Unleashing Multi Gigabit Homes

Powered by WiFi7

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Table of Contents

1. Introduction

The growing pervasiveness of bandwidth-intensive applications like 8K streaming, AR/VR experiences, and cloud gaming could benefit from wireless technology improvements. Wi-Fi 7 emerges as an answer, promising a multi-gigabit solution. However, achieving an increased speed consistently across a typical home environment can be challenging. Multi-Link Operation (MLO) is a feature in Wi-Fi 7 that enables devices to concurrently transmit and receive data on multiple wireless links. This mechanism allows Wi-Fi 7 devices to aggregate available bandwidth, effectively creating a wider data pathway, signifying an increase in speeds compared to traditional single link operation.

While a Wi-Fi 7 router equipped with MLO offers improvements, physical barriers and distance can still limit signal strength, potentially hindering multi-gigabit Wi-Fi speeds in certain areas of a home. This is where Wi-Fi 7 extenders come into play. A strategically positioned extender acts as a bridge, receiving the Wi-Fi signal from the router and retransmitting it to previously out-of-reach areas. This paper explores the role of Wi-Fi 7 extenders and various multi-extender configurations in attempting to achieve the goal of maximizing the range of multi-gigabit Wi-Fi coverage.

2. WiFi7 Throughput Enhancements and Practical Limitations

2.1. 4K QAM and New MCS Indices

Wi-Fi 7 introduces 4096-QAM (Quadrature Amplitude Modulation), an upgrade from Wi-Fi 6's 1024-QAM. This higher modulation density allows for the transmission of 12 bits per symbol, compared to 10 bits in Wi-Fi 6, resulting in a 20% increase in the raw data rate for the same channel bandwidth. The higher order QAM enables more efficient use of available spectrum by packing more data into each transmission, theoretically boosting throughput by up to 1.2 times compared to Wi-Fi 6 under identical configurations. However, the increased modulation density of 4096-QAM comes with trade-offs. It requires a higher signal-to-noise ratio (SNR) to maintain reliable communication, making it more susceptible to interference and signal degradation over distance. This limitation means that 4096-QAM may be most effective in short-range, line-of-sight scenarios or in environments with minimal obstacles and interference.

2.2. 320 MHz-Wide Available Bandwidth

Wi-Fi 7 enables the utilization of wider 320 MHz bandwidth, which is currently available only in the 6 GHz spectrum band. The 7 GHz spectrum band (7.125-8.4 GHz), which is currently allocated to federal and non-federal fixed link, satellite and mobile radar operators, is being evaluated by federal regulators for potential commercial unlicensed shared, shared licensed or exclusive mobile licensed use. If made available for unlicensed sharing, it could create additional 320-MHz channels to significantly enhance Wi-Fi 7, and future Wi-Fi generations', capabilities, and increase Wi-Fi throughput, speeds and capacity.

2.3. Multi Resource Units (RU) and Puncturing

Multi-RU and Puncturing was introduced in Wi-Fi 6E (IEEE 802.11ax), but Wi-Fi 7 (IEEE 802.11be) mandates the support for puncturing along with some enhancements to this feature.

Puncturing allows the communication to be more robust when incumbents or interference are introduced at certain frequencies of the operating bandwidth.

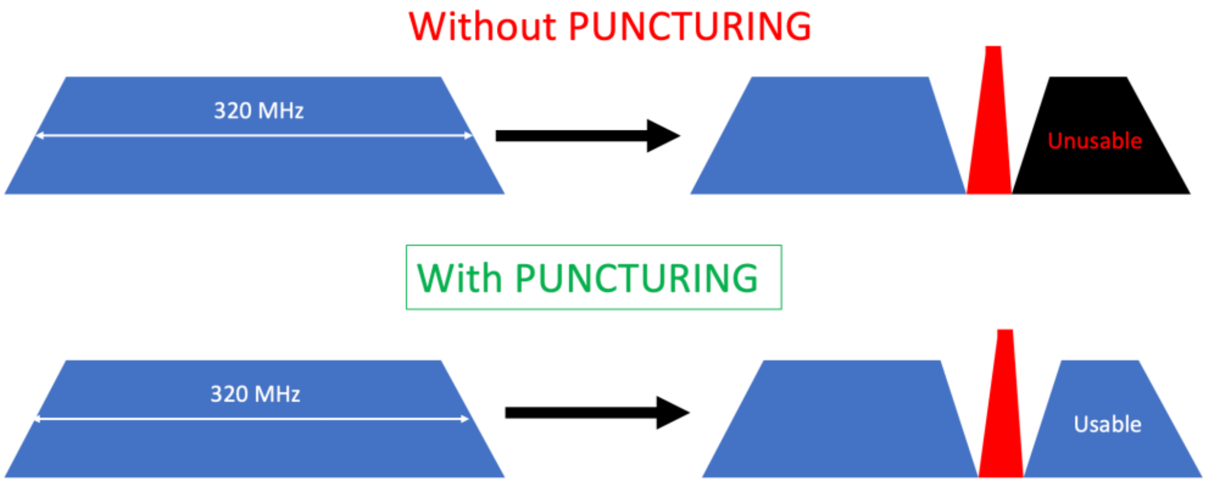


Figure 1: Effect of Incumbents with and without puncturing

As shown in Figure above, without puncturing, when an incumbent or interference is introduced in the operating bandwidth, legacy operations avoid the frequencies containing the incumbents or interference, which reduces the operating bandwidth by half and also reduces operating throughput by half.

Alternatively, the Multi-RU capability provides an option to avoid frequencies with incumbents or interference with puncturing that can be performed at a bandwidth granularity of 20 MHz. To illustrate: if when operating in 320 MHz of bandwidth incumbents or interference render 20 MHz unusable, puncturing provides a way to operate in the remaining 300 MHz of bandwidth by omitting only the problematic 20 MHz, which increases reliability.

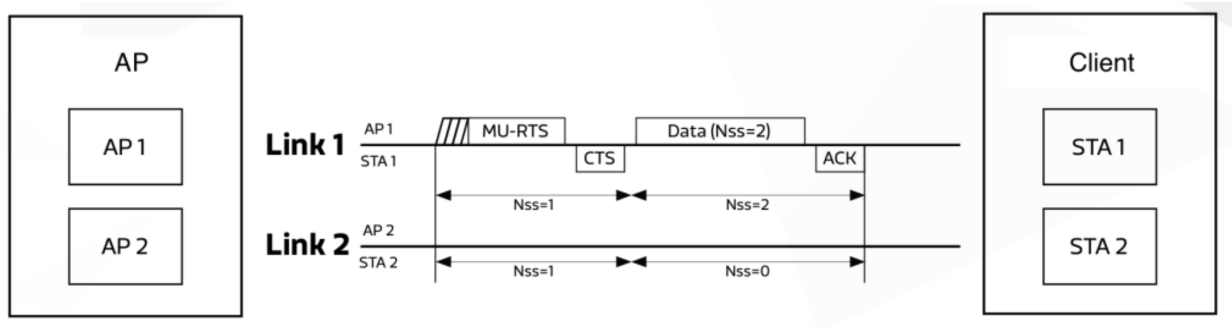
Without enhancements, the 5 GHz band has maximum channel bandwidths of 160 MHz, but the Multi-RU concept in Wi-Fi 7 enables the combination of 160 MHz and 80 MHz channel bandwidths , effectively creating a 240 MHz channel. Alternatively, this can be viewed as a punctured 320 MHz channel (with 80 MHz removed), which represents an improvement over the previous 160 MHz unenhanced limit. This Multi-RU enhancement can increase the throughput capability in the 5 GHz band by approximately 1.5 times (as compared to the standard 160 MHz throughput), which offers performance benefits within the constraints of the 5 GHz spectrum.

2.4. Multi-Link Operation (MLO)

Multi-Link Operation (MLO) is a feature of Wi-Fi 7 (802.11be) that enables devices to simultaneously communicate over multiple frequency bands and channels, which enhances network performance. A detailed explanation of MLO and its supported modes follows.

2.4.1. Enhanced Multi Link Single Radio (eMLSR)

eMLSR is a method of MLO where the client devices can associate and maintain connection across multiple bands with the Access Point (AP) at the same time but the communication between AP and the client can occur only on a single band at any given time.

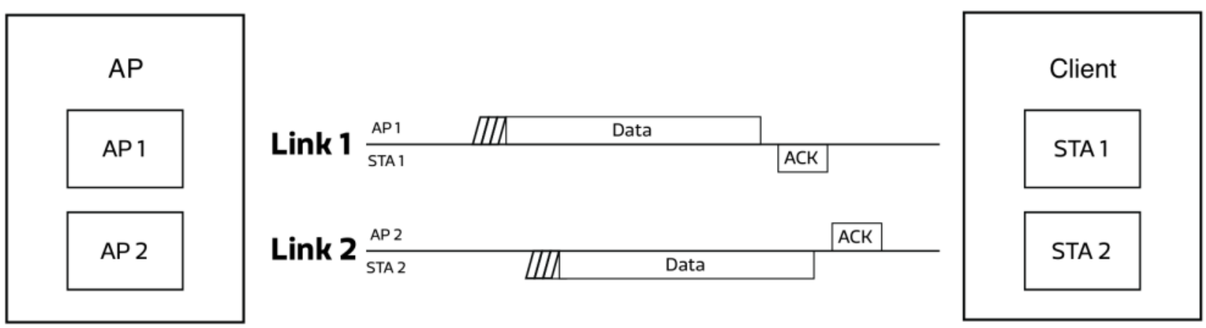


This is an enhanced version of basic MLSR where the number of radio chains can be seamlessly altered based on availability and requirement.

2.4.2. *Multi Link Multi Radio – Simultaneous Receive and Transmit (STR-MLMR)*

MLMR is another method of MLO that allows communication to happen between client and AP on multiple bands at any given time. There are two sub flavors of MLMR: Non-Simultaneous Receive and Transmit (NSTR-MLMR), which is discussed in detail in Section 2.4.3, and STR-MLMR (also termed “asynchronous MLMR” or “aMLMR”).

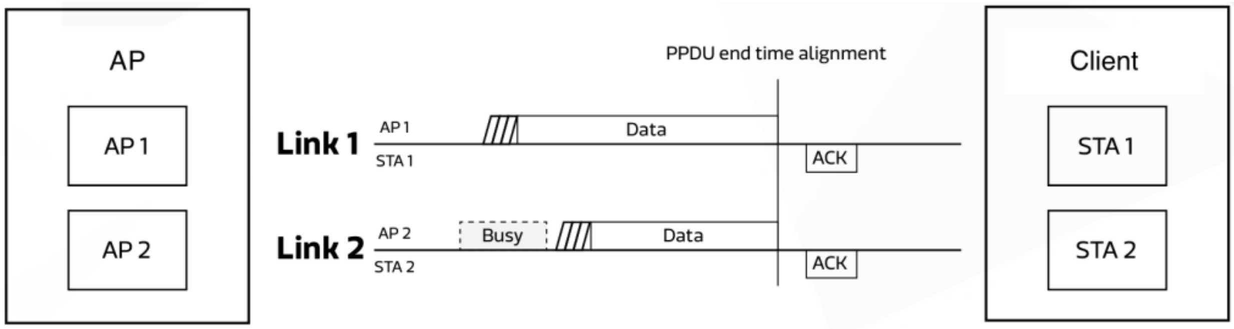
STR-MLMR allows communication between the client and AP on one band without any restriction from the operation on other bands that are part of MLO.



Most vendors are expected to support the STR-MLMR option as it is easy to implement and has the potential to take advantage of the available airtime efficiently.

2.4.3. *Multi Link Multi Radio – Non-Simultaneous Receive and Transmit (NSTR-MLMR)*

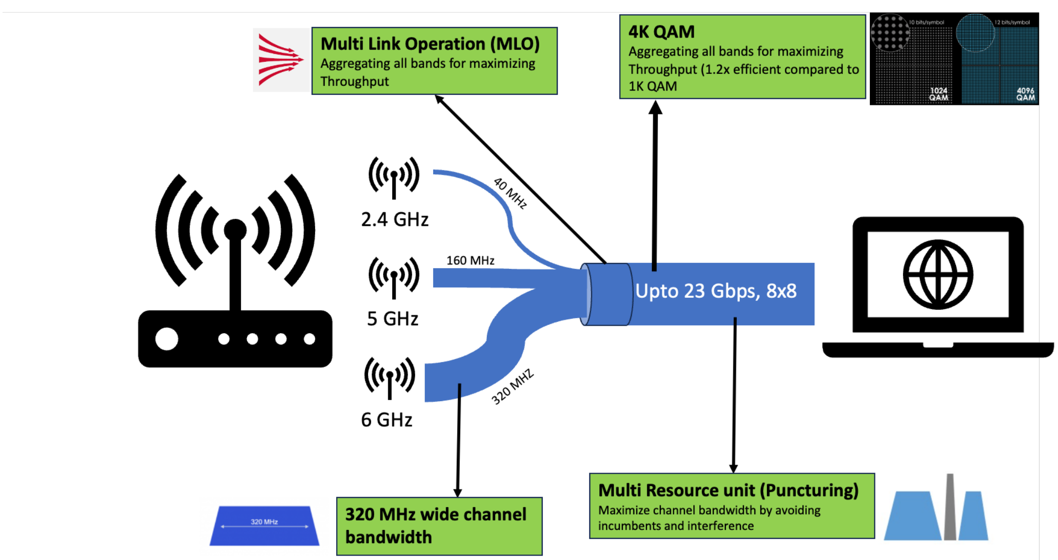
Unlike STR-MLMR, NSTR-MLMR places a restriction on the operation of one band based on the operation in other bands that are part of MLO. NSTR-MLMR restricts the AP and client to either transmit or receive on all the bands of MLO at any given time. Transmitting on one band while receiving on other bands is prohibited when operating in NSTR-MLMR. As such,when transmitting in multiple bands, it is necessary to coordinate the physical layer protocol data unit (PPDU) end times for synchronization across bands.



NSTR-MLMR is an algorithm to implement both on the client and AP sides. NSTR-MLMR does not utilize airtime efficiently as all bands must wait until every band is clear to send – or at least align such that end times can be aligned.

Multi-Link Operation in Wi-Fi 7 represents an advancement in wireless networking technology. By offering various modes of operation, MLO accommodates different device capabilities and use cases. This feature enables efficient spectrum utilization, improved performance, and enhanced reliability, including potentially for next-generation wireless applications and services.

The implementation of MLO in Wi-Fi 7 devices will depend on factors such as hardware capabilities, power constraints, and intended use cases. As the technology matures, we might expect to see a wide range of devices leveraging MLO to deliver wireless connectivity experiences.



2.5. Practical Limitations and Comparison

In wireless communication systems, particularly Wi-Fi networks, the maximum data rate often cited refers to the maximum Physical Layer (PHY) rate. This rate encompasses not only the user data but also overhead introduced at both the Medium Access Control (MAC) and PHY layers. The PHY rate is composed of data bits augmented by wireless headers at the MAC and PHY layers, resulting in a composite bit stream that forms the basis for transmission.

Actual throughput, in contrast, is a measure of the effective data transfer rate, considering only the user data bits successfully transmitted. The relationship between PHY rate and throughput is quantified by MAC efficiency, defined as:

MAC Efficiency = (Actual Throughput / PHY Rate) * 100%

For broad applicability in theoretical analyses, the PHY rate serves as the foundation for throughput estimations. A standardized MAC efficiency factor is applied to derive the estimated throughput from the theoretical PHY rate. In optimal scenarios, MAC efficiency is typically assumed to be 85%. However, it is important to note that real-world implementations exhibit variability:

1. High-performance systems may achieve MAC efficiencies exceeding 90%

2. Suboptimal implementations or challenging network environments may result in MAC efficiencies below 80%

For consistency and comparative purposes in this document, all throughput calculations employ a standardized MAC efficiency of 85%. This approach facilitates a normalized analysis of system performance while acknowledging the potential for variation in practical deployments. The estimated throughput is thus calculated as:Estimated Throughput = Theoretical PHY Rate * 0.85

This methodology provides a balanced framework for evaluating the theoretical performance capabilities of Wi-Fi systems while accounting for the inherent overhead in wireless protocols.

Note: It is important to note that these calculations are based on idealized conditions and theoretical models. Real-world performance may vary due to factors such as environmental obstacles, interference, and specific implementation details of both client devices and access points.

2.5.1. WiFi-6E Versus WiFi-7 Single Link

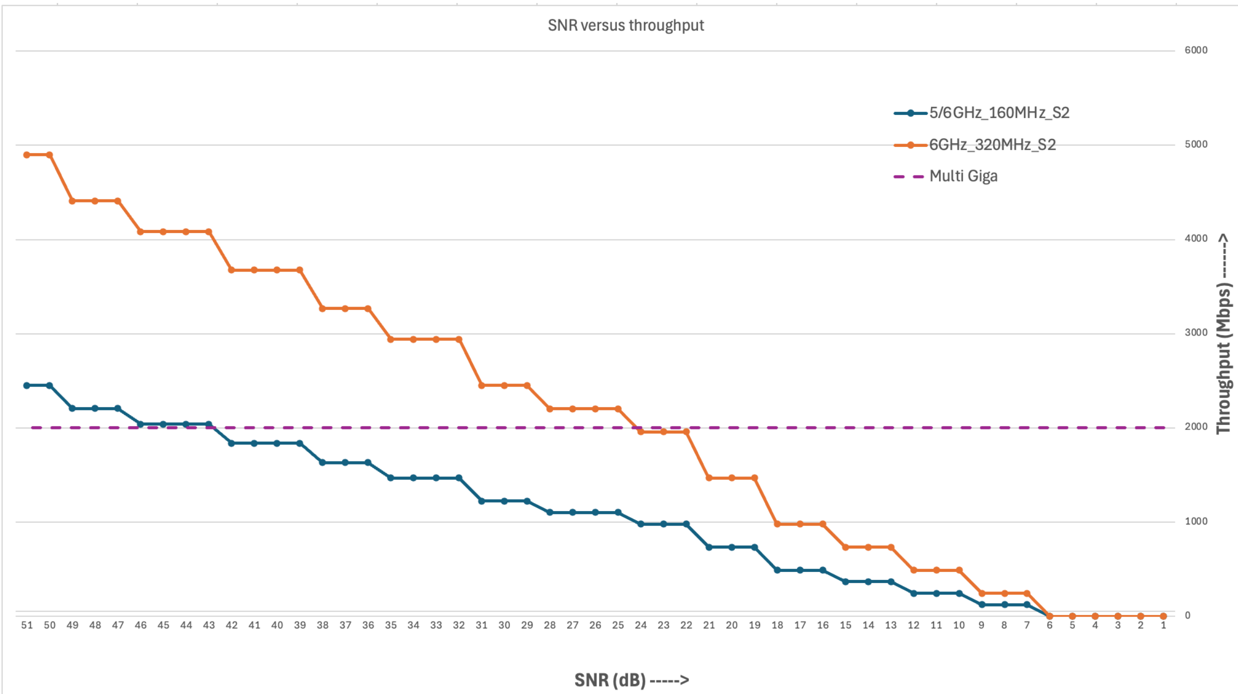
In contemporary Wi-Fi networks, most client devices utilize a dual-antenna system for router connectivity, despite the advanced capabilities of modern access points. While commercial Wi-Fi 6E (IEEE 802.11ax) and Wi-Fi 7 (IEEE 802.11be) routers frequently offer up to 4x4 Multiple-Input Multiple-Output (MIMO) configurations, client devices are typically constrained to 2x2 MIMO implementations due to form factor limitations and power consumption considerations.

This disparity between access point and client device capabilities has significant implications for system performance and theoretical throughput calculations. The effective number of spatial streams in a Wi-Fi connection is limited by the lesser of the two communicating devices' antenna configurations. Consequently, even when a router supports higher-order MIMO, the connection is often constrained by the capabilities of the client device.

For the purposes of this analysis and to maintain consistency with real-world usage scenarios, all device-specific calculations and performance projections assume a 2x2 MIMO configuration for client connectivity to the router or range extender. This assumption aligns with the predominant hardware configurations in the current consumer device ecosystem and provides a more realistic basis for evaluating expected performance in typical deployment scenarios.

It is worth noting that while this approach may underestimate the potential performance for high-end devices with more advanced antenna configurations, it offers a conservative and broadly applicable model for assessing Wi-Fi system capabilities in the context of prevailing consumer hardware limitations.

The graph below shows the potential throughput of the client when connected to a Wi-Fi 7 router versus a Wi-Fi 6E router against the signal-to-noise ratio (SNR).



This study focuses on multi-gigabit coverage and range capabilities of Wi-Fi 7 compared to Wi-Fi 6E. The graph illustrates the relationship between throughput and SNR for both standards, with particular emphasis on performance above 2 Gbps, which is denoted by the purple dashed line.

<u>SNR Requirements for 2+ Gbps Throughput:</u>

Analysis of the graph reveals significant differences in SNR requirements for achieving multi-gigabit speeds:

- Wi-Fi 6E: Requires SNR ≥ 43 dB to surpass 2 Gbps

Wi-Fi 7: Achieves 2+ Gbps at SNR ≥ 23 dBThis 20 dB disparity in SNR translates to a difference in effective range due to the logarithmic nature of the decibel scale. Specifically, a 20 dB improvement corresponds to a 100-fold increase in signal strength, which, under ideal free-space path loss conditions, could theoretically result in a 10-fold increase in distance.

The SNR requirements suggest that for Wi-Fi 6E, multi-gigabit speeds are achievable only in very close proximity to the access point. In contrast, Wi-Fi 7's lower SNR threshold for equivalent performance implies a significantly extended range for multi-gigabit connectivity.

To contextualize this difference, if a Wi-Fi 6E client requires a 2-foot distance from the router to achieve 2 Gbps, a Wi-Fi 7 client could theoretically maintain the same performance at up to 20 feet under ideal conditions. It is important to note that this extrapolation is based on theoretical free-space path loss and does not account for real-world factors such as obstacles, interference, and multipath fading. Actual performance will vary depending on the specific environment and implementation.(Note: Precise distance calculations based on SNR values will be provided in subsequent sections, accounting for realistic propagation models and environmental factors.)

2.5.2. WiFi-6E Versus WiFi-7 Multi Link

This section extends the single-link operation analysis conducted on the 6 GHz band to encompass the Multi-Link Operation (MLO) capabilities introduced in Wi-Fi 7. MLO, as detailed in Section 2.3, enables client devices to operate concurrently across multiple frequency bands, potentially enhancing throughput and reliability.

For the purposes of this study, we concentrate on the Simultaneous Transmit and Receive Multi-Link Multi-Radio (STR-MLMR) mode of MLO. This mode allows for simultaneous, independent operation on multiple frequency bands.

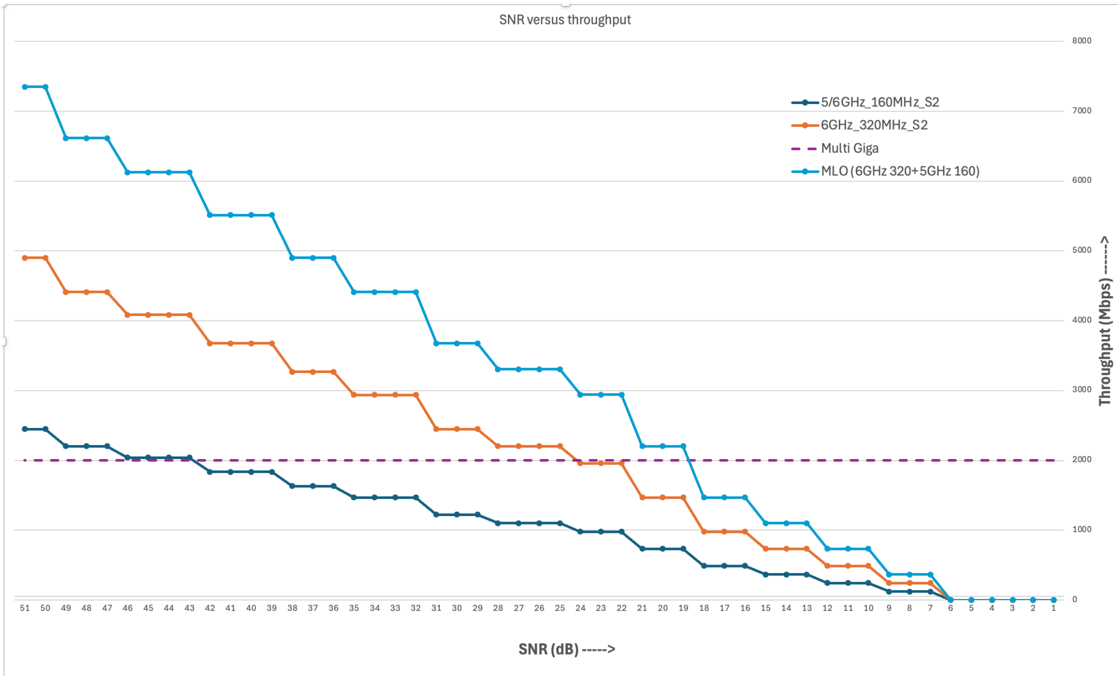
While Wi-Fi 7 standards permit three-band STR-MLMR configurations, our analysis focuses on a two-band implementation combining 5 GHz and 6 GHz operations. This decision is predicated on two key factors:

- Current hardware limitations and power efficiency considerations in client devices favor dual-band over tri-band implementations.
- Market analysis and product roadmaps suggest that near-term commercial deployments could predominantly feature dual-band STR-MLMR configurations.

The subsequent analysis will evaluate the performance characteristics of Wi-Fi 7 using a dual-band STR-MLMR configuration operating in the 5 GHz and 6 GHz bands. This approach aligns with anticipated real-world deployments and provides a pragmatic assessment of achievable multi-gigabit throughput ranges in Wi-Fi 7 systems.

By focusing on this specific MLO configuration, this paper aims to provide insights that are both technically rigorous and practically relevant to the evolving landscape of high-performance Wi-Fi networks.

The graph below shows the potential throughput of the client when connected to a WiFi-7 router with and without MLO versus a Wi-Fi 6E router against SNR.



The graphical analysis demonstrates that a client device employing MLO across the 5 GHz and 6 GHz bands exhibits superior performance characteristics compared to single-link Wi-Fi 7 operation on the 6 GHz band alone. Specifically, to achieve a throughput of 2 Gbps, the MLO configuration requires approximately 4 dB less SNR than its single-link counterpart.

This 4 dB reduction in SNR requirement translates to an enhancement in signal strength and, consequently, an extension of the effective range for high-throughput operations. Given that the decibel scale is logarithmic, a 4 dB improvement corresponds to more than double the signal strength (10^(4/10) ≈ 2.51).

In free-space path loss scenarios, this signal strength improvement can be approximated to a range extension factor of approximately 1.5 (√2.51 ≈ 1.58, adjusted for real-world conditions). This theoretical range extension can be contextualized as follows:

- Wi-Fi 6E: 2 Gbps achievable at ~2 feet from the router
- Wi-Fi 7 (Single-link, 6 GHz): 2 Gbps achievable at ~20 feet
- Wi-Fi 7 (MLO, 5 GHz + 6 GHz): 2 Gbps achievable at up to ~30 feet

The extended range for multi-gigabit throughput offered by MLO in Wi-Fi 7 has significant implications for network design and deployment strategies. It allows for more flexible access point placement and potentially reduces the number of access points required to cover a given area with high-throughput connectivity.

The scope of this document covers 160MHz bandwidth in 5GHz. There are ways to achieve 240MHz in 5GHz band but due to its limited adaptation, it will not be analyzed as part of this paper.

3. Multi-Link Operation: Revolutionizing Extenders

While the preceding analysis has demonstrated the superiority of Wi-Fi 7 over Wi-Fi 6E in terms of throughput and range for multi-gigabit connectivity using a single access point, the introduction of Wi-Fi

7 extenders into the network topology further amplifies these advantages. The primary objective of this study is to determine the maximum distance from the primary router at which multi-gigabit throughput remains achievable, and the incorporation of extenders significantly impacts this metric.

Traditionally, wireless extenders have been employed to expand the overall coverage area of a Wi-Fi network. In the context of Wi-Fi 7, however, extenders play a more nuanced role:

- Overall Connectivity Range: The general connectivity range of a Wi-Fi 7 network with extenders may not differ substantially from that of the primary router alone, due to the already enhanced range capabilities of Wi-Fi 7.
- Multi-Gigabit Coverage Extension: The strategic placement of Wi-Fi 7 extenders can increase the area over which multi-gigabit throughput is maintainable, compared to both single-router configurations and networks utilizing Wi-Fi 6E extenders.

When deployed under similar conditions and network topologies, Wi-Fi 7 extenders offer several advantages over their Wi-Fi 6E counterparts in extending multi-gigabit coverage:

- Higher Modulation Support: Wi-Fi 7 extenders can maintain higher-order modulation schemes at greater distances, preserving multi-gigabit capabilities over extended ranges.
- Enhanced MLO Capabilities: The Multi-Link Operation feature of Wi-Fi 7 allows extenders to more efficiently utilize available spectrum, potentially doubling the effective bandwidth in optimal conditions.
- Improved Interference Mitigation: Advanced features like preamble puncturing in Wi-Fi 7 enable extenders to operate more effectively in congested environments, maintaining high throughput where Wi-Fi 6E extenders might suffer degradation.

Subsequent sections will provide quantitative analysis of the multi-gigabit coverage extension achievable with Wi-Fi 7 extenders, including optimal placement strategies and performance comparisons with Wi-Fi 6E extender configurations.

3.1. Single Extender Configurations and Comparisons

Extenders are available in various configurations, designed to enhance network coverage and performance. This section examines the radio configurations of Wi-Fi 6E and Wi-Fi 7 routers and extenders, and outlines the comparative study of multi-gigabit range capabilities.

WiFi-6E and WiFi-7 routers incorporate a tri-band setup, consisting of 2.4GHz, 5GHz, and 6GHz radios. While this three-radio configuration is standard, quad-band routers featuring either dual 5GHz or dual 6GHz radios are exceptionally rare.

Extenders are primarily designed to expand network range by maintaining a consistent wireless backhaul connection to the router. To mitigate time-sharing issues between the fronthaul and backhaul on the band connected to the router, extenders often include an additional radio. This supplementary radio, operating on the same band but a different channel, serves as the fronthaul while the primary radio functions as a dedicated backhaul.

Unlike their router counterparts, four-radio extenders are more common, though still relatively rare due to cost and form factor constraints. This configuration allows for more efficient bandwidth utilization and improved overall performance.

This study will focus on comparing the multi-gigabit range capabilities of Wi-Fi 7 and Wi-Fi 6E systems in the following configurations:

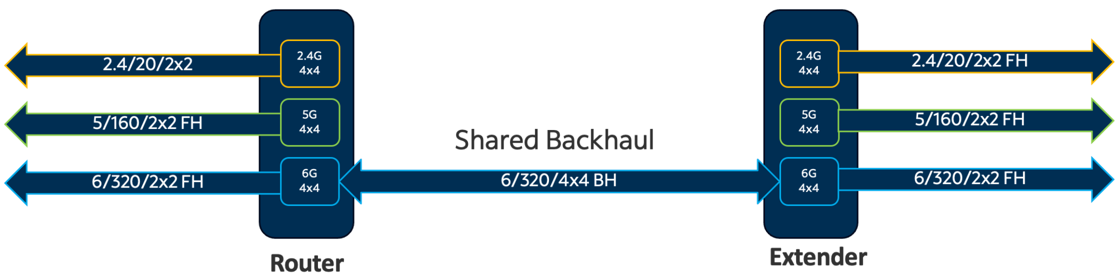
1. Three-radio Wi-Fi 7 extender system versus three-radio Wi-Fi 6E extender system
2. Four-radio Wi-Fi 7 extender system versus four-radio Wi-Fi 6E extender system (dual 6GHz radios)
3. Four-radio Wi- Fi 7 extender system versus four-radio Wi-Fi 6E extender system (dual 5GHz radios)

Compared to client devices, extenders have an advantage for the backhaul. That advantage is a 4x4 connection. We have analyzed the multi-gigabit throughput for clients with a 2x2 connection between the router and client, but extenders have radios that have the capability to maintain a 4x4 connection with the router.

3.1.1. Three Radio Extender system comparison

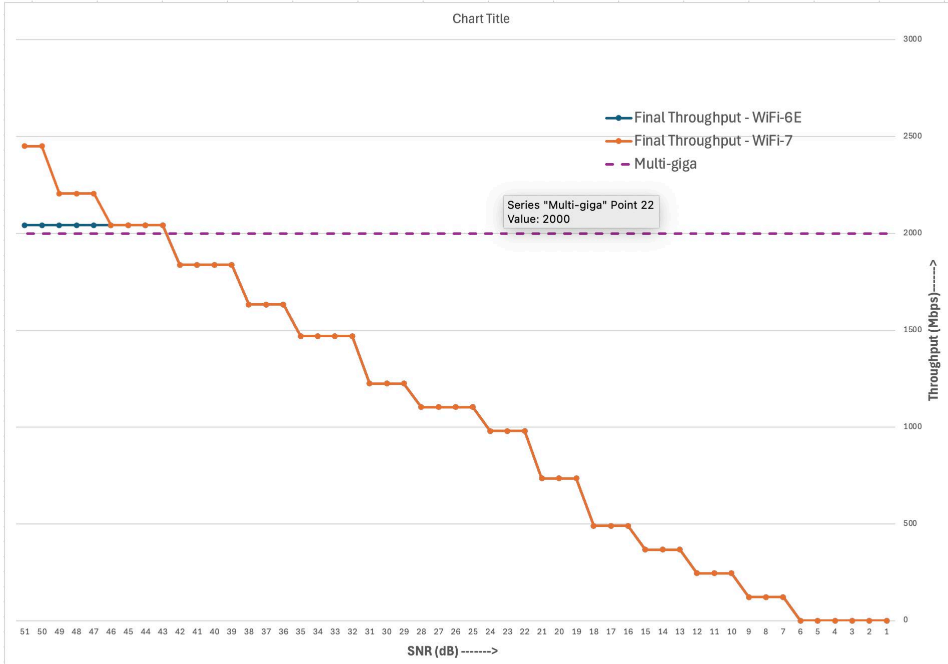
We will explore and expand on the following configurations similar to the comparisons we have performed in sections 2.4.1 and 2.4.2.

3.1.1.1. Configuration 1 – Shared Backhaul 6 GHz

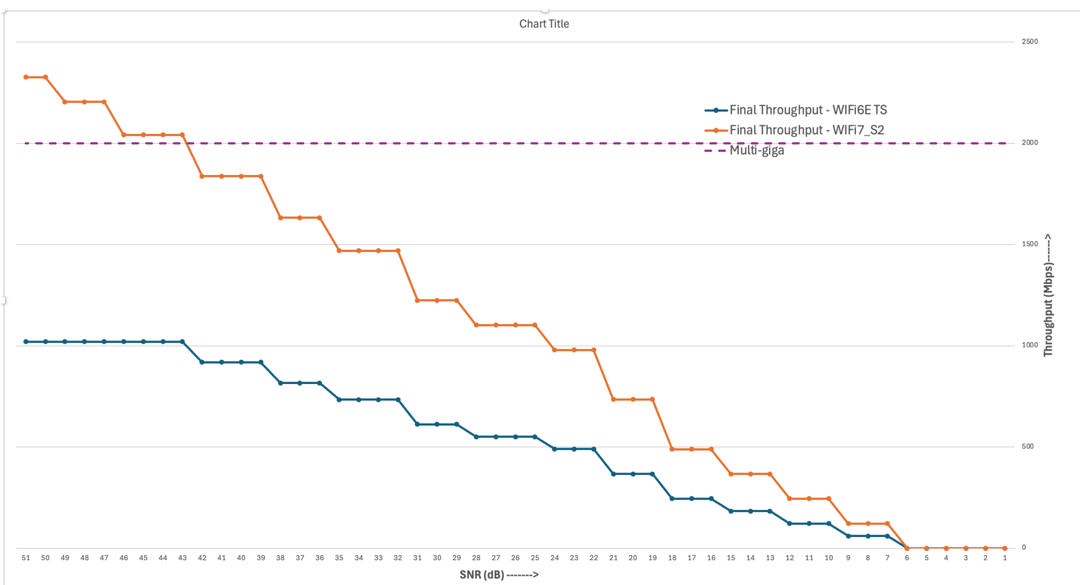


Our analysis assumes the extender is placed at a good SNR location to balance the coverage and speed. Based on the router only RvR curve, a good SNR location is at 30dB SNR. As the backhaul is 4x4, the client is connected to the extender fronthaul 5GHz with 2x2 max BW. Here, the bottleneck is the 5GHz front haul because when the extender is placed at SNR 30 dB and in 4x4 mode Wi-Fi 6E can reach the maximum throughput of 2x2. A 5% loss is added to backhaul when backhaul bottlenecks to account for multi hop losses.

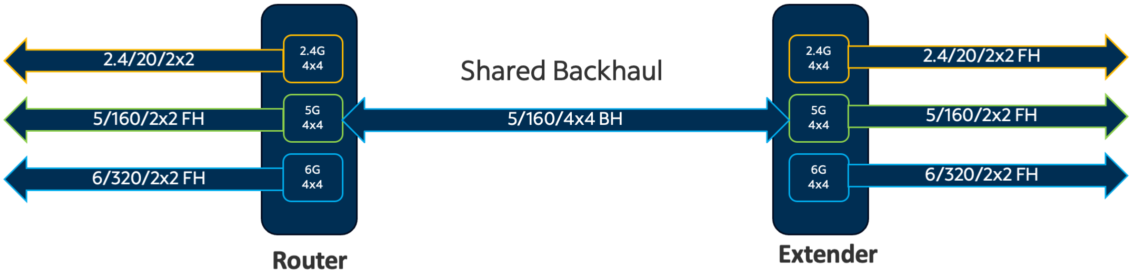
In this scenario of 5GHz, 2x2 and 160MHz fronthaul, the performance bottleneck and multi-gigabit range is no different from Wi-Fi 7 to Wi-Fi 6



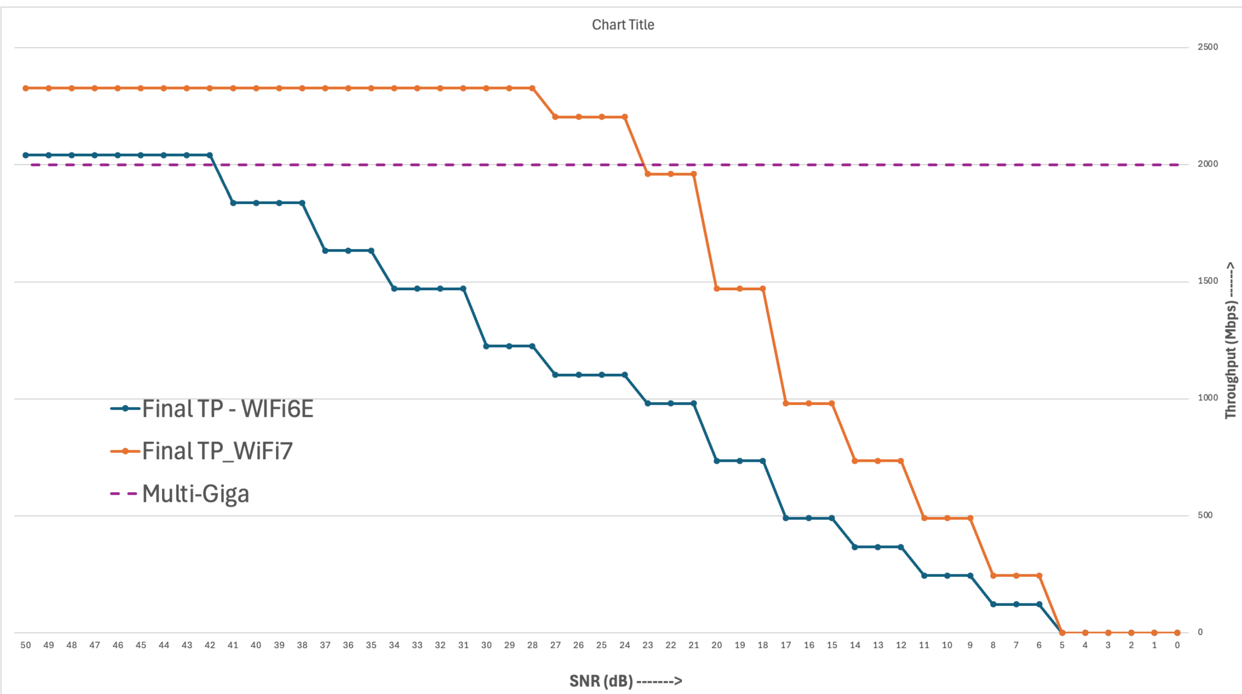
The second scenario is 6GHz backhaul and 6GHz fronthaul on the radio. In this scenario, the 6GHz radio on the extender has to time share between fronthaul and backhaul. As we have learned so far, Wi-Fi 6E can only operate at 160MHz. This shows that when 6Ghz is time shared, fronthaul 6Ghz can never reach multi-gigabit. The max speed comparison looks something like below. WiFi-7 can reach multi-gigabit due to 320MHz on 6GHz.



3.1.1.2. Configuration 2 – Shared Backhaul 5 GHz

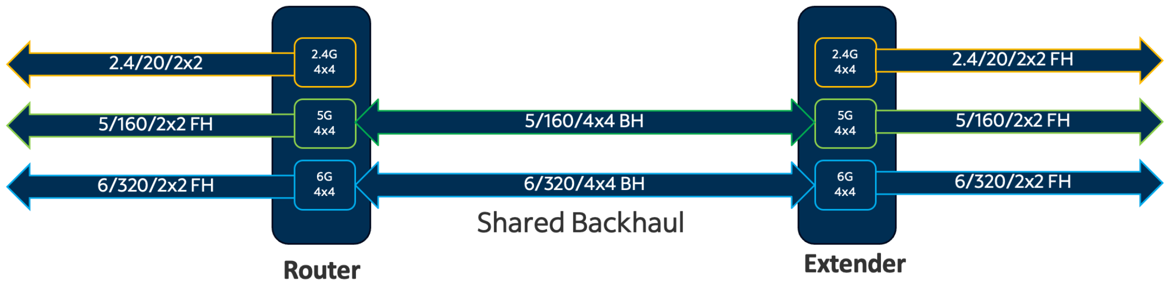


In Wi-Fi 7, 5GHz with 160MHz and 4x4 configuration produces same throughput as 6GHz with 320MHz and 2x2 configuration. For this configuration in Wi-Fi 6, the bottle neck will be the fronthaul 6Ghz throughput as the bandwidth is limited to 160MHz. The output with 5GHz 160MHz BW with 4x4 config and 6GHz 160MHz and 2x2 is going to have the same throughput as the first picture in section 3.1.1.1. The comparison looks something like below.

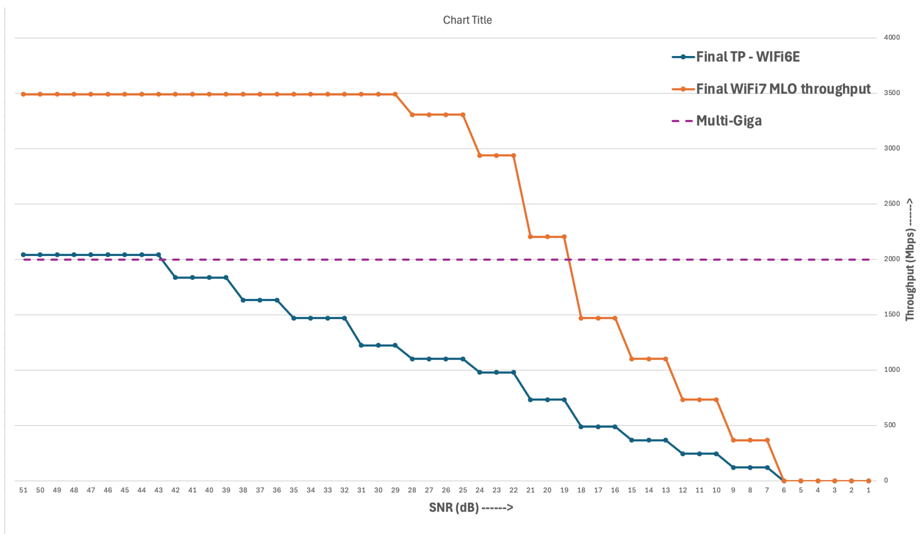


It is evident that the Wi-Fi 7 holds multi-gigabit range farther. This is likely because the bottleneck is the backhaul due to the position it is placed. If you move the extender closer to the router, increasing SNR on the extender, the ceiling will be higher but the range of multi-gigabit stays the same relative to the extender. The overall range for multi-gigabit decreases as the extender is now closer to the router. This is a 18dB difference in multi-gigabit range.

WiFi7 Multi-Link backhaul configuration

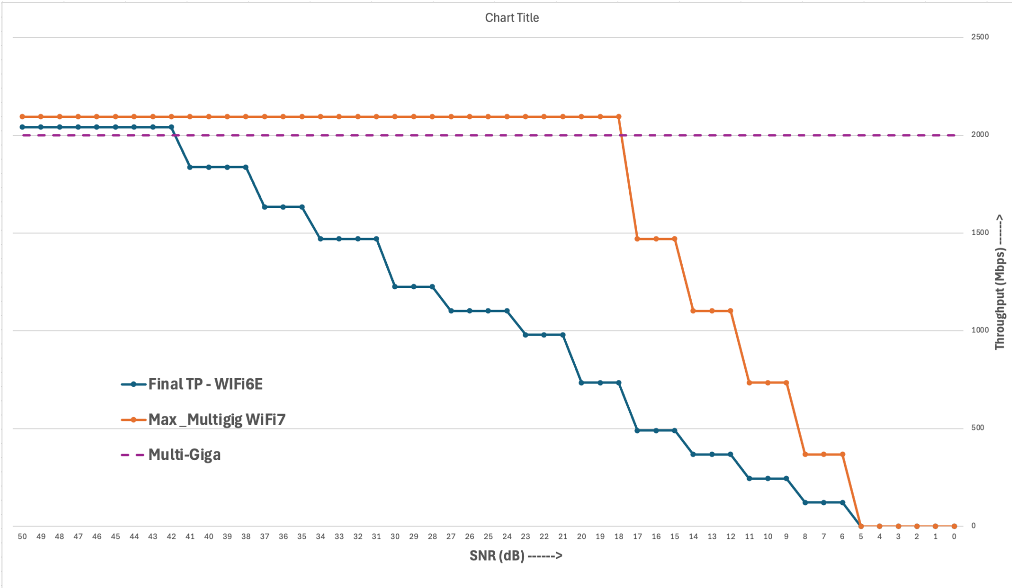


With MLO, the comparison with best case scenario on Wi-Fi 6E looks something like below.



The multi-gigabit range with Wi-Fi 7 is 25dB better compared to Wi-Fi 6E from the graph. As the graph is reaching its limit when SNR is high, it indicates that the bottleneck is backhaul connection. When operating at max, the radios start to time share and the result will be this. The multi-gigabit range can be further increased by placing the extender even further away. The above analysis is with the extender placed at the same distance relative to the Wi-Fi 6E or Wi-Fi 7 router.

The next analysis, which is the intention of this paper, is the max range of multi-gigabit irrespective of extender position. When the extender is placed at SNR 18dB instead of SNR 30dB for Wi-Fi 7, the Wi-Fi 7 system can still reach multi-gigabit. The comparison is below with this new placement. Wi-Fi 6E can also produce similar results to the graph below with Wi-Fi 6E extender placed at SNR of 26dB.



Overall, the standard noise floor is generally at -90dBm. SNR in general is addition of signal strength and noise floor.

For final maximum range analysis, transmit power of 23dBm was considered.

For the Wi-Fi 7 system, SNR of 18dB translated to -72 dBm signal strength.

For the Wi-Fi 6E system, SNR of 26 dB translated to -64 dBm signal strength.

Just with extender placement, the difference in range is 8dB which translated to 6.3 times the distance.

In addition, the extender fronthaul range for multi-gigabit is 24dB, which is 15.8 times the distance.

To summarize, with a one extender system, if Wi-Fi 6E can provide multi-gigabit at R1+R2 feet, then a Wi-Fi 7 extender system can provide Multi-gigabit at 6.3R1+15.8R2 feet.

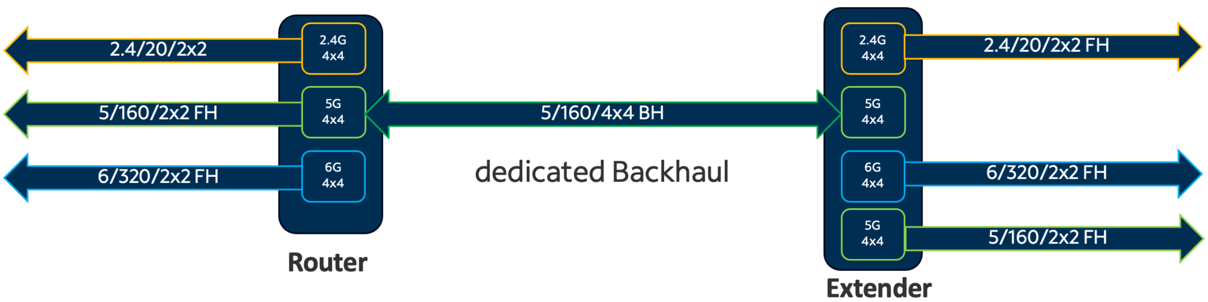
3.1.2. Four Radio Extender System Comparison (Dual 6GHz Radios)

The range of the multi-gigabit stays the same with a four radio solution. The peak throughput may vary but range of multi-gigabit is not highly varied (very minimal in MLO scenario). The overall range increment is ~3dB compared a three radio extender solution, which is insignificant. Further analysis was deemed unnecessary. A four radio extender configuration was provided below for completeness.

3.1.2.1. Dedicated Backhaul 6GHz

3.1.3. Four Radio Extender System Comparison (Dual 5GHz Radios)

3.1.3.1. Dedicated Backhaul 6GHz



4. Strategies for Optimal Placement

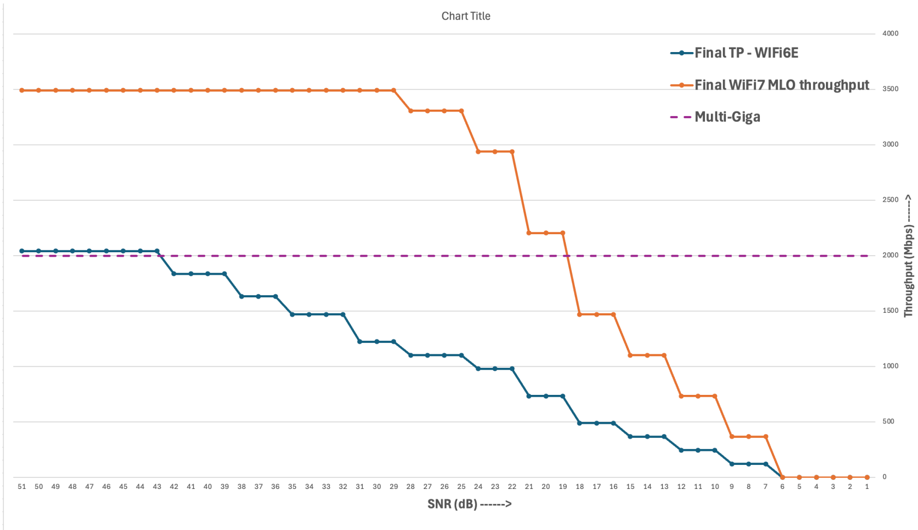
Based on the analysis performed in Section 3, It is evident that the placement of the extender depends on the following:

- Router configuration
- Extender configuration
- Size of the home
- Client user needs

The positioning of Wi Fi 7 extenders is needed for balancing throughput and range requirements. For optimal performance, it is recommended to place the extender in a location where the SNR falls within the range of 20-23dB. However, this placement can be adjusted based on specific home layouts and client needs.

- Coverage Priority: If extended coverage is the primary concern and performance is secondary, the extender can be positioned farther from the router. This configuration maximizes the network's reach but may result in reduced speeds in the extended area.
- Performance Priority: In smaller homes with a high density of client devices requiring robust speeds, the extender should be placed closer to the router. This setup ensures stronger signal strength and higher data rates for connected devices.
- Balanced Approach: For most scenarios, adhering to the recommended 20-23 dB SNR range provides an effective compromise between coverage and performance.

It is important to note that the optimal placement may require some experimentation, as factors such as building materials, interference sources, and specific usage patterns can influence the extender's effectiveness. Regular assessment and adjustment of the extender's position can help maintain an optimal network configuration as needs evolve.



With optimal placement, the throughput from extender will be as shown above.

5. Market MLO Trend

Currently, MLO technology is being implemented in both routers and client devices, offering several key functionalities:

- Simultaneous Multi-Band Operation: Devices can communicate over multiple frequency bands (2.4 GHz, 5 GHz, and 6 GHz) concurrently.
- Enhanced Throughput: By aggregating multiple channels across different frequency bands, MLO increases data transfer speeds.
- Reduced Latency: MLO improves network responsiveness by utilizing the most efficient channels available.
- Improved Reliability: The ability to switch between bands dynamically helps mitigate interference and congestion.

Two main operating modes are being implemented:

- STR (Simultaneous Transmit and Receive): Allows devices to manage multiple Wi-Fi connections on different channels simultaneously.
- EMLSR (Enhanced Multi-Link Single-Radio): Optimizes the setup and recovery processes of multi-link operations.

NSTR (Non-Simultaneous Transmit and Receive) mode is not implemented in any of the commercially available devices at this time.

Current high-end routers support up to two MLO networks simultaneously.

5.1. Future Outlook:

1. Increased Adoption: As Wi-Fi 7 becomes more widespread, we can expect a growing number of devices to support MLO, including smartphones, laptops, and IoT devices.

2. Enhanced Performance: Future MLO implementations may further improve throughput and latency, especially in quad-band routers.

3. Focus on Latency Reduction: MLO is being developed with a specific emphasis on reducing latency, for emerging applications like VR/AR, online gaming, and cloud computing.

Regarding client device support for 3-band MLO in the future:

While specific implementations may vary, it's likely that future client devices may support 3-band MLO. The exact configuration will depend on the device's capabilities and power constraints:

- High-end devices (e.g., premium smartphones, laptops) may support STR-MLMR across all three bands, allowing for maximum performance and flexibility.
- Mid-range devices might implement a hybrid approach, using eMLSR for 3-band operation to balance performance and power consumption.
- Entry-level or power-constrained devices may use eMLSR for 2-band operation, with the option to extend to 3 bands when needed.

The specific implementations will likely evolve as the technology matures and manufacturers find the optimal balance between performance, power consumption, and cost.

6. Conclusion: A Secured Multi-Gigabit Domain

- Wi-Fi 7 extenders, armed with MLO, offer a solution to extend the reach of gigabit Wi-Fi connections soon
- From section 2 analysis, it is evident that Wi-Fi 7 routers can provide multi-gigabit Wi-Fi speeds at 10x distance when using single link and 15.8x distance when using multi-link compared to a Wi-Fi 6E router.
- When a three radio extender system is employed, the multi-gigabit speeds can be achieved at a distance 6.3*R1+15.8*R2 compared to R1+R2 distance from the Wi-Fi 6E extender system.
- When a four radio extender system is employed, the range for multi-gigabit speeds is not significantly impacted. The only range advantage may occur in backhaul MLO and front haul MLO scenarios but that too is minimal (<3dB).
- More advanced MLO implementation may come up, which are cost-effective and power-optimized, using all the bands of operation. Devices that require a smaller form factor will continue to employ eMLSR as the main source of MLO operation which gains latency advantage but minimal throughput gains.

Abbreviations

AP	access point
Gbps	gigabits per second
FEC	forward error correction
Hz	Hertz
K	Kelvin
MAC	Medium Access Control
MLO	Multi-Link Operation
MIMO	Multiple-Input Multiple-Output
eMLSR	Enhanced Multi Link Single Radio
MLMR	Multi-Link Multi Radio
NSTR	Non-Simultaneous Transmit and Receive
PHY	Physical Layer
PPDU	Physical Layer Protocol Data Unit
SCTE	Society of Cable Telecommunications Engineers
SNR	Signal-to-Noise Ratio
STR	Simultaneous Transmit and Receive

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