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SURVEY

Multi-Link Operation in IEEE802.11be Extremely High Throughput: A Survey

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ABSTRACT The evolution of wireless communication has led to the introduction of IEEE 802.11be, a leading-edge wireless standard also referred to as Extremely High Throughput (EHT) or Wi-Fi 7. Multi-Link Operation (MLO) is the most innovative and disruptive technology proposed in this amendment, which holds the potential to revolutionize wireless networks. MLO aims to increase throughput through link aggregation, enhance reliability through redundant frame transmission over multiple links, and decrease latency by utilizing the earliest available link. However, to the best of our knowledge, there is no specific survey or review paper is dedicated solely to MLO, despite the extensive research conducted on Wi-Fi 7. Thus, this survey paper will bridge the gap by presenting an exhaustive overview of cutting-edge research spanning from 2010 to 2023, exclusively focused on MLO characteristics, current status and future directions. This study has discovered several open issues, including backoff count overflow, channel selection, load balancing and channel access fairness. These findings lay the groundwork for future research that has the potential to impact the current status of wireless communication significantly.

INDEX TERMS Wi-Fi 7, IEEE 802.11be, extremely high throughput, multi-link operation.

I. INTRODUCTION

The landscape of Wireless Fidelity (Wi-Fi), a dominant technology, has continually experienced swift and dynamic transformations [1]. Significant progress was made with the introduction of Wi-Fi 6 in 2019 and Wi-Fi 6E in 2021 [2]. This momentum of technological development has also propagated to other versions and respective standards. One of which is the IEEE802.11be, known as Extremely-High-Throughput (EHT) or Wi-Fi 7, which is expected to become a reality by 2024 [3], [4]. Furthermore, discussions have already begun within IEEE 802.11 in 2022 to envision the next generation of Wi-Fi, tentatively named Wi-Fi 8. This new generation, designated as IEEE 802.11bn Ultra High Reliability (UHR), is anticipated to be released by 2028 [5], [6]. Additionally, a significant amount of work is currently being done to make Ultra Low Latency (ULL) application accessible via the subsequent version of Wi-Fi [7]. EHT is focused on attaining an extremely high rise in the peak of throughput, reaching at least 30 Gbps, which is three times higher or more than Wi-Fi 6, while concurrently minimizing the amount of latency experienced by users [8], [9], [10].

The Task Group BE (TGbe) is responsible for defining the Physical (PHY) and Medium Access Control (MAC) layers in the context of EHT. The 2019 Project Authorization Report (PAR) stipulated the scope of IEEE 802.11 PHY and MAC layer amendment [11]. 11be provides a novel Physical Layer Convergence Protocol Data Unit (PPDU) design. The structure can be divided into three principal blocks: EHT Preamble, Legacy Preamble, and data [12]. Moreover, the 11be standard introduces a variety of innovative new features in the beginning, including Multi-Access Point Coordination (MAPC) and MLO. However, the MAPC is not yet implemented in the current amendment and is being considered for use in future WLANs such as beyond-11be and beyond-11ay [13], [14], [15].

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MLO refers to the simultaneous utilization of multiple links[1] operating on various frequency channels[2] by an Access Point (AP), a station, or both [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27]. Fig.1 illustrates the topology of MLO communications and clarifies its underlying concept. This configuration supports the Multi-Link Device (MLD) and the Single-Link Device (SLD). While the SLD has only one station, the MLD consists of multiple stations, ranging from two to even more. The MLD employs its stations architecture to facilitate data transmission across the interconnected links, resulting in high throughput. In addition, the MLD has the potential to leverage multiple links depending on the employed topology [26]. MLD can function as SLD in situations where there is an absence of an available channel for transmission.

MLO has become one of the most important features of the IEEE 802.11be standard [28], [11], and [29]. This upcoming standard aims to enhance Wi-Fi dependability through multi-link operation [3], [30], [31]. The advent of MLO marks a turning point for Wi-Fi because multi-link communications are now the norm due to its adoption. However, its implementation presents new challenges for the management of resources, channel access, transmission modes, and the architectural design of both Access points (Aps) and stations(STAs) [32], [33].

The motivation for MLO stems from its projected benefits across various dimensions [20]. Firstly, the introduction of the multi-link framework enables significantly improved coordinated operations across multiple links [34], [35]. Through unified and cooperative link management, Wi-Fi 7 can more easily accomplish additional throughput for data flows separated across links than earlier Wi-Fi technologies with separate and independent operations across multiple bands. Secondly, using several lines concurrently enhances the likelihood that a channel will be accessed, considerably reducing latency [36]. Thirdly, MLO permits duplication across numerous connections[3] to guarantee the successful transmission of crucial data that demands extremely high reliability. Finally, depending on the application's requirements, MLO can be used to assign data flows to specific links to accomplish traffic separation [37].

These attributes have formed the motivation to conduct an in-depth survey and analysis of IEEE802.11be MLO. This paper is presented in the following order. The survey purpose and survey strategy will be discussed. Then, the Acronyms and their definitions used in this paper are presented in Table 1. The rest of this survey paper is presented in five sections. An extensive comparison of related surveys or reviews done in this area that has substantiated our survey is presented in Section II. Section III explores essential MLO characteristics and features such as multi-connectivity, traffic allocation policies, channel access, power savings, MLO for real-time applications (RTA), multi-link device architecture, and network architecture. Section IV provides a brief literature review of relevant state-of-the-art research and summarizes research issues related to MLO, including contributions, evaluation tools used, and limitations of existing studies. Section V highlights research open issues and discusses the future direction of MLO. Lastly, Section VI contains the conclusion of this survey paper.

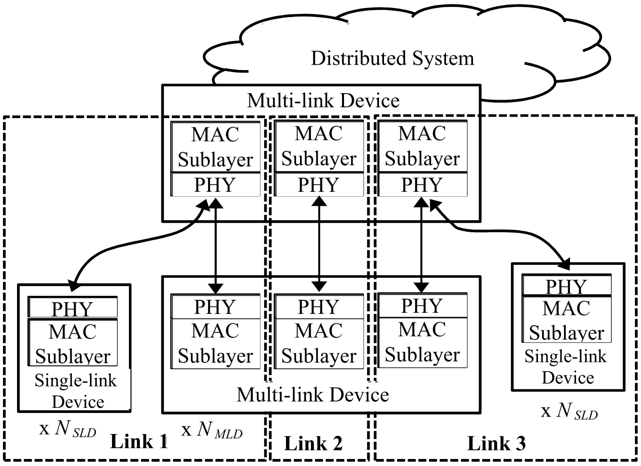

FIGURE 1. **The topology of MLO communications [26].**

SURVEY PURPOSE

With the increasing demands for Wi-Fi usage in Augmented Reality (AR) and Virtual Reality (VR) applications, this survey aims to explore the crucial role of MLO in meeting these demands. Additionally, it aims to provide readers with an overview of existing research and key trends related to the application of MLO in resolving specific Wi-Fi performance issues.

Through this survey, we aim to contribute to the growing body of knowledge, theoretical advancements, and empirical findings surrounding the impact of MLO on Wi-Fi networks' performance. By investigating the effects of MLO on throughput and delay, this study will complement and expand upon the findings of other related research.

Furthermore, this survey will facilitate the identification of any remaining research gaps in this area, thereby offering valuable insights to researchers. It is intended to be a comprehensive resource valuable to newcomers and seasoned professionals in the field seeking an extensive review of recent studies focused on enhancing Wi-Fi performance through Multi-Link Operation.

Ultimately, we hope the findings presented in this survey will inspire readers to contribute fresh ideas and novel approaches to this evolving field of study.

A. SURVEY STRATEGY

This survey on increasing Wi-Fi performance with MLO began by employing a method of literature evaluation known as a systematic literature review ([38], [39]. In the first step of

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[1] A link refers to a specific connection between devices.

[2] Channel represents the physical or logical pathway for data transmission.

[3] A connection represents the logical pathway for data exchange.

TABLE 1. List of acronyms and corresponding definitions.

Acronyms	Definitions	Acronyms	Definitions
EHT	Extremely High Throughput	LMAC	Lewer Media Access Control
MLO	Multi-Link Operation	UMAC	Upper Media Access Control
SLO	Single Link Operation	LLC	Logical Link Control
TGbe	Task Group BE	ACK	Acknowledgment
RTA	Real Time Application	BA	Block Ack
ULL	Ultra Low Latency	QoS	Quality Of Service
WFA	Wi-Fi Alliance	MLSR	Multi-Link Single Radio
AP	Access Point	EMLSR	Enhanced Multi-Link Single Radio
MC	Multi-Connectivity	NSTR-MLMR	Non-Simultaneous Transmit-Receive Multi-Link Multi-Radio
MLO-STR	Multi-Link Operation Simultaneous Transmit and Receive	EMlMR	Enhanced Multi-Link Multi-Radio
APP	Application Layer	RF	Radio Frequency
TRA	Transport Layer	TIM	Traffic Indication Map
NW	Network Layer	TWT	Target Wakeup Time
MAC	Media Access Control	EDCA	Enhanced Distributed Channel Access
MLO-NSTR	Multi-Link Operation Non- Simultaneous Transmit and Receive	EDCAF	Enhanced Distributed Channel Access Function
MLD	Multi-Link Device	TXOP	Transmission Opportunities
SLD	Single-Link Device	STA	Station
NSTR	Non- Simultaneous Transmit and Receive	UHR	Ultra-High Reliability
STR	Simultaneous Transmit and Receive	TID	Traffic Identifier
PHY	Physical	CW	Contention Window
PS	Power Save	BSS	Basic Service Set
SINR	Signal To Interference Plus Noise Ratio	ML	Machine Learning
LD	Legacy Device	MLA	Multi-Link Aggregation

our research, several databases were searched (IEEE Xplore, ACM, Elsevier, and Wiley). The keywords used in the query included "multi-link operation", "IEEE 802.11be", "Wi-Fi 7" and "Extremely High Throughput". This resulted in as many as 2577 papers from 2010 to 2023. Fig. 2 illustrates the number of publications found during the research process, which was conducted in the first half of 2023.

The papers were initially screened based on their titles first and then on the abstracts. If the abstracts failed to provide sufficient details, the entire manuscripts were read. Therefore, papers are included in this evaluation based on a rigorous examination of their subject matter and quality. This permits us to provide a comprehensive and lucid explanation of multi-link operation.

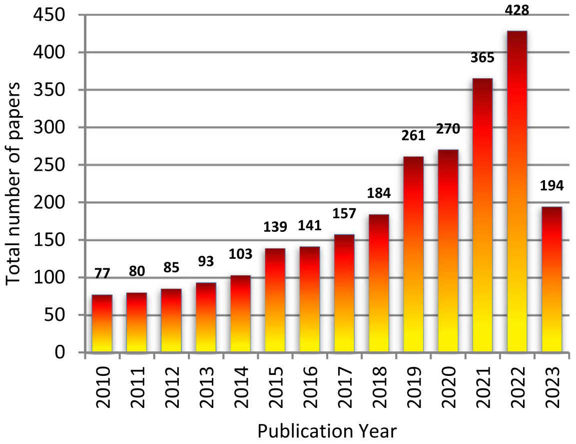

FIGURE 2. Number of publications related to MLO per year.

The filtration process, as shown in Fig. 3, began by excluding papers that were irrelevant to the aim of the study, first according to the title and then based on the abstract. Additionally, publications that were discovered through cross-citation analysis were included. Finally, a hundred relevant papers in total are identified. Additionally, eleven survey and review papers related to MLO are referenced in Section II.

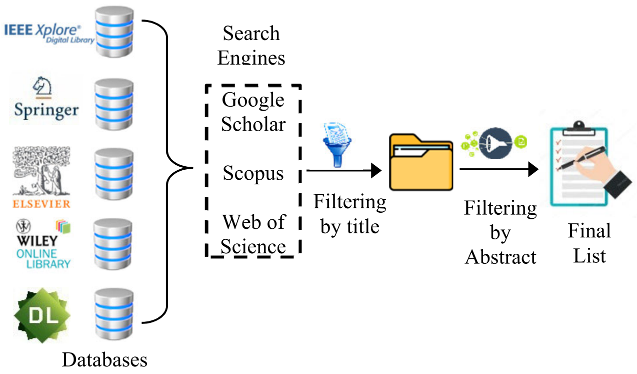

FIGURE 3. Searching steps.

II. RELATED SURVEYS AND REVIEWS

This section provides a detailed content comparison between this survey and relevant tutorial/survey articles. Table 2 illustrates the number of references for recent surveys related to MLO and presents their main scope and addressed features. It is clear from this table that the content showcases a collection of research papers covering a wide range of topics related to Wi-Fi technology advancements.

References [10] and [40] discuss in their main scopes the standards IEEE802.11be, its main innovations and its new challenges. [41], [42] discusses topics related to channel selection and medium access. The rest of the references include topics such as performance evaluation of Wi-Fi 7, new standards, multi-connectivity, multipath transmission, and medium access control protocols. The most common scope discussed by these article papers focuses on the standard IEEE802.11be and Wi-Fi 7 in general; however, none of them specifically concentrate on MLO and its features.

Table 3 compares and contrasts eleven review papers related to our study based on a number of criteria, including MLO state-of-the-art, which means whether the paper mentions or discusses any cutting-edge topic related to MLO or not, similarly to the remaining criteria, such as power saving, supporting legacy devices, RTA, QoS, graphical presentation and taxonomy. This allows for a quick understanding of their focus and contributions to the topic.

Based on the comparison, reference number [40] appears to be the most comprehensive paper, as it mentions the most criteria (√) compared to other papers. Reference [43] mentions the criteria related to the MLO state-of-the-art and graphical presentation. Some criteria like "Support legacy devices," "RTA," and Quality of Services (QoS) are rarely mentioned or not mentioned at all in the papers. None of the papers fully cover all the provided criteria. In fact, to the best of our knowledge, no specialized survey or review comprehensively describes MLO. The vast majority of them discuss the standard IEEE 802.11be and highlight the utilization of MLO as the primary innovation incorporated into this standard. This survey will cover and discuss all the features and criteria related to MLO specifically to determine the open issues and potential solutions.

III. CORE MLO RELATED TOPICS

This section discusses six topics related to MLO, as illustrated in Fig.4. These topics include multi-connectivity, transmission and reception via multiple links, multi-link channel access, traffic allocation policies, power saving in MLO, and multi-link operation for RTA.

A. MULTI-CONNECTIVITY

Multi-connectivity (MC) enhances the reliability and latency of wireless networks [46], [49], [50]. Utilizing multiple communication channels, RATs and spatial diversity, it entails simultaneous data transmission across multiple frequency channels [51], [52], [53], [54], [55]. Fig.5. Shows how pathways can be divided at the sender and recombined at the receiver across OSI layers [56], [57]. Multi-link strategies are utilized by various OSI layers, including PHY, MAC, network, transport, and application layers.

Methods at a higher layer, such as MAC Layer MC, are necessary for packet-level pathway consolidation. In contrast to the PHY layer, which integrates approaches at the signal level, PHY MC improves the bit error rate for a given SINR through path combination or increases receiver SINR through coordinated multi-point.

1) LEGACY METHODS FOR WIDE SPECTRUM USAGE

IEEE 802.11be utilizes (2.4, 5, and 6) GHz frequency channels [58], [59]. APs and STAs can utilize multiple radios across frequencies [60], [61], [62], [63], [64]. To avoid interference, only one radio is capable of multi-band operation [43], [45], [65], [66], [67]. Wide channels promise a greater throughput. However, they present obstacles: flawless sync across sub-bands, primary channel obstructing access, power increase, and a higher peak-to-average power ratio resulting from more Orthogonal Frequency Division Multiplexing (OFDM) tones [9]. Modern APs feature dual/tri-band operation and extensive channel support. Multi-band in IEEE 802.11ad ensures reliable transmission when obstructions disrupt mmWave line-of-sight links. Fast Session Transfer facilitates a seamless transition between channels [40].

2) MULTI-LINK DEVICE AND NETWORK ARCHITECTURE

IEEE 802.11be's MLD redefines wireless networks [19], [68], [69]. MLDs with numerous interfaces replace APs and STAs. Link setup, power control, and synchronization are their duties. MLDs support MLO and Single-link Operation (SLO). Legacy SLDs only support SLO [70].

AP MLDs handle AP and non-AP STAs, while non-AP MLDs link to multiple non-AP STAs [20], [71]. As illustrated in Fig.6. AP-MLD and STA-MLD can be connected through more than one channel with different frequencies such as 2.4GHz, 5GHz and 6GHz. Each MLD has PHY and LMAC components per STA and a UMAC that pools logical link control (LLC) layer MAC Service Access Points (SAPs) [16], [26], [72]. For easy reassembly and switching, MLDs produce sequence numbers from MAC addresses.

Restricted and dynamic link switching are IEEE802.11be modes. Restricted limits data to single links that negotiate independently. Dynamic link switching allows simultaneous transmission across links, improving efficiency. MLDs modify networks to accommodate multiple links and efficient modes [40].

3) MULTI-LINK AGGREGATION

Multi-link aggregation (MLA) in wireless technology combines multiple network connections within the 11be standard. This enhances channel access delay, boosts bandwidth, and overall network performance [73], [74]. Typically used in enterprise and campus setups, MLA employs methods like bonding (merging connections into one logical link using protocols such as Link Aggregation Control Protocol(LACP) or Adaptive Load Balancing (ALB), load balancing (optimizing performance through traffic distribution), and failover (ensuring continuity by utilizing alternate connections in case of failure) [75].

MLA benefits applications like video conferencing, online gaming, and unreliable internet areas.

TABLE 2. Summarizes the existing surveys related to MLO.

Ref.	Main scope	Addressed features	Year
[41]	Channel bounding techniques in IEEE802.11bd	Primary channel selection	2022
[37]	Performance Evaluation of Wi-Fi 7	MLO, PHY enhancements, and QoS management enhancement	2022
[43]	Reviewing Wi-Fi 7	Current Wi-Fi limitations and Wi-Fi 7 enhancements	2021
[40]	IEEE802.11be and Wi-Fi 7	Main innovation in IEEE802.11be	2020
[10]	IEEE802.11be & Wi-Fi 7	New challenges and opportunities	2020
[44]	Wireless IoT Networks	multiple Radio Access Technologies (Multi-RAT)	2020
[45]	Extremely High Throughput, WLAN, IEEE802.11be	A concise summary of Wi-Fi 7, including the intended scenario and technical objective, an overview of key technologies, and the standardization procedure.	2020
[46]	Reliable Low Latency Communications as a result of multi-connectivity	The MC methodologies established in IEEE and 3GPP standards, as well as a discussion of the most recent MC layer-by-layer approaches.	2020
[42]	Multi-channel medium access control protocols	Examine and compare the most prevalent medium access control (MAC) techniques.	2017
[47]	Multipath Transmission for the Internet	1. Taxonomy of multipath transmission, including link and network layers; 2. Survey each layer and make an assessment of the solutions; 3. Determine open questions and prospective research directions for multipath transmission	2016
[48]	Next Generation of IEEE 802.11	Discuss the number of aspects such as multi-user MIMO and frame aggregation	2016

TABLE 3. Comparison of this survey with the existing reviews and surveys.

Ref.	Year	MLO state-of the-art	Power saving	Support legacy devices	RTA	QoS	Graphical presentation	Taxonomy
[47]	2016	X	✓	X	X	X	✓	✓
[48]	2016	X	X	X	X	✓	X	X
[42]	2017	X	X	X	X	X	X	X
[40]	2020	X	✓	X	✓	✓	✓	✓
[46]	2020	X	X	X	X	X	✓	✓
[10]	2020	X	X	✓	X	✓	X	X
[45]	2020	X	✓	X	X	X	✓	✓
[41]	2022	X	X	X	X	✓	X	X
[37]	2022	X	X	X	X	X	✓	✓
[44]	2022	X	X	X	X	✓	✓	X
[43]	2022	✓	X	X	X	X	✓	X
Ours	2023	✓	✓	✓	✓	✓	✓	✓

B. TID-TO-LINK MAPPING

The IEEE 802.11 standard defines a Traffic Identifier (TID) as a four-bit value (ranging from 0 to 7) used to differentiate packets for QoS purposes [37]. There are (2^4) = 16 possible TID values; 8 identify Traffic Categories (TCs), and the other 8 identify parameterized Traffic Streams (TSs). The TID is assigned to an MSDU in the layers above the MAC () [76]. In MLO, TID is crucial in directing traffic with specific QoS requirements to the appropriate connections or channels.

TID-to-link mapping associates each TID with a connection set, allowing any link within that set to transmit data frames associated with that TID. All established connections are initially linked to each TID, though this mapping can later be adjusted through negotiation processes [20], [77].

1) MAPPING OF A TID TO A LINK ON A ONE-TO-ONE BASIS (FLOW-LEVEL AGGREGATION)

The employed mapping assigns a unique link to each TID, thereby ensuring exclusive transmission of data for that TID through the designated link. This approach facilitates the distribution of distinct traffic flows to different lines, and might result in heightened throughput and reduced latency. However, the efficacy of this method is bounded, as a TID's throughput enhancement is restricted by its allocated link's capacity. Adjustments to the TID-to-link mapping are infrequent, limiting further throughput augmentation [71]. This mapping strategy not only segregates resources for high-priority TIDs, enhancing their performance but also benefits low-priority TIDs in a similar manner [20].

2) 1-TO-M TID-TO-LINK MAPPING, WHICH COMES IN AT NUMBER (PACKET-LEVEL AGGREGATION)

This mapping enables traffic associated with a particular TID to travel via any link within a designated set. This strategy accelerates the resolution of congested TID queues, enhancing traffic handling capacity. UMAC manages TID-specific packet routing on the transmitter's

FIGURE 4. Core MLO Related topics.

end. However, this approach introduces packet reordering, requiring the receiver's UMAC to temporarily store data and orderly transmit packets to the LLC layer [20]. In other words UMAC serves as a shared component within the MAC sub-layer across all interfaces. Within the UMAC, operations that re independent of specific links are carried out. Examples include the assignment of sequence numbers and the aggregation/de-aggregation of MAC service data units (MSDUs). It is crucial to note that the assignment of sequence numbers is specifically conducted at the UMAC, as packets from the same traffic flow may undergo fragmentation and transmission across different links. This approach facilitates the reordering of packets at the receiver's end. Furthermore, this layer is responsible for executing common management functions applicable to all links, such as setup, association, and authentication [71].

C. MULTI-LINK CHANNEL ACCESS

MLO offers a distinct advantage over a single wide channel by facilitating asynchronous channel access and data transmission across multiple links. This enables simultaneous transmission and reception in separate frequency bands [40], [61], [78], [79]. However, interference concerns arise due to shared antennas among MLO devices, leading to potential conflicts when using the same band [21], [80], despite efforts to use distinct channels. This interference is exacerbated by the transmitter's stronger signal compared to the receiver's signal [40], [61].

As channels in MLO devices become closer, power leakage between them increases, posing challenges for transmission and reception. Solutions such as asynchronous multi-link operation and synchronous transmissions are being explored. Synchronous operation reduces interference, but at the

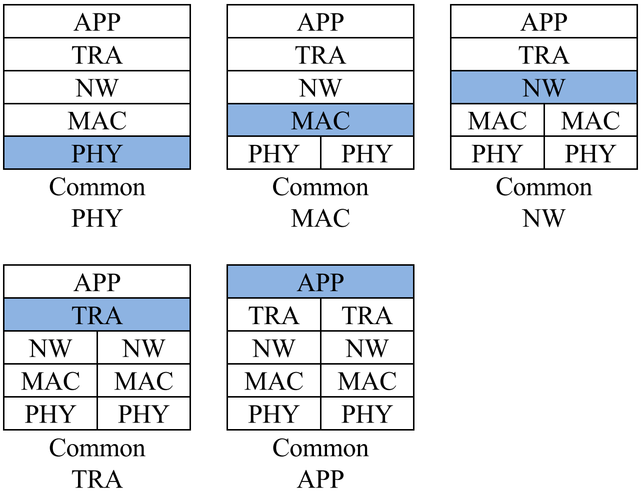

FIGURE 5. MC paths separation and combination at different OSI Layers [51].

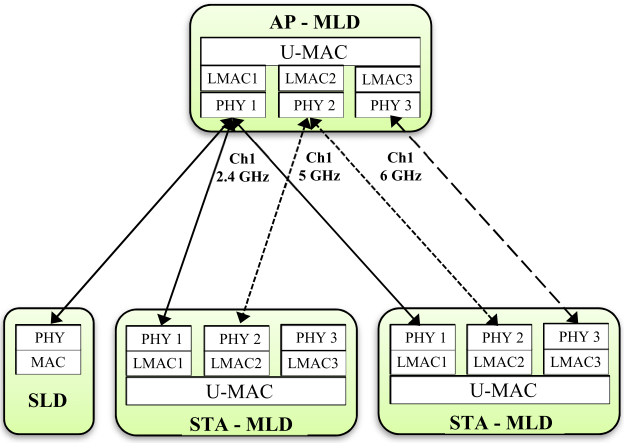

FIGURE 6. Multi-link architecture.

expense of throughput due to less frequent channel access. An alternative involves avoiding transmissions while the intended receiver transmits, reducing interference. For example, during MLO transmission over one link, adjacent bands are kept clear to ensure proper reception of frames like Block Acknowledgments (BAs) [40], [81].

1) SIMULTANEOUS TRANSMIT AND RECEIVE (STR) AND NON-STR

IEEE 802.11be introduces MLO modes: MLO-STR and MLO-NSTR [3], [61], [82], [83]. For a dual radio interface access point compared to SLO, as shown in Fig 7. SLO adheres to the default Wi-Fi operations, involving the sequential transmission of packets. In the MLO-STR scenario, incoming packets are assigned to the first available interface, leading to a notable reduction in delay for packets #1, #2, and #4 [26], [32]. However, In the context of MLO-NSTR, occasional interference between both channels can impede the efficient utilization of the two radio interfaces. Consequently, unlike MLO-STR, the delay for packets #1 and #4 cannot be minimized compared to SLO [26], [84], [85].

IEEE 802.11be also considers (SLO) and MLO device variations in Wi-Fi 7:

1) Multi-link Single Radio (MLSR) communicates sequentially with one link, supporting MLO modes.
2) Enhanced Multi-Link Single Radio (EMLSR) devices listen on multiple links and simultaneously transmit /receive on only one link at a time [86]. The EMLSR is an enhanced feature within MLO framework allows for dynamic band switching cost-effectiveness and optimal power utilization [87].
3) Non-simultaneous Transmit-Receive Multi-Link Multi-radio (NSTR-MLMR) devices can transmit over multiple links synchronously or receive (sync/async), however, it cannot transmit-receive simultaneously.
4) Simultaneous Transmit-Receive multi-link multi-radio (STR-MLMR) communicates over multiple connections simultaneously.
5) Enhanced Multi-link Multi-Radio (EMLMR) adjusts spatial multiplexing via Radio Frequency (RF) chain configurations for various frequencies [28].

MLO-STR involves two schemes, asynchronous and synchronous transmission as illustrated in Fig 8.

In asynchronous transmission, each station (STA) in a MLD accesses its link independently, allowing simultaneous uplink and downlink frames across networks [20], [26]. This suits Synchronous Transmit-Receive (STR) MLDs but impedes non-STR MLDs due to interference [81].

Synchronous multi-link operation avoids the problem of power leakage from a transmitting affiliated device to the others at the cost of reduced throughput caused by more rare channel access. While initially designed for non-STR MLDs, this approach accommodates both STR and non-STR setups, reducing RF power leakage between links. However, considering idle channel requirements, asynchronous transmission might be more efficient for multi-channel utilization [20], [40].

D. MANAGEMENT

This section will discuss important topics in MLO such as Multi-link element (MLE), discovery and setup:

1) MULTI-LINK ELEMENT

The MLE is a crucial component within the 802.11be standard, serving the purpose of facilitating the exchange of capabilities and operational parameters among devices through various management frames. The MLE is ingeniously designed to function as a common element across different management actions, such as discovery and setup, as illustrated in Fig 9.

To implement this versatility, the MLE incorporates a type sub-field within the control field. This sub-field maps each operation to a specific value, ensuring that the information field remains type-dependent. The attributes of the information field are conveyed through a presence bitmap,

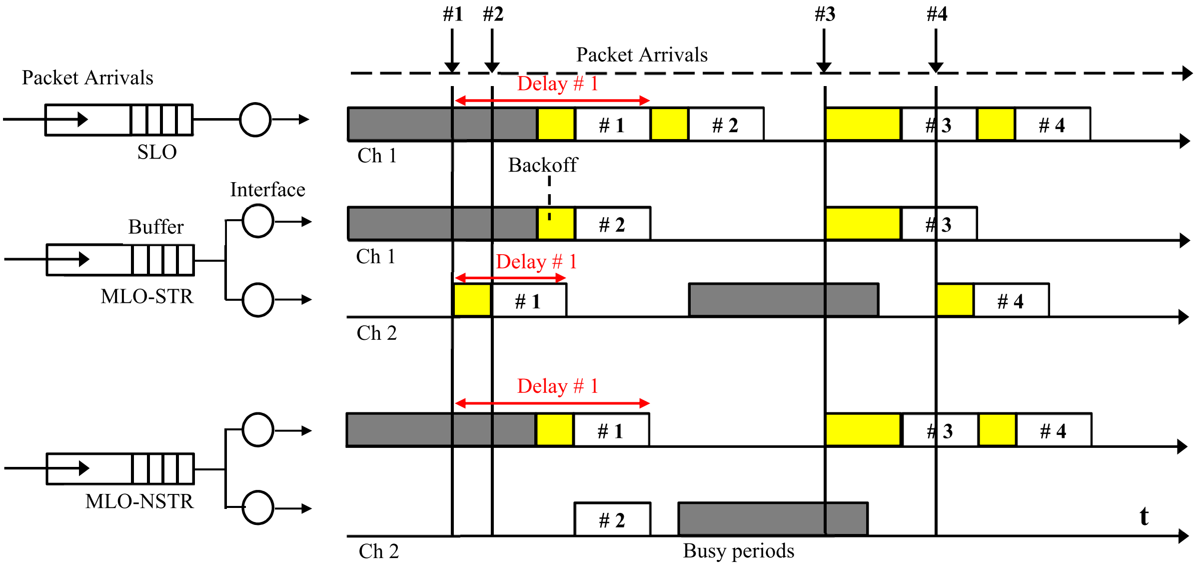

FIGURE 7. Illustrate SLO, MLO-STR, & MLO-NSTR operations. Occupied channels, random backoffs, and packet transmissions are represented by grey, yellow, and white bars, respectively. Packet transmissions encompass both the data segment and the corresponding ACK, along with DIFS and SIFS inter-frame spaces [84].

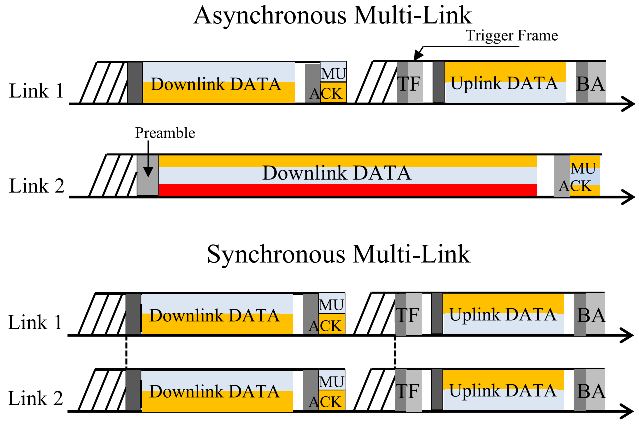

FIGURE 8. Asynchronous vs. synchronous multi-link operation [40].

thereby establishing a flexible structure for carrying type-specific information. This design choice effectively mitigates frame bloating and minimizes overhead.

The current revision of 802.11be introduces two distinct MLE types. Firstly, there is the basic type, primarily intended for use in beacon frames. This type conveys only information common to all interfaces, such as the MLDMAC address, the set of enabled links, and the STR capability. Secondly, the multi-link request/response type is designed for deployment during the multi-link setup. In addition to common information, this type incorporates complete information regarding interfaces other than the advertising one through an individual and independent field.

In instances where a parameter is not advertised in the field of a particular interface, it is considered to have the same value as the advertising one. Noteworthy parameters include channel allocation (e.g., primary channel and bandwidth) and the number of available spatial streams. Although there are presently only two defined MLE types, the standard allows for potential extensions. Proposals are being explored to incorporate additional MLE types, such as announcing buffered traffic information through the reporting of a traffic indication map (TIM) or indicating changes related to the mapping between TID values and links [71].

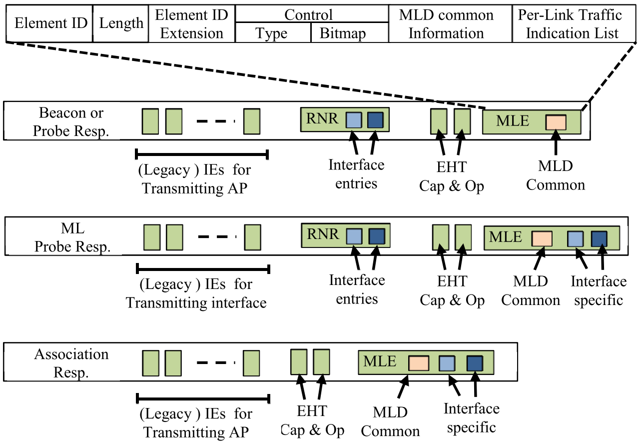

FIGURE 9. Multi-link Element and management frames.

2) DISCOVERY AND SETUP

The 802.11be discovery mechanism adheres to the established principles outlined in the 802.11 standard. Stations can acquire information about nearby aps through a discovery process employing either passive or active scanning. However, the incorporation of MLDS necessitates certain adjustments. As elaborated earlier, beacons and probing frames convey only partial information at the multi-link level, specifically Uplink-MAC (U-MAC) related information. This implementation may extend the time required for stations to execute the discovery process, as they are obligated to scan all interfaces of the MLD before initiating the multi-link setup [71].

To circumvent this challenge, 802.11be utilizes the pre-existing Reduced Neighbor Report (RNR) element to disseminate fundamental information about different interfaces within the same AP MLD. Notably, this information pertains solely to the interfaces that are not transmitting beacon frames. Consequently, stations can directly probe an AP MLD to request its comprehensive set of capabilities, parameters, and operational elements of other interfaces. This probing necessitates the use of the multi-link request/response MLE type. Despite initial perceptions of inefficiency due to the need for an additional multi-link request/response, this approach proves advantageous by conserving energy. Specifically, it avoids compelling non-AP MLDs to activate multiple radios for scanning other bands/channels of thE AP MLD. Additionally, it minimizes air-time occupancy of management frames and reduces the time stations need to transition from the discovery process to the multi-link setup, as illustrated in fig 9.

Regarding the setup process, 802.11be will repurpose the existing association request/response frames by incorporating the additional MLE. Through this MLE, AP MLDs and STA MLDs will engage in negotiations and establish their subsequent operational scheme by exchanging capabilities. Notably, the multi-link setup process is designed to operate on a single link to mitigate overhead. It is important to highlight that the set of enabled links for each STA MLD is determined by assessing link qualities at all interfaces. Interfaces with a quality value surpassing the Clear Channel Assessment (CCA) threshold are designated as enabled, while others ARE DISABLED. GIVEN THE POTENTIAL MOBILITY OF USERS, ANY LINK MARKED AS DISABLED CAN BE ADDED SUBSEQUENTLY through a re-setup request. Analogously, the re-setup process employs the predefined re-association request/response frames, as depicted in Fig 9. [71].

E. TRAFFIC ALLOCATION POLICIES

A traffic manager at the Access Point (AP) controls the distribution of newly incoming packets among available interfaces at each station [32], [33], [88]. The following are three strategies for directing traffic proposed:

1) Single-Link Less Congested Interface (SLCI): New flows are assigned to interfaces with the smallest volume of ongoing traffic.
2) Multi-Link Same Load to All Interfaces (MLSA): The distribution of incoming traffic across active connections.
3) Multi-Link Congestion-Aware Load Balancing at Flow Arrivals (MCAA): Upon the initiation of a new traffic flow, allocate the incoming data traffic in accordance with the channel occupancy observed at the Access Point, taking into consideration the enabled interfaces at the receiving station [32], [71], [77].

MLO can be utilized by the next iteration of Wi-Fi to meet complex application requirements. However, the effectiveness of MLO is highly dependent on the traffic allocation policy in place. Notably, congestion-aware policies that adapt dynamically to network conditions produce the best performance. Research indicates that distributing incoming flows proportionally across interfaces is less efficient than designating flows to the interface with the least traffic. This conclusion simplifies traffic allocation and reduces undesirable exposure [33].

F. MULTI-LINK AND POWER SAVE

The fundamental power management method involves two modes: active and power save (PS). In active mode, the device continuously sends and receives frames. In PS, the device periodically turns off its radio, entering a doze state where no signal transmission or reception occurs.

Referring to the MLDs, typically containing a minimum of two embedded devices, energy usage becomes significant, especially for battery-powered devices, where a combined energy cost is twice that of individual devices [71]. To address this, TGbe has proposed adopting and modifying two methods of power saving:

1) THE TRAFFIC INDICATION MAP (TIM)

The TIM mechanism serves the purpose of informing stations that their associated Access Point (AP) has stored data awaiting delivery. Consequently, the AP incorporates the TIM element into beacons to periodically broadcast this information. The TIM element comprises a bitmap consisting of 2007 bits, each corresponding to a distinct associated station. If the bit in the bitmap corresponding to a specific station is 0, the station remains in a doze state; however, if the bit is set to 1, the station transitions to an awake state, ready to retrieve data from the AP.

While the TIM mechanism effectively functioned for single-link stations, the advent of Multiple Link Dependencies (MLDs) necessitated a reassessment. To accommodate information for all potential multiple links to which a station might be connected, TGbe proposed appending a link indication field following the TIM element. This field includes a link mapping bitmap, with each bit indicating a designated link. Therefore, if a Station Multiple Link Dependency (STA MLD) identifies its corresponding bit set to 1 in the TIM element, it further examines the link mapping to identify the specific link(s) to which the buffered traffic is mapped. Fig 11. illustrates the multi-link TIM indication mechanism described. The multi-link TIM enhances the traditional TIM by enabling stations to selectively awaken specific interfaces during predetermined periods, thereby minimizing power consumption and extending battery cycles [71].

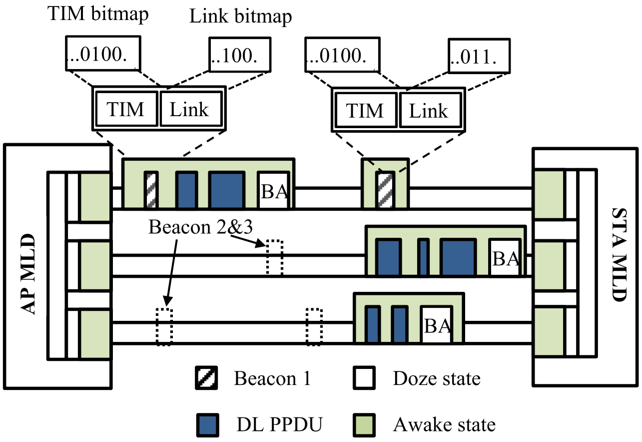

FIGURE 10. **Multi-link TIM [71].**

2) TARGET WAKE TIME (TWT)

TWT is a power-saving mechanism introduced in the 802.11ah and 802.11ax amendments. It involves an initial negotiation to establish a common wake schedule (session period) for stations to send or receive data. For efficient TWT operation in the MLO framework, stations use a single link to negotiate TWT agreements for different enabled links, identified through a bitmap. TWT helps stations switch between awake and doze states as needed, reducing power consumption. [89], [90], [91].

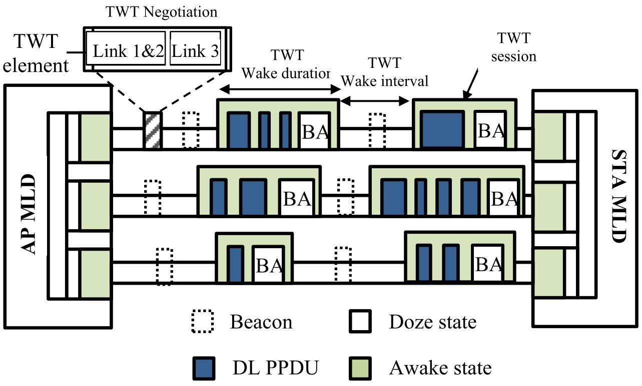

FIGURE 11. **Multi-Link TWT [71].**

Implementation of TWT necessitates an initial negotiation phase to establish the session period (SP) parameters. To streamline TWT operations within the MLO framework, TGbe proposes conducting TWT agreements (i.e., the negotiation phase) for the various enabled links through a single link. In this approach, Station Multi-Link Descriptors (STA MLDs) incorporate different TWT elements in the TWT request, with each element corresponding to a specific link identified through a bitmap. This identification is crucial due to potential variations in TWT parameters among links, such as wake-up time, wake interval, or minimum wake duration. Conversely, if the same parameters are applicable to all links, only one TWT element is required. Fig 10. illustrates the described multi-link TWT mechanism. Similar to the Traffic Indication Map (TIM), stations transition between awake and doze states as needed under TWT, contributing to a reduction in power consumption [71], [89].

IV. RESEARCH ISSUES IN MLO

In this section of the survey, various scholarly works pertaining to the utilization of MLO in wireless networks are examined and presented. Table 4 contains a compilation of references that significantly contribute to the study of MLO. The table encompasses essential details, such as the reference citation, publication year, contributions made, employed methodology, and identified limitations. Furthermore, the table was systematically analyzed to ascertain whether the references address specific aspects, such as PS, Real Time Application (RTA), Quality of Services (QoS), and supporting Legacy Devices (LD). Evidently, the majority of researchers have adopted simulation-based evaluations due to their advantages over experimental and analytical approaches. Two references [21] and [55] used an analytical approach, and two used a test bed in their evaluation.

In the contribution column, it is clear that the trend in 2023 research focuses on the use of Artificial Intelligent (AI) and machine learning approaches in MLO to improve intelligent channel selection, find the best MLO-Link allocation strategy to avoid interference, and propose new MLO schemes for collision avoidance. In 2022 the research articles contributed to solving problems such as head-of-line blocking and null padding, proposed a new connection selection technique, and MAC protocol to improve EMLSR and achieve lower latency overall in asymmetrical MLO. Moreover, they improved station efficacy in scenarios with multiple RTA stations. The articles in 2021 tried to implement MLO and evaluate the network's performance, especially when legacy devices exit. Reference [20] proposes four methods (repicking a backoff count, doubling CW size, transitioning to another CW set, and compensating the backoff count) to address MLO utilization. However, due to the several compensations of the backoff count, the station became unable to secure a transmission opportunity through its own backoff completion. (Research is cycled in nature; as one problem is addressed, another will arise; hence, no work is completely perfect).

Wisnu Murti proposed a solution in 2022 to address the backoff problem by limiting a compensated value using the contention window value of a main link and balancing transmissions between links. However, only the 5 GHz spectrum was used in the experiment. In 2022, Lopez-Raventos and B. Bellalta introduced a traffic manager atop MLO and evaluated different high-level traffic-to-link allocation policies to distribute incoming traffic over the set of enabled interfaces. The articles from 2009 to 2019 discussed aspects related to the use of multi-links to carry more data, improve the throughput, and reduce the latency.

In conclusion, the state of MLO is presently in its nascent stage, and it has not yet reached its culmination.

TABLE 4. Literature review of MLO related articles.

Ref	Year	Contributions	Evaluation methods	Limitations	PS	RTA	QoS	LD
[92]	2023	Propose a collaborative ML approach to learn the best MLO-Link Allocation (LA) strategy to avoid interference.	S	Did not support power saving and Legacy devices.	X	X	X	X
[93]	2023	Improve intelligent channel selection in IEEE802.11be MLO-capable networks.	S	Did not support PS, RTA and Legacy devices.	X	✓	X	X
[2]	2023	Present a Reinforcement Learning (RL) algorithm (MH-RSAC) to distribute incoming traffic in MLO capable networks.	S	Tackle more effectively non-Markovian scenarios in wireless networks.	X	✓	X	✓
[94]	2023	Propose a new multi-link operation scheme for collision awareness.	S	Fairness regarding the presence of legacy devices.	X	X	✓	X
[79]	2022	Solve head-of-line blocking and null padding problems.	S	They use only throughput as performance evaluation.	X	✓	X	X
[84]	2022	Achieves lower latency overall in asymmetrical MLO.	S	The experimental study uses 5 GHz spectrum only. So, it did not use 2.4GHz and 6GHz.	X	X	X	X
[21]	2022	Simulating NSTR operation and calculates the throughput in a saturated network.	A	Not using metrics such as packet delay and ignoring scenarios involving unsaturated traffic and concealed STAs.	✓	X	X	✓
[77]	2022	Evaluate various high-level traffic allocation policies for links.	S	In the presence of heterogeneous stations, link aggregation at channel access is not supported, and traffic differentiation strategies need more research.	X	X	X	X
[87]	2022	Propose a new connection selection technique and media access control protocol to significantly improve EMLSR.	S	Did not support QoS.	X	X	X	✓
[95]	2022	Improves station efficacy in scenarios with multiple RTA stations.	S	An increase in the variance of the data arrival time reduces the Smart PCA's performance.	X	✓	X	✓
[80]	2022	Achieves lower latency overall in asymmetrical MLO.	S	The experimental study use 5 GHz spectrum only. So it did not use 2.4GHz and 6GHz	X	X	X	X
[96]	2021	Demonstrates that the efficacy of multi-link devices degrades when legacy devices are present.	S	Incompatible devices disrupt the synchronization of channel states across multiple connections.	X	X	X	✓
[20]	2021	(repicking a backoff count, doubling CW size, transitioning to another CW set, and compensating the backoff count) to address MLO utilization.	S	A backoff count overload issue may develop. Due to repetitive compensations, the backoff count of an MLD becomes excessively high.	X	X	X	X
[97]	2021	By using both multi-band and hybrid automatic repeat request methods, you can improve the efficiency of retransmission.	S	The algorithm in this study only takes into account the 2.4 GHz and 5 GHz frequency bands, not the 6 GHz band.	X	X	X	X
[7]	2021	Thought about how well WiFi-7 worked in real-world TI application settings.	S	Power saving and Legacy devices are not considered.	X	✓	✓	X
[98]	2021	Make a logical queue for RTA traffic and a backoff system based on when MLO traffic is due to arrive.	S	Power saving and legacy devices were not considered.	X	✓	✓	X
[99]	2020	Lowers both the average and maximum latency of traffic for video streaming.	S	Work did not include simulation of connection overheads and mobility,	X	X	X	✓
[100]	2020	Aligns simultaneous downlink frames in accordance with medium access conditions and reception capability of a constrained STA.	S	Study only downlink and did not support legacy devices, PS, RTA and QoS.	X	X	X	X
[61]	2019	Eliminate the effect of self-transmission on channel usage characteristics.	S	As the Primary channel PCH becomes more congested, STA loses TXOP more frequently to other STA's frame transmission.	X	X	X	X
[101]	2017	Optimizes the configuration of multiple interfaces in order to increase throughput and decrease power consumption.	T	RTA, QoS and LD are not considered.	✓	X	X	X
[53]	2015	Demonstrating that the multi-channel concealed terminal problem can be solved using control channel reservation	S	Did not support QoS , power saving and real time application.	X	X	X	✓
[55]	2012	provide a very high stochastic reliability	M & A	Basic study, did not support RTA, QoS and PS.	X	X	X	X
[102]	2009	identify the reasons behind the low performance	T	Did not support A Mobility analysis and QoS.	X	X	X	✓

TABLE 5. Comparison of research articles contributions in the context of MLO.

Ref	Year	Backoff overflow	Channel selection	Channel Access fairness	Using ML	Load Balancing
[92]	2023	X	✓	✓	✓	X
[93]	2023	X	✓	X	✓	X
[2]	2023	X	✓	X	✓	X
[79]	2022	X	X	X	X	X
[84]	2022	X	✓	X	X	X
[21]	2022	X	X	X	X	X
[77]	2022	X	✓	✓	X	✓
[87]	2022	X	✓	X	X	X
[95]	2022	X	✓	✓	X	X
[80]	2022	✓	✓	✓	X	X
[20]	2021	✓	✓	X	X	X
[97]	2021	X	✓	X	✓	X
[7]	2021	X	X	X	X	X
[98]	2021	X	✓	X	X	X
[99]	2020	X	✓	X	X	X
[100]	2020	X	✓	X	X	X
[61]	2019	✓	X	✓	✓	X
[101]	2017	X	X	X	✓	X
[53]	2015	X	✓	X	X	X
[55]	2012	X	X	X	X	X
[102]	2009	X	X	X	X	X

A considerable portion of the reviewed papers endeavors to develop innovative MLO implementation algorithms, scenarios, or protocols. However, there is always no completely perfect work. Noteworthy limitations persist, including the lack of support for real-time applications, utilization of all available unlicensed bands (2.4GHz, 5GHz, and 6GHz), power-saving capabilities despite the prevalence of battery-powered mobile devices, provision of quality of services and priority differentiation, and support for legacy devices – the latter being a particularly significant drawback. These challenges will remain unresolved issues, inviting further research and investigation until the final release of Wi-Fi 7, which is anticipated in May 2024.

Table 5 presents a comparative analysis of 21 recent research articles focusing on specific topics related to MLO. The topics examined include Backoff Overflow, Channel Selection, Channel Access Fairness, Machine Learning, and Load Balancing.

It is observed that channel selection is the most critical aspect mentioned or addressed by the researchers, where 14 articles out of 21 discuss it. Backoff overflow, channel access fairness, and the use of Machine learning (ML) are mentioned in 3,5,6 articles, respectively. A considerable number of articles have been dedicated to exploring these aspects in recent years. Load Balancing is found to be less frequently discussed compared to the other features, suggesting that it might be a more challenging or specialized research area.

The presence of significant attention to channel access fairness and ML indicates a growing interest in achieving equitable network access and leveraging machine learning techniques in the domain of networking research. On the other hand, backoff overflow and load balancing appear to be underrepresented, highlighting potential research opportunities in these domains for further investigation and exploration. The subsequent section of this survey will delve into the exploration of open issues and future directions for MLO.

V. OPEN ISSUES

MLO presents a compelling opportunity for improving Wi-Fi networks' throughput, latency, and stability. To realize the maximum potential of MLO, however, it requires the effective coordination of multiple connections, which is a crucial obstacle. This section examines the complexities of employing MLO and the associated obstacles.

ML has emerged as a crucial tool for enabling devices to make informed connectivity decisions based on anticipated connection quality. To maximize the benefits of ML optimization, it is imperative to ensure that channel scanning and association are executed with minimal effort and cost. One pivotal objective is to establish MLO connections between APs and STAs.

A review of the existing literature, as presented in Table 4, clearly indicates that recent research in the integration of ML with MLO primarily concentrates on link allocation strategies and channel selection. However, it is noteworthy that these studies do not address or support critical aspects such as power conservation, RTA, and the coexistence of legacy devices within the network. These issues are likely to remain open challenges for future research.

Excessively conservative interference avoidance measures may result in inefficient spectrum utilization. Adoption of opportunistic backoff mechanisms may improve spectrum utilization for STR nodes. The introduction of MLO-enabled Transmission Opportunity (TXOP) aggregation could potentially disadvantage nodes with a single connection, making it imperative to guarantee equitable channel access.

Another open issue is load balancing techniques for MLO in WLANs. It is essential to take a comprehensive approach that includes both uplink and downlink traffic. Utilizing ML can aid in predicting network dynamics and traffic patterns, thereby enhancing the performance of load-balancing mechanisms.

Despite the fact that MLO holds considerable promise for Wi-Fi networks, it is evident that additional research is required. In order to maximize the benefits of MLO and improve the efficacy of Wi-Fi networks, it is essential to address these pertinent issues and challenges. The following table concisely summarizes the most prevalent issues and potential solutions.

TABLE 6. **Open issues and potential solutions.**

Open issues	Potential solution
Using Machine Learning (ML) to improve MLO	ML algorithms can estimate link quality according to previous use.
Backoff count overflow problem	Limiting the compensation of the backoff count and contention window
Channel access fairness	Democratizing the usage
Load balancing	Distribute the traffic according to the links' ability
MLO power save problem	Apply target wakeup time (TWT) mechanism

VI. CONCLUSION

The IEEE 802.11be standard incorporates MLO, which presents a potentially valuable technique. This survey paper has presented a comprehensive examination of various fundamental aspects related to the advancement of MLO, encompassing multi-connectivity, multi-link architecture, channel access, power conservation, and real-time applications. Moreover, beyond providing an overview of MLO's characteristics, this paper strives to offer valuable insights into unresolved issues that pique the interest of both industrial and academic researchers. These outstanding concerns involve algorithms that surpass the bounds of the IEEE 802.11be standard and the requisite procedures that should be incorporated into the standard itself. In conclusion, it is expected that this study will serve as a catalyst for scholars to engage in extensive investigations and devise effective solutions to the aforementioned open challenges, thereby fostering the development of the next generation of Wi-Fi.

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