GEO) satellites, offer speeds between 12 and 50 Mbps but suffer from high latency due to long propagation paths [52]. More recent innovations, such as LTE-based FWA, provide up to 100 Mbps using existing cellular infrastructure, while LowEarth Orbit (LEO) satellite systems can achieve 50–500 Mbps with reduced latency owing to lower orbital altitudes [53]. Copper-extended technologies like Fiber-to-the-Cabinet (FTTC) or VDSL2 reach 200 Mbps [54,55] and G.fast can deliver up to 1 Gbps over short distances [56–58]. Hybrid Fiber-Coaxial (HFC) systems, supported by DOCSIS 3.1/4.0 standards, enable downstream speeds up to 10 Gbps but still rely on shared coaxial segments, leading to potential congestion and variable latency under high demand [59,60]. A complete explanation of the overall comparison of these technologies can be seen in Table 1.

Table 1. Comparative Performance of Broadband Access Technologies.

Technology	Typical Data Rate	Latency	CAPEX Requirement	Deployment Time	Area Suitability	References
ADSL/ADSL2	Up to 24 Mbps	20–40 ms	Very low (existing copper)	Short	Urban/suburban (legacy)	[36,45,50]
GEO Satellite	12–50 Mbps	>500 ms	Moderate–high	Medium	Remote/rural (wide coverage, high latency)	[53]
LEO Satellite	50–500 Mbps	20–40 ms	High	Medium	Remote/maritime/Rural	[53]
LTE FWA	Up to 100 Mbps	20–50 ms	Moderate	Short	Suburban/semi-rural	[36,42]
FTTC/VDSL2	Up to 200 Mbps	10–20 ms	High	Medium–long	Urban/dense Suburban	[54]
G.fast	100 Mbps–1 Gbps	5–10 ms	High	Long	Urban (short copper loop)	[53,56]
HFC (DOCSIS 3.1/4.0)	Up to 10 Gbps	10–30 ms	High	Long	Urban/suburban	[60]
5G FWA (Sub-6 GHz/mmWave)	1–10 Gbps	1–10 ms	Moderate	Short	Urban/suburban/rural (depending on spectrum)	[12,21,26,38,61]
FTTH/XGS-PON	2.4–40 Gbps	<1 ms	Very high	Very long	Urban/high-demand areas	[62]

5G Fixed Wireless Access (FWA) represents a paradigm shift in broadband delivery, offering competitive performance metrics that challenge traditional wired solutions while addressing unique deployment scenarios. Performance analysis reveals that 5G FWA can deliver throughput ranging from tens of megabits per second to several gigabits per second, depending on spectrum allocation and deployment configuration [12,26,42]. This performance envelope positions 5G FWA as a viable alternative to fiber-to-the-home (FTTH), particularly in scenarios where fiber deployment faces economic or logistical constraints. In contrast, 5G FWA bridges the gap between fixed and wireless access by offering data rates from 1 to 10 Gbps through sub-6 GHz and millimeter-wave (mmWave) spectrum bands, combined with network slicing, edge computing, and low-latency capabilities [13,63].

At the upper end of the broadband hierarchy, FTTH and XGS-PON architectures deliver symmetric throughput from 2.4 Gbps up to 40 Gbps, representing the current benchmark for ultra-high-capacity fixed broadband [61,64]. The comparative range depicted in Figure 2 thus underscores the strategic positioning of 5G FWA as a transitional and complementary solution—providing near-fiber performance with lower capital expenditure and faster deployment timelines, particularly in suburban and rural markets where full fiber rollout remains economically challenging [22,48].

2.3. Key Enabling Technologies for 5G FWA

The performance, scalability, and efficiency of 5G Fixed Wireless Access (FWA) systems are determined by a combination of enabling technologies that jointly optimize throughput, flexibility, and latency. These include Massive MIMO and hybrid beamforming at the physical layer, Software-Defined Networking (SDN), Network Function Virtualization (NFV), and network slicing at the management and control layers, and Multi-access Edge Computing (MEC) at the service layer [26,61]. Collectively, these innovations establish the foundation for high-performance, adaptive broadband access that bridges the gap between fixed and mobile networks. The explanation of each key technology is as follows:

1. Massive MIMO and Hybrid Beam Forming.

Massive MIMO leverages large-scale antenna arrays to improve spectral efficiency and link robustness through spatial multiplexing. It enables multiple simultaneous transmissions over the same spectrum, thereby enhancing network capacity without additional bandwidth [65]. In mmWave-based FWA, hybrid beamforming combines analog and digital precoding to reduce hardware cost and energy consumption while maintaining beam accuracy [66–68]. This architecture mitigates propagation losses and improves coverage continuity critical for suburban and dense-urban 5G FWA deployments [39,69]. Together, these technologies enhance throughput, extend coverage, and reduce interference, enabling 5G FWA to achieve near-fiber performance levels in dense urban and suburban areas [39].

2. SDN, NFV, and Network Slicing.

At the network management layer, SDN and NFV enable dynamic orchestration and programmable control, allowing operators to virtualize network functions and reduce dependency on proprietary hardware. SDN separates the control and data planes, while NFV hosts virtualized network functions (VNFs) such as firewalls and gateways on general-purpose servers [70,71]. When integrated with network slicing, these technologies allow the logical partitioning of a single physical infrastructure into multiple virtual networks tailored to specific service types such as enhanced Mobile Broadband (eMBB), ultra-reliable low-latency communication (uRLLC), or fixed broadband access [72]. This architecture ensures optimized resource allocation and end-to-end Quality of Service (QoS) for different customer segments, ranging from residential users to enterprise and industrial clients [73,74]. When coupled with network slicing, operators can logically partition

network resources into service-specific slices, ensuring differentiated QoS for various applications such as residential broadband, industrial IoT, and enterprise VPNs. This approach supports adaptive resource allocation and service orchestration in heterogeneous traffic environments [72].

3. Edge Computing Integration.

At the network edge, Multi-access Edge Computing (MEC) reduces latency by processing data closer to end users. MEC nodes host localized content caching, AI-based analytics, and low-latency applications, minimizing backhaul congestion [75,76]. In 5G FWA, MEC enhances interactive services (e.g., cloud gaming, AR/VR, and remote monitoring) and supports real-time orchestration alongside SDN and NFV frameworks [77,78]. The synergy between edge intelligence and network programmability drives energy-efficient, responsive FWA deployments aligned with smart city and Industry 4.0 ecosystems [79].

The convergence of these technologies transforms 5G FWA into a highly efficient, flexible, and scalable broadband platform capable of bridging the digital divide and enabling new service ecosystems. As summarized in Table 2, each enabling technology contributes distinct advantages across performance, flexibility, and deployment efficiency dimensions.

Table 2. Comparative summary of key enabling technologies for 5G FWA.

Technology	Primary Function	Key Advantages	Challenges	Impact on 5G FWA	Reference
Hybrid Beamforming	Combines analog and digital precoding	Reduces power consumption and hardware cost, enhances beam accuracy	Complex design of trade-offs between analog and digital domains	Improves link reliability and mmWave propagation efficiency	[66,68]
SDN/NFV	Network control and virtualization	Centralized control, vendor-agnostic architecture, cost efficiency	Integration complexity and interoperability issues	Enables agile network management and dynamic service deployment	[70]
Network Slicing	Logical partitioning of network resources	QoS differentiation, customized services per user segment	Complex orchestration and SLA enforcement	Allows flexible resource allocation and service-tier differentiation	[70]
Edge Computing (MEC)	Local data processing and service delivery	Reduces latency, offloads core network, enables real-time analytics	Limited edge resource capacity, security and synchronization issues	Enhances user experience and supports ultra-low-latency services	[77]
Massive MIMO	Spatial multiplexing and antenna array gain	Increases throughput, improves coverage, enhances spectral efficiency	High computational complexity, cost of antenna hardware	Enables multi-gigabit performance and extended coverage in dense areas	[65,67,80]

3. Deployment Technique and Performance Evaluation

The deployment techniques and performance evaluation methodologies are fundamental components in determining the success of 5G Fixed Wireless Access (FWA) deployment as a next-generation broadband solution. This technology leverages the advanced capabilities of 5G New Radio (NR), including massive multiple-input–multiple-output (mMIMO), adaptive beamforming, and support for network slicing and edge computing, to achieve high efficiency and reliability across diverse propagation environments. By integrating these technologies, 5G FWA enables enhanced capacity, improved spectral utilization, and low-latency service delivery, making it a competitive alternative to traditional fiber-based broadband systems in both urban and rural scenarios [68]. Fifth-Generation FWA planning with implementation flexibility without physical excavation requires the adjustment of network architecture according to geographic and demographic conditions; and allows operators to provide broadband services in urban, suburban, and rural areas with faster deployment times and better cost efficiency [21]. According to a Samsung report, 5G-based

FWA can provide a throughput of up to 1 Gb/s with latency <10 ms through the utilization of dynamic beamforming, carrier aggregation, and flexible spectrum allocation [81].

In addition to technical aspects, FWA performance evaluation focuses on metrics such as throughput, end-to-end latency, coverage, and energy efficiency, which reflect the extent to which FWA services can match the quality of fiber-to-the-home (FTTH) [15,25,82,83]. Recent studies have shown that the combination of high-capacity mmWave bands and wide-coverage mid/low-band bands results in an optimal hybrid deployment model for operators [21,84]. Furthermore, economic and business dimensions play a crucial role in assessing the viability of FWA as a commercial service. Cost analysis between capital expenditure (CAPEX) and operational expenditure (OPEX), customer adoption behavior, and QoS-based pricing strategies are key factors in determining a sustainable business model [85–88]. Patil, A. et al. [87] examine the strategic monetization opportunities and business models enabled by 5G technology through a comprehensive case study analysis using qualitative research methodology, analyzing the direction, forecast, and market readiness of 5G technology in India. Another study conducted by Kuzovkova, T. A. et al. [88] analyzed the development of cellular networks and technologies, systematized national monetization and investment practices, and developed proposals to ensure the synchronization of the development of the latest generation of cellular communications, by supporting the best monetization and investment models for the development of cellular infrastructure in accordance with the needs of the informatization and intellectualization of society. Therefore, this section will describe the deployment scenario, performance metrics, and economic and business aspects in the context of the implementation of 5G FWA globally and nationally.

3.1. Deployment Scenario

The implementation of 5G Fixed Wireless Access (FWA) is heavily influenced by user density, the physical conditions of the area, and the availability of network transport infrastructure. Several recent studies have categorized FWA implementation strategies into three broad categories: urban, suburban, and rural, each with distinct propagation characteristics and network designs [21,84,89].

1. Urban deployment.

In dense urban areas, mmWave bands with a frequency range above 24 GHz are the preferred choice for implementation because they provide wide bandwidth, resulting in multi-gigabit throughput. Several studies have also been conducted to develop 5G FWA networks for urban areas using both mid-band and mmWave frequencies [11,85,90]. Adityo, M. K. et al. conducted a deployment on the 3.5 GHz mid-band frequency and mmWave on the 26 MHz frequency, providing results that with a case study in Indonesia, the implementation of 5G FWA in mmWave is more feasible due to the availability of frequencies at 26–28 GHz, which is currently the only spectrum available for the implementation of 5G FWA, and in terms of economic considerations, the use of mmWave provides better cost savings in terms of CAPEX and OPEX [85]. Millimeter-wave (mmWave) signal propagation is highly sensitive to physical obstructions such as buildings, foliage, and other environmental barriers, which often lead to multipath effects and signal attenuation. Nevertheless, multiple studies have demonstrated that these limitations can be effectively mitigated through advanced network coordination and signal processing techniques. In order to reduce inter-cell interference and maintain the stability of the Signal-to-Interference-plus-Noise Ratio (SINR), mechanisms such as Coordinated Multi-Point (CoMP) transmission and cross-sector beam coordination are employed to enhance link reliability and ensure consistent network performance [91]. This is evidenced by research by M. Morini et al. which shows that the upper 6 GHz band can provide extensive urban coverage (up to

600 m) with stable gigabit-level downlink throughput, even in Non-Line of Sight (NLoS) scenarios. The mmWave frequency, traditionally considered unsuitable for NLoS, shows strong performance through urban reflection, reaching up to 1.3 Gbps in the downlink and 250 Mbps in the uplink [90].

2. Suburban deployment.

Fifth-generation FWA deployments in semi-urban or sub urban areas with medium density tend to favor mid-band frequencies, typically 3–6 GHz. Mid-band spectrum is the primary option, as it can reach 3–5 km per cell with an average throughput of 300–600 Mbps [36,91]. Suburban areas have moderate user density with the main goal of deployment in this area being cost efficiency per Mbps and wide coverage with stable performance [89]. This frequency offers longer range and better penetration than mmWave, while still offering significant capacity. For customers located close to the node, operators typically add a boost channel in the form of mmWave frequencies to increase local throughput. Many operators also employ a strategy of using sub-6GHz frequencies as anchors and mmWave as additional channels. To optimize coverage, antenna placement at medium altitudes and optimized beam tilts also help achieve broader coverage without many small cells [92]. Suburban architecture typically uses a macro-small cell hybrid, with the macro cell acting as an anchor and additional small cells for local capacity expansion. Adaptive antenna tilt is used to balance coverage and interference, while backhaul can be a fiber or microwave network, depending on infrastructure availability [21].

3. Rural Deployment.

Rural areas present unique challenges for network deployment due to low population density, uneven terrain, and the limited availability of fiber infrastructure and reliable power sources. Although global mobile broadband coverage is extensive, significant access gaps persist in rural and remote areas, indicating the need for cost effective wireless access solutions to achieve universal connectivity [93]. Under these conditions, low-frequency bands such as 700–900 MHz and mid-band frequencies in the range of 2.3–3.5 GHz are typically utilized to enhance signal penetration and achieve wider coverage distances compared to higher frequency bands [89,92]. Lappalainen et al. [16] carried out the planning of a rural 5G FWA multi-user using massive fixed MIMO to offer fixed broadband service to homes on the 3.5 GHz frequency, specifically to determine the user limit, the maximum number of homes that can simultaneously receive target minimum bit rates (MBRs) on the downlink (DL) and on the uplink (UL) given a set of network resources and a cell radius. The results provide some insight into how networks can be dynamically operated to provide MBR DL and UL coverage to FWA homes. However, some studies have also used the mmWave frequency band for implementation in rural areas. Chaudhuri, K. et al. [13] used mmWave spectrum for 5G FWA testing with a high-power Customer Premises Equipment (CPE) using several optimizations on gNode B to achieve a distance of 5 km with a speed of 100 Mbps. These results demonstrate the feasibility of 5G FWA using the mmWave spectrum, especially for rural areas. However, the use of mmWave waves for 5G often faces challenges due to significant signal attenuation due to blockages on the signal. The use of 5G FWA as a mmWave application promises the economic viability of FWA, but high frequencies typically require line-of-sight (LoS) connections. The number of LoS FWA links can be increased by increasing the antenna height. Saba, N. et al. [94,95] introduced a new approach to optimize the cost-effectiveness per household of a 5G FWA network. For LoS connection estimation, the approach uses a digital 3D point-cloud map model, which provides much higher precision measurements compared to other models. The results of the study show that higher antenna heights will reduce path loss. Thus, the height of the BTS tower and the customer equipment (CPE) antenna affect the availability of FWA

services in rural environments [94]. A complete explanation of 5G FWA deployment in these three categories can be seen in Table 3.

Table 3. Comparison of 5G fixed wireless access deployment.

Deployment Area	Key Challenges	Spectrum and Network Design	Technical Solutions	Representative Performance (KPIs)	Reference
Urban (Dense)	• High interference and blockage (mmWave) • Severe path-loss and rain attenuation • High deployment and energy cost	• mmWave 24–39 GHz (400–800 MHz BW) • Small-cell grid 200–300 m spacing • Directional multi-beam antennas	• Hybrid beamforming + fast beam-tracking • CoMP/inter-cell beam coordination • Dense layout (~300 EN km⁻² for >95% coverage) • Edge computing (MEC) for <10 ms latency	• >1 Gb/s (LOS ideal) • <10 ms latency (edge) • 0.5–1 km cell radius	[11,13,90]
Suburban	• Balance coverage vs. CAPEX • Mid-band congestion and uneven traffic • Limited spectrum availability	• Mid-band 3.3–3.8 GHz (~100 MHz BW) • Macro + small-cell hybrid • Adaptive antenna tilt and dynamic sectorization	• Dynamic load-balancing and adaptive scheduling • Network slicing for FWA/mobile traffic • Hybrid fiber–microwave backhaul	• 300–600 Mb/s average throughput • 20–30 ms latency • >99% availability (~5 km radius)	[21,36,89,91]
Rural	• Non-LOS Propagation and topographic loss • Limited fiber/power infrastructure • High OPEX and energy costs	• Low-band 700–900 MHz + 2.3–3.5 GHz • mmWave 24–39 GHz (400–800 MHz BW) • High-gain antennas (20–30 dBi) • Sparse macro sites (1–3 per 10 km²)	• Higher Antenna Height • 3D point-cloud map model • Solar–battery systems for off-grid nodes • Partial-mesh microwave backhauls	• 400–700 Mb/s (sub-6 GHz) • 8–15 ms E2E latency (with edge) • >99.9% reliability; 5–7 km radius	[13,16,89,92,94]

3.2. Performance Metrics

In the implementation of a 5G Fixed Wireless Access (FWA) system, network performance evaluation is a crucial element in assessing how far this wireless service can match or approach the performance of traditional wired networks such as fiber-to-the-home (FTTH). The main parameters used in this evaluation include throughput, end-to-end (E2E) latency, coverage radius, energy efficiency, and spectrum utilization. All of these performance metrics are necessary because the design and operation of FWA networks must be able to respond to propagation conditions, subscriber densities, and frequency configurations that vary greatly between environments and depending on whether the area is urban, suburban, or rural [83,96,97]. Oktarian, A. et al. stated that the QoS parameters of 5G FWA are throughput, latency, and Mean Opinion Score (MOS). However, in 5G FWA, apart from the QoS parameters as the main performance metric, these parameters are not enough to assess user satisfaction, so the alignment between Quality of Service (QoS) and Quality of Experience (QoE) remains a reference factor for measuring network performance [83]. Gokcesu, H. et al. [96] emphasized the need to integrate user perception and feedback into QoE evaluation in FWA systems. Customer Experience Index (CEI), which is a commonly used metric by mobile operators serves to model customer satisfaction and experience through Quality of Service (QoS) metrics, thus proposing CEI adjustment using Key Performance Indicator (KPI) correlation with user feedback to obtain a calibrated QoE metric. Another research, El-Saleh, A.A. et al. [97] stated that the evolution of Mobile Broadband, including 5G FWA, requires assurance that the network provides a high-quality user experience. This experimental study was conducted to analyze the actual performance of national mobile network operators (MNOs) in Oman. The measurement parameters as performance metrics

used for measurement and demonstrated were KPI values: RSRP, RSSI, RSRQ, CQI, ping, throughput, and handover rate. Measurement data was collected for all MNOs.

4. Challenges

Although the implementation of 5G Fixed Wireless Access (FWA) has successfully expanded broadband coverage and achieved greater cost efficiency compared to conventional fiber-optic infrastructure, its deployment in real-world environments continues to face multidimensional challenges. The complexity of 5G network architecture, the densification of small cells, and the demand for energy efficiency and network reliability present significant technical issues, particularly regarding the Total Cost of Ownership (TCO) and backhaul limitations across diverse geographical conditions. Moreover, the growing demand for capacity and coverage in urban, suburban, and rural areas makes FWA network planning increasingly demanding, as these require optimal solutions between technical performance and long-term investment cost efficiency.

Evaluating the Total Cost of Ownership (TCO) across broadband technologies provides critical insight into the financial and operational feasibility of each deployment model [37]. As presented in Table 4, the major broadband technologies FTTH-GPON, DSL (FTTdp G. Fast), Hybrid Fiber-Coaxial (HFC), and 5G Fixed Wireless Access (FWA) demonstrate distinct cost compositions influenced by infrastructure type, local regulations, customer density, and network scalability [26,30]. For FTTH-GPON, civil works represent the most substantial portion of capital expenditure, encompassing underground or aerial construction activities, trenching, and regulatory compliance [98]. The cost of fiber cabling scales with the total distance required to connect all customer premises remains stable while the number of GPON splitters and optical line terminals (OLTs) depends on the number of subscribers and the split ratio configuration (1:x) [63]. Additionally, the installation of active equipment at local exchanges further increases deployment complexity, making FTTH highly reliable yet capital-intensive [63,64]. In DSL-based solutions, particularly FTTdp G. fast, expenditures are primarily associated with Distribution Point Units (DPUs), short copper sub-loops, and the fiber backhaul linking them to the central office.

These costs are sensitive to the range of copper loops, number of ports, and subscriber density. While G.fast reduces the need for extensive fiber rollout, it remains limited by distance-related signal degradation, resulting in constrained scalability for high-bandwidth services [99]. For Hybrid Fiber-Coaxial (HFC) systems, the main cost components include both civil works and active network equipment such as amplifiers, optical nodes, taps, and splitters. The cost varies depending on the total coaxial length and the number of premises served, while fiber infrastructure is needed for backhaul connections between nodes. Terrain conditions, local permitting requirements, and the extent of existing coaxial infrastructure also play critical roles in determining deployment cost efficiency [63].

In contrast, 5G Fixed Wireless Access (FWA) introduces a fundamentally different cost model by replacing most of the physical cabling with radio access infrastructure. Its primary cost elements include gNodeBs, baseband units, spectrum licensing, and backhaul links, complemented by software licensing fees [61,100]. Customer Premises Equipment (CPE), particularly outdoor units, adds to the per-subscriber cost but remains significantly lower than the civil work required for wired solutions. The total cost is influenced by the spectrum band utilized (Sub-6 GHz or mmWave) and the desired capacity coverage [22]. Owing to its minimal infrastructure requirements and rapid deployment, 5G FWA emerges as a cost-effective and scalable broadband alternative for both urban densification and rural connectivity [22,61,100].

Beyond technical aspects, FWA implementation also depends on national and regional spectrum policies and regulations, which influence frequency band availability, license

pricing, and operator business models. The fragmentation of spectrum allocations across regions in low-band, mid-band, and mmWave is a major obstacle to building a uniform and interoperable device ecosystem globally. Differences in licensing models (exclusively licensed, shared, and unlicensed) also create uncertainty in implementation strategies, especially for new operators focusing on FWA-based services.

Therefore, this section discusses three main groups of challenges faced in 5G FWA deployment: Technical Challenges, Spectrum and Regulatory Challenges and Economic and Business Challenges. These three groups of challenges serve as the basis for understanding the fundamental limitations in 5G FWA deployment and provide a foundation for network optimization strategies and more adaptive spectrum policies in the future.

Table 4. TCO models at fixed broadband deployment. Adapted from [37].

Technology Broadband	Main Cost Item	Drivers
FTTH GPON	Civil works (underground/overground, own/rented)	Local terrain characteristics, local regulations
	Fiber cable	Total length to reach all premises
	GPON splitters and split ratio (1:x)	Number of premises served
	Equipment at the local exchange	Number of premises served
	G. fast DPUs	Coverage (range of copper sub-loop) and capacity (number of ports)
DSL (FTTdp G. Fast)	G. fast DPUs	Coverage (range of copper sub-loop) and capacity (number of ports)
	Fiber cable and infrastructure	Local terrain characteristics, local regulations, distance to DPUs to be served, number of premises to be served
	Customer premises equipment (CPE)	Number of subscribers
Hybrid Fiber Coaxial	Civil works (underground/overground, own/rented)	Local terrain characteristics and local regulations
	Coaxial cable	Total length to reach all premises
	Active equipment (amplifiers, splitters, taps, optical nodes)	Depending on coaxial cable length and number of premises served
	Fiber cable and infrastructure	Local terrain characteristics, local regulations, distance to optical nodes to be served, number of premises to be served
	Last drop to customer premises (including CPE)	Number of subscribers, availability of infrastructure at customer premises
5G FWA	Passive infrastructure (tower, shelter)	Fixed cost depending on coverage and capacity needs
	Active infrastructure (including gNodeB, baseband, backhaul and software fees)	Fixed cost depending on spectrum band used and coverage and capacity needs
	Customer premises equipment (CPE)	Number of subscribers, use of outdoor units

4.1. Technical Challenges

The digital divide between rural and urban communities is a significant problem in today's connected world. To date, infrastructure costs still limit the effectiveness of fixed broadband internet services. To bridge the digital divide, Fixed Wireless Access in rural areas must be able to provide a comprehensive experience comparable to fixed broadband services in urban areas [17,53,101]. Fifth-Generation FWA is here to address this by planning and operating 5G FWA networks primarily for rural areas by improving

fixed broadband using 5G. From the technical challenge side, there are several solutions as follows:

1. Infrastructure Sharing Challenges.

According to GSMA [102] and Koratagere, S. et al. [23], there are 4 main categories of infrastructure sharing strategies in 5G networks, as shown in Figure 3. The four categories are the No sharing, Passive sharing, Active sharing and Neutral Host Network (NHN) models. In the No sharing model, each operator builds their own network independently. For Passive sharing, in its implementation, several operators will share non-electronic infrastructure components such as towers and land locations. Meanwhile, in active sharing mode, operators can share all telecommunication components, both passive and electronic, except for the spectrum band and core network. In the NHN model, operators share all passive and active components, including with other network slice tenants [23,102]. Based on the results of current techno-economic studies, it shows that managing 5G business using infrastructure sharing can increase operator revenue, especially resulting from more efficient infrastructure use [82,86]. On the other hand, the infrastructure sharing model in 5G FWA also allows operators to lower Total Cost of Ownership (TCO) by spreading investment (CAPEX) and operational (OPEX) costs over a larger base. However, the effect is highly dependent on the type of broadband infrastructure deployment adopted. There are three broadband infrastructure deployment scenarios [23,103,104].

- Greenfield Deployment

This scenario refers to conditions where no existing broadband infrastructure is available, requiring operators to build and prepare network assets from the ground up. Although developing a greenfield network involves substantial capital investment, it provides operators with greater flexibility in system design and implementation, as there are no legacy systems to maintain or integrate. However, it also necessitates strategic decision-making to select the most appropriate and cost-effective technologies that can meet operational and service requirements efficiently [105].

- Brownfield Deployment

Unlike greenfield deployments, brownfield deployments leverage existing 4G/LTE and fiber infrastructure, such as towers, shelters, and legacy transport networks. This approach technically reduces initial capital expenditure (CAPEX). However, the main challenge is the complexity of integrating legacy and new networks, which can increase operational costs (OPEX) due to the need for network orchestration, multi-vendor interoperability, and more complex maintenance. Nevertheless, brownfield upgrades are a primary option for operators in urban/suburban areas due to their fast time-to-market and low financial risk.

- Hybrid deployment

Hybrid deployment combines both approaches, upgrading existing (brownfield) sites in densely populated areas and building new (greenfield) sites in new expansion areas. This strategy offers a balance between coverage, cost, and expansion flexibility. However, technically, hybrid deployment creates a combined network architecture that requires an automated management system to maintain operational efficiency.

A complete explanation of each of the deployment scenarios above can be seen in Table 5.

Table 5. Comparative analysis of TCO component and technical considerations in 5G FWA deployment models.

Deployment Model	Network Architecture Characteristics	CAPEX Components	OPEX Components	Key Technical Challenges	Optimization Strategies and Technologies	References
Greenfield	- Fully new 5G Standalone (SA) architecture with independent core; - Site densification up to 200–400 cells/km² in urban environments. - Wireless backhaul via E-/V-band; - Often relies on off-grid renewable energy (solar + battery) in rural sites.	High: - includes new RAN and core equipment, tower and shelter construction, mmWave PtP backhaul, and - renewable power systems.	Moderate: - Dominated by energy cost, site maintenance, and analytics-based monitoring. - Higher initial maintenance due to untested conditions.	- High CAPEX (up to +80%) due to new site rollout. - Power reliability in off-grid conditions. - Backhaul attenuation under rain fade (mmWave).	- Solar–battery hybrid power (reduces OPEX 15–20%) - AI-based predictive maintenance for fault detection; - SON and digital twin for auto-optimization; - Multi-hop wireless backhuls with adaptive routing.	[23,82,104,105]
Brownfield	- Non-Standalone (NSA) 5G leveraging existing LTE/4G infrastructure. - Reuse of towers, shelters, and fiber backhaul. - Employs DSS and carrier aggregation for incremental migration.	Moderate: - Reuse of legacy RAN; - Transport assets lower CAPEX 40–50%.	High: - Integration costs; - Multi-vendor orchestration, - software licensing; - Complex O&M lifecycle.	- Complex interworking between LTE and NR layers; - Latency due to heterogeneous hardware/software. - Spectrum partitioning between legacy and new users.	- SDN/NFV orchestration for unified control; - DSS for cost-efficient coexistence; - Edge caching to minimize latency; - AI-driven anomaly detection to reduce downtime.	[23,82,104,105]
Hybrid	- Combination of Greenfield and Brownfield: - Reuse of existing LTE infra (urban) + new SA build (rural/suburban); - Mixed fiber + wireless backhaul; - Integrated SDN/NFV control plane.	Balanced: - Hybrid reuse and targeted rollout. - Cost distributed between new and existing sites.	Balanced: - Lower O&M via automation. - Improved energy efficiency. - Shared infra with neutral-host model.	- Dual-core operation (NSA + SA). - Multi-domain orchestration and vendor interoperability. - Coordination between shared and dedicated backhaul.	- Infrastructure sharing and neutral-host model (TCO ↓30%); - AI-driven traffic prediction and RAN slicing; - Reinforcement learning-based energy orchestration (power ↓25–30%); - Zero-touch management (ETSI ZSM).	[23,82,104,105]

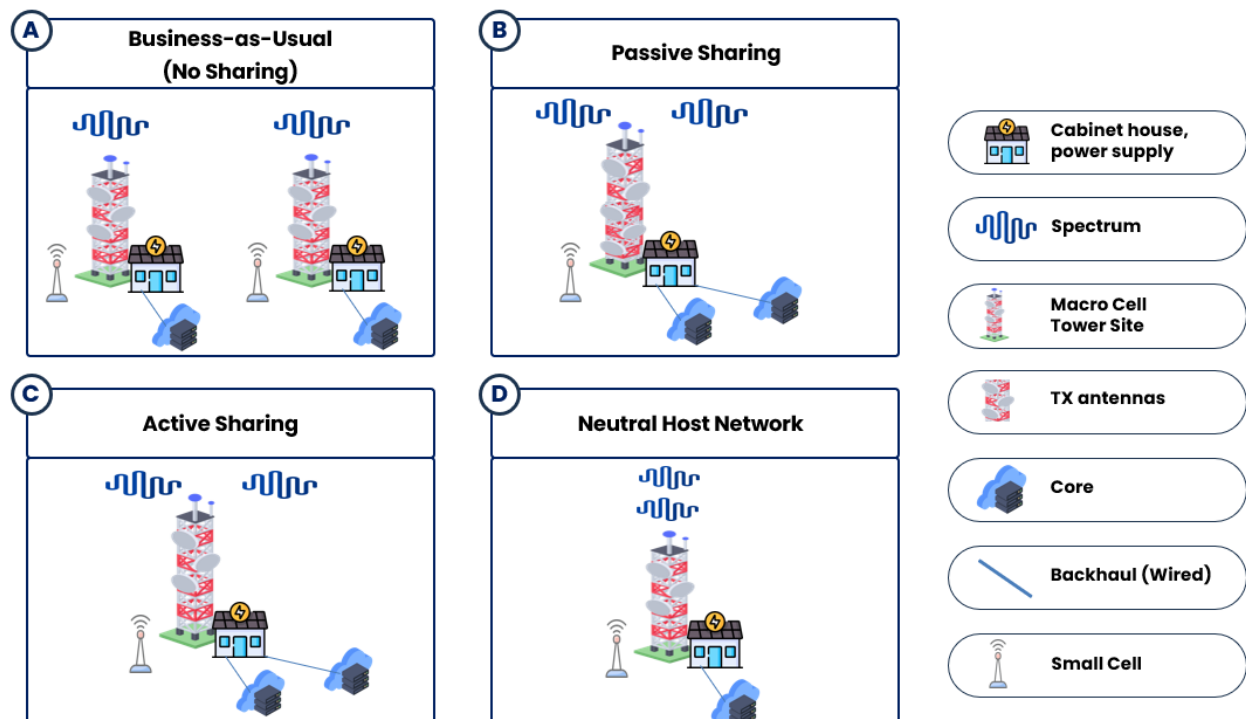


Figure 3. Infrastructure sharing strategies models: (A) Business-as-Usual (No Sharing), (B) Passive Sharing, (C) Active Sharing, and (D) Neutral Host Network [23].

2. Backhaul Challenges.

Backhaul plays a crucial role because it directly impacts the Quality of Experience (QoE) received by end users. In rural areas, backhaul connectivity is typically provided through Microwave Point-to-Point (MWP2P) technology, known as a cost-effective solution for delivering low to medium data rates over long distances. Starting with 3GPP Release 16, the concept of backhaul connections between adjacent Base Stations (BSs) has been developed, utilizing the same antennas, frequency bands, and radio protocols as those used in the Radio Access Network (RAN). With this approach, each BS can be directly interconnected using 5G New Radio (NR). This new functional architecture, known as Integrated Access and Backhaul (IAB), combines user access and backhaul functions in a single, integrated infrastructure, thereby improving spectrum efficiency and extending network coverage in areas with limited cable infrastructure [53,106]. Integrated Access and Backhaul (IAB) has been introduced as an alternative to conventional fixed access and backhaul systems, offering flexible resource allocation between access and backhaul to enhance overall network efficiency. The main advantage of IAB lies in its ability to utilize the same hardware and radio technology for both the access and backhaul segments, thereby significantly reducing hardware costs. Furthermore, by relying on wireless backhaul, IAB eliminates the need for fiber-optic cable installations, resulting in substantial reductions in infrastructure expenditure and deployment time [106]. In areas where Microwave Point-to-Point (MWP2P) backhaul links are already established; one potential approach is to integrate IAB technology to augment existing backhaul capacity. In this scenario, Mobile Network Operators (MNOs) must evaluate the technical conditions under which IAB serves as an appropriate alternative or complement to MWP2P, considering factors such as operating frequency range (mmWave vs. mid-band), spectrum usage mode (in-band vs. out-of-band), and Maximum Bit Rate (MBR) requirements [53]. However, the combined IAB–MWP2P approach still faces standardization challenges, as IAB is currently defined as a standalone backhaul technology without formal specifications regarding

its coexistence with other backhaul technologies. Fundamental differences in protocol architecture and transmission mechanisms are the main reasons: IAB utilizes protocols and scheduling mechanisms similar to those used in Radio Access Network (RAN) access systems, while MWP2P relies on its own protocols and data path management systems. Nevertheless, efforts towards convergence between 3GPP and non-3GPP access continue to be developed in recent releases, such as 3GPP Release 17, which introduced enhanced heterogeneous access integration functions. Therefore, further research on the coexistence and interoperability of backhaul technologies such as IAB and MWP2P is crucial for realizing a more efficient, flexible, and integrated 5G network architecture [53,106,107].

4.2. Spectrum and Regulatory Challenges

Spectrum is the most crucial factor in determining the strategic direction of 5G Fixed Wireless Access (FWA) implementation for network operators. Fifth-Generation New Radio (NR) technology opens significant expansion opportunities through the utilization of new spectrum in the mid-band and high-band (mmWave) bands, as well as the development of NR in low-band bands such as 600–700 MHz, which plays a crucial role in expanding network coverage in low-density areas. The combination of these three bands allows operators to balance capacity, coverage, and cost efficiency, according to the demographic conditions and traffic needs in a particular region. In general, low-band provides the widest coverage with limited capacity, while high-band offers large capacity but limited coverage, while mid-band provides the optimal compromise between the two [21]. Wulandari, A. et al. [108], evaluated the impact of deploying 5G Fixed Wireless Access (FWA) networks across the 1400 MHz, 2300 MHz, and 2600 MHz frequency bands in Indonesia, with a focus on deployment capacity and coverage performance. The results indicate that the 1400 MHz band offers the most advantageous option for 5G FWA implementation, as it requires the smallest number of sites to provide service over an equivalent coverage area. While these findings highlight the technical benefits of lower-frequency deployment, they remain limited to radio and coverage considerations. However, to complement this analysis, a more comprehensive technoeconomic study is needed, for example, by adopting the eTOM framework as a reference model to support network planning, operations, and management, specifically for 5G FWA deployment [108].

One of the major challenges in implementing 5G Fixed Wireless Access (FWA) is the fragmentation of spectrum allocation between regions and countries. Despite ongoing global harmonization efforts by the International Telecommunication Union (ITU) and regional regulatory bodies, disparities in frequency and licensing policies remain stark between regions such as North America, Europe, and Asia-Pacific. Some countries prioritize mid-band (3.3–3.8 GHz) for FWA services, while others rely on high-band (mmWave 24–28 GHz) to meet their large capacity needs, resulting in device ecosystem asymmetry, difficulties in cross-border interference management, and differences in network economic efficiency [105]. From a regulatory perspective, differences in the shape and size of license areas exacerbate this fragmentation. Geospatial analysis shows that most rural areas only require ≤ 50 MHz, while urban areas may require >60 MHz; this situation illustrates the imbalance in spectrum needs that does not always align with allocation patterns [93].

The direct impact of this fragmentation on operators is an increase in the Total Cost of Ownership (TCO), as they are required to utilize multi-band equipment, perform spectrum refarming, and adapt their implementation strategies to varying local regulatory environments. Consequently, achieving network efficiency and economies of scale on a global level becomes increasingly difficult. Therefore, the establishment of international spectrum harmonization policies is essential to promote cross-regional sharing mechanisms and dynamic spectrum access (DSA) frameworks, aiming to reduce fragmentation,

enhance spectrum utilization efficiency, and ensure consistent 5G FWA service quality worldwide [105,109]. In addition to inter-regional fragmentation, another increasingly prominent challenge is the emergence of various new licensing models for shared and unlicensed spectrum, which are used to support the expansion of coverage and efficiency of FWA networks. In a global context, adaptive licensing mechanisms such as dynamic spectrum access (DSA) or spectrum sharing frameworks are also increasingly important to address mid-band limitations and the high cost of fully licensed spectrum. However, the success of these models heavily depends on regulatory synchronization across regions and the interoperability of spectrum management systems, to avoid creating new layers of fragmentation at the operational level [110].

4.3. Economic and Business Challenges

From an economic perspective, the success of 5G Fixed Wireless Access (FWA) implementation is determined not only by technical capabilities, but also by cost efficiency, monetization strategies, and supportive policies. Careful cost planning and appropriate financing strategies are crucial aspects of 5G FWA implementation. The total investment required for the construction and operation of an FWA network can reach enormous amounts, even reaching billions of dollars, depending on the scale of implementation and geographic conditions. Therefore, each implementation stage must include a comprehensive calculation of the initial capital costs (Capital Expenditure) and ongoing operational expenses (OPEX). In this context, the integration of various financing sources and mechanisms, both public and private, is necessary to consider and integrate all possible forms and sources of financing to determine the optimal financing solution [23,30,103].

Topyan, K. et al. [30] in their study stated that there are several important factors for building 5G FWA, namely spectrum, infrastructure, region, and mobility. Related to infrastructure, the availability of infrastructure makes a big difference in Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), where for new industry entrants who do not have the infrastructure, there will be major architectural components resulting in large costs. Fifth-Generation FWA offers a cost advantage over FTTH because it does not require expensive last-mile trenching. However, the initial costs are still high if there is no infrastructure sharing and efficient spectrum management. Ioannou, N. et al. [86] emphasized that the sustainability of CAPEX is highly dependent on inter-operator collaboration and adaptive public investment policies.

Calculation of OPEX value in 5G FWA is highly dependent on business efficiency strategy, network automation, and operational design. Several studies have examined 5G FWA deployment by calculating CAPEX and OPEX. Research by Adityo, M. K. et al. [90] calculated CAPEX/OPEX in 5G FWA deployment in Indonesia by comparing the needs of 3.5 GHz mid-band and 28 GHz mmWave frequencies. The study results showed that the second deployment scenario, which uses 28 GHz mmWave frequencies, is more economical than 3.5 GHz mid-band and is feasible due to the availability of frequencies in 26–28 GHz, which is currently the only spectrum available for 5G FWA deployment.

Another aspect related to the economics and business of 5G FWA is the Average revenue per user (ARPU) and monetization strategies for business models in 5G FWA implementation. Average Revenue Per User (ARPU) is a key indicator used by operators to measure the average revenue per customer in a certain period (usually monthly). In the context of 5G Fixed Wireless Access (FWA), ARPU is a strategic factor in assessing business feasibility and network profitability, because it directly affects the Net Present Value (NPV), Return on Investment (ROI), Internal Rate of Return (IRR) and Payback Period of the project [12,86,111]. Ericsson Mobility Report [12,38] states that FWA is one of the main drivers of household broadband revenue growth, with a projection of 350 million global

connections by 2030 and a relatively stable average ARPU due to high customer loyalty and low churn rates. Factors that influence the ARPU of 5G FWA technology are pricing models, market segmentation and service bundling, geographic region, purchasing power, and technology and operational efficiency [12,36,38].

Regarding monetization strategies, according to GSMA, 5G monetization is the process of converting 5G network technology capabilities into economic value and revenue through new services, products, or business models. The goal is to maximize the return on investment (ROI) on high-value 5G infrastructure by creating, managing, and commercializing 5G-based services for various customer segments (consumer, enterprise, and vertical industries) [111]. Patil, A. et al. [87] examine strategic monetization opportunities and business models enabled by 5G technology through a comprehensive case study analysis. This study reveals that successful monetization strategies center on three main pillars: managed service integration, IoT application development, and partner ecosystem development. This study identifies six distinct business models for Communications Service Providers (CSPs), leveraging 5G capabilities through network slicing, edge computing, and URLLC to generate new revenue.

Monetization in 5G FWA has been reported by the Ericsson Mobility Report (EMR) in June 2025 which shows that more than half (51 percent) of global CSPs offering FWA now include speed-based options (up from 40 percent in the same period in June 2024) driven by high adoption rates in North America, as well as growth in Europe and the Middle East [112]. FWA plays a crucial role in expanding broadband access, especially in areas where wired infrastructure is less feasible, as it leverages the advantages of flexible and fast implementation using existing cellular infrastructure.

5. Future Directions and Network Management Framework

The future development of 5G Fixed Wireless Access (FWA) will be characterized by increasing network architecture complexity, growing pressure for cost efficiency, and a stronger emphasis on the sustainability of operators' business models. Following the initial deployment phase focused primarily on coverage expansion and capacity enhancement, the major challenges for operators are now shifting toward strategic network and business management, where every investment and network design decision has a direct impact on profitability and competitiveness. Failure to implement effective network planning, resource management, and operational cost control can lead to a significant increase in the Total Cost of Ownership (TCO) and a decrease in the Return on Investment (ROI), potentially resulting in long-term financial unsustainability [12,105].

Therefore, the future sustainability of 5G FWA requires the implementation of two key complementary elements. First, AI-driven autonomous network operations, which play a role in improving technical efficiency, performance stability, and real-time network resource optimization through automation and adaptive learning. Second, the implementation of a network management framework that serves as a strategic management framework for operators to ensure that investment decisions, network planning, and service management are carried out in a structured and value-driven manner. The integration of these two approaches is expected to not only maintain operational efficiency but also ensure business continuity and competitive advantage for operators in the future broadband ecosystem.

5.1. AI-Driven and Autonomous Network Operation

The evolution of FWA networks toward a fully autonomous future will rely on AI-driven orchestration capabilities to improve technical performance, reduce operational burden, and accelerate real-time, data-driven decision making. Within this architecture, machine learning (ML) and reinforcement learning (RL) are applied to optimize radio

resources, prioritize traffic, and perform predictive maintenance on network devices [113]. In an AI-driven orchestration architecture, the FWA network operating system will utilize three main components: perception, decision, and action. The perception phase involves collecting real-time network telemetry data (such as throughput, latency, interference, and spectrum utilization). This data is then analyzed in the decision phase using ML and reinforcement learning (RL) algorithms to identify traffic patterns and detect anomalies. Finally, in the action phase, the system applies automated decisions such as dynamic resource allocation, beamforming optimization, or traffic steering to improve network performance without manual intervention.

Closed loops are a successful automation driver and are widely used by the industry. The Zero-touch network and service management (ZSM) framework introduces standard components that enable the creation, execution, and governance of multiple closed loops, enabling end-to-end zero-touch service management across multiple management domains. Furthermore, the application of Reinforcement Learning (RL) in self-optimization enables the system to learn from historical conditions and dynamically adapt to traffic fluctuations and environmental disturbances. This aligns with the Zero-Touch Network and Service Management (ZSM) principles initiated by ETSI, where the network has the ability to perform closed-loop assurance and is able to detect, analyze, and repair disturbances without human intervention [114].

Recent studies indicate that machine learning can also play an important role in the deployment phase of 5G FWA networks, where infrastructure investment and rollout costs are significant. In addition to operational optimization, data-driven approaches can support deployment planning through coverage prediction, service feasibility assessment, and intelligent site selection. For instance, AI-based analytics combined with RF propagation modeling can assist operators in identifying feasible service areas and optimizing Customer Premises Equipment (CPE) placement during installation, thereby improving service quality and reducing deployment errors [115]. Furthermore, cost-efficient deployment strategies such as joint planning of FWA and fiber access networks have been proposed to minimize overall capital expenditure while maintaining broadband coverage targets [116]. These studies demonstrate that machine learning and data-driven analytics can support not only network operation but also the deployment stage of large-scale FWA rollouts, enabling more efficient infrastructure investment and network expansion.

In 5G FWA, AI-driven and autonomous network operations serve as the foundation for the efficiency and sustainability of modern networks. Through closed-loop orchestration, reinforcement learning, and digital twins, operators can dynamically optimize network performance, lower operational costs, and improve reliability and customer experience. This approach marks the transition to an era of AI-native network management, where FWA networks adapt and self-manage to achieve maximum technical and economic efficiency.

5.2. eTOM-Based Network Management Models for Operators

A carefully executed competitive strategy is a critical requirement for telecommunications companies. Historically, vendor and operator failures have been driven by errors in competitive strategy analysis, resulting in costly losses and even customer abandonment. The International Telecommunication Union has issued recommendations for telecommunications management and operations based on an enhanced telecom operations map (eTOM) [117]. eTOM is a business process framework that describes and analyses various levels of enterprise processes according to their importance and priority to the business. The framework is defined as generally as possible so that it remains independent of organization, technology, and service. For operators (MNOs), eTOM serves as a blueprint for development direction [118]. eTOM provides comprehensive, globally applicable op-

erational standards, as well as regularly updated operational standards for all countries. eTOM works through process decomposition techniques, with a structured approach that takes into account the Company's business processes and internal structure [119].

Process decomposition for the Business Process Framework (eTOM) begins at the enterprise level and defines business processes in a series of groupings. The Business Process Framework uses hierarchical decomposition to structure business processes, where all process descriptions are sequentially described and defined, starting with inputs and outputs and other key elements, and representing the entirety of a service provider's enterprise environment. The framework is generally defined to be independent of organization, technology, and services. There are two main process areas within the framework: Strategy to Readiness, which covers planning, capability delivery, and lifecycle management, and Operations, which covers the core of operational management, as shown in Figure 4 [120].

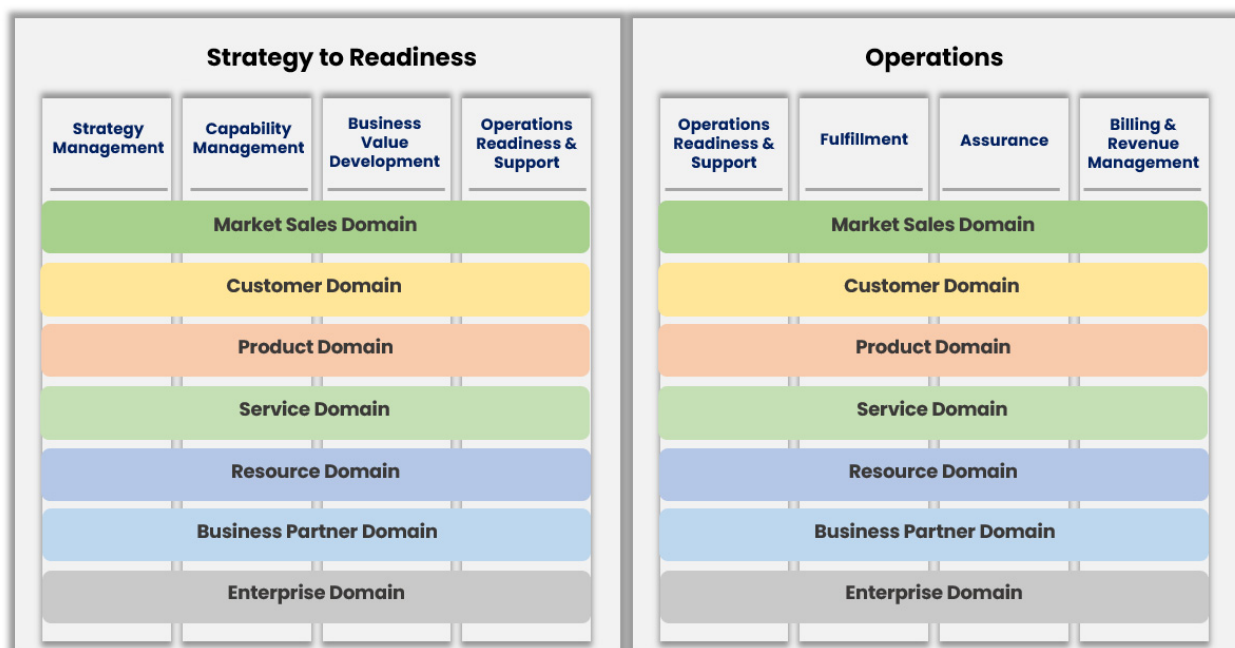


Figure 4. Business Process Framework eTOM. Adapted from [120].

A study conducted by Saputra, D. et al. proposed the development of a Business Process Management Standardization method based on operator conditions. This research method refers to the decomposition of the eTOM framework as a foundation for building Business Process Management that is appropriate to the company's conditions [121]. Another study by T., Olga et al. showed that the mapping of the eTOM business framework carried out on OSS/BSS is expected to provide solutions to telecommunications problems in Russia [122]. Table 6 presents several studies that have modeled use cases using the eTOM approach. This diversity of applications demonstrates eTOM's adaptability to a variety of technical and business needs, while also providing a common language that facilitates integration across divisions and platforms. Therefore, eTOM is an appropriate framework to serve as a basis for proposing a model for the implementation of 5G Fixed Wireless Access (FWA) services, which require a structured and comprehensive understanding of operational processes for consistent implementation by operators.

Table 6. Comparative review of eTOM framework implementation across selected studies.

Reference	Domain/Use Case	How eTOM Is Used	Strengths of eTOM Use
[123]	NFV + IMS service management	Maps Level-1 eTOM business processes (OSR, Fulfillment, Assurance, BRM) to NFV blocks (NGOSS, EMS, VNE, NFVI). Defines bidirectional mapping functions f and f^{-1} .	Provides formalized process mapping between business processes and virtualized network elements. Helps align operations with NFV-based 5G architectures.
[124]	OSS/BSS modernization	Uses eTOM to standardize business processes (Levels 0–2) for OSS/BSS alignment, terminology, and decomposition. Emphasizes need for regulatory standardization	Shows that eTOM provides a universal process structure, supports multivendor OSS/BSS, and clarifies process definitions.
[125]	QoE/QoS management using SDN + eTOM	Uses eTOM for structuring management functions, combined with SDN to enable dynamic QoE correction. Implements SLA verification integrated with eTOM Assurance.	Strong integration of eTOM with SLA/QoE monitoring; suitable for wireless and 5G performance optimization.
[126]	NFV, MANO, 5G virtualized service chaining	Maps Level-2 eTOM processes (Fulfillment, Assurance, Resource Management) to NFV orchestration; defines service-chaining mapping functions.	Technically strong; integrates eTOM with 5G architecture; validated via testbed.
[121]	Fulfillment and Assurance (OSS)	Uses eTOM Level-2 & Level-3 processes to standardize OSS fulfillment and Assurance. Provides detailed decomposition.	Strong detailed implementation; maps 27–29 business functions; identifies redundancy and missing processes.
[119]	Telecom Enterprise Architecture (EA) transformation	eTOM is used as the baseline operational process architecture that anchors the EA transformation. The study maps key business processes from eTOM into an enterprise-wide architecture and demonstrates alignment between business, information, and technology layers.	Provides a structured method for integrating eTOM into modern EA frameworks; shows how legacy and digital processes can be harmonized; supports strategic alignment between business processes and network modernization.
[127]	Integration of OTT services into telecom operations	Uses eTOM to identify relevant service lifecycle processes (Fulfillment, Assurance, Billing). The study maps OTT-related tasks to eTOM process areas and highlights gaps in traditional telecom processes when OTT services are introduced.	Demonstrates adaptability of eTOM to new digital service models; clearly identifies process gaps when integrating non-traditional services; shows applicability of eTOM beyond conventional telecom operations.
[128]	ICT operations transformation to support smart cities and non-human customers (IoT)	eTOM is used as the reference process framework for deconstructing existing operations. Level 2 to Level 4 eTOM processes are decomposed and redesigned using BPR, SSM, and Enterprise Knowledge Development (EKD). ArchiMate diagrams show the redesigned processes aligned with eTOM.	Strong practical demonstration of using eTOM for new service contexts; shows capability of eTOM to support IoT/smart-city customers; combines eTOM with formal modeling (ArchiMate) and BPR techniques for end-to-end transformation.
[129]	Enterprise Architecture (EA) integration	Maps TOGAF EA phases (A–D) to TMForum Framework (eTOM, SID, TAM). Shows where eTOM fits in EA models.	Demonstrates that eTOM is foundation for business processes in telecom EA; it provides detailed mapping tables.
[130]	High-level business architecture for IT strategy formulation	eTOM is cited as an industry-grade reference architecture that exemplifies how standardized business process frameworks provide structure for enterprise IT planning. The paper benchmarks eTOM alongside other industry frameworks.	Validates eTOM as a mature, widely accepted reference model with clear hierarchical layers (Level 0–3). Reinforces the suitability of eTOM as a foundation for aligning enterprise capabilities, IT systems, and business strategy.
[131]	Business process restructuring and digitalization in telecom	eTOM provides the foundational process taxonomy for identifying operational, management, and supporting processes. The study references eTOM as the standard model used in telecommunications to classify and reengineer business processes during digital transformation.	Clearly articulates eTOM's role in telecom digitalization. Offers systematic classification of processes, supporting transparency, governance, and standardization as key factors in large-scale restructuring efforts.
[132]	Cloud-network integrated OSS/BSS and intelligent O&M	eTOM is used to structure OSS functional domains and capabilities. The study references eTOM and NGOSS as widely adopted models that guide functional decomposition and capability integration in cloud-network architectures.	Shows eTOM's relevance in next-generation OSS architectures, cloud-network orchestration, and AI-driven O&M. Demonstrates compatibility between eTOM and modern frameworks (AITOM, ONAP) in 5G/6G environments.
[133]	Organizational process analysis (marketing + AI)	Uses eTOM as the underlying business process map to identify contradictions and process issues using Activity Theory.	Shows how eTOM supports organizational modeling and identifies process misalignments.

5.3. The Importance of Proposed Modeling for 5G FWA Implementation Based on eTOM Framework

The implementation of 5G Fixed Wireless Access (FWA) presents various technical, spectrum, and operator readiness challenges that require a structured and standardized process modeling approach. As a broadband technology based on Fixed Wireless Access, 5G FWA is projected to be a strategic solution to improve digital inclusion and expand service coverage in both urban and rural areas, while simultaneously reducing the digital divide between urban and rural areas [17,53,101,134]. Various industry reports, including Ericsson and Gartner, confirm that FWA will be one of the main drivers of global broadband growth in the next five years, especially in developing countries that still face obstacles to fiber optic deployment [12,135].

According to Ericsson, 5G FWA connections are expected to reach around 280 million by 2029, or nearly 85 percent of total FWA connections. In the Asia-Pacific (APAC), the number of FWA connections is expected to triple, bringing the total FWA contribution to over 45% by 2029 [12]. However, based on the results of a Gartner survey on Cellular and Wired Infrastructure Development Indexes, Selected Countries, as shown in Figure 5, it shows that in developing countries, for example, Indonesia is at the lowest point of the countries analyzed. This means that broadband penetration for wired (fiber, sDSL, coaxial) is still very low and many customers outside of large cities do not have a quality fixed connection. The cellular infrastructure development index parameter is also at a low level, which means that cellular coverage exists, but is not yet supported by high-quality 5G cellular infrastructure evenly [135]. This has strategic implications that 5G FWA is a solution to increase digital inclusion, especially in developing countries.

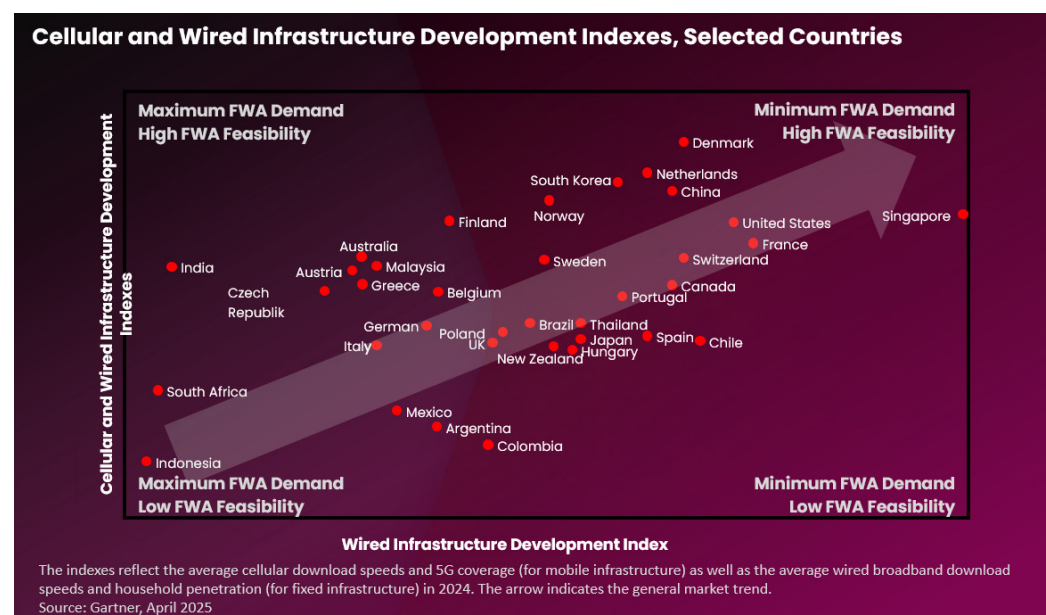


Figure 5. Cellular and wired infrastructure development indexes, selected countries. Adapted from [135].

In the context of developing countries such as Indonesia, the implementation of 5G FWA presents challenges that extend beyond spectrum availability. Deployment models including greenfield, brownfield, and hybrid approaches require distinct processes for capacity planning, utilization of existing infrastructure, and resource orchestration. Moreover, the readiness of mobile network operators (MNOs) is a critical determinant of 5G FWA success, as operators exhibit significant differences in spectrum holdings, transport network quality, device preparedness, and organizational capability.

These variations underscore the need for a process model capable of mapping all 5G FWA implementation activities in an end-to-end manner. The Business Process Framework (eTOM) offers an appropriate foundation, as it provides a comprehensive process structure spanning the Strategy to Readiness (S2R), Operations, and Enterprise Management domains. TM Forum explicitly states that eTOM is designed as a global standard for describing the full telecommunications service lifecycle, encompassing strategy formulation, planning, design, implementation, and daily operations [120].

Although various previous studies have discussed the technical, economic, and operational aspects of 5G and FWA service delivery, no approach has comprehensively mapped the needs of 5G FWA implementation within a standardized business process framework. Existing studies utilizing eTOM for NFV mapping, OSS/BSS standardization, service lifecycle modeling, and enterprise architecture demonstrate that eTOM has become a stable and reliable foundation for describing end-to-end operational flows in the telecommunications industry. However, the existing literature remains fragmented and generally focuses on specific domains such as network virtualization, service quality management, digital transformation, or external service integration. None of these models provide comprehensive FWA implementation modeling from a holistic business process perspective. Therefore, a more structured analysis is needed regarding the urgency of eTOM-based 5G FWA implementation modeling. This analysis can be structured into four key dimensions that collectively describe the methodological, operational, and strategic needs of the proposed approach, as follows:

1. The Need for Process Standardization in 5G FWA Implementation.

The implementation of 5G Fixed Wireless Access (FWA) requires cross-domain process orchestration involving capacity planning, spectrum management, customer-premises equipment (CPE) provisioning, transport and core network integration, as well as coordination across marketing and operational functions. In the absence of a standardized process framework, mobile network operators (MNOs) are likely to encounter several challenges, including:

- Duplication of activities across organizational units;
- Misalignment between technical planning and business strategy;
- Unclear service development workflows;
- Inconsistent operational procedures across regions.

Industry reports indicate that MNOs lacking structured and standardized processes tend to experience slower time-to-market, escalating CAPEX and OPEX, and significant difficulties in scaling FWA services in a consistent and sustainable manner [12,37,105]. Therefore, process standardization becomes a critical foundation to ensure that all 5G FWA activities follow workflows that are consistent, measurable, and replicable across the various operational regions of the MNO.

2. The Role of eTOM in Mapping Mobile Network Operator (MNO) Readiness.

The Business Process Framework (eTOM) provides a hierarchical process structure that enables operators to assess their internal readiness for 5G FWA service requirements. The framework encompasses the Strategy-to-Readiness (S2R), Operations, and Enterprise Management domains, allowing operators to:

- Evaluate the preparedness of both business and technical units;
- Identify gaps between existing capabilities and the requirements of 5G FWA;
- Ensure alignment between process blueprints and industry standards;
- Enhance cross-functional coordination throughout the organization.

One study by Prihatmanto et al. demonstrates that eTOM functions not only as a process blueprint but also as an analytical instrument for identifying contradictions, misalignments, and inefficiencies within actual organizational processes [133]. This is highly relevant for operators deploying 5G FWA, as discrepancies often arise between the intended processes and the actual practices observed in the field. Consequently, eTOM serves as a comprehensive evaluation framework for assessing operator readiness from the perspectives of process integrity, organizational capability, and alignment between business and technical functions.

3. Integration in Techno Economic Models with eTOM Modeling.

The successful implementation of 5G FWA is highly dependent on the integration of technical and economic analyses. FWA exhibits cost characteristics that differ from conventional mobile broadband services due to factors such as:

- Investments in customer-premises equipment (CPE);
- Transport network readiness;
- Varying spectrum utilization;
- Differing capacity requirements across deployment areas.

Techno-economic assessments such as CAPEX, OPEX, ROI, and TCO analyses must therefore be embedded within a clearly defined business process flow to ensure that investment decisions remain aligned with operational activities. eTOM domains including Resource Strategy Management, Resource Capability Delivery, Resource Lifecycle Management, and Operations Readiness & Support are directly related to the lifecycle processes required for managing 5G FWA networks. GSMA Intelligence emphasizes that a successful 5G FWA implementation model is one that effectively integrates technical dimensions such as coverage, radio capacity, and integration readiness with economic dimensions, including feasibility, revenue projection, and cost optimization [37,105]. Through this integration, MNOs are not only able to conduct technical planning but also ensure that their investments can be executed through workflows that adhere to established industry standards.

4. 5G FWA Process Improvement Based on eTOM Best Practices.

The implementation of 5G FWA requires well-structured operational processes to ensure that each stage of the service lifecycle is executed consistently, efficiently, and in alignment with industry standards. eTOM best practices offer a comprehensive reference framework that can be used to refine, clarify, and enhance these operational processes. By leveraging the standardized process structure defined by TM Forum, operators can reassess their internal workflows and ensure that the operational sequences employed adequately cover all critical activities required throughout the 5G FWA service lifecycle. In the context of process enhancement, eTOM functions as a process reference model that enables operators to identify undocumented areas, activities lacking clear role definitions, and operational steps that are not logically interconnected. This framework allows operators to:

- Clarify the stages required for end-to-end service provisioning;
- Establish activity sequences that align with internationally recognized service lifecycles;
- Define clear boundaries of responsibility for each organizational unit or functional domain;
- Align supporting activities with core operational processes;
- Ensure that quality monitoring and continuous improvement mechanisms are integrated within the same workflow.

Accordingly, the enhancement of 5G FWA processes based on the eTOM framework serves as a foundational element for improving operational effectiveness, strengthening service governance, and ensuring the long-term sustainability of FWA operations.

5.4. Outlook Forward 6G

The evolution toward sixth generation (6G) wireless systems is expected to further enhance the role of Fixed Wireless Access (FWA) as a key broadband delivery mechanism, particularly in scenarios where terrestrial infrastructure deployment remains challenging. Recent studies emphasize that future 6G networks will be characterized by the deep integration of terrestrial and non-terrestrial networks (NTNs), enabling seamless global coverage, ultra-high reliability, and flexible service provisioning. In this context, the integration of 5G FWA with NTN architectures represents a natural progression, allowing FWA deployments to leverage satellite-based connectivity as an alternative or complementary backhaul solution, especially in rural, remote, and underserved regions [136].

From an architectural perspective, the convergence of 5G New Radio (NR) with NTNs introduces new opportunities to enhance FWA performance through extended coverage, improved resilience, and diversified transport options. The adoption of NTN-enabled backhaul can mitigate limitations related to fiber availability while supporting high-throughput broadband services for fixed users. However, the integration also introduces technical challenges, including latency variation, feeder link handover, spectrum coexistence, and dynamic resource management across heterogeneous network segments. These challenges highlight the necessity for advanced network coordination mechanisms and standardized operational frameworks to ensure service continuity and quality of experience for FWA users [137].

Looking toward 6G, the literature underscores the importance of intelligent, service-aware network management to support highly heterogeneous access and transport networks. Concepts such as AI-driven orchestration, end-to-end network slicing, and integrated terrestrial–NTN management are envisioned as fundamental enablers for future FWA systems. In this regard, the evolution of FWA beyond 5G toward 6G will not be driven solely by physical-layer advancements, but also by the adoption of structured and scalable network management frameworks capable of aligning technical performance, operational efficiency, and service requirements across terrestrial and non-terrestrial domains [136,137]. Moreover, management principles based on the Enhanced Telecom Operations Map (eTOM) and intent-based orchestration will serve as the foundation for AI-native network operations in the 6G era, where fully autonomous decision making will be enabled by digital twins, predictive analytics, and cross-domain orchestration. Consequently, the evolution of 5G FWA toward 6G will not only enhance network technical capabilities but also transform how operators manage assets, optimize resources, and derive business value across the entire network ecosystem.

6. Conclusions

This survey provides a comprehensive and multidisciplinary review of 5G Fixed Wireless Access (FWA), covering its technological foundations, deployment strategies, performance characteristics, techno-economic considerations, and operational management within modern telecommunications environments. As global demand for high-speed, low-latency broadband connectivity continues to accelerate, FWA has emerged as a strategic and cost-efficient solution capable of complementing or substituting fiber-based broadband, particularly in regions with infrastructural limitations. The literature consistently demonstrates that 5G NR capabilities including massive MIMO, beamforming, mmWave spectrum utilization, edge computing, SDN/NFV, and network slicing enable FWA to deliver performance approaching fiber-grade connectivity while significantly reducing deployment time and capital expenditure.

Across diverse deployment scenarios, ranging from dense urban clusters to rural and hard-to-reach geographies, the findings indicate that 5G FWA can be optimized through

tailored spectrum strategies, hybrid access architectures, advanced radio planning, and integrated access-backhaul mechanisms. Comparative analyses also highlight that FWA's techno-economic viability strongly depends on spectrum availability, infrastructure readiness, and the adoption of infrastructure-sharing models such as passive sharing, active sharing, or neutral-host configurations. Multiple studies reveal that operators can achieve substantial reductions in TCO and improved ROI when network design decisions are supported by structured cost modeling, customer-behavior analytics, and adaptive business models.

Despite these opportunities, FWA deployment continues to face significant challenges, including fragmentation of global spectrum allocation, backhaul constraints, regulatory disparities, multi-vendor integration complexity, and the need for sustainable operational models. These challenges underscore that technical optimization alone is insufficient; operators must also establish standardized, end-to-end business processes to ensure scalable, reliable, and economically sustainable FWA service delivery.

In this regard, the Enhanced Telecom Operations Map (eTOM) emerges as a critical framework for bridging technical implementation with organizational readiness and business governance. The review highlights the absence of holistic, standardized process models for 5G FWA within the existing literature, despite the rapid expansion of FWA deployments worldwide. eTOM provides a complete hierarchical structure from Strategy-to-Readiness (S2R) to Operations and Enterprise Management that enables operators to map capabilities, identify process gaps, align technical plans with business objectives, and ensure consistency across service fulfillment, assurance, and lifecycle management. Prior studies, including those applying eTOM to OSS/BSS integration, NFV mapping, and enterprise architecture, demonstrate its robustness and adaptability for modern telecom ecosystems.

The integration of techno-economic models with eTOM-based process flows is therefore essential to ensuring that FWA investment decisions such as CAPEX/OPEX forecasting, CPE provisioning, transport readiness, and spectrum strategy are tightly coupled with operational feasibility and long-term service sustainability. Furthermore, advancements in AI-driven and autonomous network operations, including closed-loop orchestration, reinforcement learning, and digital twins, position FWA networks toward an AI-native architectural future, where eTOM will act as the foundational governance layer supporting intent-based, zero-touch network management.

Looking ahead, the evolution of 5G FWA toward 6G will involve deeper integration with Non-Terrestrial Networks (NTNs), more intelligent spectrum management, and fully autonomous, cross-domain orchestration systems. As network architecture becomes more complex and service expectations continue to rise, operators will increasingly depend on standardized, interoperable, and analytics-driven management frameworks. This survey concludes that eTOM-based network management provides the most comprehensive and scalable foundation to support the next generation of FWA deployments, ensuring that technical excellence, economic viability, and operational governance remain aligned throughout the entire service lifecycle.

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