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Master's Thesis

Performance Analysis of Multi-Link Operation in IEEE 802.11 Networks

Analiza wydajności mechanizmu Multi-Link Operation w sieciach standardu IEEE 802.11

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I want to express my deep gratitude to my supervisor, Professor Szymon Szott, for his boundless patience, invaluable help, and professional guidance, which supported me throughout the entire process of writing this thesis.

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1. Introduction

The rapid technological growth and an increasing number of connected devices are creating new demands for wireless networks. Applications, such as virtual reality and the Internet of Things for healthcare [1] require not only higher throughput and reliability, but also lower latency. To meet these requirements, Wi-Fi has been under continuous development, with each generation bringing new ways to improve performance and better use the available resources. The introduction of the 6 GHz band in Wi-Fi 6E provided access to additional spectrum and more transmission capabilities. However, until introducing Wi-Fi 7, communication was limited to a single link, restricting the ability to fully utilize available resources. The latest Wi-Fi generation addresses this issue by its most important feature, Multi-Link Operation (MLO), which enables simultaneous use of multiple links. Although this innovation is expected to address requirements posed by modern applications by offering high throughput and lower latency, it also introduces new challenges. These include the architectural design changes to make communication over multiple links possible, careful consideration of potential coexistence issues with legacy devices, and also other aspects described later in this work.

The purpose of this thesis is to evaluate MLO performance through the analysis of throughput and latency, to recreate simulation scenarios from existing literature related to MLO, to assess the consistency of these results, and finally, to examine the suitability of the used tool for simulating Wi-Fi networks by comparison of results obtained in simulations with findings reported in the selected articles. The performance analysis covers the evaluation of throughput and latency, comparison with legacy, single-link operation (SLO), assessing the impact of coexistence with legacy devices, and examining MLO's capability to support VR applications.

The simulations are conducted in MATLAB using the WLAN Toolbox, which provides dedicated features for Wi-Fi analysis and has recently introduced support for MLO. In addition to the methods provided in the toolbox, custom functions were developed to support the configuration of advanced simulation settings. This code is available online[1].

The remainder of this thesis is structured as follows. Chapter 2 introduces Wi-Fi 7, with a particular focus on MLO, and provides an overview of the relevant literature in a dedicated subsection. Chapter 3 presents MATLAB and its WLAN Toolbox capabilities, including functions used in simulations, and then describes simulation settings, network topologies, configuration parameters, and performance metrics.

[1] https://github.com/jokozo/MLO-Performance-Analysis

Chapter 4 discusses the obtained results, their interpretation, and comparison. Finally, Chapter 5 provides a summary of the work.

2. Background

This chapter includes a description of Wi-Fi 7 with a focus on its most prominent feature – Multi-Link Operation (MLO). It discusses different MLO modes, their characteristics, and the underlying MLO architecture. In addition, the chapter presents an overview of the related literature.

2.1. Wi-Fi 7

IEEE 802.11be, commonly known as Wi-Fi 7 or Extremely High Throughput (EHT) [2], aims to meet the growing need for higher data rates, lower latency, and overall improvement of the network performance. This demand is primarily driven by applications such as virtual and augmented reality, high-definition video streaming, and online gaming. Wi-Fi 7 introduces considerable advancements to both the physical (PHY) and medium access control (MAC) layers to meet these requirements.

2.1.1. Physical Layer Enhancements

One of the key features of Wi-Fi 7 is the use of 320 MHz wide channels. Additionally, the new standard introduces 4096-QAM (4K-QAM) modulation, which enables higher data rates. This enhancement adds two new modulation and coding scheme indices – MCS 12 and MCS 13 [3]. Wi-Fi 7 further improves resource allocation by allowing multiple resource units (RUs) to be assigned to a single user, addressing the limitations of previous standards where only one RU per user was permitted [3]. Moreover, enhancements to the preamble structure aim to maintain coexistence with legacy devices across the 2.4 GHz, 5 GHz, and 6 GHz bands, while also enabling future compatibility. The preamble in Wi-Fi 7 introduces several new fields that provide both version-independent and version-specific information, enabling more efficient communication, simplified protocol detection, and improved support for technologies such as MIMO [4][5].

2.1.2. MAC Layer Enhancements

At the MAC layer, Wi Fi 7 employs multiple significant innovations, such as multi-AP coordination that allows neighboring APs to exchange data and control information [4]. An essential feature of Wi Fi 7 is its support for MLO, which is described in detail in the following sections of this work.

One of the key extensions in Wi-Fi 7 are the updates to the stream classification service (SCS). Wi-Fi 7 SCS allows stations to provide detailed information about their traffic characteristics and service requirements. It enables the access point to make informed scheduling decisions and manage traffic more effectively [3].

Another significant enhancement is restricted target wake time (rTWT), which complements the existing TWT mechanism by allowing the AP to reserve dedicated service periods for specific stations or applications that require higher reliability and reduced jitter [3][5]. It is particularly useful in managed networks, such as factory floors, as it can almost eliminate latency in environments where all devices support this feature.

Wi-Fi 7 also introduces a traffic identifier to link mapping (T2LM), which allows the AP to assign specific traffic categories to individual links. For example, latency-sensitive traffic can be directed exclusively over the 6 GHz band, optimizing overall performance through better link utilization [3].

Collectively, the improvements in Wi-Fi 7 create a faster, more reliable, and efficient environment, better suited for modern high-demand applications like streaming, gaming, and real-time communication.

2.2. Multi-Link Operation

Multi-Link Operation (MLO) is one of the most prominent new features introduced in the latest IEEE 802.11be standard. The functionality enables devices to concurrently transmit and receive data across multiple frequency bands including 2.4 GHz, 5 GHz, and 6 GHz, so as to enhance network performance. The expected improvements include increased throughput, reduced latency, and higher reliability [3].

Devices communicating over a single link, called SLDs (single-link devices), are prone to risks of reduced quality of service, increased latency, packet loss, and low throughput, especially in high-density environments. The introduction of MLO and multi-link devices, called MLDs, addresses some of the limitations of previous Wi-Fi standards that relied on single-link operation. To make MLO possible, different modifications are introduced in terms of link and traffic management, transmission operation, and node architecture. These changes enable various MLO modes, each designed to optimize performance in different networking scenarios.

2.2.1. MLO Modes

IEEE 802.11be defines different MLO modes that can be split into two main categories depending on the capabilities of the device (Fig. 2.1). Most modes use multiple radios, but EMLSR (Enhanced Multi-Link Single Radio) operates using a single radio and supports multiple links by switching between bands. Meanwhile, multi-radio modes, in which devices can communicate on multiple links at the same time, consist of MLMR (Multi-Link Multi Radio) STR (Simultaneous Transmit and Receive), MLMR NSTR (Non-Simultaneous Transmit and Receive), and EMLMR (Enhanced Multi-Link Multiple Radio) [2]. All of these modes are described next.

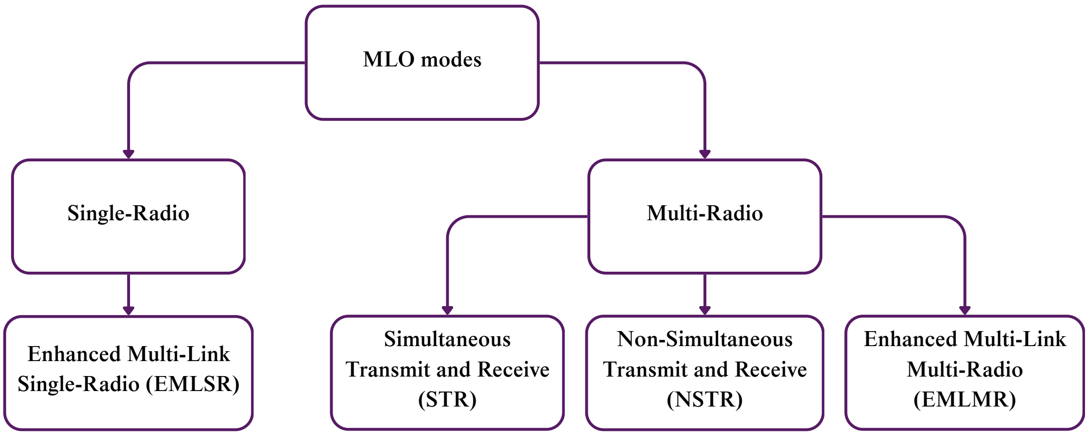


Fig. 2.1. Categorization of MLO modes [2].

Enhanced Multi-Link Single Radio (EMLSR)

The EMLSR mode enables a single radio device to listen to more than one link simultaneously. This listening process includes performing clear-channel assessment and detecting control frames from the AP. A single fully functional 802.11be radio is used alongside several low-capability radios dedicated to decoding control frame preambles [6]. However, the station is restricted to receiving/transmitting data only on one link at a given time. When a station receives the Initial Control Frame from the AP on a link associated with one of the low-capability radios, the main radio must be reconfigured to receive data on this channel. This tuning process requires some time, so the MAC padding delay field is added to the ICF [7][8]. The communication between the EMLSR station and the AP is shown in Fig. 2.2.

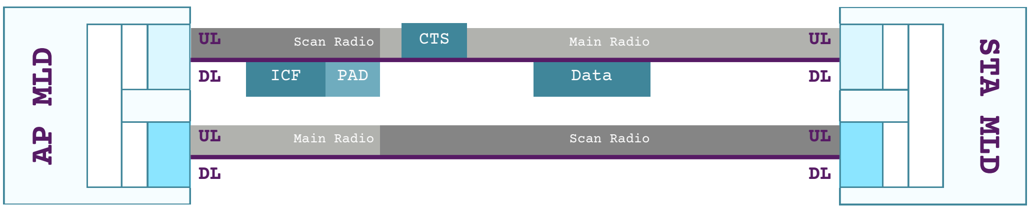


Fig. 2.2. EMSLR operation.

Simultaneous Transmit and Receive (STR)

The STR mode allows concurrent uplink and downlink communication [9], which means a device can transmit data on one link and simultaneously receive packets on another link. Each of the two (or more) links has its own backoff counter, and by using orthogonal channels, data frames can be sent and received independently. This independence allows each link to function without waiting for the channel on the other link to be free, potentially reducing channel access delay. However, the STR mode is susceptible to the risk of power leakage between interfaces called in-device coexistence (IDC) interference if there is not enough frequency separation between channels [9], which can lead to performance degradation, including increased packet loss. Fig. 2.3 shows exemplary frame exchange between an STR station and an AP. The station transmits data to the AP on link 1, while receiving packets from the AP on link 2.

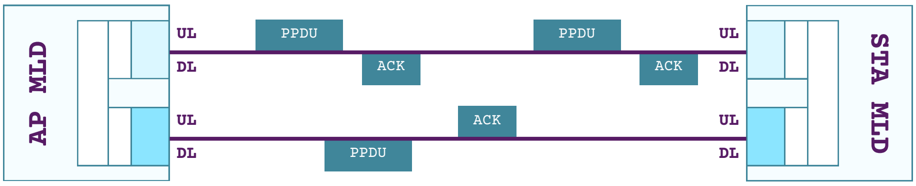


Fig. 2.3. Example frame exchange in STR mode.

Non-Simultaneous Transmit and Receive (NSTR)

Another MLO mode is NSTR, in which one link operates as the primary link, while the remaining links function as secondary and depend on the state of the primary link. The primary link runs a single backoff counter, and if any of the other links are idle, they can be used for transmission [10]. Otherwise, transmission occurs only over the primary channel. In this mode, a station cannot transmit and receive data simultaneously on different channels. NSTR allows to mitigate some of the STR problems caused by IDC interference [9]. Fig. 2.4 shows an illustrative scenario of frame exchange between an NSTR station and the AP.

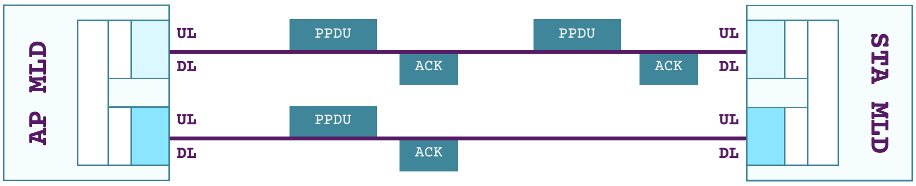


Fig. 2.4. Example frame exchange in NSTR mode.

Enhanced Multi-Link Multi Radio (EMLMR)

This mode enables stations to listen to multiple links simultaneously and dynamically reconfigure available radios across different links to adapt to varying transmission requirements. For example, a station may support two spatial streams on one link or two links with single spatial streams [3]. This flexibility allows for a more efficient utilization of available radio resources.

2.2.2. MLO Architecture

The introduction of MLO functionality requires modifications to the device architecture and the implementation of MLDs capable of handling multiple channels simultaneously. Both the AP MLDs and station MLDs refer to individual devices equipped with multiple wireless interfaces. However, the operation on the physical layer has to remain transparent to the upper layers to ensure proper functioning. To achieve this goal, the MAC layer is divided into two sublayers [9].

First, upper MAC (U-MAC) is the common sub-layer for all interfaces and is responsible for management functions and link-agnostic operations such as MSDU aggregation and de-aggregation, sequence number assignment, encryption, and traffic identifier to link mapping [11]. However, the standard does not define scheduling mechanisms that allocate data frames to links, making this a topic of multiple research studies [12][13][14].

Next, each interface operates with an independent low MAC (L-MAC) sub-layer, which is responsible for managing link-specific functions such as channel access, MPDU generation, MCS selection, and other transmission-related processes [11]. The separation of these functionalities remains seamless to the upper layers. The visualization of MLO architecture is shown in Fig. 2.5

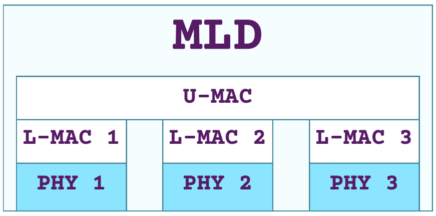


Fig. 2.5. MLO device architecture.

2.3. State of the Art

The introduction of the new Wi-Fi standard, 802.11be, and its main feature – Multi-Link Operation – has brought forward novel concepts, challenges, and research questions that have become a focal point of interest for scientists and researchers in their articles. Most scientific works on Wi-Fi 7 revolve around maintaining and enhancing Quality of Service (QoS) using MLO.

One of the most crucial questions raised by scientists is whether – and to what extent – multi-link operation outperforms single-link operation, particularly in terms of throughput and latency. The authors of [15] analyze the performance of MLO in comparison to SLO in two scenarios. In an isolated BSS with one AP and one station, MLMR provides throughput gains proportional to the number of links and significantly reduces delay, while MLSR achieves throughput similar to SLO regardless of the number of links. In a second scenario with two BSSs operating on the same channels, using MLMR operating on two links leads to increased delay due to simultaneous transmissions on multiple links and blocking access for the contending BSS. In [5], the authors evaluate the uplink and downlink throughput performance for different MLO modes in a simple setup involving an AP and a single station under varying OBSS activity. Then, they compare this performance to legacy single-link operation. The results show that, in general, all MLO modes considerably enhance throughput compared to the single-link scenario. Similarly, the authors of [16] investigate the downlink performance in both SLO and MLO networks that comprise 1, 4 or 10 stations. Their findings demonstrate that MLO significantly improves throughput – by approximately 92% for 80 MHz channels and around 84% for 160 MHz channels – compared to using a single link. In addition, using two links instead of one results in a noticeable reduction in average packet latency. Moreover, using two 80 MHz channels yields better throughput than a single 160 MHz channel. In [17], researchers use a simple scenario (one AP and one station, two links) but use real 5 GHz spectrum occupancy measurements to model OBSS activity. The findings indicate that both MLO modes (STR and NSTR) outperform SLO regarding achieved throughput. However, when using two asymmetrically occupied links in STR mode, performance may degrade due to packets being allocated to a link before running the backoff procedure, potentially allocating frames to the more congested link. To overcome this problem, the authors propose another channel access mechanism called STR+, which runs parallel backoffs and assigns packets to the interface that gets access to the channel first, thus reducing delays. Meanwhile, the authors of [6] bring to attention another anomaly regarding delay in crowded scenarios when using EMLMR mode (also referred to as STR EMLMR). They call this anomaly the starvation phenomenon, which occurs in high-load and high-contention scenarios when one STR device occupies all the available links, blocking contending BSSs from transmitting. Then, the authors present potential solutions, including using two channels, one reserved exclusively for each BSS and one shared with other BSSs, or using more channels than there are contending BSSs. Their findings show that channel assignment is the most effective approach among those analyzed.

Despite MLO already being more efficient than legacy SLO, research continues to explore methods for further optimizing available resources and enhancing performance by reviewing different traffic-to-link allocation policies. The authors of [18] review and compare the effectiveness of allocation policies, including SLCI (Single-Link Less Congested Interface), MLSA (Multi-Link Same load to All interfaces) and MCAA (Multi-Link Congestion-Aware load balancing at flow arrivals). The results of this comparative evaluation of the aforementioned algorithms show that the performance of MLO heavily depends on the chosen policy and that congestion-aware approaches (SLCI and MCAA) are the most effective. Another study, in [9], presents a new traffic allocation policy that the authors refer to as VDS (Video and Data Separation). This algorithm differentiates traffic flow types and allocates data and video flows to separate links, selecting the least congested one. The performance of VDS was evaluated and compared with SLO, SLCI, MCAA and MLSA. The results indicate that the VDS policy maintains average throughput losses below a 5% threshold for both video and data only in 50% of the evaluated scenarios. In contrast, SLCI and MCAA achieve this threshold in 75% of all scenarios. In [14], the authors introduce a dynamic congestion-aware policy called MCAB (Multi-Link Congestion-aware Load balancing), which operates similarly to MCAA but periodically adjusts traffic allocation across links based on congestion levels. Their performance evaluation shows an improved congestion distribution and a more balanced utilization of links compared to SLCI and MCAA, highlighting the advantages of dynamic policies over nondynamic ones. Furthermore, in [19], researchers identify the MPDU aggregation issue, where too many MPDUs are sent on one link. The remaining links may experience an MPDU shortage, leading to reduced throughput. To address this, they propose an aggregation algorithm called DAMLA (Dynamic Algorithm for Multi-Link Aggregation) that adjusts A-MPDU sizes based on network conditions and previous transmissions. The results show that DAMLA improves throughput up to 50% in a simple scenario. In addition to traffic allocation mechanisms, ongoing research explores schedulers, as seen in [13]. The authors focus on Service Level Agreements (SLAs) in industrial scenarios, where devices have varying requirements, particularly concerning latency. They propose a novel MLO scheduler, SLA-MLO, designed to manage per-flow SLA, which they define as the maximum allowed percentile latency. Packets are assigned for transmission based on the maximum allowed latency, the percentage of packets that can exceed this latency, and the time during which the number of these packets stays below the percentage threshold. The simulations results show a reduction in SLA deviation by 50% compared to algorithms based on least congestion control such as [18].

Besides efficient traffic allocation and scheduling algorithms, transport-layer performance is also an important topic to consider when exploring MLO's capabilities. One aspect is TCP traffic behavior, where its reliance on ACK packets can introduce delays and performance variations because of the bidirectional nature of the transmission. The authors of [20] examine MLO to assess its impact on TCP performance. They analyze various metrics, depending on the type of traffic, the number of links, transmission direction, and network density. The results show that while throughput improves with more links, metrics such as RTT, latency, number of retransmissions, and out-of-order packets also increase. The researchers identify collisions as the root of performance issues and propose a TID-to-link mapping solution to mitigate the problems. In [21], the authors investigate the interaction between TCP and multi-link STR mode. This work also focuses on different TID-to-link mapping configurations. The simulation results indicate that using the TID-to-link mapping on MLO stations significantly increases the performance of TCP.

Apart from network protocol optimization, MLO might be crucial for ensuring proper performance of VR/AR applications, which require ultra-low latency and high reliability. One of the works exploring this topic is [22]. This research evaluates MLO and different policies for supporting AR applications compared to single-link operation. The authors examine various traffic-to-link allocation policies including greedy, uniform-load, congestion-aware and condition-aware, alongside different link configurations (changing numbers of links and bandwidths). The results show that greedy policy performs better than informed (aware) policies, which can be surpassed even by single-link operation in certain link configurations. Another study in [23], based on real VR traffic distribution, analyzes if MLO can meet the requirements described by the Wi-Fi Alliance for VR gaming [24]. The study verifies the impact of MCS and channel bandwidth selection on delivering a satisfactory user experience. The findings indicate that MLO can support up to 50% more users than SLO, offers lower delays and requires less bandwidth and a lower MCS to meet the requirements. Overall, MLO has a great potential to significantly improve the performance of VR/AR applications.

While MLO introduces new opportunities for performance enhancement, the coexistence of MLDs and legacy stations operating on a single link raises important considerations. Numerous research studies have investigated this topic, identifying potential problems such as compromised performance, proposing solutions, and outlining methods for improving overall network performance and fairness without impairing the functionality of MLO devices. Researchers in [15] consider three BSSs: two SLO BSSs operating on orthogonal channels and one MLO BSS using both, thus contending with each SLO BSS. The results show that MLSR achieves throughput comparable to that of SLO, while MLMR increases its own throughput at the expense of SLO BSSs. Another study in [10] analyzes the impact of legacy devices on the performance of stations operating in NSTR mode, stating that the coexistence of single-link devices reduces the probability of starting an NSTR transmission. The considered simulation scenario consists of two bands, legacy devices operating on one link, and MLDs utilizing both links. Simulation results indicate that using two links increases throughput by 55-65%. However, the legacy devices affect NSTR stations, preventing them from reaching the expected doubling of throughput. In [25], researchers evaluate how different band assignment policies affect the performance of a network consisting of MLDs and legacy stations. The authors consider three bands and propose different assignment policies, with legacy single-link devices operating on the 2.4 GHz band and the MLDs operating on 5 and 6 GHz links, or all three links, with single or multiple RTS acceptance policies. The results suggest that network optimization strategies should vary based on the nature of the network. In dense environments with a high percentage of legacy devices, the most effective approach is to allocate separate links for legacy and MLD stations while enabling multiple RTS acceptance. Another study in [14], mentioned earlier, provides results on the MCAB algorithm's performance in coexistence with legacy networks. The findings indicate that an excessive number of legacy devices degrade the performance of multi-link devices. However, MCAB may reduce this negative impact by 10% compared to MCAA. Surprisingly, the study shows that legacy BSSs may benefit from coexisting MLO networks. On the other hand, in [12], researchers note that legacy devices may be negatively impacted by coexisting MLDs. To address this, they describe a novel algorithm called LFTA (Legacy Friendly rate and congestion-aware Traffic Allocation at flow arrivals), which allocates flows from MLDs only to a certain limit while also considering link occupancy and the rate of the links. Therefore, there is enough spare channel capacity left exclusively for single-link devices. A comparison with SLCI, MCAA and MLSA [18] shows that LFTA achieves more balanced channel occupancy, therefore outperforms these algorithms and ensures better performance for both MLO and legacy devices.

While the majority of existing research on MLO relies on ns-3 or custom simulation tools, this thesis explores the use of MATLAB as an alternative environment. It aims to test the capabilities of MATLAB in terms of network modeling and analysis, and complement the existing knowledge of simulation tools suitable for Wi-Fi performance evaluation. The evaluation scenarios presented in [16], [15], [5], [19], [6], [17], [25] and [23] served as a baseline for simulations conducted as a part of this thesis.

3. Simulation Tools and Settings

This section presents an overview of the tools and software utilized to conduct simulations and analyze the performance of MLO. It describes MATLAB, with a particular focus on the WLAN Toolbox, which provides various functions for simulating and testing wireless LAN communications systems. The following subsections describe the network topology and settings in the evaluated simulation scenarios, as well as performance metrics used to assess the system's behavior. Finally, the tools and methods applied for data analysis and visualization are described.

3.1. MATLAB

MATLAB is a programming language and a numeric computing platform developed by MathWorks [26]. The software offers numerous capabilities in data analysis, simulation, data visualization, and algorithm development, supported by a variety of functions and specialized toolboxes.

3.1.1. WLAN Toolbox

In this work, the primary tool used is the WLAN Toolbox, which provides standard-compliant features for designing, simulating, and analyzing wireless local area network systems. The toolbox enables the study of signal transmission and reception, testing propagation channel models for IEEE 802.11, and conducting both end-to-end and system-level simulations. It also supports testing and measurements through waveform generation, signal visualization, and transmitter performance analysis. When integrated with other toolboxes, it provides extended functionality, such as AI, positioning, and sensing capabilities. The functions enabling the system-level performance analysis of Multi-Link Operation were essential to this work.

3.1.2. Simulation Capabilities

The WLAN Toolbox's functions support the physical (PHY) and medium access control (MAC) layers modeling, enabling end-to-end and system-level simulations. Application layer behavior can also be emulated through user-defined traffic models.

To simulate different network scenarios, the `wirelessNetworkSimulator` object is employed, created by the `wirelessNetworkSimulator.init()` method. This object provides core functions – such as `addNodes`, `addChannelModel`, and `run` – which are used to configure the topology, define the channel or path loss model, and execute the simulation.

In addition to these core functions, several other objects and methods are used to define nodes and their configuration:

- `addTrafficSource` - adds the data traffic source to a specified node,
- `associateStations` - associates the list of stations to the access point,
- `statistics` - returns performance metrics for each node, such as the number of transmitted or received packets, data frames, retransmissions, etc.
- `wlanDeviceConfig` - contains properties used for configuration of a WLAN node. The most relevant parameters include:
  - `Mode` - specifies the operating mode of the device (station, access point, or mesh),
  - `BandAndChannel` - determines the operating frequency band and channel number,
  - `TransmissionFormat` - sets the physical layer transmission format, the available options include "HE-SU", "Non-HT", "HT-Mixed", "VHT", "HE-EXT-SU", "HE-MU-OFDMA", and "EHT-SU",
  - `ChannelBandwidth` - defines the maximum bandwidth for transmission or reception, which depends on the selected band and transmission format,
  - `MCS` - indicates the modulation and coding scheme, depends on the chosen transmission format.

  Additional configuration parameters control features such as the number of transmit antennas, number of space-time streams, MAC Protocol Data Unit (MPDU) aggregation capabilities, MAC queue size, and transmission power.

  In the case of MLO, the parameters related to channel and link configuration, such as `BandAndChannel`, are no longer applied at the device level. Instead, each link within a multi-link device is configured individually using the `wlanLinkConfig` object. This enables independent specification of PHY and MAC layer settings for each link. In addition, the `wlanMultilinkDeviceConfig` object is used to define parameters shared across the entire MLD, for example, an operating mode or additional configuration settings related to the EMLSR mode.
- `wlanNode` - Used to define and configure the individual nodes. The properties of the wlanNode object include:

- `Name` - assigns a name to the node,
- `Position` - specifies a position of the node using 3D Cartesian coordinates,
- `MACFrameAbstraction` - Indicates whether MAC frames are abstracted,
- `PHYAbstractionMethod` – defines the abstraction method of the physical layer. Supported options include “tgax-evaluation-methodology”, “tgax-mac-calibration”, or “none”.

The WLAN Toolbox also features several network traffic models designed to emulate realistic traffic patterns. These models are consistent with the IEEE 802.11ax Evaluation Methodology [27], as well as other specifications, such as 3GPP [28]. The available models include the following.

- `networkTrafficFTP` - defines the configuration settings for File Transfer Protocol application traffic pattern,
- `networkTrafficOnOff` - specifies the configuration parameters for On-Off traffic model,
- `networkTrafficVideoConference` - sets the configuration values to generate a video conference application traffic pattern,
- `networkTrafficVoIP` - defines the configuration inputs to generate a voice over Internet protocol (VoIP) traffic.

Beyond these elements, the toolbox includes a set of helper functions to support the creation and management of objects and methods. These functions are particularly useful in complex simulations involving multiple nodes or advanced features, such as Multi-link Operation. They simplify tasks such as configuring channel and path loss models, validating simulation setup, or visualizing performance metrics. The detailed description of the functions relevant to this work is as follows:

- `hCheckWLANNodesConfiguration` - checks whether all nodes have identical values for the MACFrameAbstraction and PHYAbstractionMethod properties, and if all devices operating on the same channel frequency use the same channel bandwidth. Additionally, it ensures that all WLAN devices are configured with appropriate values for MPDU aggregation, the number of transmitting antennas, and the number of spatial streams.
- `hSLSTGaxMultiFrequencySystemChannel` - creates a system channel object for an array of WLAN nodes with reciprocal links. It supports configurable parameters, including the prototype link type (TGax, TGac, TGn), shadow fading standard deviation, and path loss models (free-space, residential, enterprise). The object manages channels for each frequency and provides methods to access specific link or channel instances for transmission and reception.
- `hSLSTGaxAbstractSystemChannel` - creates a channel manager object for an abstracted PHY layer, based on a specified channel configuration (TGax, TGac, or TGn) and antenna array per node. It also supports retrieval of per-link channel statistics.

– hSLSTGaxSystemChannel - creates a channel manager object for full PHY simulations using a specified TGax, TGac, or TGn channel configuration and an array defining the number of antennas per node, assuming reciprocal channels and identical configuration across links.

– hSLSTGaxSystemChannelBase - provides a channel manager object using a TGax, TGac, or TGn channel configuration and an array specifying the number of antennas per node, assuming reciprocal channels with identical configurations. The object manages detailed link information, including fading channel objects, node IDs, sample rates, shadow fading, and path loss parameters. It offers methods to reset and initialize channels, retrieve channel and link details, and calculate path delays, filters, gains, shadow fading, and path loss.

– hPlotPacketTransitions - provides a live visualization of packet transmissions over time and frequency for nodes during a simulation. It includes legends for node states and types, a time slider that can be used to go to a specific time period, and export options as shown in Fig. 3.1.

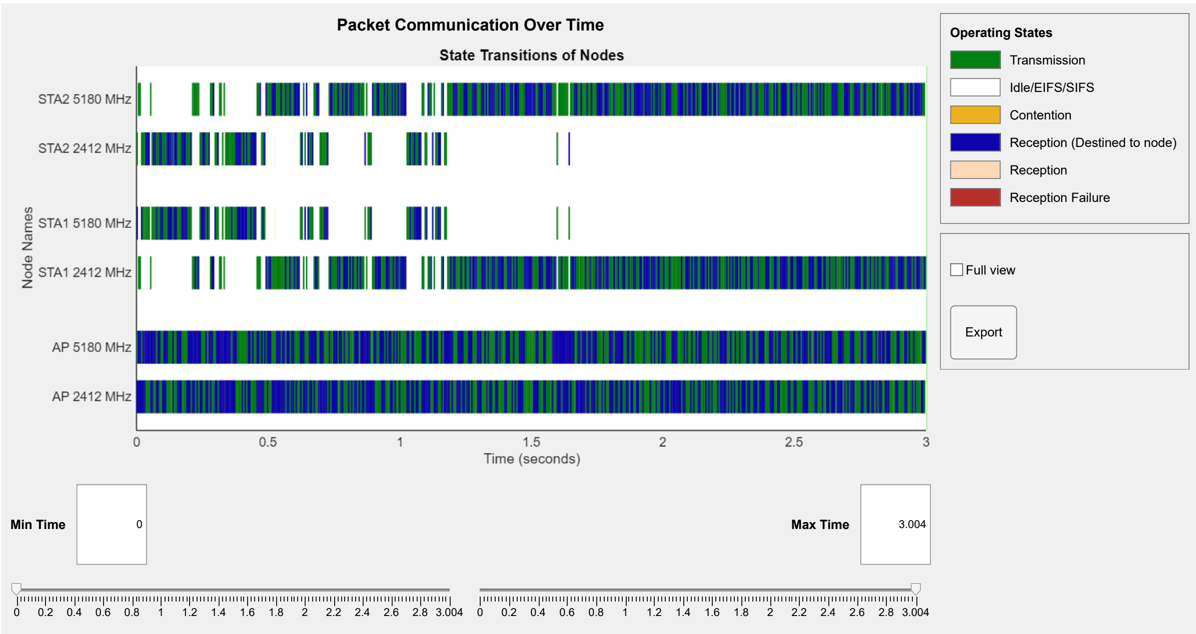


Fig. 3.1. Packet communication over time – MATLAB window.

– hPerformanceViewer - provides methods for visualization and analysis of key performance metrics, such as throughput, average packet latency, and packet loss ratio for a set of Bluetooth and WLAN nodes over a defined simulation time.

– hCompareMLOvsNonMLOThroughput - displays a bar chart comparing the throughputs of different types of stations connected to the same access point. It distinguishes between devices operating in STR mode, EMLSR mode, and traditional single-link stations.

3.1.3. MLO in MATLAB

MathWorks offers an example titled "802.11be System-Level Simulation Using STR Multi-Link Operation" [29], which illustrates the basic concept and operation of STR mode. The example also provides an overview of MATLAB capabilities for simulating MLO networks and serves as a guide to understanding the built-in functions and helpers. The code from the example may be considered a baseline for further code development.

In this scenario, the simulation environment consists of one station and an access point, each configured to operate over three independent frequency bands: 2.4 GHz, 5 GHz, and 6 GHz. All links are separate and can be active simultaneously, allowing concurrent data transmission and reception, which reflects the key capability of the STR mode.

The simulation workflow begins with the initial configuration of key parameters, including seed for the random number generator, simulation time, and initialization of the wireless network simulator. Then, the frequency bands and channel numbers for each link are specified.

In the next step, the access point (AP MLD) and station (STA MLD) nodes are created and configured using the `wlanNode`, `wlanMultilinkDeviceConfig`, and `wlanLinkConfig` objects. These components are assigned appropriate values, such as node mode (AP or STA), position, selected frequency band and channel, modulation and coding scheme (MCS), and other relevant parameters. The configuration of the nodes is shown in Listing 3.1.

```
bandAndChannelValues = [2.4 1; 5 36; 6 1];
numLinks = size(bandAndChannelValues,1);
for linkIdx = 1:numLinks
    apLinkCfg(linkIdx) = wlanLinkConfig(...
        BandAndChannel=bandAndChannelValues(linkIdx,:),...
        MCS=2,...
        MPDUAggregationLimit=100,...
        TransmitPower=15);
    staLinkCfg(linkIdx) = wlanLinkConfig(...
        BandAndChannel=bandAndChannelValues(linkIdx,:),...
        MCS=3,...
        MPDUAggregationLimit=100,...
        TransmitPower=15); %#ok<*SAGROW>
end
apMLDCfg = wlanMultilinkDeviceConfig(Mode="AP",LinkConfig=apLinkCfg);
apMLD = wlanNode(Position=[0 0 0],Name="AP",DeviceConfig=apMLDCfg);

staMLDCfg = wlanMultilinkDeviceConfig(Mode="STA",LinkConfig=staLinkCfg);
staMLD = wlanNode(Position=[10 0 0],Name="STA",DeviceConfig=staMLDCfg);

nodes = [apMLD staMLD];
```

Listing 3.1. MLO nodes configuration from MATLAB example.

Following the node configuration, the STA is associated with the AP using the `associateStations` function. At this stage, full-buffer traffic is defined in both uplink and downlink directions, ensuring continuous data flow. To model realistic wireless propagation, a fading channel between nodes is introduced using the `hSLSTGaxMultiFrequencySystemChannel` helper function. It contains a set of parameters passed to the simulator through the `addChannelModel` object function.

Once the channel model is established, all configured nodes are added to the wireless network simulator. Finally, the `hPerformanceViewer` helper object is invoked to enable the node performance visualization, which includes the depiction of packet communication over time, throughput of specific nodes and links, packet loss ratio (PLR), and average packet latency. In addition, detailed statistics from the application, MAC, and physical layers are also available.

3.1.4. Supporting functions

This section presents custom functions created in order to simplify the configuration of simulation scenarios. These functions enable reproducibility of simulation settings and, therefore, of the results.

Node placement

To generate the spatial coordinates of the stations, the `randomPositionsFermat` function was implemented. It takes a number of stations and a maximum coverage radius as input arguments and allocates the stations using a Fermat's spiral pattern, with the access point placed at a predefined position. This approach was chosen to achieve a semi-random yet even distribution across the entire area, while preventing stations from overlapping. The exemplary coordinates generated by the function are shown in Fig. 3.2. The function code is presented in Listing 3.2.

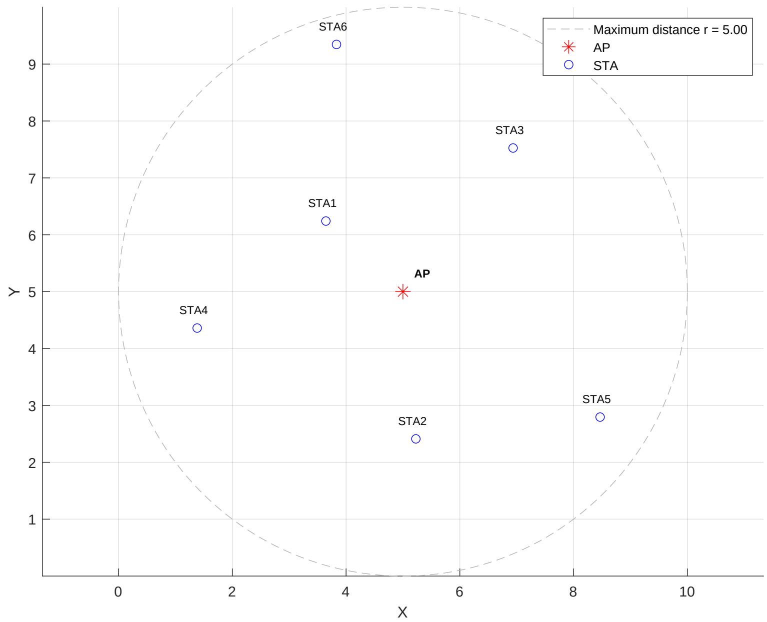


Fig. 3.2. Exemplary node positions for 6 stations and maximum distance r = 5m.

```
function [staPositions, apPosition] = randomPositionsFermat(numStations, radius)
    apPosition = [radius, radius, 0];
        %Fermat spiral - golden angle ~137deg
    goldenAngle = pi * (3 - sqrt(5));
    i = (1:numStations)';
        %normalized radius
    r = sqrt(i / numStations) * radius * 0.9;
    theta = i * goldenAngle;
    x = apPosition(1) + r .* cos(theta);
    y = apPosition(2) + r .* sin(theta);
    staPositions = [x, y, zeros(numStations, 1)];
end
```

Listing 3.2. The randomPositionsFermat function for nodes distribution.

Generation of Traffic Parameters

The custom generateTrafficParams function determines the traffic parameters for the networkTrafficOnOff object described in Section 3.1.2, which is essential for scenarios that require a specified traffic load. It takes the maximum achievable throughput, a number of stations, and an expected traffic load as input parameters, and from these values calculates the data rate, onTime and offTime durations using the fixed packet size, which can be directly used to configure the networkTrafficOnOff object. The code of the generateTrafficParams function is presented in Listing 3.3.

```
function [pktSize, dataRate, onTime, offTime] = generateTrafficParams(maxThr, numSTA
    , expectedLoad)

    maxThr_bps = maxThr * 1e6;  %max received thr in bps
    totalOfferedTraffic = expectedLoad * maxThr_bps;
    trafficPerUser = totalOfferedTraffic / numSTA;

    pktSizeBits = 1500 * 8;
    pktRate = trafficPerUser / pktSizeBits;
    burstInterval = 8.3e-3;
    pktsPerBurst = max(1, round(pktRate * burstInterval));
    onTime = pktsPerBurst * 1e-3;
    offTime = burstInterval - onTime;
    offTime = max(offTime, 1e-9);
    pktSize = 1500;
    dataRate = trafficPerUser / 1000;  %rate in kbps
end
```

Listing 3.3. The generateTrafficParams function for calculating on/off traffic model parameters.

Generation of OBSS Traffic Parameters

The generateTrafficParamsOBSS function is a custom utility used to generate traffic parameters for the networkTrafficOnOff object. It was created specifically to generate OBSS traffic loads to model the occupancy of the channel (applied similarly to the simulation scenario in [5]). Unlike the general version, this function fixes the offered traffic to 10% of the maximum achievable throughput, which serves as a baseline unit for OBSS traffic. Thus, to achieve channel occupancy equal to 70%, an OBSS consisting of an AP and seven stations is required. The function calculates the data rate, onTime and offTime durations using the fixed packet size, which can be used to configure the networkTrafficOnOff object. The code of the generateTrafficParamsOBSS function is presented in Listing 3.4.

```
function [pktSize, dataRate, onTime, offTime] = generateTrafficParamsOBSS(maxThr)

    maxThr_bps = maxThr * 1e6;  %max received thr in bps
```

```
    trafficPerUser = 0.1 * maxThr_bps;

    pktSizeBits = 1500 * 8;
    pktRate = trafficPerUser / pktSizeBits;
    burstInterval = 8.3e-3;
    pktsPerBurst = max(1, round(pktRate * burstInterval));
    onTime = pktsPerBurst * 1e-3;
    offTime = burstInterval - onTime;
    offTime = max(offTime, 1e-6);
    pktSize = 1500;
    dataRate = trafficPerUser / 1000;  %rate in kbps
end
```

Listing 3.4. The generateTrafficParamsOBSS function for calculating on/off traffic parameters to model channel occupancy.

3.2. Default Settings and Topology

This chapter presents the simulation parameters and network topologies employed throughout the performance evaluation. The description of the simulation scenarios is organized as follows: throughput scenarios are presented first, followed by latency scenarios, the legacy scenario, and finally the VR scenario. Although multiple simulation scenarios are considered, a common set of parameters has been defined and applied in all test cases (unless otherwise specified) to maintain consistency. These parameters are summarized in Table 3.1.

Table 3.1. Common simulation parameters.

Simulation parameter	Value
PHY abstraction method	tgax-evaluation-methodology
Spatial streams	2
Simulation time	10 s
Number of independent runs	7
Pathloss model	residential
A-MPDU size	1024

3.2.1. Baseline Throughput Scenario

The baseline scenario, inspired by [16], aims to provide initial throughput values. The network topology consists of a single AP and one station communicating in the downlink direction as shown in Fig. 3.3. Simulations are conducted under varying settings, including single-link and dual-link configurations, channel bandwidths of 80 MHz and 160 MHz, and different MPDU aggregation limits. Specifically, the limit of aggregation is varied between 64, 512, and 1024 MPDUs. The devices operate in the 5 GHz band, with channels 1 and 100 used for the MLO configuration and channel 1 for the single-link. The simulation parameters are presented in Table 3.2.

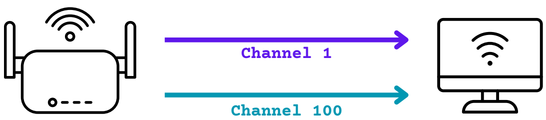


Fig. 3.3. Baseline Throughput Scenario – topology.

Table 3.2. Baseline Throughput Scenario – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	1, 100
Channel width	80 MHz, 160 MHz
Number of links	1, 2
MLO mode	STR
MCS	0 – 13
A-MPDU size	64, 512, 1024
AP – STA distance	1 m

3.2.2. Throughput Scenario #1

The throughput scenario #1 is based on [15]. Its goal is to compare the throughput of SLO and MLO modes in a basic setting. The scenario consists of an AP and one station, communicating in the downlink direction under a full-buffer traffic model. Depending on the configuration, devices may use one, two, or three 80 MHz channels allocated in the 5 GHz band. MLO devices operate in either STR or EMLSR mode using two or three links. The physical layer is configured to use MCS 8, and the MPDU aggregation limit is set to 1024. Detailed information on simulation parameters is provided in Table 3.3.

Table 3.3. Throughput Scenario #1 – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	1, 100, 136
Channel width	80 MHz
Number of links	1, 2 or 3
Number of stations	1
MLO mode	STR, EMLSR
MCS	8
AP – STAs distance (r)	5

3.2.3. Throughput Scenario #2

The throughput scenario #2 is based on [15]. Its purpose is to evaluate the coexistence of MLO and SLO devices. The scenario consists of three BSSs, each comprising an AP and one associated station communicating in the downlink direction. All APs generate full buffer traffic. Two BSSs operate in single-link mode, while the third BSS operates in either STR mode or EMLSR mode. Two SLO BSSs, denoted as BSS A and BSS C, operate independently on 80 MHz channels – channel 1 and channel 100 in the 5 GHz band, respectively. A third BSS, BSS B, is configured as MLO and uses both channels, thereby competing for medium access with both BSS A and BSS C as shown in Fig. 3.4. Devices operate with MCS 8, and are configured to use an MPDU aggregation limit of 1024. Detailed information on simulation parameters is provided in Table 3.4.

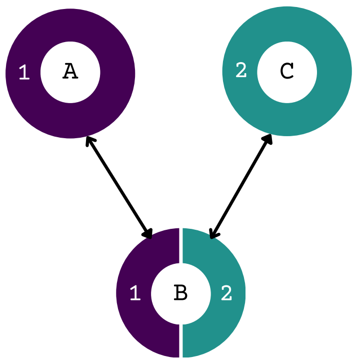


Fig. 3.4. Throughput Scenario #2 – topology.

Table 3.4. Throughput Scenario #2 – configuration parameters.

Simulation parameter	**Value**
Band	5 GHz
Channels	1, 100
Channel width	80 MHz
Number of links	1, 2
Number of BSSs	3
MLO mode	STR, EMLSR
MCS	8
AP – STAs maximum distance (r)	5

3.2.4. Throughput Scenario #3

The throughput scenario #3 is based on [5]. It aims to evaluate the throughput of MLO under different OBSS activity. The scenario comprises a main basic service set (BSS) with one AP and one station communicating over one or two links with channel width of 80 MHz, and two overlapping BSSs (OBSSs) – one per link. Each OBSS contains a variable number of single-link stations, ranging from 0 to 10, to model different levels of channel occupancy on the corresponding link. Only symmetrical channel occupancy is considered, meaning OBSSs consist of the same number of stations at the same time. The scenario includes single-link stations as well as multi-link STR or EMLSR stations. The PHY is configured to use MCS 13, and the MPDU aggregation limit is set to 1024. The two links operate in the

5 GHz and 6 GHz bands, respectively, with a single channel selected in each band. SLO devices operate in the 5 GHz band. Detailed information on the simulation parameters is provided in Table 3.5.

Table 3.5. Throughput Scenario #3 – configuration parameters.

Simulation parameter	**Value**
Band	5 & 6 GHz
Channels	5 GHz: 1, 6 GHz: 1
Channel width	80 MHz
Number of links	1, 2
Number of stations (main BSS)	1
Number of stations (OBSS)	1 - 10
MLO mode	STR, EMLSR
MCS	13
AP – STAs maximum distance (r)	5

3.2.5. Throughput Scenario #4

The throughput scenario #4 is based on [19]. Its purpose is to evaluate the impact of MPDU aggregation settings on throughput. The scenario consists of an AP and one MLO STR station communicating in the downlink direction, with the AP operating under a full buffer traffic model. Two 80 MHz channels in the 5 GHz band are available for transmission. The occupancy of the second channel changes between 10% and 70%, while the first channel is free for transmission or subject to an external load of 10%. Channel occupancy is modeled as OBSS traffic, configured using the `generateTrafficParamsOBSS` function. The physical layer operates with MCS 11. The MPDU aggregation limit – crucial for this scenario – is varied among 64, 512, and 1024. Additionally, the TXOP limit is set to either 0 ms or 3 ms; this parameter defines the maximum duration a device can continuously transmit frames when it gains access to the medium. A detailed list of configuration parameters is provided in Table 3.6.

Table 3.6. Throughput Scenario #4 – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	1, 100
Channel width	80 MHz
Number of links	2
Number of stations	1
MLO mode	STR
MCS	11
A-MPDU size	64, 512 or 1024
AP – STA distance (r)	5

3.2.6. Latency Scenario #1

The latency scenario #1 is based on [16]. It aims to analyze how different numbers of links and stations affect latency. The scenario involves a single BSS consisting of one AP and a varying number of stations communicating over one or two links with channel widths of 80 MHz or 160 MHz per link. The MCS value is equal to 11. The MPDU aggregation limit in the simulations was set to the MATLAB default value of 64. Detailed information on the simulation parameters is provided in Table 3.7.

Table 3.7. Latency Scenario #1 – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	1, 100
Channel width	80 MHz, 160 MHz
Number of links	1, 2
Number of stations	1, 4, 10
MLO mode	STR
MCS	11
A-MPDU size	64
AP – STAs maximum distance (r)	5

3.2.7. Latency Scenario #2

The latency scenario #2 is based on [6]. Its purpose is to evaluate how different traffic loads affect latency. The scenario consists of one AP and one station, which operates either as a single-link device or in STR multi-link mode. In the SLO case, devices operate on a single link in the 5 GHz band. In the MLO case, the AP and station communicate in the downlink direction over two or four links, each with a channel bandwidth of 80 MHz in the 5 GHz and 6 GHz frequency bands. All links are configured with two spatial streams. An MCS index of 8 is applied, and the MPDU aggregation limit is set to a maximum value of 1024. To generate the desired traffic load (ranging from 100 to 2500 Mb/s), the `networkTrafficOnOff` object is used, with its parameters configured through the `generateTrafficParams` function. A detailed overview of the simulation parameters is provided in Table 3.8.

Table 3.8. Latency Scenario #2 – configuration parameters.

Simulation parameter	Value
Band	5 & 6 GHz
Channels	1, 100 (in each band)
Channel width	80 MHz
Number of links	1, 2 or 4
Number of stations	1
MLO mode	STR
MCS	8
AP – STAs distance (r)	5

3.2.8. Latency Scenario #3

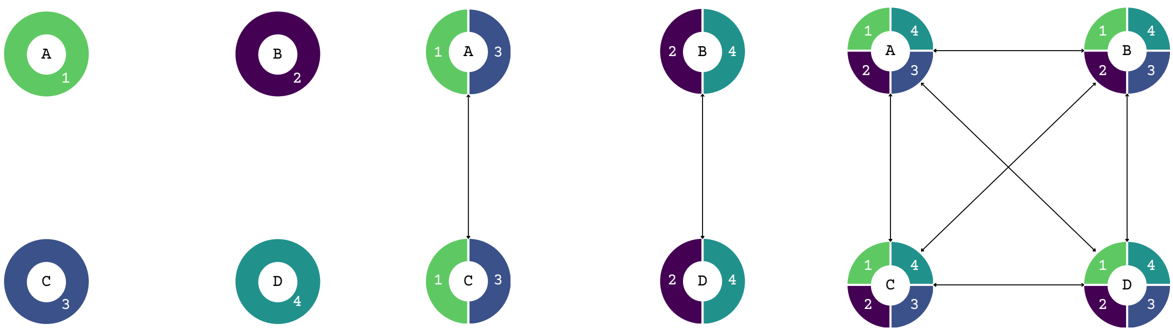
The latency scenario #3 is based on [15] and aims to evaluate how varying traffic loads and link configurations affect the latency of different MLO modes. The scenario consists of an AP and one station communicating in the downlink direction over one, two, or three links, each with a channel bandwidth of 80 MHz allocated in the 5 GHz band. MLO devices operate in either STR or EMLSR mode using two or three links. The physical layer is configured to MCS 8, and the MPDU aggregation limit is set to 1024. The desired traffic load is generated using the `networkTrafficOnOff` object, with its parameters set via the `generateTrafficParams` function. A summary of the simulation parameters is provided in Table 3.9.

Table 3.9. Latency Scenario #3 – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	1, 100, 136
Channel width	80 MHz
Number of links	1, 2 or 3
Number of stations	1
MLO mode	STR, EMLSR
MCS	8
AP – STAs distance (r)	5

3.2.9. Latency Scenario #4A

The latency scenario #4A is based on [6] and its purpose is to evaluate the impact of different traffic loads on latency in a contended network. The scenario consists of four BSSs, each involving one AP and one station, communicating in the downlink direction. Two channels are allocated in the 5 GHz band and two in the 6 GHz band, and all simulations are performed using MCS 8 and the MPDU aggregation limit of 1024. In this scenario, three modes of operation are considered. In the first case (SLO), as shown in Fig. 3.5a, all four BSSs operate in single-link mode, with one 80 MHz channel exclusively assigned to each BSS. In the second mode (MLO-STR:2), depicted in Fig. 3.5b, each BSS uses two links, with each channel shared with one additional contending BSS. In the final mode of operation (MLO-STR:4), shown in Fig. 3.5c, all four channels are shared among four BSSs. Detailed parameters of the simulation scenario are summarized in Table 3.10.



(a) SLO, a single 80 MHz channel reserved for each BSS.

(b) MLO-STR:2, two 80 MHz channels per BSS, shared with another BSS.

(c) MLO-STR:4, four 80 MHz channels, all shared among four BSSs.

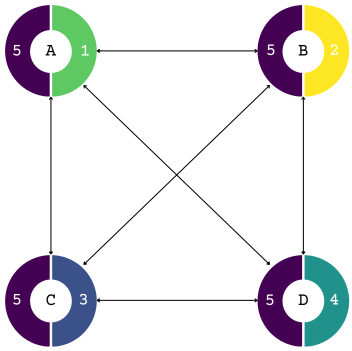
Fig. 3.5. Modes of operation considered in Latency Scenario #4A [6].

Table 3.10. Latency scenario #4A – configuration parameters.

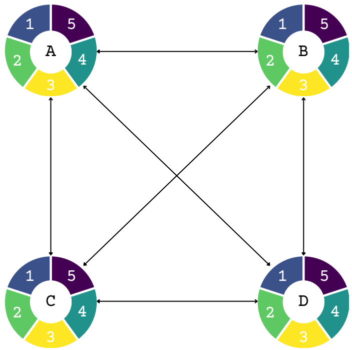
Simulation parameter	Value
Band	5 & 6 GHz
Channels	1, 100 (in each band)
Channel width	80 MHz
Number of links	1, 2 or 4
Number of BSSs	4
MLO mode	STR
MCS	8
AP – STAs maximum distance (r)	5

3.2.10. Latency Scenario #4B

Building on the latency scenario #4A described in Section 3.2.9, latency scenario #4B explores additional channel configurations and their potential to reduce latency in a contended environment. The scenario consists of four BSSs, each with one AP and one station communicating in the downlink direction. Two channels are allocated in the 5 GHz band and three in the 6 GHz band, and all simulations are performed using MCS 8. In addition to the SLO and MLO-STR:2 modes described in Section 3.2.9, three additional modes are considered: MLO-EMLSR:2 in which each BSS uses two links, with each channel shared with one additional contending BSS; MLO-STR:1+1, where one link is shared among all four BSSs while another link is exclusively assigned to each BSS as shown in Fig. 3.6a; and MLO-STR:5 where all 5 links are shared among 4 BSSs, as visible in Fig. 3.6b.



(a) MLO-STR:1+1, one 80 MHz channel reserved for each BSS, one shared with all BSSs.



(b) MLO-STR:5, five 80 MHz channels per BSS, all shared among four BSS.

Fig. 3.6. Modes of operation considered in Latency Scenario #4B.

Table 3.11. Latency Scenario #4B –configuration parameters.

Simulation parameter	Value
Band	5 & 6 GHz
Channels	5 GHz: 1, 100 & 6 GHz: 1, 100, 200
Channel width	80 MHz
Number of links	2 or 5
Number of BSSs	4
MLO mode	STR
MCS	8
AP – STAs maximum distance (r)	5

3.2.11. Latency Scenario #5

The latency scenario #5 is based on [17] and aims to assess how different channel occupancy levels affect latency. The scenario involves a main BSS consisting of one AP and one station communicating over one or two links with a channel width of 80 MHz in the 5 GHz band. Communication within the main BSS is in the downlink direction, with full-buffer traffic applied. Additionally, two OBSSs are employed – one per link. Each OBSS contains a variable number of single-link stations, ranging from 0 to 10, to model different levels of channel occupancy. Each station generates an equal portion of traffic, based on throughput values derived from the baseline throughput simulation presented in Section 4.1.1, using the function `generateTrafficParamsObss`. The channels can be occupied either symmetrically or asymmetrically, which means that the OBSSs may contain a different number of stations at the same time. Single-link devices always use the less congested channel. The PHY layer is configured to use MCS 11 and the MPDU aggregation limit of 1024. The simulation setup is presented in Fig. 3.7

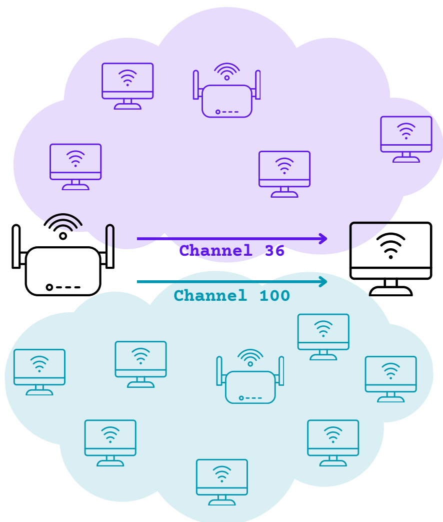


Fig. 3.7. Latency Scenario #5 – topology.

Table 3.12. Latency scenario #5 – configuration parameters.

Simulation parameter	Value
Band	5 GHz
Channels	36, 100
Channel width	80 MHz
Number of links	1, 2
Number of stations (main BSS)	1
Number of stations (OBSS)	1, 4 or 7
MLO mode	STR
MCS	11
AP – STAs maximum distance (r)	5

3.2.12. Legacy Scenario

The legacy scenario is based on [25] and aims to investigate the coexistence of MLO and legacy devices. The scenario consists of an AP and 50 stations, each positioned randomly within a maximum distance of 7.5 meters from the AP. Devices operate with uplink full-buffer traffic over three links in three different bands, each with an 80 MHz channel width. Legacy devices are configured as single-link HE-SU stations operating solely in 2.4 GHz band, while multi-link stations operate in either STR or EMLSR mode in all three available bands. Additionally, the proportion of legacy stations is varied between 10% and 90%. The physical layer is configured to use MCS 8, and the MPDU aggregation limit is the MATLAB default value of 64. A detailed list of configuration parameters is provided in Table 3.13.

Table 3.13. Legacy Scenario – configuration parameters.

Simulation parameter	Value
Band	2.4 & 5 & 6 GHz
Channels	2.4 GHz: 1, 5 GHz: 1, 6 GHz: 1
Channel width	80 MHz
Number of links	1, 2
Number of stations	50
Percentage of legacy devices	10 - 90
Legacy transmission format	HE-SU
MLO mode	STR, EMLSR
MCS	8
A-MPDU size	64
AP – STAs maximum distance (r)	7.5

3.2.13. VR Scenario

The VR scenario is based on [23]. Its purpose is to evaluate MLO capability to support VR applications. The scenario consists of an AP and one station communicating in the uplink or downlink direction, depending on the scenario. The simulation employs the `networkTrafficOnOff` object, configured to emulate the VR traffic pattern presented in [23], as illustrated in Fig. 3.8.

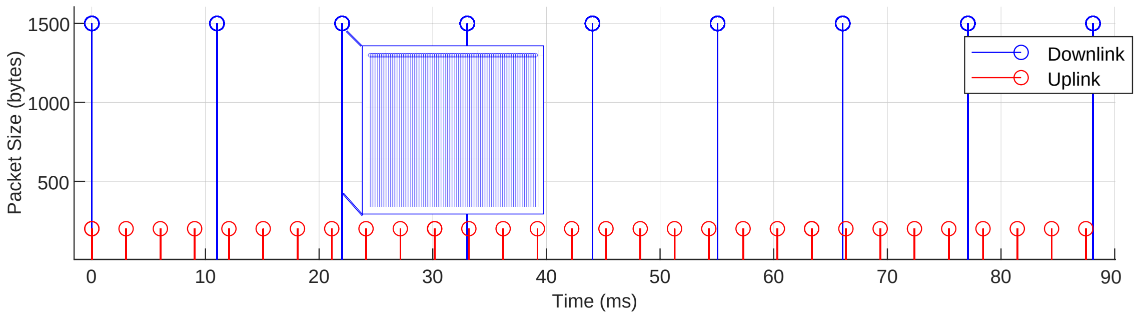


Fig. 3.8. VR traffic visualization [23].

MLO devices operate in the STR mode, while in the SLO configuration, only the first channel is used. The MCS is changed between 0 and 13, and the channel bandwidth is varied from 20 to 320 MHz to evaluate the performance in different configurations. The MPDU aggregation limit is set to 1024. The simulation parameters are listed in Table 3.14.

Table 3.14. VR Scenario – configuration parameters.

Simulation parameter	**Value**
Band	6 GHz
Channels	29, 151
Channel width	20, 40, 80, 160 or 320 MHz
Number of links	1, 2
Number of stations	1
MLO mode	STR
MCS	0 – 13
AP – STAs distance (r)	5 m

3.3. Metrics

In this work, two metrics are used to evaluate network performance: throughput and latency. This section describes each metric and outlines the methods used to calculate them.

3.3.1. Throughput

Throughput measures how much data is successfully transmitted over the network in a given time. The following formula is used to determine the throughput value:

$$Throughput\ (Mb/s) = \frac{TransmittedPayloadBytes \times 8 \times 10^{-6}}{SimTime} \tag{3.1}$$

where $TransmittedPayloadBytes$ represents the total number of successfully transmitted bytes, and $SimTime$ is the total simulation time in seconds. The throughput calculation is integrated in the `hPerformanceViewer` function, with the implementation illustrated in Listing 3.5.

```
function throughput = calculateThroughput(~,techName,stats,simulationTime)
    %calculateThroughput Calculate the throughput based on the technology

    switch techName
        case "WLAN"
            throughput = (sum([stats.MAC.TransmittedPayloadBytes])*8*1e-6)/
                simulationTime;
        % Other cases omitted as they are not used in this work
    end
end
```

Listing 3.5. Throughput calculation function.

3.3.2. Latency

Latency refers to the time required for a packet to move from the source to the destination within a network. In this work, latency is evaluated using two common metrics – average latency and percentile-based latency.

Average latency

Average latency represents the mean delay experienced by packets transmitted over the network during the simulation time. The average packet delay is calculated within the `hPerformanceViewer` function during simulation. The formula is given by:

$$Average\ Latency = \frac{\sum_{i=1}^{N} (t_{arrival,i} - t_{generation,i})}{N} \tag{3.2}$$

where $t_{\text{arrival},i}$ is the time when packet i was received, $t_{\text{generation},i}$ is the time of a generation, and N is the total number of received packets.

Percentile-based latency

Percentile-based latency indicates the delay threshold below which a certain percentage of packets are received. For example, the 95th percentile latency means that 95% of the packets experience a delay lower than or equal to this value.

In this work, the calculation of the percentile packet latency is performed by a custom function, `getPetLatencyVector`, which takes a specified percentile p as input and processes packet latencies stored in `pPacketLatencyVector` for each node (obj). It filters out entries equal to zero to ensure that only valid measured packet delays are included in the calculation. Then, it uses the built-in `prctile` function to determine the delay threshold below which $p\%$ of packets fall. If no valid latency values are present, the function returns NaN. The function code is presented in Listing 3.6

```
function percentiles = getpPacketLatencyVector(obj, p)

    latencies = obj.pPacketLatencyVector;
    percentiles = zeros(size(latencies, 1), 1);

    for i = 1:size(latencies, 1)
        rowData = latencies(i, 2:end);
        nonZeroRow = rowData(rowData ~= 0);
        if ~isempty(nonZeroRow)
            percentiles(i) = prctile(nonZeroRow, p);
        else
            percentiles(i) = NaN;
        end
    end
end
```

Listing 3.6. Percentile-based latency calculation function.

3.3.3. Jain's Fairness Index

Jain's Fairness Index (JFI) indicates how fairly resources are distributed among users. In this study, it is used to evaluate whether stations achieve balanced access to the medium. The formula is given by:

$$JFI = \frac{\left(\sum_{i=1}^{n} t_i\right)^2}{n \cdot \sum_{i=1}^{n} t_i^2} \tag{3.3}$$

where t_i is a throughput for station i and n is the total number of stations.

3.4. Data Analysis

Data processing and analysis were carried out in three main stages. First, the simulations were performed in MATLAB, producing data sets with different network performance metrics based on the scenario. These outputs were then exported to CSV files, uploaded to a Google Colab notebook, and subjected to further processing using Python data analysis libraries, including Pandas and NumPy. The mean and standard deviation values of performance parameters obtained from the simulations were calculated for each scenario by combining the results of seven independent runs. The plots presented in the following chapters of this thesis were created using the Matplotlib library. The data processing methodology is shown in Fig. 3.9.

Fig. 3.9. Data processing methodology scheme.

4. Performance Analysis

This chapter presents the results of a performance analysis of Multi-link Operation, focusing on its potential to improve throughput and reduce latency in various network scenarios. The research and simulations presented in the following sections were inspired by evaluation setups proposed in recent studies on MLO.

4.1. MLO Throughput Performance Analysis

The first metric considered in the performance evaluation is throughput, as it directly reflects how efficiently the available spectrum and resources are utilized. This is useful for assessing the advantages of MLO over SLO, as the use of multiple links is expected to enhance throughput performance.

The analysis starts with a baseline evaluation of throughput under different conditions. This serves as a reference point for subsequent tests, providing the maximum achievable throughput for different MCS values and MPDU aggregation settings. This enables the normalization of traffic loads for different MLO configurations and simulation scenarios.

4.1.1. Baseline Throughput Evaluation

The simulation scenario is based on [16]. It aims to provide baseline throughput values for traffic load normalization in later simulations, as well as to support a better understanding of MLO capabilities. The scenario models a single BSS composed of one access point and one station communicating in the downlink direction over one or two links. The simulation settings are described in detail in Section 3.2.1.

The key values used for simulations conducted in this work are presented in Table 4.1. Similarly to the findings presented by the authors, the results show an improvement in throughput when using two separate links, even in cases where the total available bandwidth remains the same (2 links with channels of 80 MHz each vs 1 channel of 160 MHz) with an MPDU aggregation limit of 64. This improvement can be explained by the ability to transmit simultaneously on multiple links, which in the best case can double the throughput compared to using a single link. However, this effect does not occur when using a single link with double the bandwidth, since devices cannot perform parallel transmissions on a single channel, and throughput is limited by medium access limitations and the aggregation limit.

Additionally, throughput depends on the MPDU aggregation limit as expected, as higher limits allow devices to transmit more data once they gain access to the medium.

Table 4.1. Achievable throughput for MCS 11 for a single and multiple links and MPDU aggregation limits.

Number of Links	**Achievable throughput**	
	MPDU aggregation limit = 64	MPDU aggregation limit = 1024
1 link (80 MHz)	670 Mbps	927 Mbps
1 link (160 MHz)	1008 Mbps	1854 Mbps
2 links (80 + 80 MHz)	1340 Mbps	1854 Mbps
2 links (160 + 160 MHz)	2015 Mbps	3147 Mbps

4.1.2. Throughput Evaluation #1

This scenario was based on the work presented in [15] and aims to evaluate how network coexistence and contention impact throughput and latency, as well as to compare the performance of different MLO modes – STR and EMLSR – both with each other and with SLO. The simulation setup consists of a single AP and one station communicating in the downlink direction over a variable number of links. MLO employs two or three links depending on the configuration scenario. A detailed description of the simulation setup and parameter settings is provided in Section 3.2.2.

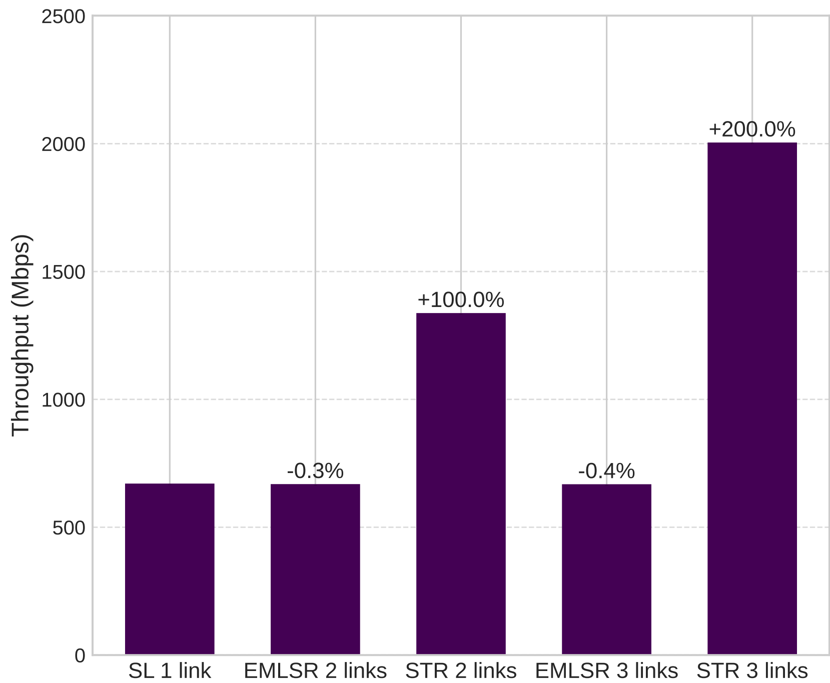


Fig. 4.1. Throughput of MLO and single-link devices operating on different number of links.

Fig. 4.1 illustrates the throughput achieved by each operation mode. For EMLSR, throughput is almost identical to that of SLO and remains independent of the number of links, because EMLSR is limited to transmit over one link at a time. In contrast, STR throughput increases proportionally with the number of links, achieving twice the throughput of SLO when using two links and three times the throughput of SLO when using three links. This significant difference is due to the ability of STR to transmit data simultaneously over multiple links. In a scenario with no contention, it can take full advantage of this feature. Again, the results confirm the findings of [15].

4.1.3. Throughput Evaluation #2

This simulation scenario is based on the work presented in [15]. It is designed to evaluate the coexistence of MLO and single-link devices, with a focus on throughput performance.

The setup consists of three BSSs: two single-link BSSs, denoted as BSS A and BSS C, which operate on separate channels, and one multi-link BSS, denoted as BSS B, which uses both channels and therefore competes for medium access with both BSS A and BSS C. All BSSs comprise one AP and one station communicating in the downlink direction with full buffer traffic. A detailed description of the simulation parameters is provided in Section 3.2.3.

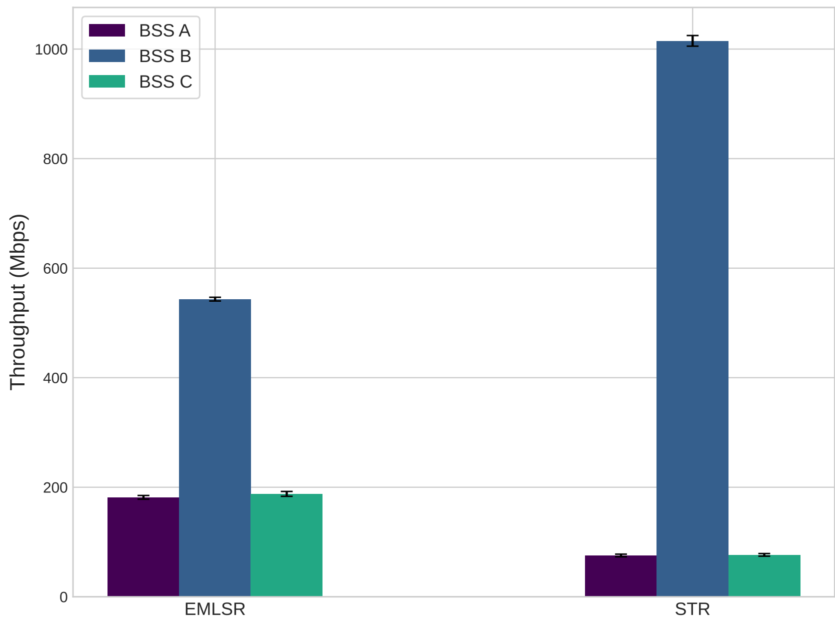


Fig. 4.2. Throughput of contending BSSs.

Fig. 4.2 presents the throughput achieved by all three BSSs in both configurations, with BSS B operating in EMLSR mode and in STR mode. When the multi-link BSS (BSS B) operates in EMLSR mode, the single-link BSSs (BSS A and BSS C) achieve higher throughput compared to the case when BSS B operates in STR mode. Specifically, in EMLSR mode, the SLO BSSs achieve throughput of nearly 200 Mb/s, while in STR mode, their throughput drops to below 100 Mb/s. However, BSS B achieves higher throughput in STR mode, exceeding 1000 Mb/s, compared to EMLSR mode. The higher throughput in STR mode is due to simultaneous transmissions over two links, but this reduces the medium access available to the single-link BSSs, worsening their performance.

These results are partially in line with the findings presented in [15]. In contrast to the article, EMLSR achieves higher throughput than the SLO BSSs. However, consistent with the article, STR operation significantly degrades the performance of single-link BSSs compared to EMLSR.

4.1.4. Throughput Evaluation #3

The scenario presented in this subsection is inspired by the work described in [5] and aims to evaluate the throughput performance of different modes of MLO and SLO under varying OBSS activity. The main purpose of this simulation was to investigate how different levels of channel occupancy affect MLO performance in comparison to SLO.

The simulation setup consists of a BSS with one AP and one station, along with one (the single-link scenario) or two OBSSs containing a variable number of stations to model different levels of channel occupancy. The simulation settings are described in detail in Section 3.2.4.

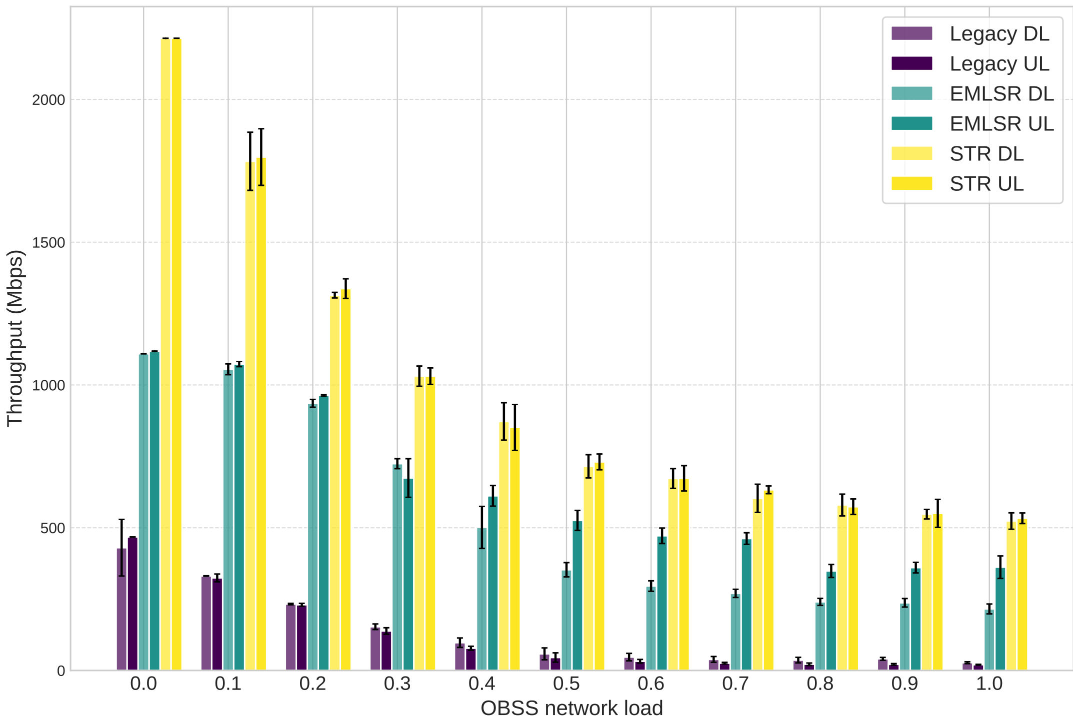


Fig. 4.3. Throughput of MLO and single-link devices vs varying OBSS network activity.

Fig. 4.3 shows the throughput of different operation modes depending on OBSS network load. The values of OBSS network load correspond to fractions of the maximum throughput obtained in Baseline

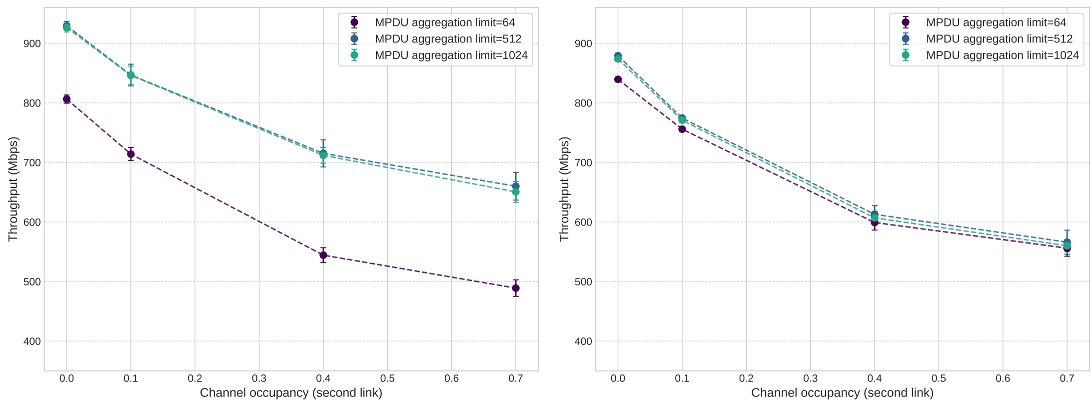
Throughput Scenario (Section 4.1.1). The results are consistent with those reported in [5]. All multi-link modes achieve significantly higher throughput than single-link configurations, even in high-density networks with OBSS activity above 60%. Among the two MLO modes, STR demonstrates the best performance, while EMLSR, although not as good as STR, still provides improved and more consistent throughput. In particular, in scenarios with higher OBSS activity, EMLSR experiences a threefold throughput drop compared to lower density conditions, whereas STR shows a fourfold drop.

These findings show that MLO provides a clear advantage over SLO in environments with different density. In addition, EMLSR, despite using only one radio, still maintains better performance relative to SLO.

4.1.5. Throughput Evaluation #4

This simulation is partially based on the work presented in [19]. Its purpose is to evaluate how different MPDU aggregation settings and configurations affect throughput.

The scenario consists of a single main BSS, comprising an AP and one station communicating over two links in the downlink direction. The devices use static MPDU aggregation limits of 64, 512, and 1024. The TXOP limit is set to either 0 ms or 3 ms to evaluate its impact on throughput in combination with the aggregation settings. The detailed description of parameters and settings is provided in Section 3.2.5.

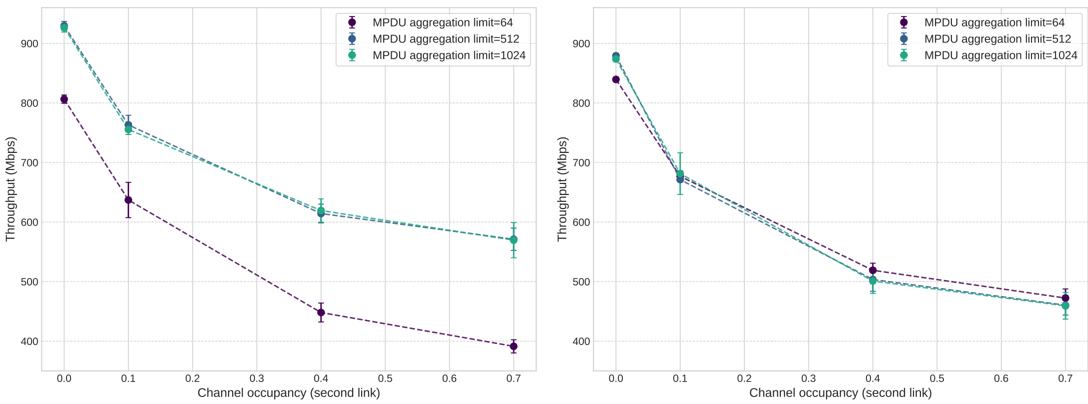


(a) TXOP limit = 0 ms (b) TXOP limit = 3 ms

Fig. 4.4. Throughput for different MPDU aggregation settings, no occupancy on first channel.

Fig. 4.4 shows throughput as a function of the second link's occupancy for different aggregation settings. The first link is fully available for MLO devices. Figures 4.4a and 4.4b correspond to the TXOP limits of 0 ms and 3 ms, respectively. The y-axis is truncated and shows throughput values ranging from approximately 500 to 950 Mb/s.

In both cases and across all MPDU aggregation limits, throughput decreases as the occupancy of the second link increases, which is expected. There is little to no difference in throughput between the MPDU aggregation limits of 512 and 1024 MPDUs. For TXOP limits between 0 and 3 ms, the most noticeable change occurs with an MPDU aggregation limit of 64 MPDUs: throughput increases significantly, reaching values similar to those observed for other aggregation limits. In contrast, for aggregation limits of 512 and 1024 MPDUs, throughput decreases at a TXOP limit of 3 ms. This indicates that simulated devices do not benefit from a longer transmission opportunity, likely because there are fewer MPDUs available for transmission, and the extended time actually reduces transmission efficiency.



(a) TXOP limit = 0 ms (b) TXOP limit = 3 ms

Fig. 4.5. Throughput for different MPDU aggregation settings, 10% occupancy on first channel.

Fig. 4.5 shows the throughput depending on the occupancy of the second link for different aggregation settings. The first link is fully available for transmission. Figures 4.5a and 4.5b correspond to the TXOP limits of 0 ms and 3 ms, respectively. The y-axis is limited to display throughput values between approximately 400 and 950 Mb/s.

The results are similar to those shown in Fig. 4.4, with throughput still decreasing as the second link's occupancy increases. Due to the 10% occupancy of the first channel, the throughput at the highest occupancy of the second link is approximately 100 Mb/s lower than in the previous scenario. As in the earlier case, a higher TXOP limit improves throughput for a packet aggregation limit of 64. The results show that although MLO implementation is beneficial for throughput, achieving optimal performance requires considering other factors, such as packet aggregation limits, TXOP settings, and channel occupancy.

4.2. MLO Latency Performance Analysis

Besides throughput, latency is a key performance indicator that can be used to assess MLO capabilities. Latency characterizes the time required for packet delivery and is therefore an important measure of network responsiveness. This metric provides information on how MLO compares with SLO at different channel occupancy levels. The following Section presents the latency results obtained in the simulations under various conditions.

4.2.1. Latency Evaluation #1

The scenario presented in this subsection was inspired by the work described in [16]. Its purpose is to analyze how a varying number of stations and link configurations affect latency.

This scenario models a single BSS composed of one access point and a varying number of stations. The traffic load in each case is normalized based on the maximum achievable throughput obtained from the baseline scenario described in Section 4.1.1 for both 80 MHz and 160 MHz channel widths. In scenarios involving 4 or 10 users, the total offered load is evenly distributed among all stations. For instance, in a scenario with a total traffic load of 670 Mb/s and 10 users, each user generates 67 Mb/s of traffic. Detailed information on simulation parameters and topology is provided in Section 3.2.6.

Fig. 4.6 shows the average packet latency for SLO and MLO stations communicating over 80 MHz channels. Fig. 4.7 presents the corresponding results for 160 MHz channels.

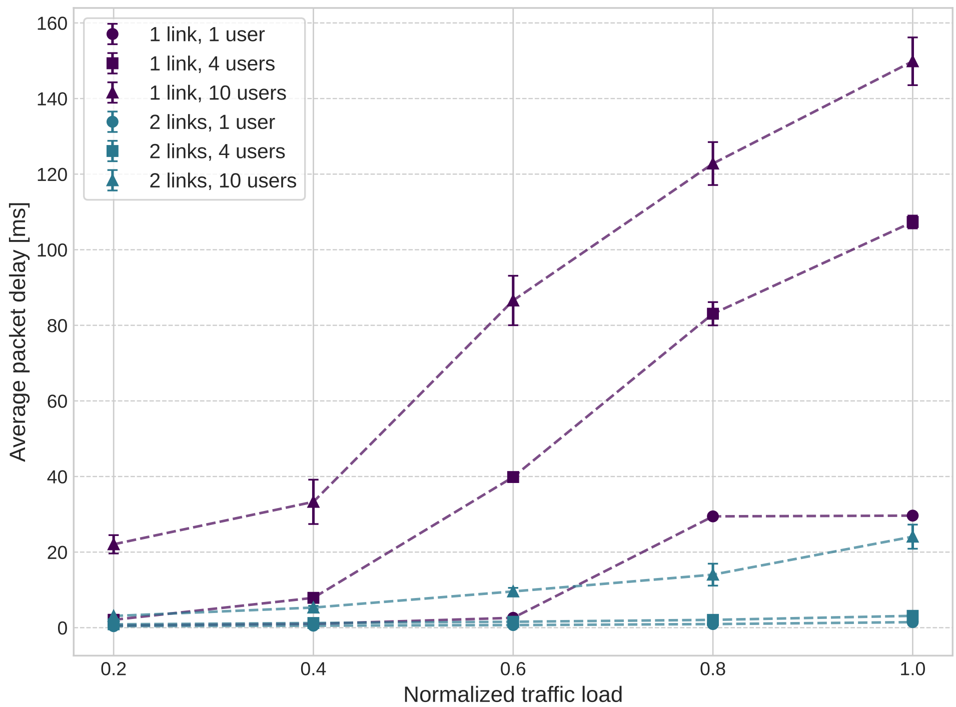


Fig. 4.6. Average packet delay for MCS 11 and 80 MHz channels per link.

The results visible in Fig. 4.6 show a significant reduction in latency when employing MLO compared to SLO. In the scenario with 80 MHz channel widths, the average latency for MLO remains below 30 ms even at the highest number of users and traffic load. In contrast, for 10 users operating on a single link, latency increases rapidly, reaching nearly 150 ms. At a medium normalized traffic load of 0.6, MLO achieves approximately 9 times lower latency than SLO.

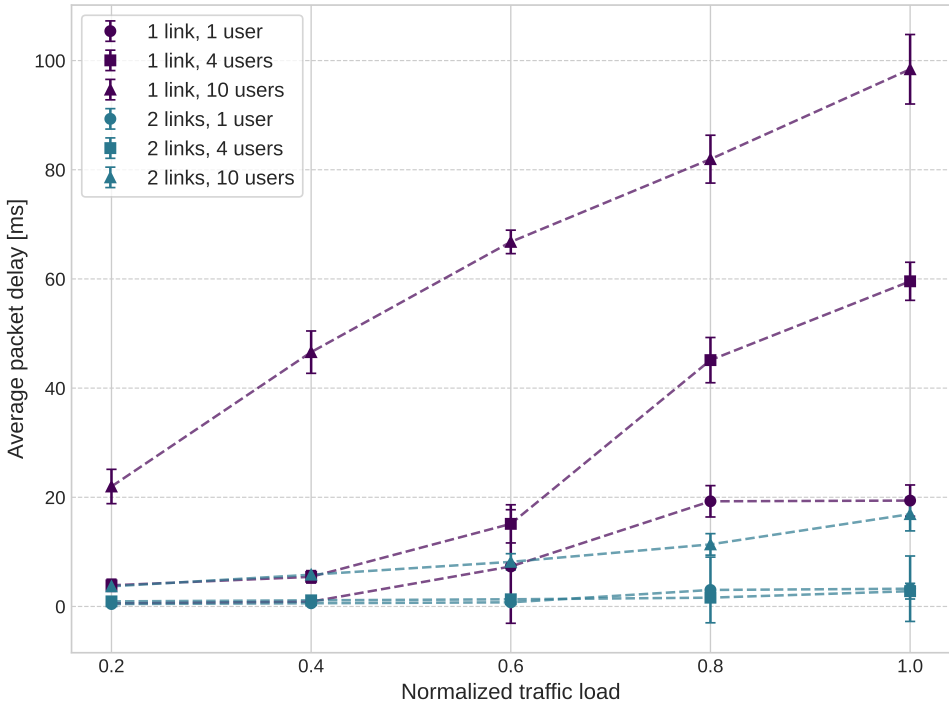


Fig. 4.7. Average packet delay for MCS 11 and 160 MHz channels per link.

A similar trend is observed in Fig. 4.7 in the scenario with 160 MHz channel widths. The most significant improvement again appears in the case of 10 users where the average latency does not exceed 20 ms for MLO stations. In comparison, SLO exhibits a steady increase in latency, reaching almost 100 ms at full traffic load for 10 users. At medium load levels, the use of MLO results in a latency reduction of nearly seven times compared to the SLO configuration.

The obtained results show that MLO consistently achieves significantly lower latency compared to SLO for both 80 MHz and 160 MHz channel widths, meaning that channel width does not affect the overall trend. The biggest benefits of MLO appear with a larger number of users, indicating that MLO might be suitable for environments with high station density that also require low latency. The results are quantitatively different but qualitatively similar to those reported in [16].

4.2.2. Latency Evaluation #2

The following scenario is based on [6]. It aims to evaluate how different traffic loads affect latency in a contention-free scenario, focusing on MLO STR configurations using either two or four links, and their performance compared to SLO.

The simulation scenario involves an AP and a station communicating in the downlink direction. Devices are configured to operate either in SLO mode or MLO STR mode, using two or four links depending on the scenario. The detailed description of the simulation setup is provided in Section 3.2.7.

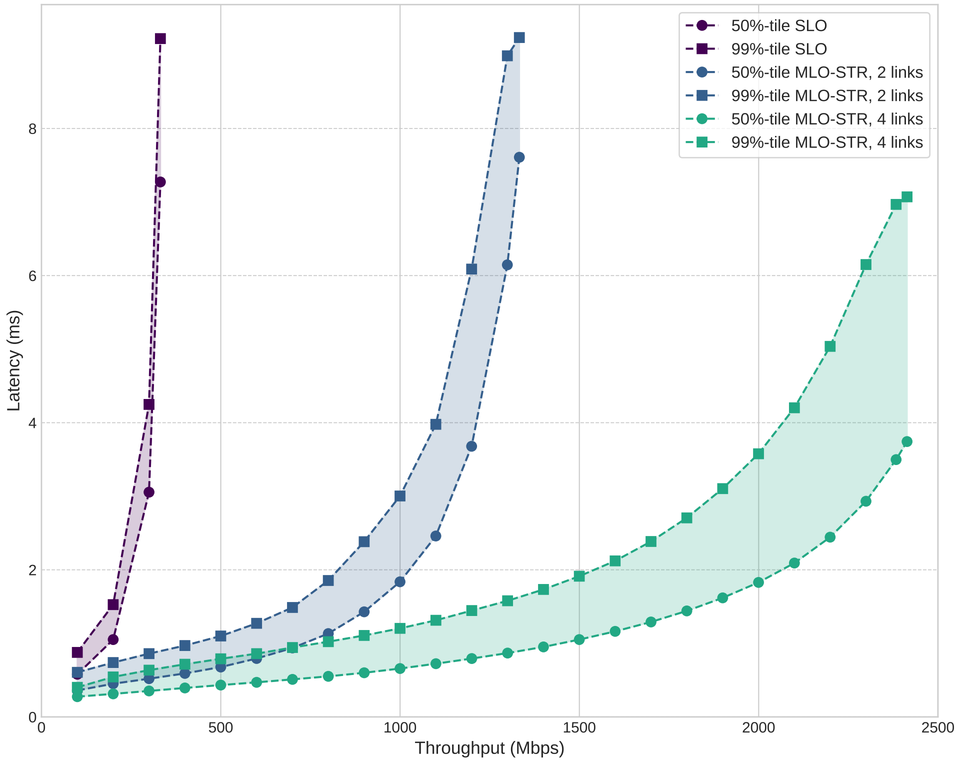


Fig. 4.8. Latency in contention-free scenario.

Fig. 4.8 illustrates latency statistics with shaded areas representing the range from the 50th to the 99th percentile for different operation modes as a function of throughput. Increasing the number of links enables achieving higher throughput while maintaining the same latency value. In the case of SLO, latency exceeds 8 ms at slightly above 300 Mb/s, whereas for MLO with 2 and 4 links, throughput can reach over 1200 Mb/s and 2400 Mb/s, respectively, without exceeding the 8 ms 99%-tile latency threshold. This also implies that, for a given throughput, adding more links results in lower latency.

The obtained results are very similar to those reported in [6]. These findings show that in contention-free scenarios, users can benefit from adding more links. Increasing the number of links not only reduces latency but also significantly enhances throughput, highlighting the advantages of MLO in these specific network conditions.

4.2.3. Latency Evaluation #3

This scenario is inspired by [15]. It aims to evaluate how different traffic loads and a varying number of links affect the latency performance of SLO and two MLO modes – STR and EMLSR – in a contention-free scenario.

The simulation setup involves an isolated BSS consisting of one AP and one station communicating in the downlink direction over one, two, or three links. The simulation settings and parameters are described in detail in Section 3.2.8.

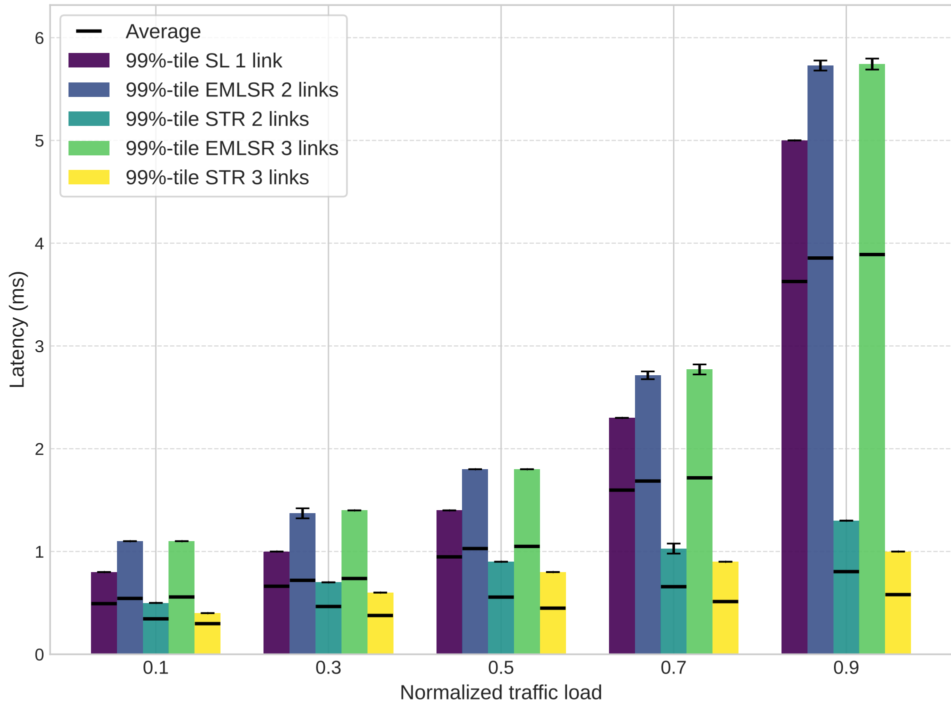


Fig. 4.9. Latency of different operation modes in a contention-free scenario.

Fig. 4.9 presents the average and 99th percentile latency for SLO, EMLSR, and STR using two or three links as a function of the normalized traffic load. Contrary to the findings reported in [15], both the average and 99th percentile latency values for EMLSR are higher than those observed for SLO. The higher delay observed for EMLSR may be explained by additional protocol overhead or by specific aspects of MATLAB's implementation of this mode, such as the modeling of link switching and related features. Unlike EMLSR, STR significantly reduces latency, as it is able to transmit over multiple links simultaneously. In a contention-free scenario, this capability can be fully utilized, leading to visible improvements for both low and high traffic loads, consistent with the results reported in the article.

4.2.4. Latency Evaluation #4A

The following scenario is based on [6]. It aims to evaluate the impact of different traffic loads on latency in a contention scenario involving four overlapping BSSs, and to investigate the presence of the latency anomaly reported in [6] – where SLO exhibits lower latency than MLO – as summarized in Section 2.3.

Three modes of operation are considered: SLO, in which devices operate on a single link exclusively assigned to the BSS; MLO-STR:2, where devices operate on two links, each shared with one additional BSS; and MLO-STR:4, in which all four links are shared among the four BSSs. The setup and parameters are described in detail in Section 3.2.9.

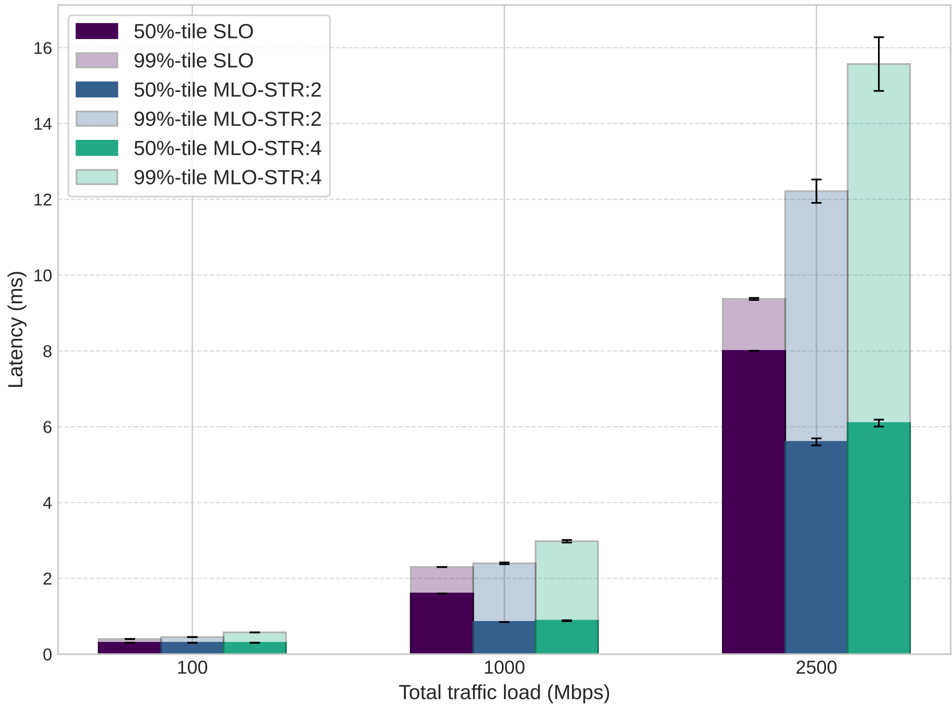


Fig. 4.10. Latency of SLO and MLO:STR in contention scenario involving four BSSs.

Fig. 4.10 presents the 50th and 99th percentile latency for SLO, MLO-STR:2, and MLO-STR:4 as a function of the total expected traffic load. Unlike the results reported in [6], the median latency improves slightly when multiple links are used. However, the 99%-tile latency increases with additional links for all traffic loads, consistent with the latency anomaly described in the article, where STR stations accessing multiple links block their contending neighbors. Adding more links does not reduce latency, as each new link adds a channel where contention can occur, potentially increasing overall latency.

4.2.5. Latency Evaluation #4B

The simulation scenario presented in this section corresponds to that described in Section 3.2.9, and is also based on [6]. It aims to evaluate link assignment strategies to overcome the aforementioned delay anomaly.

The simulation setup consists of four BSSs. In line with the approach in the article, three additional modes are considered: MLO-EMLSR:2, where devices operate on two links, each shared with one additional BSS; MLO-STR:1+1, where one link is shared among all 4 BSSs, and one reserved exclusively for each BSS; and MLO-STR:5, in which all four five links are shared among the four BSSs. A detailed description of the setup and parameters is provided in Section 3.2.10.

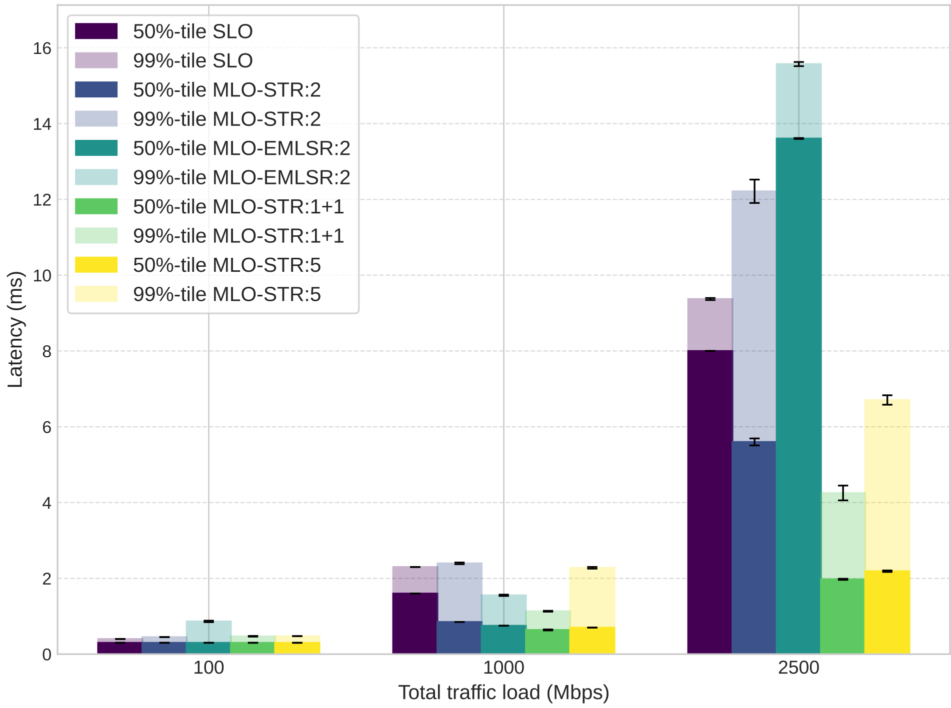


Fig. 4.11. Latency of SLO and different MLO modes in contention scenario involving four BSSs.

Fig. 4.11 shows the 50th and 99th percentile latency experienced by the three modes compared to SLO and MLO-STR:2 described in Section 4.2.4. The MLO-EMLSR:2 mode performs worse than the other modes across most traffic loads, although it achieves relatively low latency values at medium traffic loads (1000 Mb/s).

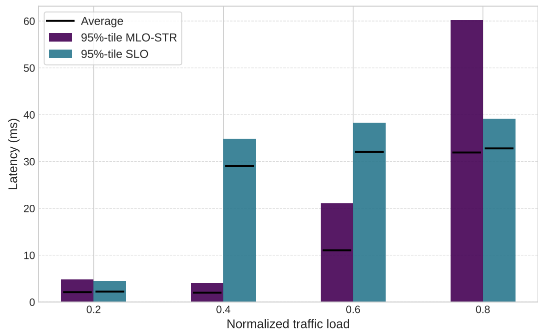
The benefits of employing more links than the number of contending BSSs, as in MLO-STR:1+1 and MLO-STR:5, are most visible at high traffic loads, where these modes achieve nearly half the latency of MLO-STR:2. The lowest latency is observed for MLO-STR:1+1, both in terms of median and 99th percentile latency. Overall, the results are mostly consistent with those reported in [6], with the main difference being the performance of MLO-EMLSR:2, which was better in the article.

The results indicate that employing more links than there are contending BSSs can effectively mitigate the issues associated with the latency anomaly, helping to lower latency in networks where several BSSs compete for limited channel resources.

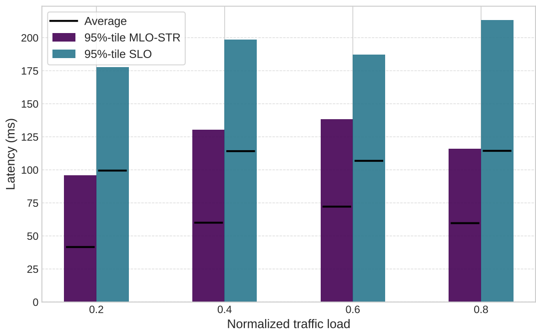
4.2.6. Latency Evaluation #5

The following simulation scenario, based on the work presented in [17], aims to assess how different channel occupancy levels influence the latency of MLO devices operating in STR mode and to evaluate their performance in relation to SLO. In addition, it examines whether the use of a second link – even when more occupied – can still contribute to latency reduction.

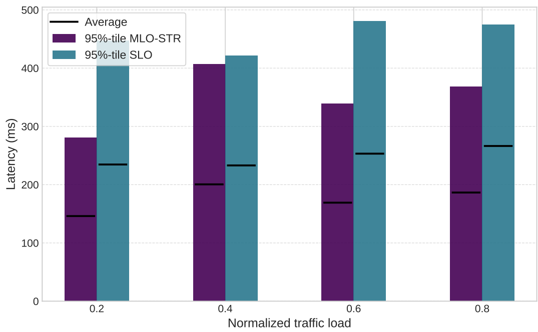
The simulation setup consists of a main BSS, which includes an AP and a single station, along with one OBSS per link – two for MLO and one for SLO. All devices communicate in the downlink direction. SLO devices always use the first channel. The occupancy of the channel is modeled as OBSS activity using the function `generateTrafficParamsOBSS` and `networkTrafficOnOff` object. A detailed description of the parameters is provided in Section 3.2.11.



(a) 10% occupancy on both channels.



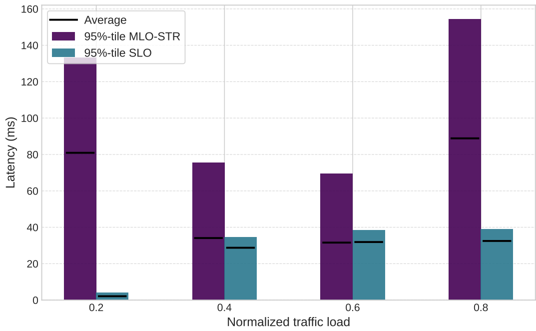
(b) 40% occupancy on both channels.



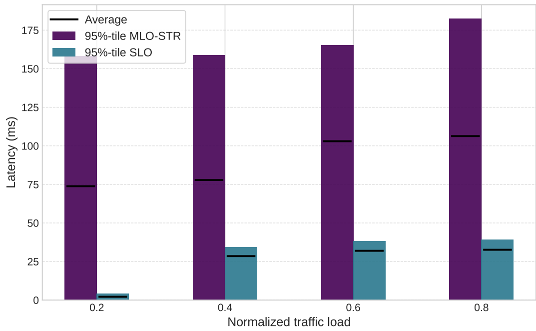
(c) 70% occupancy on both channels.

Fig. 4.12. Latency for symmetrically occupied channels vs. normalized traffic load.

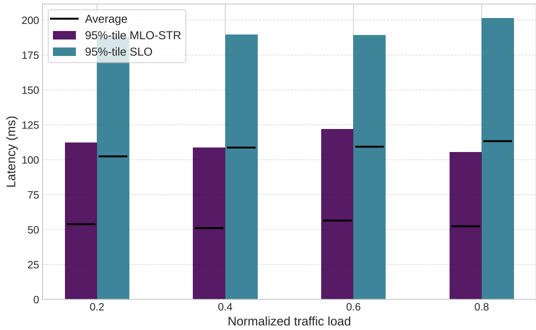
Fig. 4.12 presents the latency of MLO and SLO under symmetrical channel occupancy. The subfigures 4.12a, 4.12b, and 4.12c illustrate the results for channel occupancy levels of 10%, 40%, and 70%, respectively. In almost all cases and across different traffic loads, MLO achieves lower latency than SLO. The only exception occurs at 10% occupancy for 90% traffic load, where the 95th percentile latency of MLO is higher than that of SLO, while the average latency remains nearly identical. This can be considered an anomaly rather than a consistent trend, as it does not appear in other cases. Overall, the results show that MLO STR can decrease latency in cases with symmetrical channel occupancy. Although these findings align with those reported in [17], the latency reduction observed here is less pronounced, especially at the 70% channel occupancy.



(a) Primary of 10% and secondary of 40%.



(b) Primary of 10% and secondary of 70%.



(c) Primary of 40% and secondary of 70%.

Fig. 4.13. Latency for asymmetrically occupied channels vs. normalized traffic load.

Fig. 4.13 presents the latency of MLO and SLO under asymmetrical channel occupancy. The sub-figures 4.13a, 4.13b, and 4.13c show the results for the occupancy combinations of 10% / 40%, 10% / 70% and 40% / 70% for the first and second channels, respectively. For asymmetric channel occupancy, the results show that when the first and second channel occupancies are set to 10% / 40% or 10% / 70%, the latency of MLO increases significantly. In contrast, for the 40% / 70% combination, MLO achieves lower latency than SLO. This behavior highlights an issue reported in [17] when packets are assigned to links before backoff, which can lead to interruptions on the busier link and higher latency. However, for more symmetrically occupied links, MLO consistently outperforms SLO. While the simulation results are generally consistent with those reported in the article, some differences in latency values and their relative proportions are observed. This is likely due to differences between the simulators and possibly certain simulation parameters that were not mentioned in the article.

4.3. MLO and Legacy Stations

This scenario is based on [25] and aims to evaluate the coexistence of MLO and legacy stations. Its purpose is to analyze the overall network performance, as well as the performance of different device types, depending on varying proportions of legacy devices relative to the total number of stations in the network.

Due to MATLAB's limitations, only case "b" from the article was implemented. This scenario consists of one AP and multiple stations communicating in the uplink direction over either one or three links, with single-link devices using the same 2.4 GHz band as the MLO devices. The simulation settings are described in detail in Section 3.2.12.

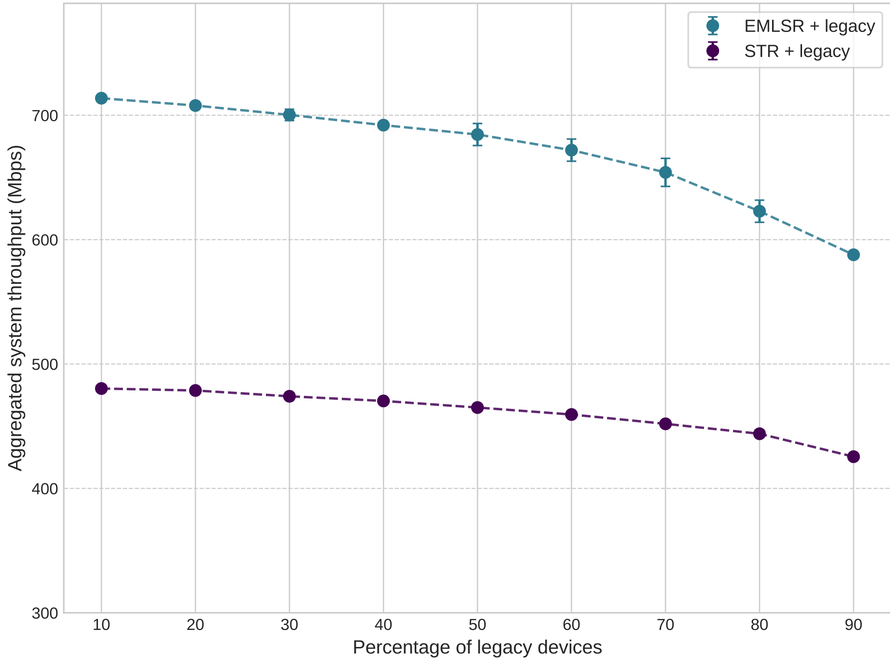


Fig. 4.14. Network throughput vs percentage of legacy stations (y-axis cropped for clarity).

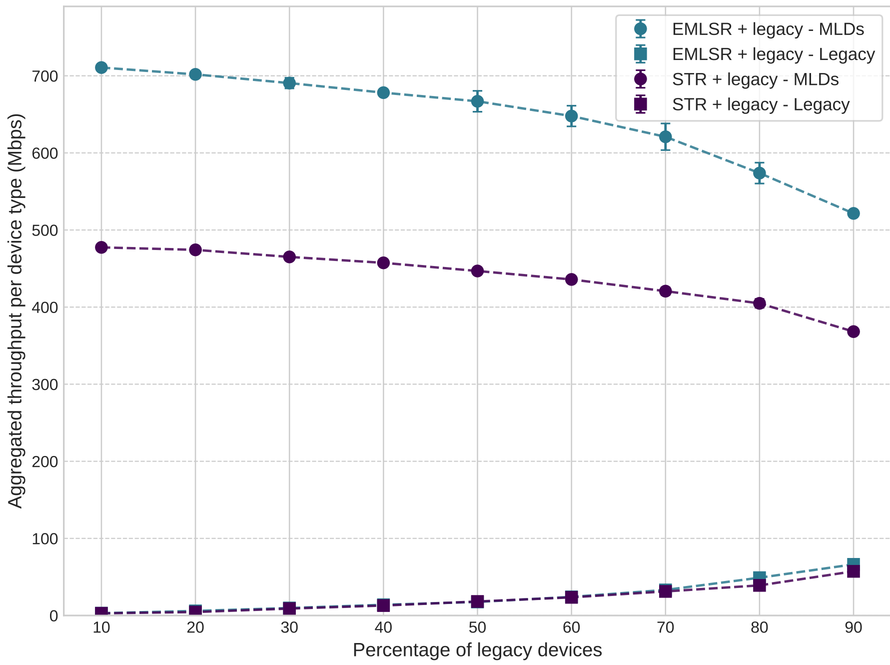


Fig. 4.15. Throughput per device type vs percentage of legacy stations.

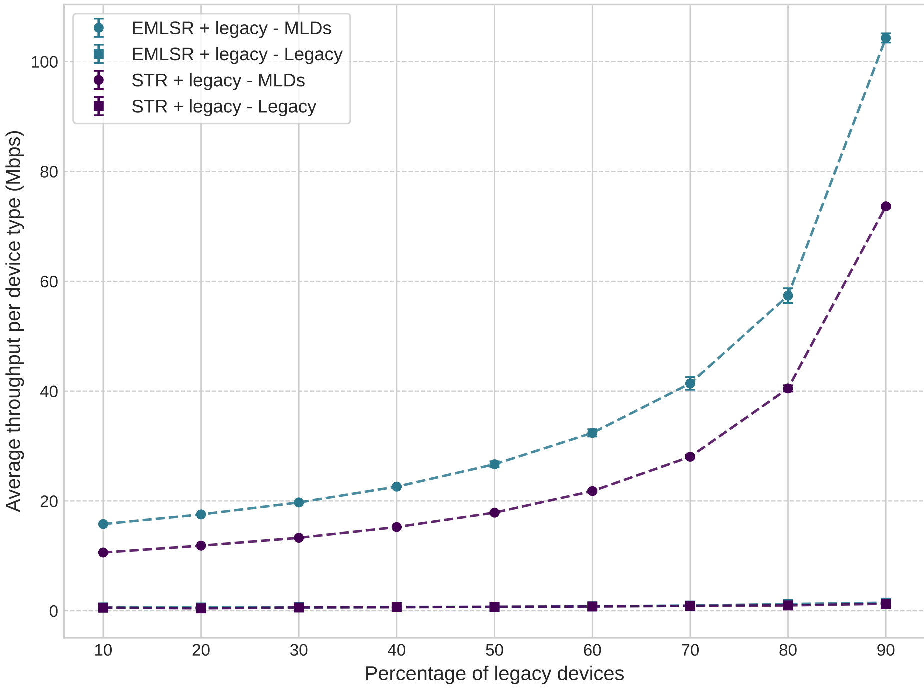


Fig. 4.16. Average throughput per device type vs percentage of legacy stations.

Fig. 4.14 illustrates the aggregated network throughput for scenarios comprising EMLSR and STR stations alongside legacy devices. A reduction in network throughput is observed in setups with a higher proportion of legacy devices. A similar trend was reported in [25], although in that study it was more pronounced, with network throughput decreasing by more than a factor of two for the corresponding case. This indicates that the high number of legacy devices can decrease overall network performance, as they are less efficient than MLO stations.

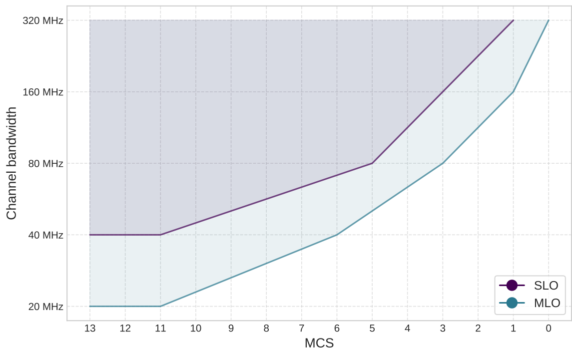
Fig. 4.15 depicts the aggregated throughput depending on the device type. Increasing the number of legacy devices does not result in a proportional increase in their aggregated throughput. Unlike in [25], the throughput for legacy devices does not rise consistently, at 70% of legacy devices is less than 5 times higher than for 10% of legacy stations. MLO stations continue to occupy a significantly larger share of the medium. The aggregated throughput of legacy devices does increase from nearly 0 to more than 50, but the effect is less pronounced than in the reference study. This may be due to the settings of the channel access mechanism in MATLAB, which could favor MLO stations. Even if this is the case, the results are qualitatively similar, indicating that the presence of MLO stations can reduce the performance of legacy devices.

Fig. 4.16 shows the average throughput per device type. The results show a major increase in average throughput for MLO devices even as the number of legacy devices grows, demonstrating that MLO stations continue to occupy a larger share of the medium, even if their number decreases. In contrast, the average throughput for legacy devices remains the same, regardless of their proportion in the network, consistent with the observations in [25]. Unlike the results shown in the article, where MLO throughput remained constant and independent of the percentage of legacy devices, the present results are more consistent with those reported for case "c", where RTS frames could be independently accepted on multiple links by the AP. Again, the differences in results can be caused by specific MATLAB's access mechanisms favoring MLO stations, as well as the tendency of STR stations to dominate the medium by using all three links simultaneously, leaving little to no space for legacy devices.

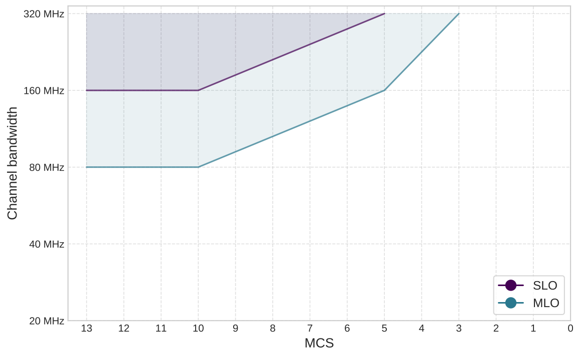
4.4. MLO in VR

This simulation scenario is based on [23] and aims to evaluate the ability of MLO to support VR applications. The Wi-Fi Alliance specifies requirements for VR gaming [24], including downlink latency below 5 ms at the 75th percentile and uplink 90th percentile latency below 2 ms.

The simulation setup consists of an AP and one station, communicating in downlink or uplink direction depending on the scenario. The VR traffic model [23] is applied using `networkTrafficOnOff` object. A detailed description of simulation parameters is provided in Section 3.2.13.



(a) Downlink (75%-tile of 5 ms).



(b) Uplink (90%-tile of 2 ms).

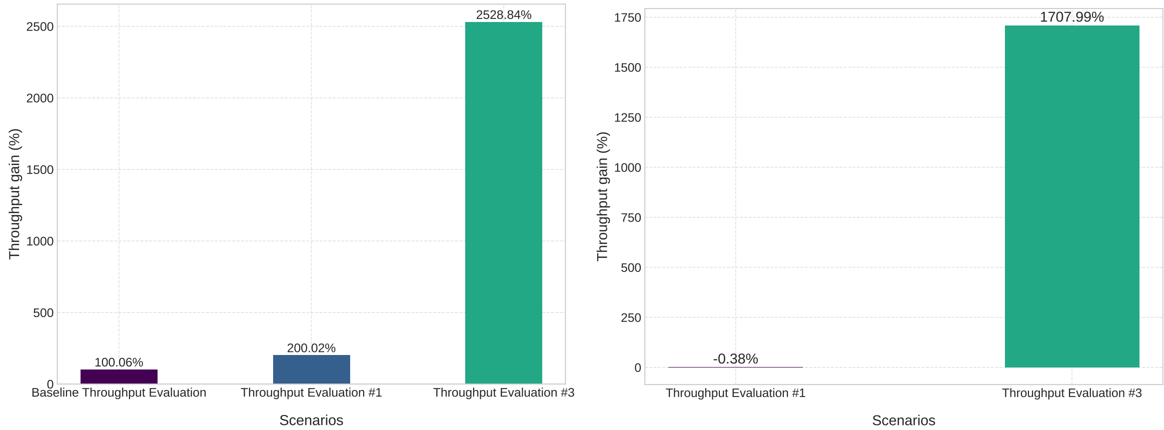
Fig. 4.17. Minimum MCS and channel bandwidth combination to meet requirements set by the Wi-Fi Alliance for VR gaming.

Figures 4.17a and 4.17b illustrate the combinations of MCS and channel bandwidth that satisfy the downlink and uplink latency requirements, with each figure presenting results for both MLO and SLO. The results show that MLO requires lower MCS values and narrower channel bandwidths than SLO to satisfy the latency requirements in both the uplink and downlink scenarios. However, due to MLO using two channels in most cases, the total bandwidth needed remains the same. Meeting uplink requirements is more challenging than meeting downlink requirements, consistent with the findings presented in the article [23]. Although the results differ in terms of channel bandwidth and MCS values at which latency requirements are met, the general conclusions are similar. Uplink traffic is more difficult to sustain, and MLO provides better performance than SLO.

4.5. Comparison of Results

The results presented in Sections 4.1, 4.2, 4.3, and 4.4 provide several insights into the performance of MLO, allowing the evaluation of its benefits and limitations under different conditions. A qualitative comparison of these results is presented below.

First, the results show that devices operating in MLO-STR mode achieve consistent throughput improvement over SLO devices in both contention-free and contention scenarios. In contrast, EMLSR shows improvement only in contention scenarios, likely due to the use of only a single link at a time, which makes its performance in contention-free scenarios almost identical to SLO. The maximum throughput gains of MLO over SLO are summarized in Fig. 4.18. The Baseline Throughput Evaluation (Section 4.1.1) and Throughput Evaluation #1 (Section 4.1.2) were conducted in contention-free settings, whereas Throughput Evaluation #3 (Section 4.1.4) represents a contention scenario with varying OBSS activity. In this contention scenario, MLO shows a notable improvement of more than 2000% for MLO-STR and around 1700% for MLO-EMLSR, highlighting its ability to maintain high performance in congested network environments.



(a) MLO-STR (b) MLO-EMLSR

Fig. 4.18. Throughput gain of MLO modes over SLO.

Moreover, MLO can provide significant latency reduction, particularly in contention-free scenarios. In these settings, latency is consistently lower compared to SLO devices as illustrated in Fig. 4.19, which shows the maximum latency reduction observed in latency scenarios (Sections 4.2.1 – scenario with one station, 4.2.2 and 4.2.3). However, in contention scenarios, latency may increase relative to SLO as shown in Fig. 4.20 which depicts maximum latency increase for MLO in Latency Evaluation Scenarios #4A (Section 4.2.4), #4B (Section 4.2.5) and #5 (Section 4.2.6). The negative impact of contention can be mitigated through channel allocation strategies. For instance, in Latency Evaluation #5B for the MLO-STR:1+1 configuration – where each contending BSS used two channels, one shared across all BSSs and one private link – latency was reduced despite contention, as shown in Fig. 4.20, which depicts the latency increase of MLO in contention scenarios. These results highlight that MLO latency performance is highly dependent on both network load and channel management.

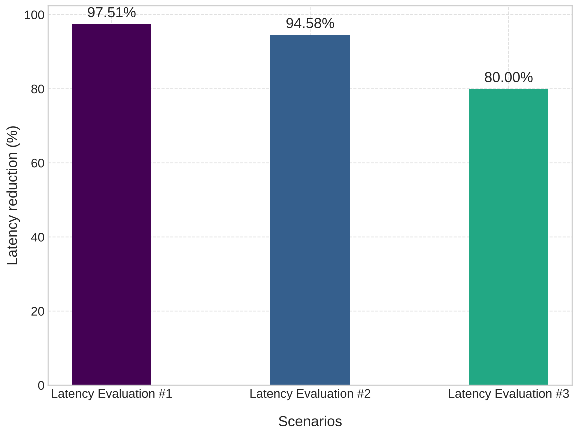


Fig. 4.19. Latency reduction of MLO compared to SLO in contention-free scenarios.

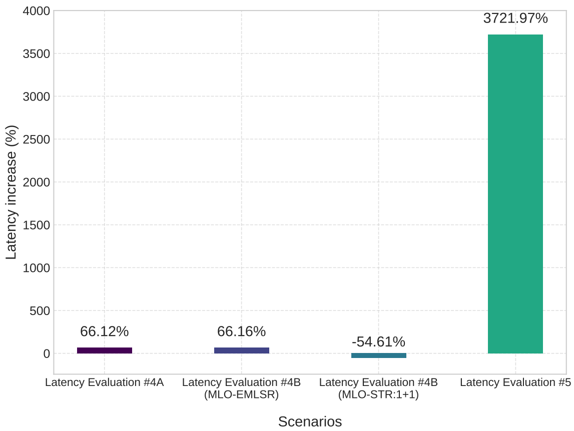


Fig. 4.20. Latency increase of MLO compared to SLO in contention scenarios.

Additionally, the findings from Throughput Evaluation #2 (Section 4.1.3) and MLO and Legacy Stations Scenario (Section 4.3) indicate that in contention scenarios, the presence of MLO stations degrades the performance of SLO devices. When different BSSs operate on the same channels, as in Throughput Evaluation #2, the throughput allocation is more balanced between BSSs, resulting in greater fairness as shown in Fig. 4.21, especially when MLO devices operate in EMLSR mode, using one link at a time. However, when SLO and MLO stations coexist within the same network, as in the MLO and Legacy Stations Scenario, resource allocation between different kinds of devices becomes highly uneven, with MLO devices dominating the network as presented in Fig. 4.21, which shows Jain's Fairness Index for the case with 90% legacy devices. However, Jain's Fairness Index remains high within groups of devices operating in the same mode, as their throughputs are similar.

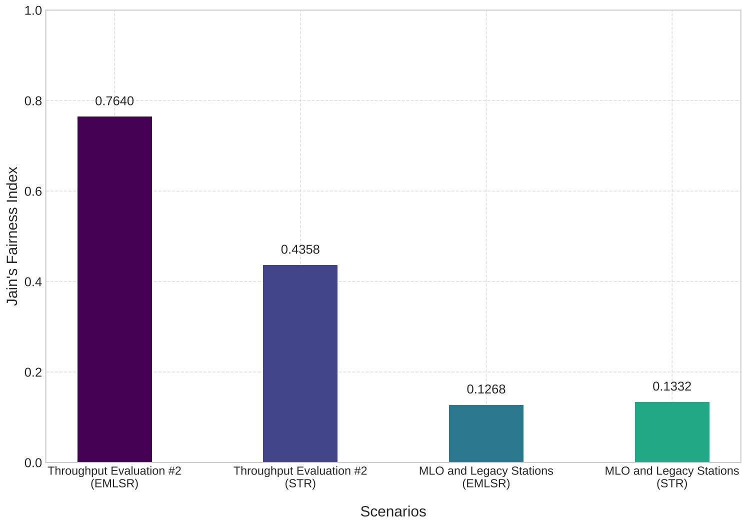


Fig. 4.21. Fairness for MLO and SLO stations in contention scenarios.

Together, the findings demonstrate that MLO can deliver significant improvements in throughput and latency compared to SLO, with MLO-STR providing more consistent performance enhancements and EMLSR offering increased throughput, particularly in contention scenarios. Although latency reduction is evident in contention-free scenarios, congested environments may lead to latency increase compared to SLO, unless mitigated through strategies such as appropriate channel allocation. Overall, the effectiveness of MLO is not solely determined by its adoption, but also by design and configuration, such as MLO mode, channel management, and other factors like MPDU aggregation.

5. Summary

The purpose of this thesis was to evaluate the performance of MLO by assessing its capabilities, potential enhancements, and limitations in comparison to traditional SLO. In addition, it provided an opportunity to analyze different approaches proposed in the literature while attempting to reproduce the reported results. A further objective was to evaluate the suitability of MATLAB's WLAN Toolbox for Wi-Fi analysis by comparing the results of the conducted simulations with the findings of existing studies. All the code developed is available online [1].

As part of this work, additional MATLAB code was developed to recreate and simulate Wi-Fi scenarios reported in the literature. The support functions were implemented to manage node placement, traffic parameter generation, and channel occupancy configuration, while helper functions provided by the MATLAB WLAN Toolbox were used for tasks such as channel configuration, collection of performance metrics and validation of simulation settings. The simulation outputs were exported and processed in Google Colab, allowing analysis and comparison of the results. This methodology allowed reproducible and comparable results for the MLO performance analysis.

Based on the simulations and analysis of the results, the key findings of this study can be summarized as follows:

– MLO achieves higher throughput than SLO, particularly when using STR mode, while EMLSR offers throughput improvements primarily in congested environments.

– MLO reduces latency in contention-free environments, whereas latency may increase in contention scenarios compared to SLO, especially when one channel is less occupied than the rest. This effect can be reduced by employing channel allocation strategies, for example, by assigning more channels than there are competing BSSs.

– MLO may negatively impact coexisting SLO and legacy devices because its ability to access multiple links creates an unfair advantage, limiting communication opportunities for traditional stations and leading to lower throughput.

– MLO can be a suitable option for VR applications, as it is able to meet VR latency requirements [24] using lower MCS indices and narrower channel bandwidths than SLO.

[1] https://github.com/jokozo/MLO-Performance-Analysis

In most cases, the obtained results were consistent with those reported in the reference articles used as the basis for the simulation scenarios. The observed differences can be explained either by limitations of the used tool, which did not allow for extensive customization, or by potential differences in simulation settings due to incomplete information about certain parameters.

The findings highlight both advantages and limitations of this study, which could be addressed in future work on this topic. First, the scenarios implemented in MATLAB could be recreated in ns-3, which would allow for comparison between the two simulators in terms of accuracy and customization capabilities. Another important aspect of future work would be to address the increased latency of MLO in congested environments by exploring more methods to mitigate this effect through traffic-to-link allocation algorithms, as in [18], [14], and [9], scheduling [13], or channel assignment strategies, especially considering most recent works, such as [30], where authors focus on performance of XR applications and propose a resource allocation algorithm to minimize latency by optimal packet allocation based on L-MAC statistics. The next step would be to investigate mechanisms that ensure fair coexistence between MLO and SLO or legacy stations, either by recreating and evaluating proposals already presented in the literature [25], [12], or by developing new approaches to this topic. Finally, future research might explore the use of machine learning as in [31], where authors propose a new RL-based link selection model that dynamically selects the optimal multi-link configuration based on RSSI, SNR, interference levels, and other factors. In summary, MLO has the potential to play an important role in future Wi-Fi networks, particularly with continuous research and development that addresses existing challenges.

Bibliography

[1] Yazdan Ahmad Qadri, Haejoon Jung, and Dusit Niyato. "Toward the Internet of Medical Things for Real-Time Health Monitoring Over Wi-Fi". In: *IEEE Network* 38.5 (2024), pp. 229–237.

[2] "IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhancements for Extremely High Throughput (EHT)". In: *IEEE Std 802.11be-2024 (Amendment to IEEE Std 802.11-2024, as amended by 802.11bh-2024)* (2025), pp. 1–1020. DOI: *10.1109/IEEESTD.2024.11090080*.

[3] Ehud Reshef, Shlomi Vituri, and Assaf Gurevitz. "Wi-Fi 7–Technology Realities and Way Forward". In: *2024 IEEE International Conference on Microwaves, Communications, Antennas, Biomedical Engineering and Electronic Systems (COMCAS)*. IEEE. 2024, pp. 1–5.

[4] Cailian Deng et al. "IEEE 802.11 be Wi-Fi 7: New challenges and opportunities". In: *IEEE Communications Surveys & Tutorials* 22.4 (2020), pp. 2136–2166.

[5] Cheng Chen et al. "Overview and performance evaluation of Wi-Fi 7". In: *IEEE Communications Standards Magazine* 6.2 (2022), pp. 12–18.

[6] Marc Carrascosa-Zamacois et al. "Understanding multi-link operation in Wi-Fi 7: Performance, Anomalies, and Solutions". In: *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE. 2023, pp. 1–6.

[7] Xiyang Lan, Xinyu Zu, and Jie Yang. "Enhanced Multilink Single-Radio Operation for the Next-Generation IEEE 802.11 BE Wi-Fi Systems". In: *Security and Communication Networks* 2022.1 (2022), p. 7018360.

[8] Stefano Avallone and Pasquale Imputato. "Understanding the New Enhanced Multi-Link Single Radio Feature of IEEE 802.11 be WLANs". In: *IEEE Journal on Selected Areas in Communications* (2025).

[9] Alvaro López-Raventós and Boris Bellalta. "Multi-link operation in IEEE 802.11 be WLANs". In: *IEEE Wireless Communications* 29.4 (2022), pp. 94–100.

[10] Nikolay Korolev, Ilya Levitsky, and Evgeny Khorov. “Analyses of NSTR multi-link operation in the presence of legacy devices in an IEEE 802.11 be network”. In: *2021 IEEE Conference on Standards for Communications and Networking (CSCN)*. IEEE. 2021, pp. 94–98.

[11] Shubhodeep Adhikari and Sindhu Verma. “Analysis of multilink in IEEE 802.11 be”. In: *IEEE Communications Standards Magazine* 6.3 (2022), pp. 52–58.

[12] Jagrati Kulshrestha et al. “LFTA: Legacy Friendly Traffic Allocation Strategy for Multi-Link Operation in WiFi7”. In: *2024 16th International Conference on COMmunication Systems & NETworkS (COMSNETS)*. IEEE. 2024, pp. 448–456.

[13] Suneel Kumar, Eduard Garcia-Villegas, and Daniel Camps-Mur. “SLA-MLO: Congestion-aware SLA-Based scheduling of multiple links in IEEE 802.11 be”. In: *2024 IEEE 21st Consumer Communications & Networking Conference (CCNC)*. IEEE. 2024, pp. 875–880.

[14] Álvaro López-Raventós and Boris Bellalta. “Dynamic traffic allocation in IEEE 802.11 be multi-link WLANs”. In: *IEEE Wireless Communications Letters* 11.7 (2022), pp. 1404–1408.

[15] Marc Carrascosa-Zamacois et al. “Performance and coexistence evaluation of IEEE 802.11 be multi-link operation”. In: *2023 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2023, pp. 1–6.

[16] Ana Jeknić and Enis Kočan. “Multi-Link Operation for Performance Improvement in Wi-Fi 7 Networks”. In: *2024 28th International Conference on Information Technology (IT)*. IEEE. 2024, pp. 1–4.

[17] Marc Carrascosa-Zamacois et al. “Wi-Fi multi-link operation: An experimental study of latency and throughput”. In: *IEEE/ACM Transactions on Networking* 32.1 (2023), pp. 308–322.

[18] Álvaro López-Raventós and Boris Bellalta. “IEEE 802.11 be multi-link operation: When the best could be to use only a single interface”. In: *2021 19th Mediterranean Communication and Computer Networking Conference (MedComNet)*. IEEE. 2021, pp. 1–7.

[19] Vladislav Paroshin et al. “Aggregation Algorithm to Increase Throughput of Multi-Link Wi-Fi 7 Devices”. In: *IEEE Wireless Communications Letters* (2024).

[20] Jagrati Kulshrestha et al. “Is Multi-Link Operation of 802.11 be TCP Friendly? Analysis and Solution”. In: *2024 IFIP Networking Conference (IFIP Networking)*. IEEE. 2024, pp. 168–176.

[21] Pasquale Imputato et al. “TCP Latency-Sensitive Applications Over MLO in Wi-Fi 7”. In: *2024 IEEE Symposium on Wireless Technology & Applications (ISWTA)*. IEEE. 2024, pp. 136–139.

[22] Molham Alsakati et al. “Performance of 802.11 be Wi-Fi 7 with multi-link operation on AR applications”. In: *2023 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2023, pp. 1–6.

[23] Marc Carrascosa-Zamacois et al. “Performance Evaluation of MLO for XR Streaming: Can Wi-Fi 7 Meet the Expectations?” In: *arXiv preprint arXiv:2407.05802* (2024).

[24] Wi-Fi Alliance. *VR Gaming Highlights*. *https://www.wi-fi.org/system/files/VR_Gaming_Highlights_20231215_0.pdf*. Accessed: 2025-09-07.

[25] Daniele Medda et al. "Investigating inclusiveness and backward compatibility of IEEE 802.11 be multi-link operation". In: *2022 IEEE Conference on Standards for Communications and Networking (CSCN)*. IEEE. 2022, pp. 20–24.

[26] The MathWorks, Inc. *MathWorks*. *https://www.mathworks.com/*. Accessed: 2025-09-16.

[27] IEEE 802.11 Task Group AX. *TGax Evaluation Methodology*. Online. Project P802.11ax, Task Group AX. 2020.

[28] 3rd Generation Partnership Project (3GPP). *Evolved Universal Terrestrial Radio Access (E-UTRA); Further Advancements for E-UTRA Physical Layer Aspects (Release 9)*. Technical Report TR 36.814. Version V9.0.0. 3GPP Technical Specification Group Radio Access Network, 2010.

[29] MathWorks, Inc. *802.11be System-Level Simulation Using STR Multi-Link Operation — WLAN Toolbox*. *https://www.mathworks.com/help/wlan/ug/802-11be-multi-link-operation-in-system-level-simulation.html*. Accessed: 2025-09-16.

[30] Lyutianyang Zhang et al. "Scheduling in IEEE 802.11 be Multi-Link Operation for Low Latency and High Reliability". In: *IEEE Transactions on Green Communications and Networking* (2025).

[31] Bhurisub Dejpipatpracha et al. "Intelligent Multi-Link Selection for IEEE 802.11 be Using Reinforcement Learning with Radiation Pattern Awareness". In: *2025 11th International Conference on Engineering, Applied Sciences, and Technology (ICEAST)*. IEEE. 2025, pp. 53–56.