Benchtop Efficiency Measurements for Residential Mesh Networking Equipment

Final Report

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Executive Summary

This report presents a comprehensive assessment of mesh networking systems (MNS) in the residential networking market. It evaluates the efficiency, performance, and energy consumption of MNS products in comparison to traditional wireless routers, addressing both technical and market aspects to guide consumer decisions.

The purpose of this study is to evaluate MNS as an emerging alternative to traditional single-router setups. These systems offer enhanced wireless coverage by utilizing multiple interconnected nodes, providing seamless connectivity throughout residential environments. The study was conducted to analyze the performance and energy implications of MNS and to identify their cost-effectiveness, energy efficiency, and practical applicability for consumers.

The study identified key market trends, including the prevalence of Wi-Fi 6 and 6E systems, which account for the majority of the 60 products analyzed from eight different manufacturers included in this evaluation. While Wi-Fi 7 is starting to emerge in the market, the number of available products is limited. Findings reveal that MNS products are often sold in multi-node bundles, which advertise broader coverage at various price points. In terms of design, mesh systems tend to prioritize aesthetics, incorporating internal antennas and simple form factors that blend seamlessly into home environments. This design shift contrasts with the more utilitarian look of traditional routers.

In terms of cost comparison, while MNS generally require a higher upfront investment compared to traditional routers, they advertise better coverage and connectivity. Notably, three-pack mesh system bundles offer more value by reducing the per-unit cost, making them more cost-effective than purchasing multiple routers of equivalent performance. From the assessed MNS, Wi-Fi 6 products had the most cost conscience packages with three-node systems only costing 51 percent more than equivalent routers. The study highlights that although consumers may pay more initially, the broader coverage and potential savings over the longer term make MNS products a viable option, but only if the system suitably fits the needs of the household.

The research team evaluated user experience of MNS and found that most devices rely on mobile apps for setup and configuration, streamlining the process and improving ease of use. However, some systems require both a mobile app and a web interface for full functionality, which may complicate the user experience by necessitating navigation through two interfaces to make essential changes to the network configuration.

Data indicates that energy consumption of an MNS increases significantly when additional nodes are energized. On average, the total system power consumption nearly tripled when the MNS configuration was expanded from one to three nodes. Additionally, active data transmission significantly impacts MNS energy use, with power consumption increasing by an average of 44.3 percent during traffic testing and 23.2 percent during attenuation testing. In some cases, overall power consumption more than doubled compared to idle conditions, depending on operating conditions and traffic throughput. When calculating the unit energy consumption (UEC) for the entire system, results showed an average energy increase of 188 percent, nearly three times higher than a single node's idle performance. Additionally, traffic conditions led to a 2.49 percent increase in UEC, and attenuation conditions resulted in an average increase of 18.25 percent.

The study recommends updating existing voluntary standards, which only assess the power consumption of a single node in an idle state, which is inadequate for evaluating the energy efficiency of multi-node MNS. These standards should be expanded to account for the entire system, including active data transmission and multiple-node configurations. Additionally, consumers would benefit from guidance on a staged setup approach, where additional nodes are added based on need, rather than deploying all nodes at once, to minimize unnecessary energy consumption.

Looking ahead, further research is recommended to improve understanding of MNS performance and energy consumption. This includes developing models to better assess how factors like signal attenuation impact performance in different home environments and identifying procedures to determine the most efficient commissioning procedures to enable full home coverage without excess energy use. Lastly, the research team recommends optimizing unit energy consumption calculations and active traffic models by conducting field testing to understand user behavior and MNS suitability within real-world environments.

Abbreviations and Acronyms

Acronym	Meaning
DUT	Device Under Test
DHCP	Dynamic Host Configuration Protocol
EPS	External Power Supply
EHT	Extremely High Throughput
IAD	Integrated Access Device
IP	Internet Protocol
ISP	Internet Service Provider
LAN	Local Area Network
MNS	Mesh Networking Systems
NAT	Network Address Translation
RNE	Residential Networking Equipment
SSID	Service Set Identifier
SNE	Small Networking Equipment
IEEE	The Institute of Electrical and Electronics Engineers
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WPA	Wi-Fi Protected Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

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Introduction

Mesh networking systems (MNS) are a relatively new product category within the residential networking equipment (RNE) market that has experienced exponential growth in recent years. These innovative systems aim to revolutionize traditional home networking setups by offering a seamless and user-friendly solution for expanding and improving wireless coverage. Unlike conventional setups that rely on a single router or Integrated Access Device (IAD), mesh networking products introduce a distributed network architecture comprising multiple wireless devices interconnected to form a unified home wireless network.

The fundamental premise of MNS lies in their ability to replace the limitations of a singular router or IAD with a dynamic and adaptable network of interconnected nodes. Each node functions as a transmitter and receiver, facilitating continuous communication among all devices within the network. Users can effortlessly expand their network coverage by adding additional wireless nodes to the existing setup, without the need for complex configuration or extensive wiring. This distributed approach fundamentally alters the way wireless signals are propagated within the home environment, effectively eliminating dead zones and ensuring consistent connectivity regardless of location.

Overall, residential MNS represents a notable departure from the traditional paradigms of home connectivity, offering an enticing alternative that promises enhanced coverage and reliability. However, despite their growing availability, there are uncertainties surrounding their widespread adoption and utility among consumers. One of the primary concerns is the potential financial implications associated with transitioning to a mesh networking setup. While the initial investment in mesh networking equipment may seem justified by the promise of superior performance, the overall cost-effectiveness is uncertain. Consumers may find themselves spending more to acquire multiple nodes to cover their desired area adequately compared to the relatively straightforward purchase of a single traditional router. Additionally, the deployment of multiple nodes may entail higher energy consumption and resource utilization compared to a single router.

This project aims to address key concerns surrounding the applicability, cost, and performance of MNS. Researchers analyzed the evolving MNS landscape, discerned emerging product trends, and conducted rigorous laboratory evaluations to assess the functionality and energy performance of prevalent MNS. Study data was used to complete a comparative analysis of MNS and traditional non-mesh residential networking systems to determine the relative efficiency and potential advantages of one system over the other.

Background

Traditional residential networking systems are comprised of a modem and router combination or, more commonly in recent years, an IAD, which is a singular device that combines the functionality of a modem, router, and possibly the voice-over internet protocol (VoIP). These devices can be rented from a consumer's internet service provider (ISP) or purchased through local and online retailers. Most traditional networking devices can operate with any ISP, allowing consumers to choose products based on preferred device features rather than basic compatibility. Because wireless signals generated from these devices originate from a single access point, to ensure adequate home coverage, the best approach is to position the access point in a central location or purchase a system with a range that fully covers the intended area.

For large homes or those where a single access point is insufficient to achieve full coverage, there are a number of commercially available range extenders and repeaters capable of extending the coverage area. However, these secondary devices offer limited performance compared to a router or IAD, often only allowing a fraction of the wireless throughput. In addition, device integration is often complex, especially when combining devices from multiple manufacturers.

MNS were developed as a response to the ever-increasing count of internet-connected devices in the home. A home computer is no longer the central or sole source of home networking needs. However, MNS may not be a one-size-fits-all solution. MNS are inarguably better suited for large, multistory homes or larger homes where the Wi-Fi signal has more ground to cover or walls to penetrate. Some sources report it is simpler and just as effective to use a standalone router in homes, especially those ranging between 1,800–2,300 square feet[1] (Domingo, 2024).

With respect to regulations, the most relevant standard for residential networking equipment is the *Voluntary Agreement for Ongoing Improvement to the Energy Efficiency of Small Network Equipment*, which sets idle-mode power allowances to limit networking equipment energy use and utilizes the ANSI/CTA-2049-A test methodology. ANSI/CTA-2049-A and the Voluntary Agreement standard are built on an older ENERGY STAR® standard, which has been expanded and is updated on a two-year cycle to keep pace with the rapidly evolving market and product capabilities. The agreement is widely accepted with most, but not all, RNE manufacturers being signatories.

However, there is a concern with the methodology's applicability to mesh networking devices as the testing only views an individual device's energy use in idle conditions. With MNS multi-node architecture, the reported energy metric will most likely not be reflective of what is happening within the home, especially when passing internet traffic.

Objectives

The objectives for this report are to:

- Present a thorough market assessment for mesh networking devices, characterizing trends in product capabilities, design, and distribution approaches.
- Explain the selection criteria for each device under test (DUT) and provide an assessment of out-of-box conditions and system configuration.
- Describe MNS testing of selected devices, enabling the characterization of product performance and energy impacts.

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[1] https://www.nytimes.com/wirecutter/blog/wi-fi-router-good-as-mesh/

- Compare MNS product performance to a traditional router and assess its overall energy efficiency.

Market Assessment Methodology

The research team's market assessment started with an exhaustive identification of mesh networking products available in California. MNS manufacturers were initially identified through existing voluntary standard's manufacturer and product lists, mainly the *Voluntary Agreement for Ongoing Improvement to the Energy Efficiency of Small Network Equipment,* which is the most established and utilized regulation standard involving RNE in the United States. The agreement is managed by the Consumer Technology Association, CableLabs, and the NCTA. The agreement assigns power allowances for various categories and features of small networking equipment (SNE), which are continuously updated and reduced to promote the development of energy-efficient solutions. The agreement currently has 20 signatories — RNE manufacturers — that have joined the agreement and adhere to the proposed power allowances. The team's search for potential mesh systems was further expanded through additional product searches on third party retailer sites (Amazon, BestBuy, and others), general search engines (Google), and listed trade show (Consumer Electronics Show) participants. Product listings and availability were gathered through online third party retailer sites and specific manufacturers' sites when direct-from-manufacturer purchasing was offered.

Particular attention was paid to gathering information on the bundling practices for MNS. Unlike traditional modems and routers where one item is contained within each package, MNS often include devices in multiple counts with subsequent discounts. This encourages consumers to initially purchase packages with more nodes than needed before they may understand their home's networking needs.

Once product listings were identified and model numbers were obtained, the research team visited the manufacturers' websites to gather available product specifications, ensuring accurate information was collected.

Results from the product search were categorized and product trends relating to product capabilities, design approaches, networking logic, and bundling practices were identified. These results were furthered used to generate an initial cost assessment for MNS devices compared to traditional approaches.

Market Assessment Findings

Identified Products

The research team identified 60 products from eight different manufacturers. On average, each manufacturer advertised seven different mesh products with varying capabilities, mostly related to the products' wireless protocols, advertised throughput speeds, and listed coverage. One manufacturer offered 24 different MNS product options which demonstrates the variety of system configurations available to the consumer. Mesh networking options from the manufacturers were comparable in number to traditional offerings, and for a few manufacturers mesh products were the only networking equipment offerings.

Table 1: Summary of Identified MNS

Manufacturer	MFG 1	MFG 2	MFG 3	MFG 4	MFG 5	MFG 6	MFG 7	MFG 8
Identified MNS	5	9	3	7	7	24	3	2
Wi-Fi 5 (count)	1	0	2	1	0	4	1	1
Wi-Fi 6 (count)	3	8	1	3	4	12	1	1
Wi-Fi 6E (count)	1	1	0	2	2	5	1	0
Wi-Fi 7 (count)	0	0	0	1	1	3	0	0
Minimum Package Cost	$170	$200	$200	$260	$400	$56	-	$116
Maximum Package Cost	$549	$750	$350	$1,000	$2,300	$1,800	-	$155
Minimum Coverage (ft^2)	4,500	4,800	4,500	4,500	5,000	3,000	-	4,000
Maximum Coverage (ft^2)	6,000	6,000	6,600	9,000	10,000	10,000	-	4,500

Source: CLTC, Product Specifications, Retailer/Manufacturer Sites.

Product Trends

On review of identified products, a number of trends emerged relating to product capabilities, such as wireless protocol and advertised coverage, as well as design choices, such as product color, form factor, and antenna design.

Wi-Fi Protocols

MNS' follow the same standards and protocols as traditional routers, developed by the Institute of Electrical and Electronics Engineers (IEEE). These systems are mainly based on the IEEE 802.11 Wi-Fi protocol. The 802.11 standard is continuously updated by the IEEE to improve wireless speeds, range, security, and reliability. Updates often establish new frequency bands for newly developed devices to leverage to allow for more capabilities.

Wi-Fi 5, also known as 802.11ac, was introduced in 2013 and is the fifth generation of the 802.11 standard. In 2019, its direct successor, Wi-Fi 6, 802.11ax, was released. Shortly after in 2021, an upgraded version of Wi-Fi 6 called Wi-Fi 6E was introduced based on an extended implementation of the 802.11ax standard. Wi-Fi 7, 802.11be – Extremely High Throughput (EHT), is the most recent Wi-Fi standard, released in 2024. Products following Wi-Fi protocols older than Wi-Fi 5 are no longer commercially available, and Wi-Fi 5 is being phased out with very few new products following the standard. Table 2 summarizes the differences between the available Wi-Fi protocols and the number of products identified with each protocol.

Of the 60 identified MNS products, only 10 products were offered as Wi-Fi 5 systems. Wi-Fi 6 devices accounted for over half the identified products (55 percent, 33 units), while another 20 percent of products were Wi-Fi 6E (12 units). Five products were identified following the newly released Wi-Fi 7 protocol.

Table 2: Identified MNS Wi-Fi Protocols

	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E	Wi-Fi 7
Date Released	2013	2019	2021	2024
IEEE Standard	802.11ac	802.11ax	802.11ax	802.11be
Max Data Rate	3.5 Gbps	9.6 Gbps	9.6 Gbps	46 Gbps
Freq. Bands	5 GHz	2.4/5 GHz	2.4/5/6 GHz	2.4/5/6 GHz
Channel Size	20, 40, 80, 80+80, 160 MHz	20, 40, 80, 80+80, 160 MHz	20, 40, 80, 80+80, 160 MHz	Up to 320 MHz
Security Options	WEP, WPA, WPA2	WEP, WPA, WPA2, WPA3	WEP, WPA, WPA2, WPA3	WEP, WPA, WPA2, WPA3
MNS Product Count	10	33	12	5

Source: CLTC, Manufacturer Specifications, IEEE.

Wireless Network Topology

Mesh network topology follows one of two approaches referred to as full mesh or partial mesh. In a full mesh network topology, every node is wirelessly connected to all other nodes. A node may communicate with any other node in the network wirelessly without routing through any other nodes. This method allows for more reliability and potential throughput but limits network range since all devices must connect to one another.

In a partial mesh network topology, nodes only need to connect with one other node at a minimum. When data needs to be transmitted between nodes that cannot communicate, the data must “hop” from node to node until it reaches its destination, which translates to more range at the cost of reliability, latency, and throughput. Figure 1 provides a graphical representation of the connected nodes.

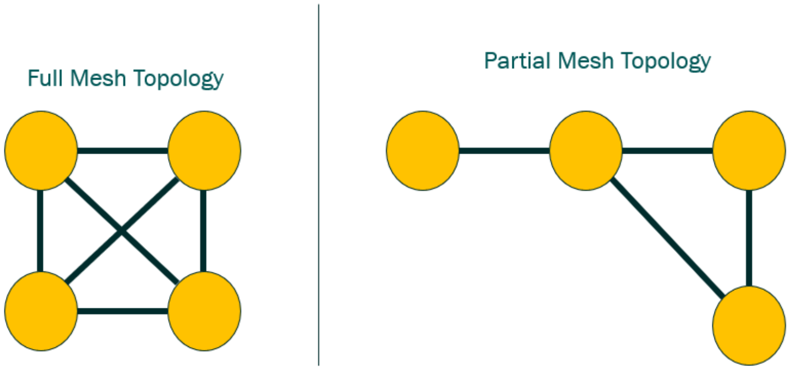


Figure 1: Full mesh vs. partial mesh topology

The identified MNS products reviewed seem to follow the partial mesh topology approach to allow for a greater range within the home, as advertised coverage increases based on how many nodes are included in the package being sold. However, systems may not be limited to maintaining a partial mesh topology and may form a full mesh topology when nodes are sufficiently close to take advantage of the full mesh benefits.

On average, the reported coverage area for a three-pack mesh network system was 6,400 square feet. The largest coverage area reported was the Orbi 970 by Netgear, which provides up to 10,000 square feet. As expected, in general, a two-pack mesh network system provides less coverage area, at an average of 4,750 square feet.

Table 3: MNS Coverage Area, Two- vs. Three-Unit Package

	Two-Pack Options	Three-Pack Options
Average Coverage Area	4,750 ft^2	6,400 ft^2
Minimum Coverage	3,000 ft^2	4,500 ft^2
Maximum Coverage	6,600 ft^2	10,000 ft^2

Source: CLTC, Manufacturer Specifications.

Product Design

Most traditional RNE devices are utilitarian in design, with function prioritized over aesthetics. Routers and modems are often black in color with prominent LED indicators displaying the local network status. External antennas are highlighted with more capable devices commonly having over six antennas, which used to be an indicator of wireless capability.

MNS design trends are noticeably different from their router counterparts; with mesh networking devices being distributed throughout the home, manufacturers seem to have designed them to blend in with home décor. The following sections discuss the aesthetic and design trends among the identified MNS.

COLORS

Of the 60 products identified in the market assessment, the vast majority (90 percent) come in white. The next most common device color is black, with only nine products offered. Two manufacturers offer device color options beyond black or white. One product line is offered in beige, pale blue, and pale yellow in addition to white. Another product line are metallic and come in either champagne or silver.

ANTENNAS

Every identified MNS product has internal antennas. Most of the antennas are hidden with the exception of one product which has a transparent region in the device housing that shows off the eight internal antennas positioned at various angles. This is a dramatic shift from the traditional router aesthetic of multiple external antennas.

EXTERNAL VENTILATION

Most MNS products incorporate ventilation in the device housing. Many mesh Wi-Fi products have obvious perforations across the top surface of the device and sometimes along additional faces. Some manufacturers attempt to hide device ventilation; one product line incorporates thermal convection into the shell of the housing, which produces a more streamlined design.

FORM FACTOR

The identified mesh systems vary from simple shapes with clean lines to complex three-dimensional profiles. Some products are cubic or cylindrical in shape, usually with rounded corners and edges. The products' designs are simplistic, and most look modern. Sizing for products range from 3.4–5.6 inches in length and width and between 2.4–9.6 inches in height.

PRODUCT PRICING

Most mesh Wi-Fi systems are sold in packages of two or three devices. Of the 60 products identified, over half (53 percent) are available in both two-packs and three-packs from the manufacturer. Of the remaining products, thirteen (22 percent) are only available in two-packs and fifteen (25 percent) are only available in three-packs. Based on this assessment, the average price for a two-pack and three-pack mesh Wi-Fi system is $390 and $460, respectively. This means that consumers save an average of $42 per device by buying a three-pack mesh Wi-Fi system compared to a two-pack.

Devices in a bundled package are interchangeable for the majority of products, meaning that any one of the devices in a two- or three-pack system can link to the modem and act as the router and the remaining devices will act as access points by default. 51 (85 percent) of the products identified in this report have interchangeable devices. The remaining nine products have a designated base station that must act as the router in the mesh Wi-Fi system.

Some manufacturers offer the option of purchasing additional nodes for even greater Wi-Fi signal coverage. However, there is little price incentive for consumers to buy extra nodes for these systems. One manufacturer offers discounts of up to 12 percent for buying multiple pods, but the discounts do not extend beyond a three-pack of devices. Other product lines are particularly costly, with an additional node costing up to 56 percent of the cost of a bundled system. Additionally, for consumers who need an extra node after purchasing, 28 percent of options do not offer single nodes for sale, making system expansion difficult and costly.

Cost Benefit Analysis

Differences in system capabilities and limited published information pose challenges to accurately comparing the price of MNS to traditional routers. While it would be ideal to compare a mesh system to a router and range extender combo, range extenders are far less capable devices and would not deliver the same performance as the MNS or router. There are currently no range extenders on the market featuring Wi-Fi 6E or Wi-Fi 7 protocols. Additionally, price points widely vary due to available channels and performance, even for devices with the same wireless protocol.

To combat these issues, the project team started by identifying router and mesh systems with comparable capabilities in terms of W-Fi protocol and channels. The team limited the mesh devices to three-pack bundles, as this is the most widely distributed package size and most accurately reflects the per-unit price paid by the consumer.

The project considers two pricing approaches to compare initial costs. The first is a “per-unit” cost equating a single mesh node to a single router. This approach assumes equal performance and range of each mesh unit to a single router unit, therefore, if three mesh units are needed and deployed within a home, then three routers of the same performance would also be required. While coverage range is reported with a MNS, generally the range of a router is not. This makes direct comparison difficult for the consumer, while also requiring collection of additional test data for accurate evaluation.

The second “package” approach is to assume that the home can be adequately serviced by a single router or a three-node MNS, enabling direct comparison of the prices of a router and a packaged MNS. This approach also assumes that a consumer who is worried about wireless coverage may not fully understand their coverage needs, thus purchasing the as-advertised “more capable” system.

Considering these approaches, the research team found that for all assessed mesh products, the “per-unit” comparison showed a reduction in costs, meaning the selected MNS would be a better value compared to an equivalent router assuming comparable performance to a single mesh node.

With the package approach comparison, the team found all packages cost more than a single equivalent router. However, the pricing did not increase equally across the various Wi-Fi performance standards. Overall mesh package price increases for Wi-Fi 6 products were the lowest, with packages only costing 35–67 percent more. Wi-Fi 5 was found to be slightly higher at 88 percent. On the newer Wi-Fi protocol products, package pricing is not as favorable, with packages for Wi-Fi 6E products being 2.75 times higher and Wi-Fi 7 being 2.5–2.67 times higher. Given that these packages assessed contain three nodes, if a house were to be serviced by these newer protocol mesh packages, pricing is significantly higher than a single router and there are only minimal savings when compared to three equivalent routers.

Table 4: MNS vs. Router Price Comparison

Wi-Fi Gen	System ID	System Type	Wi-Fi Speed (Mbps)	List Price	Package Quantity	**List Price per Unit**	**Per Unit Savings**	**Mesh Package Increase**
5	Mesh 1	Mesh	1900	$149.99	3	$50.00	37%	188%

Wi-Fi Gen	System ID	System Type	Wi-Fi Speed (Mbps)	List Price	Package Quantity	**List Price per Unit**	**Per Unit Savings**	**Mesh Package Increase**
	Router 1	Router	1900	$79.99	1	$79.99		
6	Mesh 2	Mesh	4200	$599.99	3	$200.00	26%	135%
	Router 2	Router	4200	$269.99	1	$269.99		
	Mesh 3	Mesh	1800	$199.99	3	$66.66	44%	167%
	Router 3	Router	1800	$119.99	1	$119.99		
6E	Mesh 4	Mesh	5700	$549.99	3	$183.33	8%	275%
	Router 4	Router	5700	$199.99	1	$199.99		
7	Mesh 5	Mesh	10000	$799.99	3	$266.66	11%	267%
	Router 5	Router	9300	$299.99	1	$299.99		
	Mesh 6	Mesh	22000	$1,499.99	3	$500.00	17%	250%
	Router 6	Router	19000	$599.99	1	$599.99		

Source: Product Listings, Manufacturer Specifications, CLTC.

Ultimately, it appears that Wi-Fi 6 MNS products provide the highest value with the least risk in terms of wasted performance costs. Wi-Fi 5 MNS products are not sensible to buy in any performance-oriented scenario. Wi-Fi 6E and Wi-Fi 7 show promise as the best value with the lowest per-unit cost. However, the higher package cost means that consumers could save significantly if a single router is adequate for their application.

Selected Products

Selection Methodology and Procurement

For product testing, the research team selected MNS devices that were representative of the current market; devices selected were those with the highest relevancy determined by market size. The research team also selected at least one system per wireless protocol 5, 6, 6E, and 7. A second Wi-Fi 6 device was also selected since Wi-Fi 6 is the most prevalent protocol on the market, and to provide a range of device throughput for this product category. Additionally, the selection captured products from multiple manufacturers to demonstrate market breadth. Table 5 shows all products selected for testing. For packages that only had two units, the team acquired a third individual unit to allow for equal comparison to three-unit systems.

Table 5: Selected Products

Wi-Fi Gen	System ID	Wi-Fi Speed	Wi-Fi Bands	**Coverage**	List Price	Package Quantity
5	MNS 1	AC 1900	2.4, 5	5,500 ft^2	$150.00	3
6	MNS 2	AX 4200	2.4, 5x2	5,000 ft^2	$450.00	3
6	MNS 3	AX 6600	2.4, 5x2	5,500 ft^2	$350.00	2
6E	MNS 4	AX 5400	2.4,5,6	6,000 ft^2	$549.00	3
7	MNS 5	BE 11000	2.4,5,6	9,000 ft^2	$1,000.00	2

Source: CLTC.

The research team ordered and obtained all products from reputable vendors. Product intake involved logging product packaging and initial conditions. If products had parts that needed to be attached, the team followed the provided assembly instructions prior to initial configuration.

System Commissioning

The initial configuration process for all devices was similar and the research team experienced only minor difficulties during system commissioning. Each DUT provided a brief physical start-up guide instructing the user to download a paired configuration application available for both iOS and Android devices. MNS 1, MNS 2, and MNS 5 required the creation of a user account connected to an email address before commissioning. MNS 5 also required a phone number to create an account.

The commissioning process in each app was somewhat unique, but all included the following setup procedure in some form:

1. Accept terms, license agreements, and privacy policies.
2. Choose whether to allow location access and notifications.
3. Allow the app to manage Wi-Fi connections.
4. Power off the connected modem.
5. Connect modem to mesh node 1 LAN port via ethernet cable.
6. Power on mesh node 1 followed by the modem.
7. Set Wi-Fi SSID and password.
8. Set Admin username and password.
9. Connect mesh nodes to the network.
10. (Optional) Update firmware of all components of mesh networking system.

In all cases, the nodes that came together in a single package were already paired out of the box. However, since the team acquired an additional node for MNS 3 and MNS 2, these needed to be manually added by energizing the device or pressing a sync button on the device, then searching for it through the associated app.

The one difficulty experienced during the commissioning process involved MNS 5, whose associated app did not work correctly on first launch. The app failed to respond to input when attempting to click the start setup button to begin the commissioning process. A simple closing and reopening of the app resolved the issue and nothing was impacted further during the process.

User Experience Findings

The evaluation of the user interface aimed to identify the limitations in features such as system access, Wi-Fi configuration changes, dynamic host configuration protocol (DHCP) modification, and connected devices view. These are typical features a general user may use multiple times during the life of the product.

The system access conditions explored included determining if the system had a local network browser call or address that would bring up the user interface, evaluating whether the system could be configured through the default IP address, and assessing any default usernames and passwords that may compromise system security.

Results of the assessment can be viewed in Table 6: User Interface: Ease of Access ResultsTable 6. MNS 2 and MNS 4 do not have a local network browser address, meaning the user would need to memorize or locate the IP address to access MNS 2. However, MNS 4 entirely lacks a user interface accessible through the IP address, as it can only be configured through the associated mobile app. In all cases, there were either no default usernames and passwords, or the default ones were changed during setup. This greatly improves network security, as allowing default usernames and passwords can enable easy third-party access to the MNS.

Table 6: User Interface: Ease of Access Results

Condition	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Local Call Is there a local call?	Yes	No	Yes	No	Yes
IP Address Can the product be accessed by default IP?	Yes 192.168.68.1	Yes 192.168.1.1	Yes 192.168.50.1	No	Yes 192.168.1.1
Username and Password Is the username and password specified in the documentation?	User needs a login to the router. There is no default password. Default SSID is listed on the bottom of each node.	Default SSID and password are listed on bottom of router. These are changed as	Default SSID is listed on the bottom of router. There is no default password. User creates a	There is no default SSID or password. User creates the password and username	Default SSID and password are listed on bottom of router. These are changed as

		part of the setup.	password during setup.	during setup.	part of the setup.

Source: CLTC.

The Wi-Fi modifications evaluation focused on simple network modifications, including SSID name and password changes, as well as the manipulation of the 2.4 GHz or 5 GHz bands. In most cases, modifications of the Wi-Fi signal were only available through the associated mobile apps. However, both MNS 2 and MNS 3 additionally allowed modification through the web interface.

In terms of manipulating the 2.4 GHz and 5 GHz signals, such as turning off a single band, options were limited. MNS 1 allowed this modification through its app, but MNS 3 was the only system to allow modification through the mobile app and web interface. Full responses can be seen in Table 7.

Table 7: User Interface: Wi-Fi Modification Results

Condition	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Wi-Fi Name Can the user change the Wi-Fi name?	Yes, via the app.	Yes, via the app and web interface.	Yes, via the app and web interface.	Yes, via the app.	Yes, via the app.
Password Can the user change the Wi-Fi password?	Yes, via the app.	Yes, via the app and web interface.	Yes, via the app and web interface.	Yes, via the app.	Yes, via the app.
Signal Limit Can the user modify the 2.4 GHz or 5 GHz signals?	Yes Signal limiting is available in the app under Wi-Fi Settings.	No	Yes Signal limiting is available in the app and the web interface.	No	No

Source: CLTC.

Next, the evaluation focused on DHCP modification and access to the connected device list. All devices allowed for DHCP modification, but the team found that access was either limited to the mobile app or the web interface, depending on the system. While all systems provided the ability to view the connected device list via the mobile app, only some allowed users to view devices through the web interface.

Table 8: User Interface: DHCP and Connected Devices Results

Condition	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
DHCP Can the user	Yes DHCP settings	Yes DHCP settings	Yes DHCP settings	Yes DHCP settings	Yes DHCP settings

modify DHCP?	are available in the app under Advanced Settings	are available in the web interface under LAN Setup, Advanced Settings.	are available in the web interface under LAN Settings.	are available in the app under Network Settings	are available in the web interface under Advanced Settings.
Connected Devices Can the user view connected devices?	Yes, via the app.	Yes, via the app and web interface.	Yes, via the app and web interface.	Yes, via the app.	Yes, via the app.

Source: CLTC.

Lastly, the ease of configuring the mesh network after initial commissioning was evaluated by removing and reattaching a node in each mesh system. All systems allowed for adding and removing or replacing nodes through their respective apps. However, one system did not allow for the removal of the packaged nodes that were bought with the unit. These nodes appeared to be locked to operate exclusively with the main node that it was purchased with, meaning if two packages were bought, they could not be combined to form a single network.

Table 9: Network Reduction and Expansion

Condition	MNS1	MNS 2	MNS 3	MNS 4	MNS 5
Network Reduction Ease of removing commissioned nodes	Yes, through the paired app	Yes, through the paired app. Core packaged nodes cannot be removed	Yes, through the paired app	Yes, through the paired app	Yes, through the paired app
Network Expansion Ease of adding node to existing network	Yes, through the paired app	Yes, through the paired app	Yes, through the paired app	Yes, through the paired app	Yes, through the paired app

Source: CLTC.

Overall, the research team observed a clear shift towards using mobile apps as the preferred interface for MNS. In one tested case (MNS 4) the app was the only configuration option. Other systems, such as MNS 1 and MNS 5, offered a full-service mobile app along with a limited web interface, which could be beneficial to users seeking flexibility. However, two systems (MNS 2 and MNS 3) required both the web interface and the mobile app for full system configuration, with different configuration options locked behind each interface. This dual-interface requirement significantly hampers the user experience, as it forces users to navigate between two user interfaces to make essential and critical changes to their local network.

MNS Testing Methodology

Testing Goals

Test goals aimed to characterize MNS and baseline systems under typical home conditions. Baseline testing was necessary for comparing MNS performance, energy efficiency, and overall value to a traditional system. The research team sought to:

- Characterize performance and energy use in idle- and active-power states under a variety of network traffic conditions.
- Assess wireless performance when subjected to various attenuation scenarios that would reduce the signal strength to a Wi-Fi client and/or mesh node.
- Characterize energy use through expanded and industry-accepted existing standards, such as ANSI/CTA-2049-A.

Testing Variables

- **Test Environment:** Based on ANSI/CTA 2049-A, the test environment maintained an ambient temperature of 24±3°C. The area around the DUT had an airspeed under 0.5 m/s. Relative humidity for the environment was held between 10–80 percent. The DUT was seated on a thermally non-conductive surface for the test duration.
- **Instrumentation:** All instrumentation met or exceeded specifications within IEC 62301, ed 2.0, "Household electrical appliances – Measurements of standby power" Sections 4.3 and 4.4, which outline requirements on power supply voltage and frequency, voltage waveform, and power measurement uncertainty.
- **Power Supply:** An Ametek Elgar CW 2501 power supply energized the DUT during all test phases. The CW 2501 exceeds the minimum specifications from ANSI c12.1 (§3.10.1), which are shown in Table 10. Input voltage from the supply to the DUT was set to 120 VAC at 60 Hz, in line with the North America market standard.

Table 10: ANSI c12.1 Power Supply Requirements

Variable	Minimum Precision Requirements
Voltage	±1%
Current	±1%
Frequency	±0.2%
Phase angle	±2°

THD	< 2% in current and voltage

Source: ANSI c12.1.

- **Power Analyzer**: A Xitron XT2640AH 4-channel power analyzer was used between the power supply and the DUT(s) to monitor the DUTs' power consumption throughout the various stages. The power analyzer meets the ANSI c12.1 (§3.10.2) portable standard specification, which is shown in Table 11.

Table 11: ANSI c12.1 Portable Standard Error Characteristics

Standard	Percent Error	
Portable Standard	@ 1.00 PF	@ 0.5 PF
	0.1%	0.2%

Source: ANSI c12.1.

Cabling

All cabling between the ethernet ports on the DUT and testing devices met ANSI/TIA-568.2-D category 6 specifications. Each cable was less than two meters in length.

Testing Configurations

The system configuration for each test varied based on the system requirements, connected testbed utilized, and the overall test approach. For example, the ANSI/CTA-2049-A methodology does not require a traffic generator, but traffic generation and attenuation testing do. Therefore, each test setup is presented individually.

ANSI/CTA-2049-A Test Setup

System Configuration

For ANSI/CTA-2049-A testing, each central unit of the systems were connected to a modem and wired test clients if the device supported ethernet connections, with the number of wired clients determined by populating half the available ports. A single wireless client that received a Wi-Fi signal from the MNS was connected as well. Additionally, to explore total system usage under ANSI/CTA-2049-A, additional scenarios with nodes added and metered were conducted. The additional nodes were allowed to assist in extending network connectivity to the existing wireless client if default operations supported this functionality; However, no additional wired or wireless clients were added. An example, three-node system configuration is shown in Figure 2.

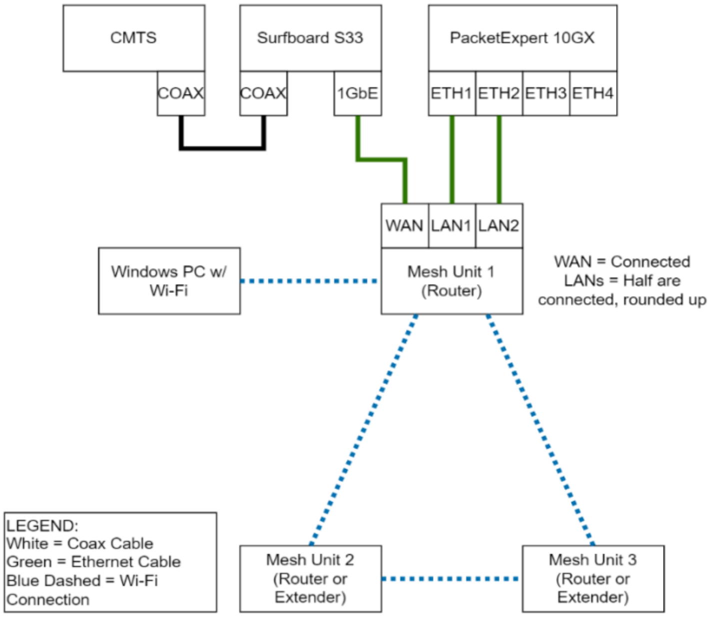


Figure 2: MNS configuration for ANSI/CTA-2049-A

Source: CLTC, ANSI/CTA-2049-A.

Testing Procedure

CTA-2049-A testing consists of six primary steps:

1. Apply power to the DUT(s).
2. Allow DUT(s) a 5-minute warm-up period.
3. After the warm-up, begin recording DUT power.
4. Measure the power over a 10-minute period.
5. Modify DUT configuration (add or remove node) and repeat steps 2-3 for all configurations shown in Table 12.
6. De-energize the DUT and stop recording power.

Table 12: Node Configuration for ANSI/CTA-2049-A

DUT	Test 1	Test 2	Test 3
Node 1	Connected	Connected	Connected

DUT	Test 1	Test 2	Test 3
Node 2	Inactive/Unpowered	Connected	Connected
Node 3	Inactive/Unpowered	Inactive/Unpowered	Connected
Total Power	Node 1	Node 1+2	Node 1+2+3

Source: CLTC.

Traffic Generation Test Setup

Testing of traffic conditions for MNS mirrors that of the CTA-2049-A setup and includes a traffic generator (packet generator). Traffic testing deploys a consistent upload and download data stream to record the effects of active transmission on a DUT. A traffic generator is necessary to deploy controlled, consistent, and repetitive data through the designated ports. The test configuration utilized a Packet Expert 10GX Network Traffic Generator, which generates active traffic via Bit Error Rate Test (BERT) configurations with a BERT pattern of 2^9-1. The traffic type was set to “constant rate” with frame size of 1518 bytes. Layering was set as: Layer 2 = Ethernet, Layer 2.5 = None, Layer 3 = IP, Layer 4 = UDP.

System Configuration

For traffic generation testing, two nodes placed one meter apart were utilized for each MNS. The third node was removed or de-energized during test events. The traffic generator connected to each node and directed wireless traffic (data) to be sent from Node 1 to Node 2, which were connected to port 1 and port 2 of the generator, respectively. Ports 3 and 4 of the traffic generator were connected to each other directly via a cable to act as a reference for traffic throughput, with similar data streams being sent through both transmission pathways. The final system configuration can be seen in Figure 3.

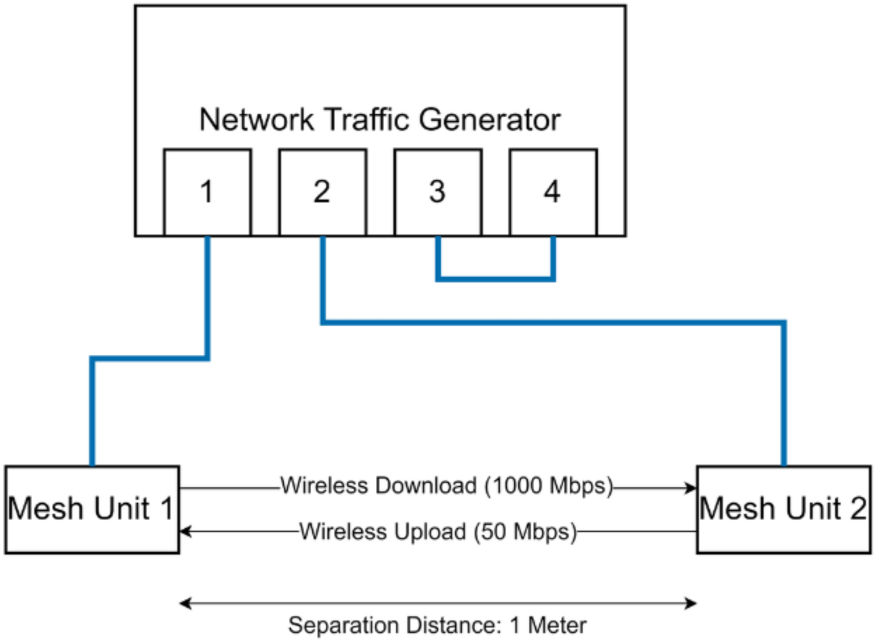


Figure 3: MNS configuration for traffic generation testing

Source: CLTC.

Testing Procedure

Network traffic testing consisted of seven primary steps for each condition shown in Table 13.

1. Apply power to DUT(s).
2. Allow DUT(s) a five-minute warm-up period.
3. Begin recording power for each DUT.
4. Begin traffic condition and maintain traffic for five minutes.
5. Document end of test duration.
6. Modify traffic speed and repeat steps 4-5 until all speeds are tested.
7. De-energize the DUT and stop recording power.

After testing was completed, the team calculated the average of the total bits received by each download port and divided it by the testing duration to get an average data download speed in megabits per second (Mbps). The team then calculated the average data upload speed, in Mbps, by using the total bits received by the upload ports and dividing it by the test duration.

Table 13: Traffic Conditions for MNS Testing

Condition	1	2	3	4	5	6	7	8	9	10	11
Target Download Speed (Mbps)	0	100	200	300	400	500	600	700	800	900	1000
Target Upload Speed (Mbps)	0	5	10	15	20	25	30	35	40	45	50

Source: CLTC.

Attenuation Test Setup

Wi-Fi attenuation testing was focused on assessing multiple anticipated conditions, each with increasing attenuation between the two mesh system nodes. This test is intended to emulate wireless signal strength loss due to physical obstructions such as building walls, furniture, and flooring that often exist within the home, resulting in a nonideal experience.

Testing captured system response under each attenuation condition, which ranged from 0 to 95 decibels (dB), and with the mesh system operating in various scenarios that captured anticipated performance conditions. Scenarios included:

1. The mesh system in idle operation where two nodes were communicating with each other, but no traffic passed.
2. The mesh system in active operation where the central node passed data to a second node connected to a data port
3. The mesh system in active operation where the central node passed data to a second node that then passed data to a third node that was connected to a data port, where the central and third node were unable to communicate directly with each other.

Each scenario with active operation had traffic set to be a constant 50 Mbps deployed via the previously defined traffic generator in BERT format.

System Configuration

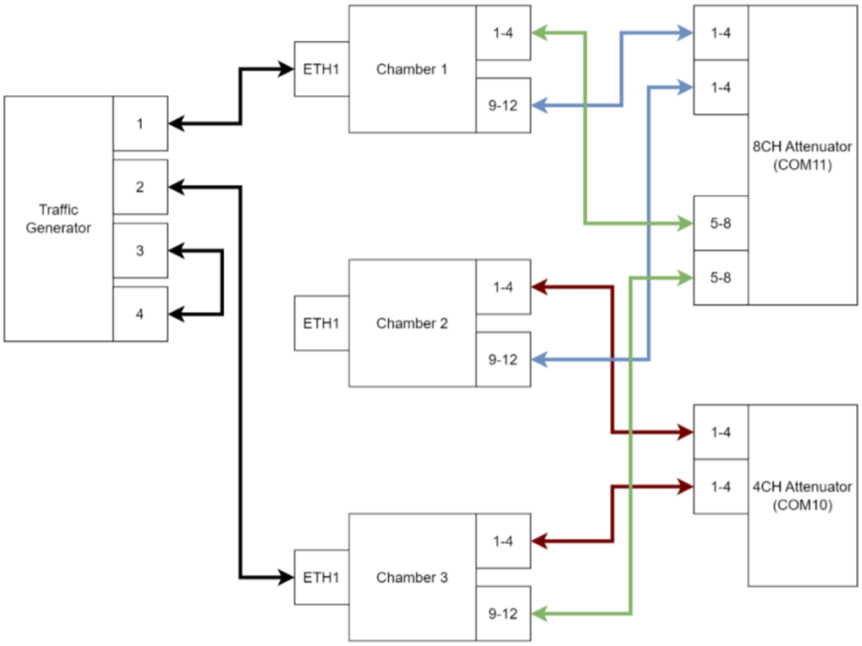
For testing, DUTs were placed in an anechoic chamber, which allowed for isolation and manipulation of the DUT’s Wi-Fi signal strength. The chambers use attenuators and a series of antennas to transfer and isolate wireless signals between chambers. The testbed consisted of three chambers, each with one node inside. A photo of one chamber is shown in Figure 4.

Figure 4: Anechoic chamber with attenuation antennas mounted

Source: CLTC.

Each chamber has a type B outlet that the DUT's power supply connects to to receive metered power, as well as ethernet throughput ports. For testing, Node 1 served as the first traffic point with either Node 2 or Node 3 acting as the receiver depending on the test scenario. Diagrams for each scenario are shown in Figure 5 through Figure 7.

In Scenario 2, Figure 6, Node 3 was isolated with connected attenuations at maximum to ensure data was only passed through Node 1 to Node 2. In Scenario 3, Figure 7, attenuation between Node 1 and Node 3 were isolated to force traffic to pass from Node 1, to Node 2, then to Node 3. Lastly, Scenario 1, Figure 5, had all channels open and attenuated.



Attenuation: Red = Variable dB, Green = Variable dB, Blue = Variable dB
Chambers 1, 2, and 3 are "equidistant" from each other, same attenuation

Figure 5: System configuration for Scenario 1 of attenuation testing

Source: CLTC.

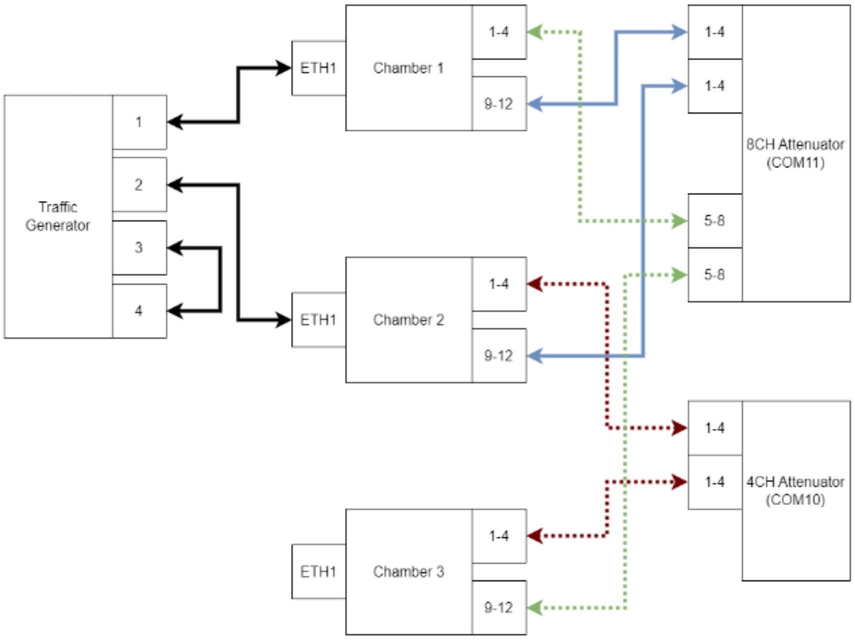


Figure 6: System configuration for Scenario 2 of attenuation testing

Source: CLTC.

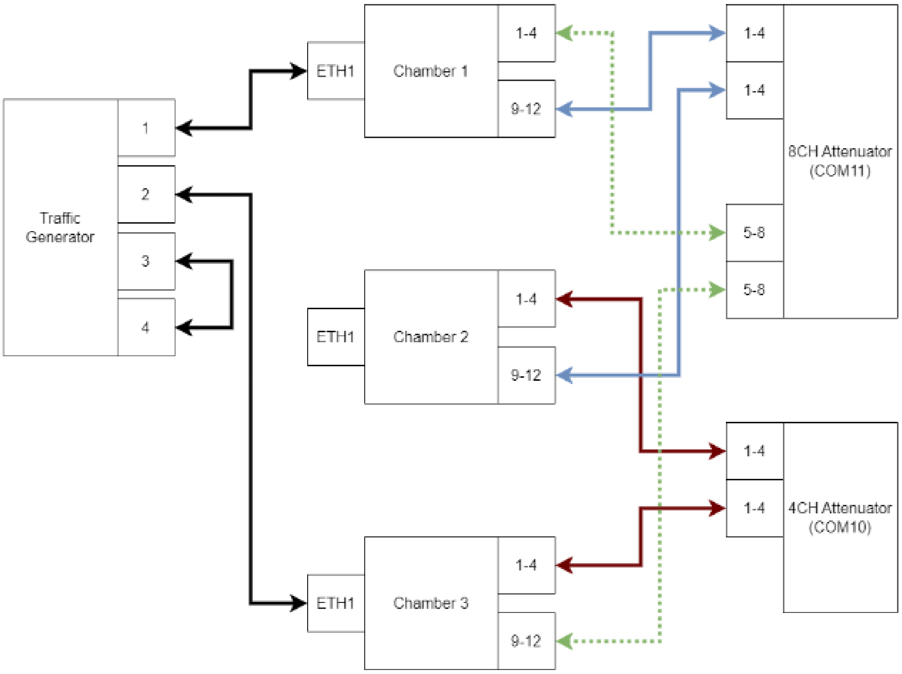


Figure 7: System configuration for Scenario 3 of attenuation testing

Source: CLTC.

Testing Procedure

The attenuation test procedure was as follows:

1. Apply power to DUT(s).
2. Allow DUT(s) a five-minute warm-up period.
3. After the warm up, begin recording power for each DUT.
4. Begin traffic condition and isolate appropriate chambers if applicable.
5. Record 2.5 minutes of data.
6. Document end of test duration.
7. Modify attenuation to the next level and repeat steps four to six until all conditions and scenarios have been tested (Table 14).
8. De-energize the DUT and stop recording power.

Table 14: Attenuation Scenarios Node-to-Node Communication

Wireless Communication Channels	Scenario 1	Scenario 2	Scenario 3
Node 1–Node 2	Attenuation Applied	Attenuation Applied	Attenuation Applied
Node 1–Node 3	Attenuation Applied	Blocked	Blocked
Node 2–Node 3	Attenuation Applied	Blocked	Attenuation Applied

Source: CLTC.

Attenuation was applied to each nonblocked channel universally. For example, in Scenario 1, a 10 dB attenuation step was applied to all three listed communication channels. Attenuation began at 0 dB and increased in 5 dB increments until Wi-Fi failure or 95 dB.

MNS Testing Findings

Results

ANSI/CTA-2049-A Test Results

Results for ANSI/CTA-2049-A testing can be viewed in Table 15 through Table 17. In the test scenario where only one node was energized, as specified in existing standards, the research team found that the MNS 1 unit had the lowest power consumption in idle conditions by a significant margin. This was followed by MNS 4, MNS 3, MNS 2, and lastly, MNS 5.

Table 15: ANSI/CTA-2049-A Power Consumption – Single Node Energized

Single Node Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Node 1 Power (W)	4.04	8.89	8.43	7.27	9.15
Total System Power (W)	4.04	8.89	8.43	7.27	9.15

Source: CLTC.

These results were expected as Wi-Fi 5 systems typically require less power than newer generations of Wi-Fi. Interestingly the Wi-Fi 6E unit also showed less power usage than both Wi-Fi 6 units.

Next, results for the expanded ANSI/CTA-2049-A scenario with two nodes active can be seen in Table 16. For all systems, Node 1 maintained a relatively constant power level compared to Node 2. The largest difference between nodes was 0.05W, and this difference was measured in multiple units. Three systems demonstrated reduced power for Node 1 compared to Node 2, and one system demonstrated increased power for Node 1 compared to Node 2.

For all tested mesh systems, Node 2 drew slightly less power than its Node 1 counterpart, with the biggest difference observed in MNS 5, where Node 2 drew 6.5 percent less than Node 1. However, total system power consumption for every system nearly doubled with Node 2 energized.

Table 16: ANSI/CTA-2049-A Power Consumption – Two Nodes Energized

Two Nodes Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Node 1 Power (W)	4.04	8.86	8.38	7.31	9.10
Node 2 Power (W)	3.93	8.45	7.95	7.08	8.53
Node 1 vs Node 2 Energy Use (% diff)	2.67%	4.73%	5.19%	3.26%	6.50%

Two Nodes Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Total System Power (W)	7.97	17.32	16.33	14.39	17.62
Total System Energy Use Single vs Two Node	197.51%	194.82%	193.79%	197.91%	192.60%

Source: CLTC.

Lastly, when all three nodes were powered on, the researchers found that in four of the mesh systems, Node 1's power consumption decreased compared to when only two nodes were energized. However, in one system, Node 1's power consumption remained constant. Additionally, Node 2's power consumption decreased in three systems, increased in one, and remained constant in another, as shown in Table 17.

With all three nodes energized, total system power consumption increased nearly threefold across all systems due to additional nodes needing nearly the same amount of power as the central node in the tested idle conditions. In most cases (four of five), the additional nodes used, on average, one to six percent less power than the central node. However, with MNS 1, Node 3 used five percent more power than the central node, indicating that this pattern is not guaranteed.

Table 17: ANSI/CTA-2049-A Power Consumption – Three Nodes Energized

Three Nodes Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Node 1 Power (W)	4.05	8.79	8.16	7.27	8.98
Node 2 Power (W)	3.93	8.60	7.77	7.02	8.39
Node 3 Power (W)	4.13	8.31	7.87	6.90	8.66

Three Nodes Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Node 1 vs Node 3 Energy Use (% diff)	1.92%	5.54%	3.60%	5.28%	3.69%
Node 2 vs Node 3 Energy Use (% diff)	5.07%	3.41%	1.25%	1.71%	3.12%
Total System Power (W)	12.11	25.70	23.81	21.19	26.03
Total System Energy Use Single vs Three Nodes	300.16%	289.13%	282.57%	291.28%	284.41%

Source: CLTC.

Traffic Generation Test Results

Results from the traffic generation testing can be viewed in Table 18, and Figure 8 through Figure 12. Idle conditions in the traffic generation testing showed a slight difference compared to conditions in the ANSI/CTA-2049-A testing. This can primarily be attributed to the simplification of the system's ethernet connections which solely allowed for traffic throughput. The main difference, due to the connection changes, is that MNS 5 had a significant drop in power, resulting in MNS 2 demonstrating the highest system power draw.

Table 18: ANSI/CTA-2049-A Idle vs. Traffic Testing Idle

	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
ANSI/CTA-2049-A Two Node Idle Power (W)	7.97	17.32	16.33	14.39	17.62
0 Mbps (Idle) Traffic Condition Power (W)	7.50	17.10	16.06	14.25	16.87

	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5
Difference between ANSI/CTA Idle and Traffic Idle (% diff)	6.08%	1.28%	1.67%	0.98%	4.35%

Source: CLTC.

Traffic testing shows that power consumption is fairly consistent regardless of speed. MNS 5 and MNS 3 maintained the most consistent performance throughout. MNS 1 struggled to maintain consistent power draw with respect to speed, resulting in unpredictable system behavior and energy use. This inconsistency was especially apparent at higher speeds. The unit did not seem damaged, nor did it give any indication via the app or onboard LEDs that there were operational issues.

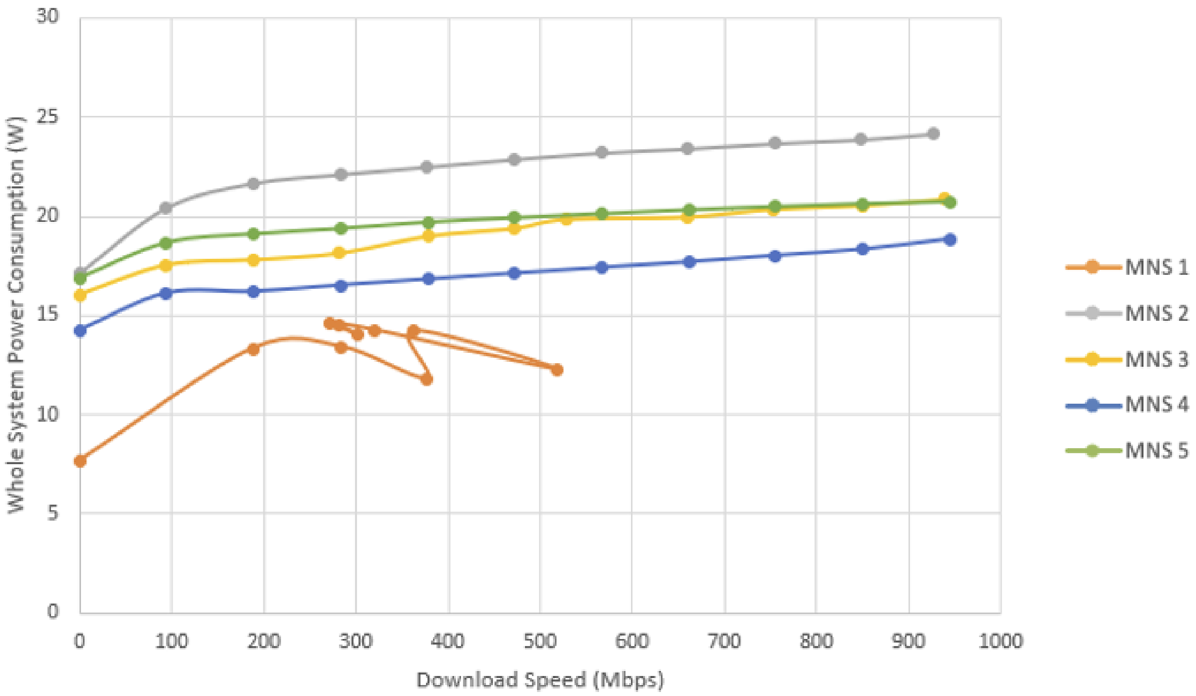


Figure 8: Power consumption vs. download speed

Source: CLTC.

Results showed that MNS experienced the highest power consumption increase during the 0–100 Mbps step, with an average increase of 10.9 (excluding MNS 1), and an average 44.3 percent power increase at maximum tested data throughput levels.

Figure 9 shows the relationship between the baseline traffic speed and the recorded speed through the MNS. Some data points overlap heavily with other units and aren't clearly displayed in the figure, MNS 2 & MNS 4 follow similar trends to MNS 5 . Excluding MNS 1, the remaining four systems all exhibited a nearly linear response, indicating that packet loss is minimal and recorded speeds were on par with the baseline.

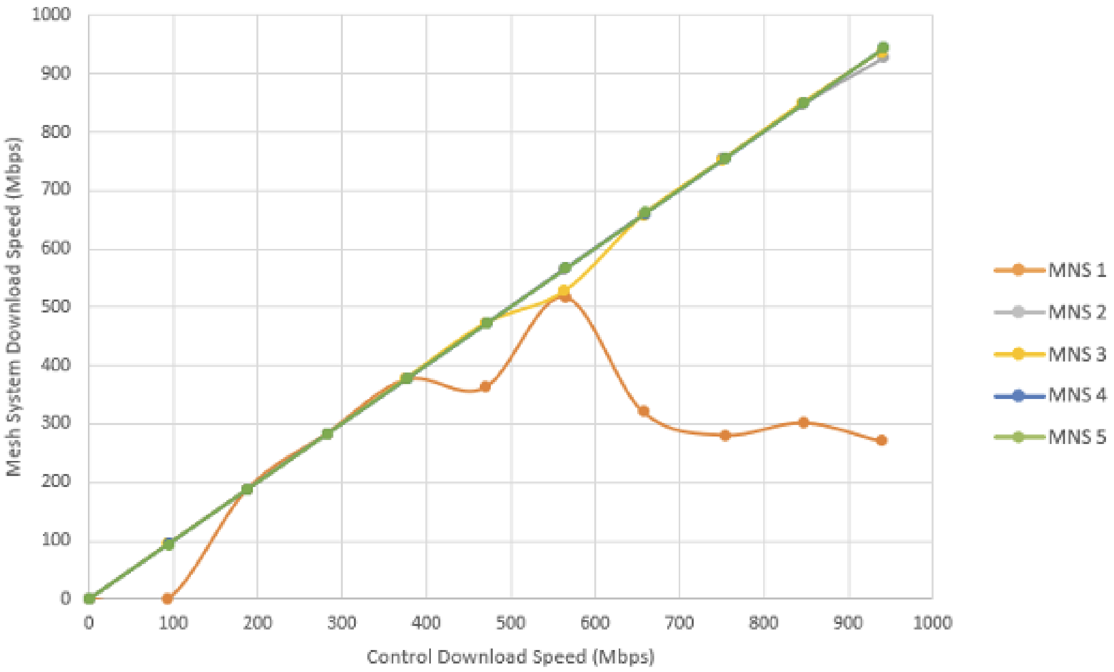


Figure 9: Throughput speed through MNS nodes vs. control traffic speed

Source: CLTC.

Attenuation Test Results

Results from Scenario 1 of attenuation testing with nodes in an idle state can be viewed in Figure 10. Idle attenuation testing showed very minimal power consumption changes throughout the attenuation ranges. This indicates that, in an idle scenario, power use for the system is mostly unaffected by signal strength, so blockages within the home won't have a significant effect on power consumption.

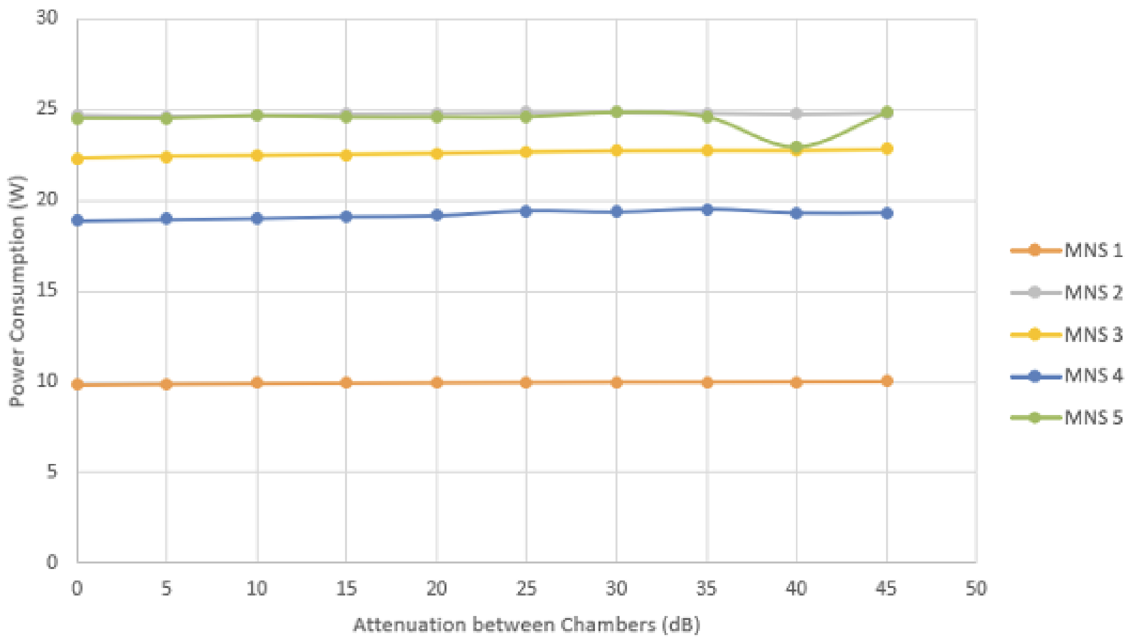


Figure 10: Power consumption of MNS with three nodes connected in idle state

Source: CLTC.

Moving to Scenario 2, results presented in Figure 11 show that data throughput has a significant effect on power consumption. The team found that, in general, MNS increased power usage when trying to pass data at higher attenuations, at least up to a certain point. For most systems, there is a turning point in the data, which is believed to be associated with the unit switching to a different Wi-Fi frequency, as all MNS units tested have the ability to optimize frequency and do not allow limiting of the available wireless frequencies. MNS 2 maintained its Wi-Fi integrity the longest, failing at 60 dB of attenuation. Three other systems failed at 50 dB, while MNS 5 failed at 30 dB. Testing indicated that despite utilizing the most recent Wi-Fi protocol, the system's wireless range suffers. Testing increased to 95 dB, but data presented here only shows power usage while the systems maintained Wi-Fi integrity. Plots for the entire data set for each system can be found in Appendix 1. Total system power for the two-node energized scenario had an average maximum power increase of 20 percent during attenuation testing over the ideal 0 dB case. MNS 1 showed the largest individual power increase at 29.7 percent.

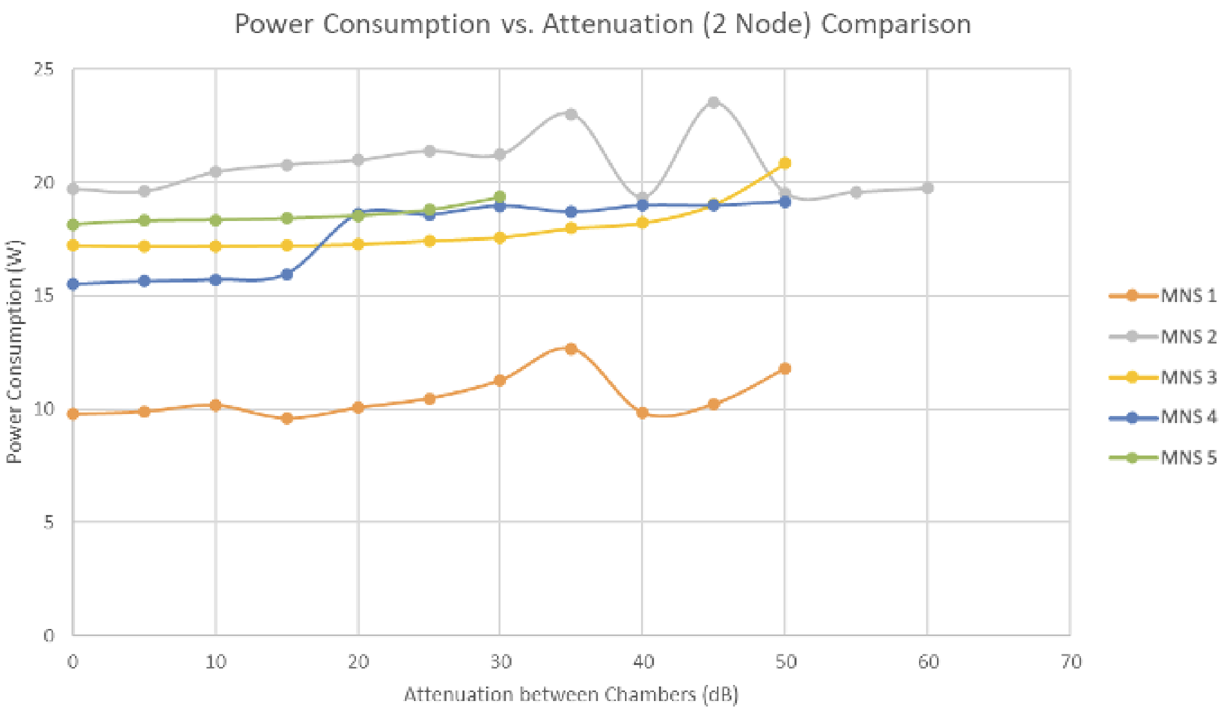


Figure 11: Power consumption of MNS with two nodes connected passing traffic with increasing attenuation

Source: CLTC.

Looking at Scenario 3, where data was passed from Node 1 through Node 2 to Node 3, the team found that signal integrity of a number of MNS decreased, MNS 5 and MNS 4 being the exceptions. This indicates that the other systems struggled to maintain data throughput when passing data from node to node, meaning customers could see diminishing area coverage returns when adding nodes to a mesh system. With other systems' wireless integrity decreasing, MNS 4 now has the highest Wi-Fi integrity with failure occurring at 50 dB of attenuation. Additionally, while MNS 5 did not decrease in Wi-Fi integrity versus Scenario 2, the system was the first to fail from the tested units. Overall system power had an average maximum power increase of 23.2 percent across test cases where Wi-Fi integrity was maintained, with a maximum individual power increase of 65.1 percent with MNS 1.

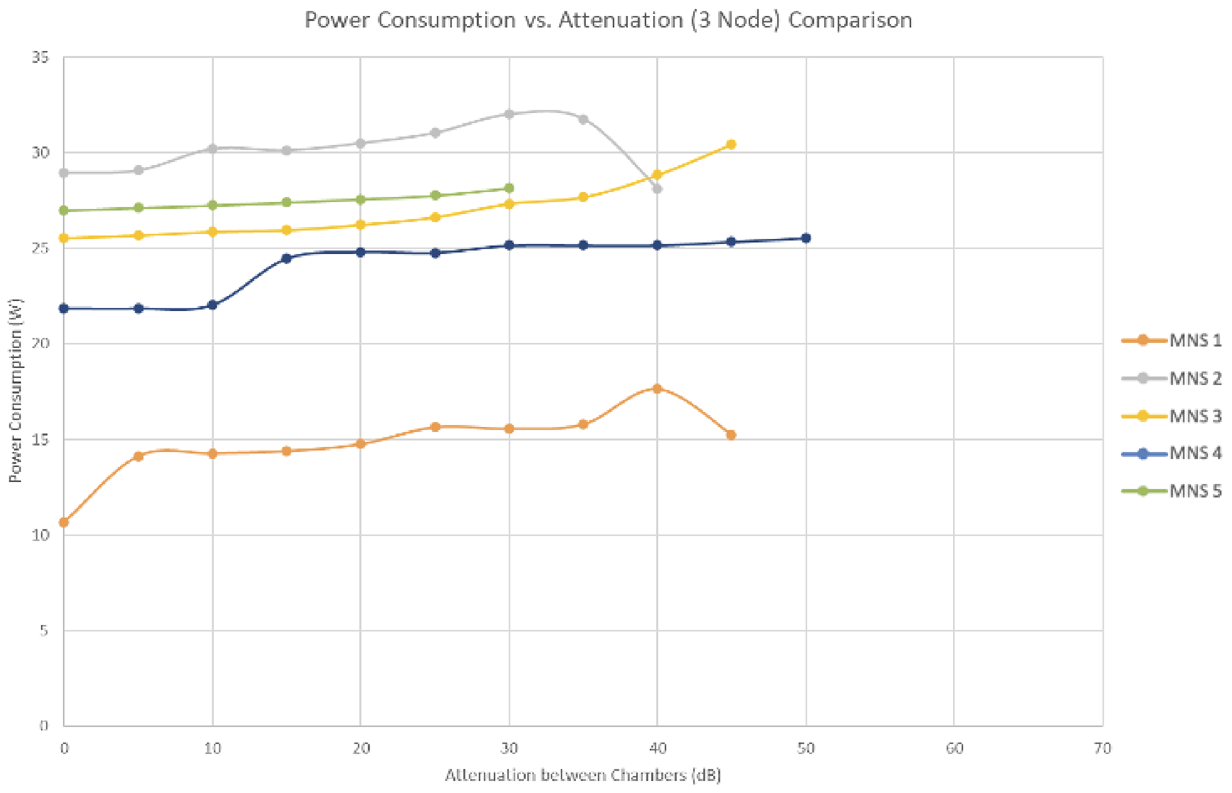


Figure 12: Power consumption of MNS with three nodes connected passing traffic with increasing attenuation

Source: CLTC.

Data Analysis

Overall

Test results show that MNS ultimately increase power fairly linearly when adding additional nodes, and therefore, the existing industry standard of ANSI/CTA-2049-A which utilizes a single-unit analysis approach to assess idle power usage of an MNS may not be indicative of the energy use within the home. Especially when paired with the selling practices and commissioning procedures of MNS, it is almost certain that homeowners would be replacing a single router with multiple mesh nodes, whether their home needs the additional nodes or not.

Active data transmission can also play a significant role in MNS energy use, with power consumption increasing by an average of 44.3 percent during traffic data testing and 23.2 percent in attenuation testing. In addition, when looking at maximum individual system increases during testing, there is potential for overall power consumption to be more than double the idle consumption based on operating conditions and traffic throughput.

When applying the testing results and calculating the unit energy consumption (UEC) of the mesh systems, the data shows a significant shift compared to UEC calculations based only on a single node's idle performance, which is currently used to assess units in the industry today. UEC calculations can be viewed in Table 19. When viewing UEC of the whole system, there is an average energy increase of 188 percent, nearly three times that of an individual node. When applying traffic, assuming traffic conditions occur three hours a day, the average system UEC increases by an additional 2.49 percent, and when applying attenuation conditions to the system, an average increase of 18.25 percent is calculated.

Table 19: UEC Calculation of Tested MNS

Annual UEC (kWh)	Idle Single Node	Idle Three Nodes	Three Nodes with Traffic	Three Nodes with Attenuation
MNS 1	35.39	106.08	118.67	175.12
MNS 2	77.88	225.13	229.00	248.97
MNS 3	73.85	208.58	211.18	248.62
MNS 4	63.69	186.41	188.93	217.75
MNS 5	80.15	228.02	230.21	237.87

Source: CLTC.

Compared to baseline

To further connect MNS to a more traditional architecture, the team ran identical testing on a router and range extender combination. The devices used for this baseline condition were a AX 1800 router and a AX 3000 range extender. Specifications for both devices can be seen in Table 20.

Table 20: Baseline Router System Specifications

Wi-Fi Gen	System ID	Wi-Fi Speed	Wi-Fi Bands	Coverage	List Price
6	Baseline Router	AX 1800	2.4 GHz, 5 GHz	2,500 ft^2	$74.99
6	Baseline Range Extender	AX 3000	2.4 GHz, 5 GHz	2,200 ft^2	$69.99

Source: CLTC

The selected systems were chosen as the most suitable for comparison based on sales data from leading online retailers, positioning them as top sellers in the market. ANSI/CTA-2049-A testing revealed that the baseline router had one of the lowest idle power consumptions among all single units tested, second only to MNS 1. Despite this, the Wi-Fi standard of the baseline system is comparable to MSN 2 and MNS 3, suggesting that individual nodes of a mesh network system may consume more power than an equivalent traditional router.

Table 21: Power Consumption of MNS Node in Idle

Single Node Energized	MNS 1	MNS 2	MNS 3	MNS 4	MNS 5	Baseline
Power (W)	4.04	8.89	8.43	7.27	9.15	5.91

Source: CLTC.

When assessing the energy consumption of the router system compared to the MNS, the team found identical trends in terms of power increase range across all test points. However, the baseline system struggled to achieve download speeds as high as the tested MNS.

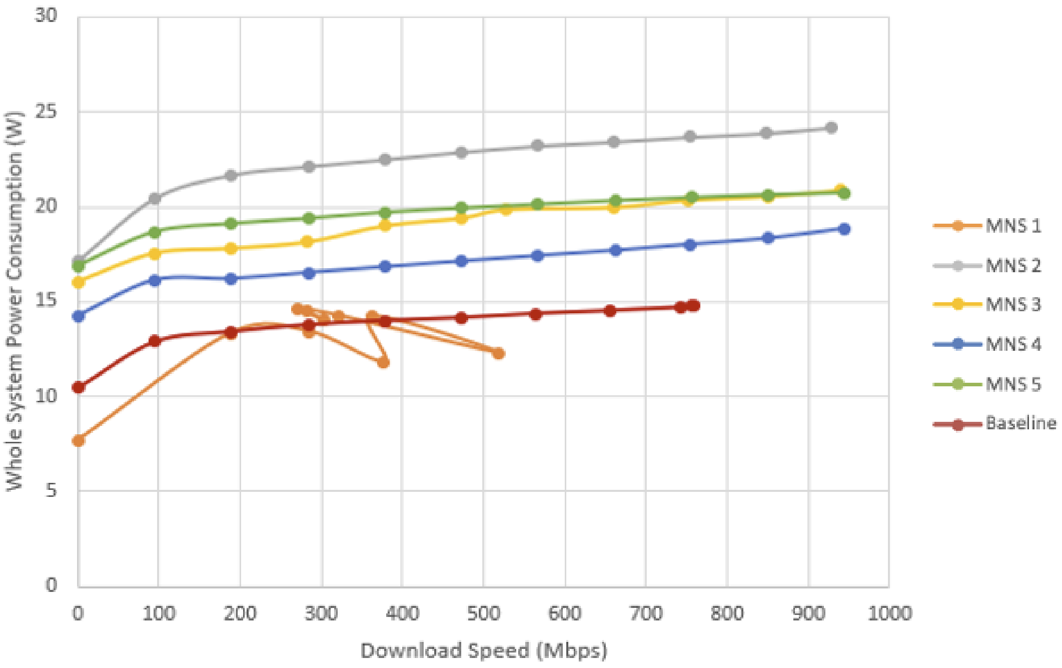


Figure 13: Power consumption of MNS with two nodes connected with increasing traffic speed

Source: CLTC.

The attenuation testing of the router system showed that the baseline system underperforms compared to most MNS, excluding MNS 5, when compared to the two-node testing. This indicates that MNS do not have reduced ranges compared to traditional routers and, in fact, may have better ranges overall. This could be a worthwhile trade-off considering the wattage increase. However, this further supports the need for a step-by-step commissioning process where nodes are added one by one within the home to ensure suitability and minimize energy consumption for the required coverage area.

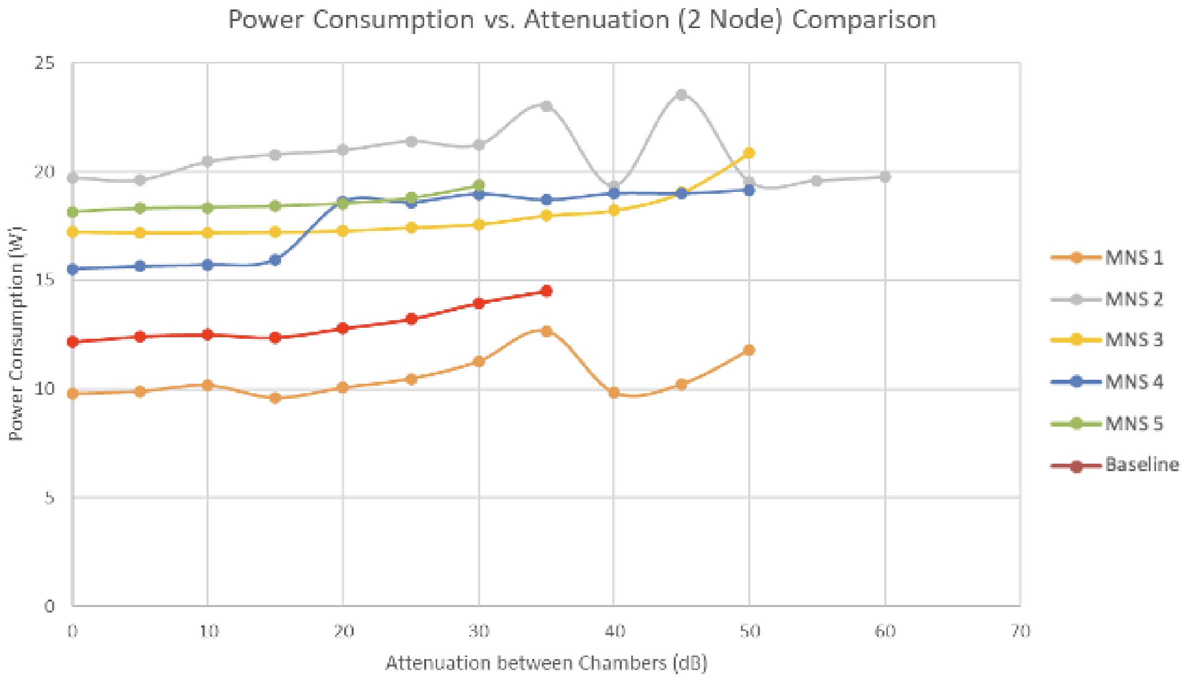


Figure 14: Power consumption of baseline router vs. MNS in two-node traffic configuration

Source: CLTC

Conclusion and Next Steps

MNS are increasingly being promoted by manufacturers as the go-to solution for improving wireless performance in homes and businesses. Typically, these systems are sold in packages containing two to three nodes, with some manufacturers not offering single-node purchase options. The promise of better performance and coverage than a traditional router often makes MNS an appealing choice. However, users are not encouraged to install these systems one node at a time to determine suitability within their home. Instead, they are advised to set up all available nodes simultaneously for optimal performance, and one of the tested systems even prevents the removal of nodes within the software.

Additionally, the current voluntary standards for evaluating MNS performance are lacking, as they focus only on the power consumption of the primary node. These standards do not specify any necessary connections to additional nodes or methods to account for additional node energy use. As a result, system performance within the home will likely differ significantly from the advertised performance metrics. This is especially true when considering that existing standards focus only on idle conditions and not active ones, as the team found a wattage increase of 44.3 percent during tested peak traffic conditions.

From the attenuation testing, the research team found that the wireless performance from a single node was stronger than that of a traditional router. This means that if a customer is experiencing wireless connectivity issues with their traditional router, upgrading to a single mesh node could resolve the issue. However, without universal metrics to compare the two products and with MNS setups not advising a gradual node deployment approach, customers may not be aware of this option and could unknowingly use more energy by deploying additional, unnecessary nodes.

Moving forward, further research is needed to refine the research team’s understanding of MNS performance and energy consumption. This could include advanced modeling to better account for how attenuation affects performance in different home environments. Identifying the most efficient product designs, especially regarding antenna performance, could also help optimize these systems. Field testing may provide further insight into which MNS setups are best suited for various situations.

Additionally, the existing voluntary standards should be expanded to include a holistic system approach when evaluating MNS. These standards should account for active data transmission and the use of multiple nodes, providing a more accurate assessment of energy consumption within real-world home environments.

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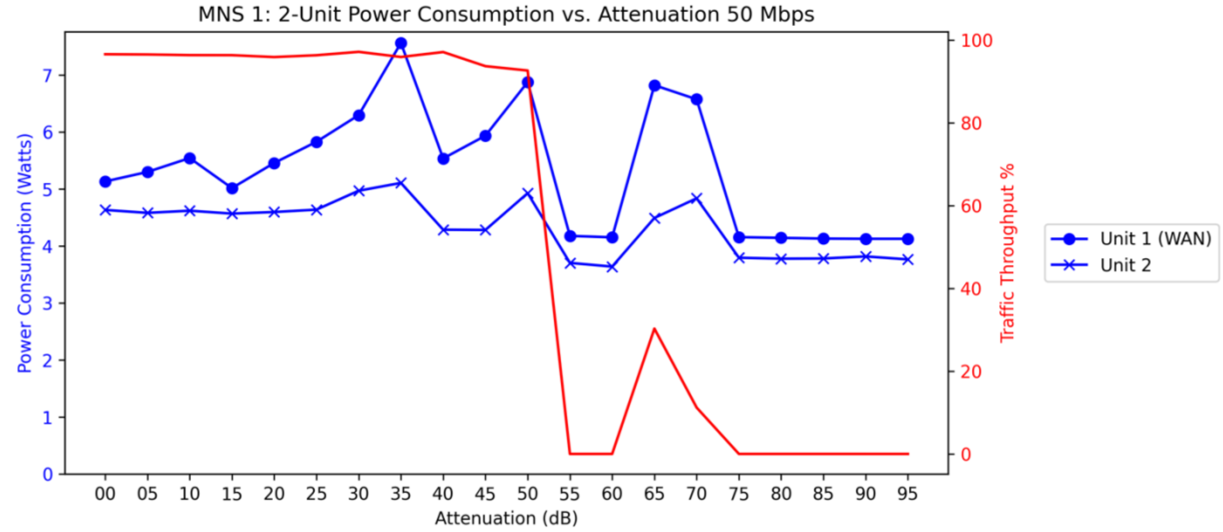
Appendix 1


MNS 1: 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
Traffic Throughput %
Attenuation (dB)
0
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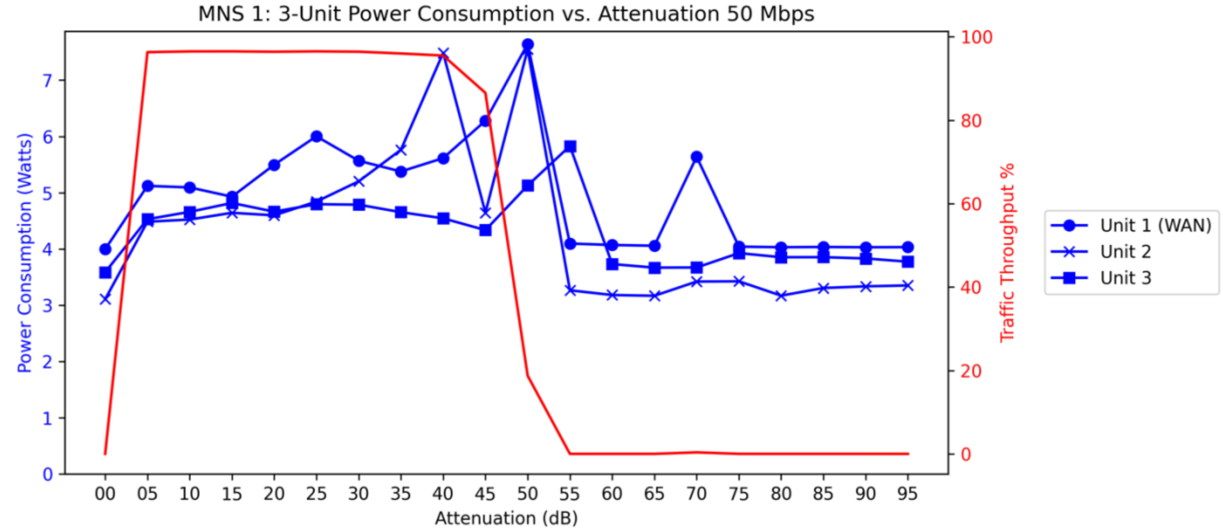
Unit 1 (WAN)
Unit 2


MNS 1: 3-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
Traffic Throughput %
Attenuation (dB)
0
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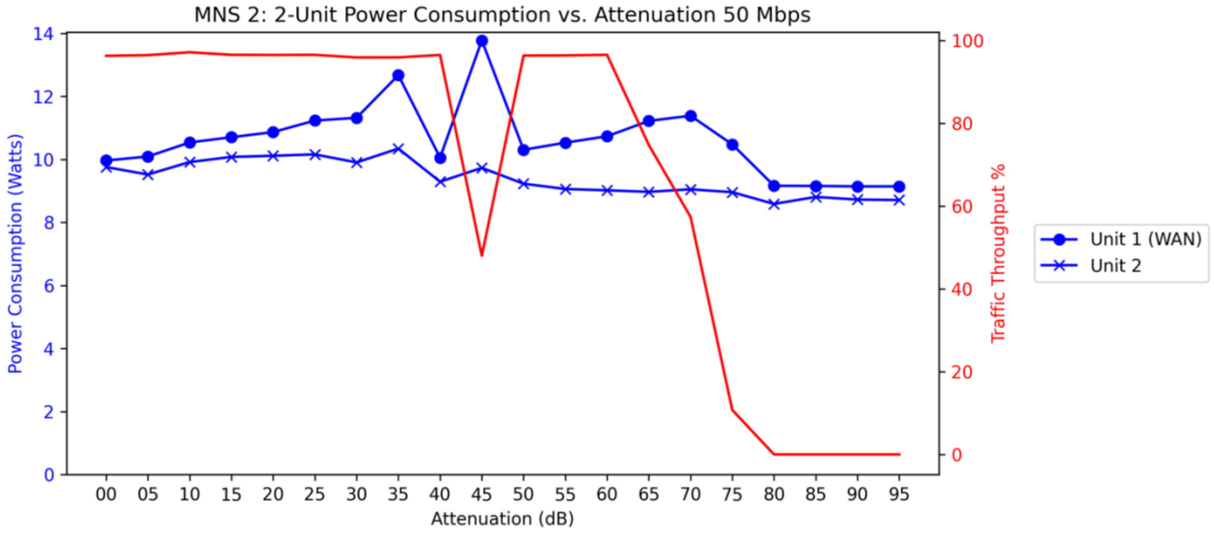
Unit 1 (WAN)
Unit 2
Unit 3


MNS 2: 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
0
2
4
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12
14
Traffic Throughput %
0
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40
60
80
100
Attenuation (dB)
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10
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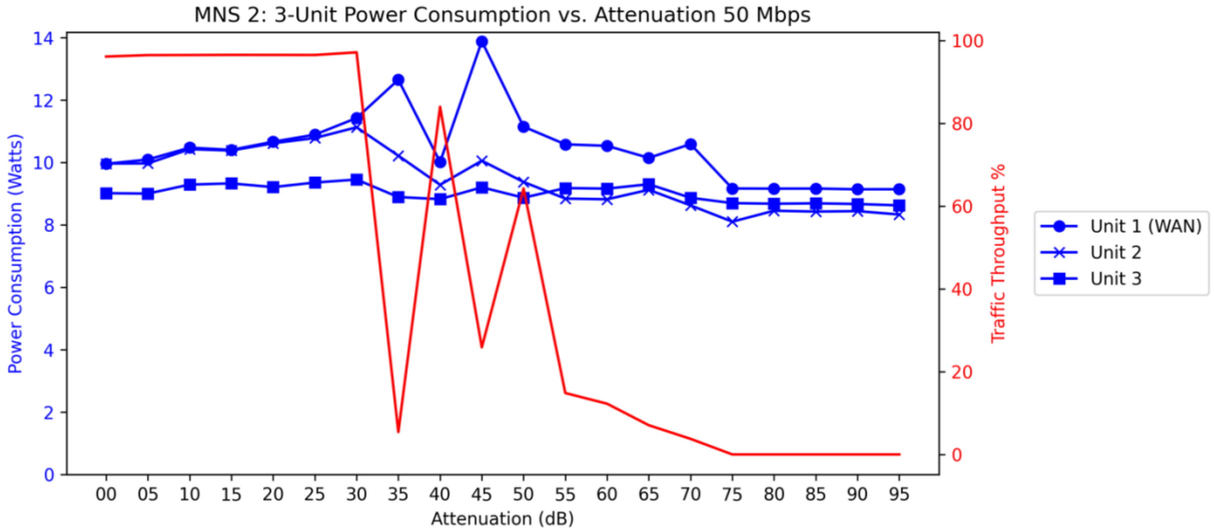
Unit 1 (WAN)
Unit 2


MNS 2: 3-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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Attenuation (dB)
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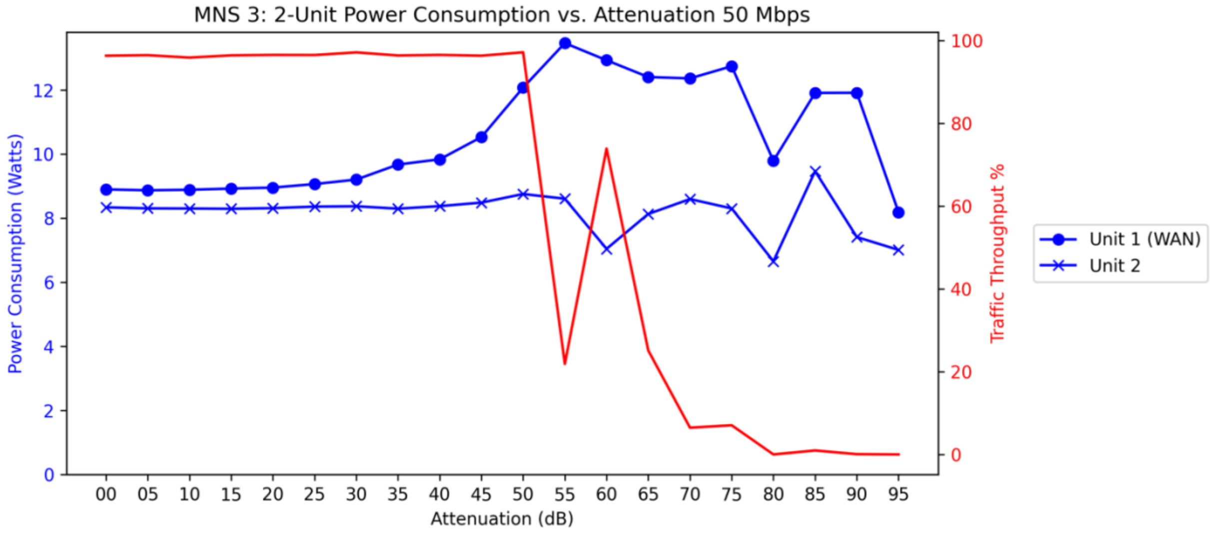
Unit 1 (WAN)
Unit 2
Unit 3


MNS 3: 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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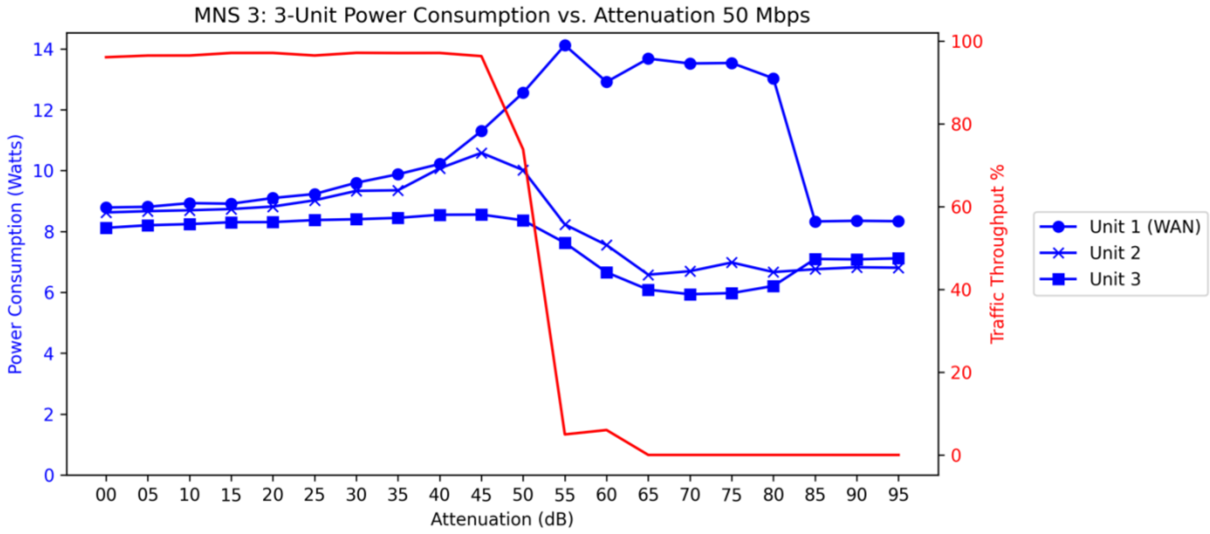
Attenuation (dB)
Unit 1 (WAN)
Unit 2


MNS 3: 3-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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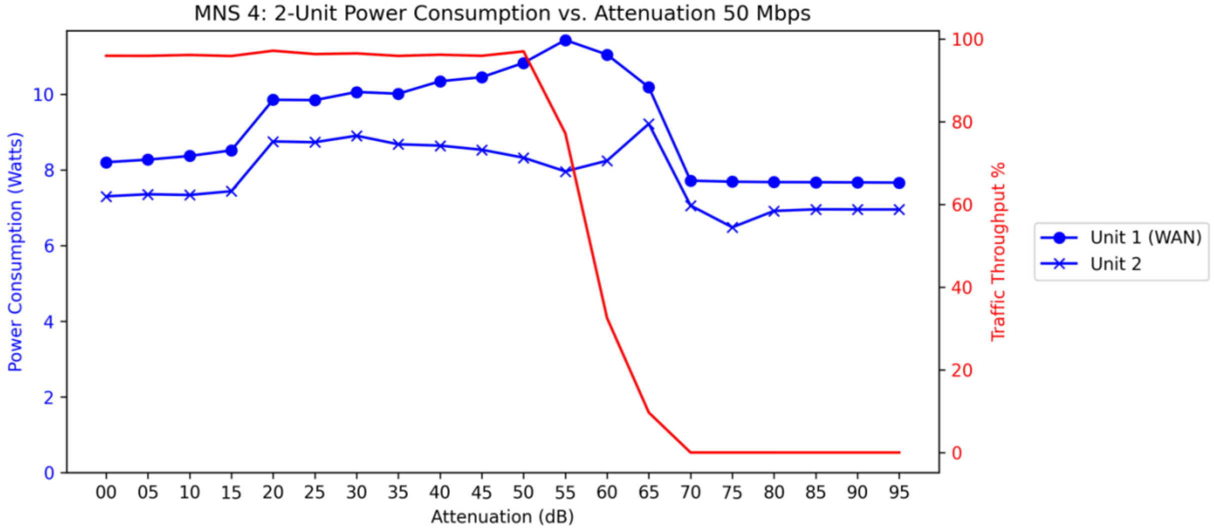
Attenuation (dB)
Unit 1 (WAN)
Unit 2
Unit 3


MNS 4: 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
Traffic Throughput %
Attenuation (dB)
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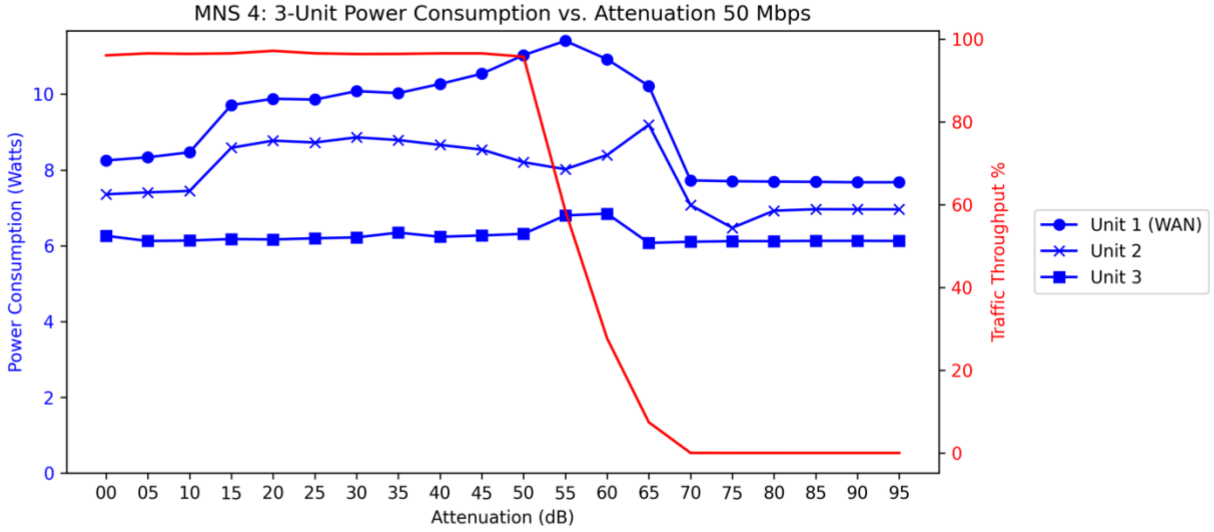
Unit 1 (WAN)
Unit 2


MNS 4: 3-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
Traffic Throughput %
Attenuation (dB)
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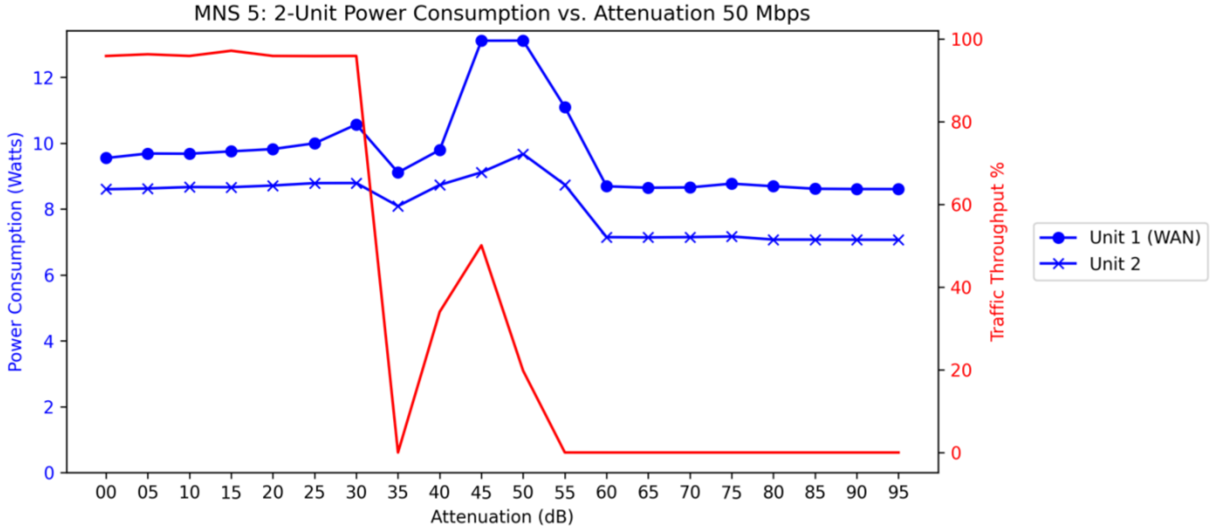
Unit 1 (WAN)
Unit 2
Unit 3


MNS 5: 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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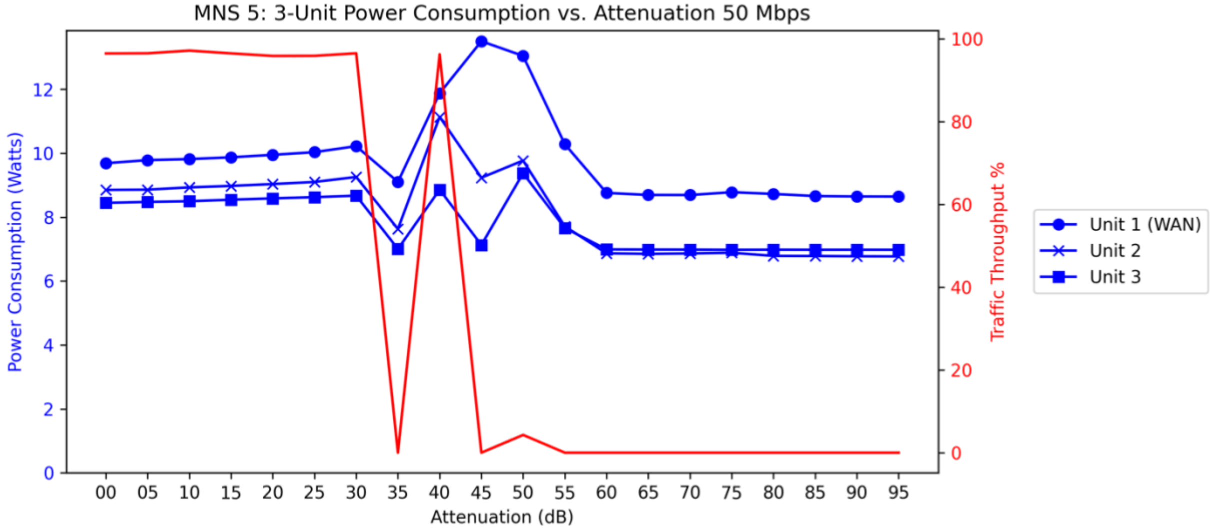
Attenuation (dB)
Unit 1 (WAN)
Unit 2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Power Consumption (Watts)
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Traffic Throughput %
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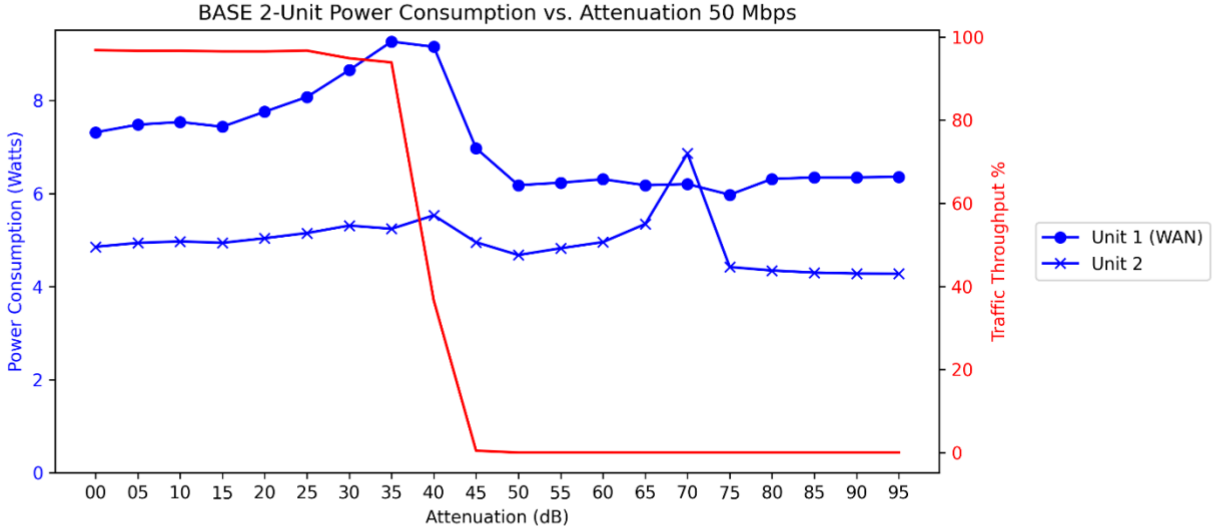
Attenuation (dB)
Unit 1 (WAN)
Unit 2
Unit 3


BASE 2-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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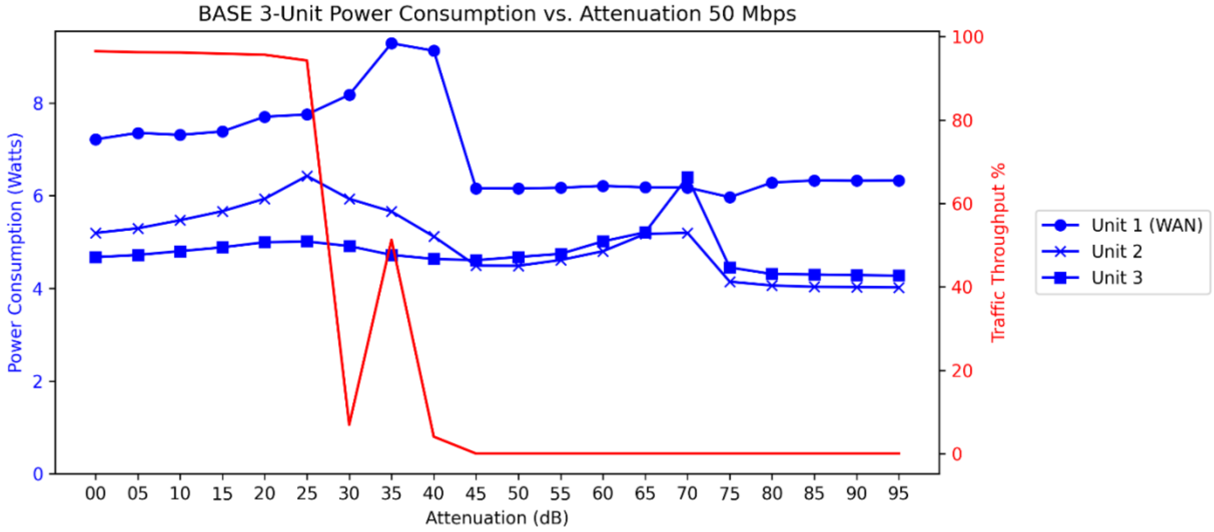
Unit 1 (WAN)
Unit 2


BASE 3-Unit Power Consumption vs. Attenuation 50 Mbps
Power Consumption (Watts)
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Traffic Throughput %
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Attenuation (dB)
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Unit 1 (WAN)
Unit 2
Unit 3