Study of Multi-Link Channel Access Without Simultaneous Transmit and Receive in IEEE 802.11be Networks

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ABSTRACT Native support for multi-link operation is a key novelty of the future Wi-Fi 7 technology defined by the IEEE 802.11be standard, which is currently under development. With the 6 GHz band recently granted for Wi-Fi operation, the novel multi-link feature enables simultaneous usage of multiple wide channels. Thus, it multiplies the capacity of Wi-Fi networks well beyond the 30 Gbps target of Wi-Fi 7. However, not all stations can simultaneously transmit and receive (STR) information on several links because of cross-channel interference. That is why it is proposed to synchronize the transmissions on different channels. The presence of legacy stations not supporting the multi-link operation raises many issues related to multi-link channel access performance and fairness. This paper evaluates various channel access approaches considered in the context of the Wi-Fi 7 non-STR operation and discusses how to organize channel access in multi-link Wi-Fi 7 congested networks to be both efficient and fair, even in the presence of legacy stations.

INDEX TERMS 802.11be, Wi-Fi 7, multi-link, simultaneous transmission and reception, channel access.

1. INTRODUCTION

Since 1997, Wi-Fi has increased its nominal data rates from 2 Mbps of the initial standard to almost 10 Gbps of IEEE 802.11ax, aka Wi-Fi 6.1 Such growth is achieved mainly by improving the modulation and coding schemes (MCS), increasing the number of streams in the multiple-input multiple-output (MIMO) technique, and expanding the bandwidth. Today we have almost reached the limit in improving MCSs, while the cost for an additional increase in the order of MIMO is the complexity of devices and the extremely high overhead of the explicit channel sounding procedure. Fortunately, the Federal Communications Commission recently granted Wi-Fi the 6 GHz band, spanning from 5925 MHz to 7125 MHz, totaling 1200 MHz of additional spectrum.

Unfortunately, the current Wi-Fi approach to wide channel usage is not efficient for many reasons. First, the channel access is mostly controlled by the primary 20 MHz subchannel. Even if the primary subchannel is busy while the rest of the subchannels are idle, the whole wide channel is blocked. Second, operation in a wide channel consumes more power, which is crucial for mobile devices. Third, as the channel width grows, so does the number of tones and, consequently, the peak-to-average power ratio. Fourth, various parts of a wide channel may have different properties and interference levels, requiring different channel access parameters, transmit power, etc. Finally, if a device supports only single-channel operation, the vendors cannot indicate on the box a higher throughput than defined in the standard. Thus, the customer

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1...or even up to 277 Gbps of IEEE 802.11ay (mmWave Wi-Fi), not considered in the paper.
has a fuzzy motivation to buy a particular device. However, if a device could use several channels, the total throughput can be a multiple of the standard limit, and the aforementioned problems are alleviated.

That is why, in addition to widening channels from 160 MHz to 320 MHz, the developers of IEEE 802.11be, also known as Wi-Fi 7, have decided to allow multi-link operation, which is the simultaneous usage of several links for data transmission with tight interaction between the links [1]. Multi-link operation addresses all the aforementioned issues.

Although modern chipsets can already use several links simultaneously in different bands, say, 2.4 and 5 GHz, the links work fully independently, which limits the efficiency of such operation. For example, the current implementations limit devices’ ability to quickly balance the load between the links, duplicate the packets to achieve higher reliability, or concurrently access the channel to reduce channel access delays. IEEE 802.11be will use such a synchronization level between the links that allows efficient use of the channel resources and does not suffer from interference in dense deployments.

Currently, the development of the IEEE 802.11be standard is at an early stage, and many issues are still open. One such issue is cross-link interference, which limits the ability of the devices to transmit and receive information on different links simultaneously. The multi-link devices commonly can perform simultaneous transmission and reception (STR) when using different bands. Otherwise, a device may discover that its links become jammed when it starts transmission on one link. This effect prevents the device from receiving or even carrier sense during its transmission. The inability of STR essentially prohibits the independent usage of multiple links and, hence, reduces the gain of multi-link operation.

Cross-link interference turns out to be a common effect that can appear even between the channels in 5 GHz and 6 GHz bands [2], so it cannot be simply ignored. While rather expensive enterprise APs will likely be able to mitigate the cross-link interference, client devices tend to be cheap and hence are equipped with simple filters. Consequently, the client devices will likely be STR-incapable (NSTR) when using close frequency channels. Still, the first estimations show that NSTR multi-link devices (MLDs) can achieve a reasonable gain with such constrained multi-link operation [3], [4]. For these reasons, Task Group “be” (TGbe) designs a dedicated logic for NSTR MLDs to provide a constrained but functional multi-link operation.

Simultaneous transmission and reception frequently happen when the frames are transmitted over links asynchronously: a receiving station needs to send immediate feedback on one link while still receiving the signal on another one. If either the transmitter or the receiver is NSTR, such a transmission fully or partially fails. Hence, a medium access control (MAC) protocol shall ensure that all transmissions over multiple links between a pair of devices shall start and end synchronously. To increase the probability of such synchronized transmissions, some authors [5] and [6] consider frame alignment extensions.

TGbe has already drafted the multi-link channel access protocol. However, there is still some debate about whether the selected approach is the best one and how its performance depends on the scenario. Thus, it is critical to study various channel access protocols for NSTR devices. Such a study shall consider scenarios similar to real deployments. For example, typically, Wi-Fi networks include devices of various generations, while the majority of existing studies do not consider how the presence of legacy devices reduces the performance of NSTR MLD and affects fairness. To the best of our knowledge, this paper is the first one that provides a solid performance evaluation and comparison of various channel access schemes for NSTR operation in Wi-Fi 7, focusing on fairness in the presence of legacy devices. This work is also aimed at becoming a short guide to multi-link operation in Wi-Fi 7 and, hopefully, a kick-off for the research community to improve multi-link for 802.11be.

The main contributions of this paper are as follows. First, we propose a classification for possible multi-link channel access schemes based on Enhanced Distributed Channel Access (EDCA). Second, we compare the throughput and fairness of these access schemes in various congested scenarios with legacy devices. Third, we confirm that being intuitively useful for NSTR MLD, frame alignment only degrades the performance of NSTR MLDs that use the standardized channel access scheme. At the same time, we reveal that the frame alignment boosts the performance of another scheme considered in the paper. Based on our results, we give recommendations on the use of channel access schemes and the directions for future research.

The rest of this paper is organized as follows. Section II describes the fundamentals of legacy and multi-link operation and reviews the prior arts. Section III describes and classifies various NSTR channel access schemes. In Section IV, we define the scenarios, and in Section V, we present and discuss the obtained key results of our study. Section VI concludes the paper.

II. BACKGROUND

In this section, first, we revisit the existing 802.11 channel access rules featuring EDCA, RTS/CTS mechanism, and wideband operation. Second, we describe the multi-link operation, as specified in the latest 802.11be standard draft, and examine the channel access ideas within TGbe itself. Finally, we review the academic literature related to the multi-link operation.

A. PRE-802.11be CHANNEL ACCESS

Modern Wi-Fi networks use EDCA as the main channel access method. With EDCA, a station (STA) performs a random backoff procedure before each transmission attempt. For that, the STA initializes its backoff counter with a random number chosen uniformly from the interval \([0, W]\), where \(W\) is the contention window. The backoff counter decrements
when the channel is idle for a slot $\sigma$. If the channel is busy, the STA suspends the backoff counter. The STA resumes the backoff counter when the channel is idle for the Arbitration InterFrame Space (AIFS).

In Wi-Fi networks, the channel is considered busy if a STA receives some signal stronger than the energy detection threshold of –62 dBm, or it has captured a preamble of a frame with power above the preamble detection threshold of –82 dBm and is still receiving that frame. The channel is also considered virtually busy if another STA has reserved such information, e.g., with the Request-to-Send / Clear-to-Send (RTS/CTS) mechanism described below.

When the backoff counter reaches zero, the STA performs a packet transmission attempt. If the STA receives an acknowledgment (ACK), the attempt is successful, and the STA sets $W$ to the minimal value $W_{\text{min}}$. Otherwise, the STA doubles the previous contention window $W$ unless it reaches the maximal value $W_{\text{max}}$.

EDCA distinguishes four access categories (voice, video, best effort, and background traffic) that are assigned different priorities and hence served differently. Each access category is assigned a dedicated queue and a dedicated backoff procedure. Backoff procedures of various queues differ by contention parameters. The higher is the priority of an access category, the smaller are $W_{\text{min}}$ and $W_{\text{max}}$.

With EDCA, two neighboring STAs may start their transmissions simultaneously, which results in collisions. The STAs may use the RTS/CTS handshake to reduce the duration of collisions. With RTS/CTS, packet transmission starts with a short RTS frame. If it is received successfully, and the channel is idle at the receiver’s side, the receiver replies with a CTS frame. After this handshake, channel access (a transmission opportunity, TXOP, as it is called in Wi-Fi) is obtained. Then the sender transmits data frames, and the receiver replies with ACKs. Both RTS and CTS frames contain information about the expected total TXOP duration to prevent other STAs from accessing the channel during the TXOP.

The channel utilization can be further enhanced by aggregating multiple packets in one frame. With Aggregated MAC Protocol Data Units (A-MPDUs), a device can transmit several packets as a single frame reducing overhead (e.g., contention, interframe spaces, RTS/CTS handshake, preambles, etc.) induced by physical (PHY) and MAC layer protocols. Typically, a receiver of an A-MPDU replies with a block acknowledgment, which indicates the correctly received packets.

On top of that, Wi-Fi devices can support wideband operation, where they adaptively select the bandwidth for frame transmission. For that, the standard defines a hierarchy of channels spanning from 20 to 160 MHz (to 320 MHz in IEEE 802.11be). First, a STA obtains channel access in the primary 20 MHz channel following the aforementioned EDCA rules. Then it can successively append secondary 20 MHz, 40 MHz, 80 MHz, and 160 MHz (the latter only in the case of IEEE 802.11be) channels if they are idle.

## B. MULTI-LINK OPERATION

Multi-link is a revolutionary novelty of Wi-Fi 7, which allows a wireless device to communicate with a peer device over multiple links seamlessly. Multi-link operation is beneficial for extremely high data rate requirements and guaranteed ultra-low latency, which are the main targets of IEEE 802.11be.

Modern dual- and tri-band APs usually cannot serve any user simultaneously in several bands. On the other hand, multi-link can flexibly and dynamically steer the packet flows over the bands. Multi-link also differs from Fast Session Transfer, introduced in the 802.11ad standard. The latter allows a device to use just one band at a time and switch the band in case of blockage or congestion. The former, multi-link, eases and accelerates the band-switching process. In addition, the multi-link feature allows simultaneous operation in multiple bands, which makes multi-link not just a complement of the wideband operation but also a better alternative.

To enable multi-link operation, IEEE 802.11be introduces a concept of an MLD with a single interface to the Logical Link Control (LLC) sublayer and several affiliated radio interfaces. Each radio interface is associated with dedicated PHY and low-MAC protocols, which perform channel access, transmit and receive packets on each link independently of the others. In other words, an MLD has several affiliated STAs, each of which runs its own MAC and PHY protocols. At the same time, the MLD has a unique MLD MAC address, common packet queues, security, and management parameters. The packets transmitted over all links belong to the same sequence number space, which allows a STA to transmit its packets on one link and retransmit undelivered packets on another one.

The standard defines two types of multi-link operation: STR and non-STR (NSTR). An MLD can perform the STR operation if the corresponding radios are isolated and the channels on which the links operate are separated by a sufficient spectral distance. Otherwise, cross-link power leakage occurs, which leads to cross-interference between the links. Specifically, if an MLD transmits on one link, the interference on the adjacent link prevents the MLD from sensing the channel and receiving any data. Thus, the ability to support STR operation depends both on the properties of the device and the operating channels. But Wi-Fi devices rarely switch the operating channels in a setup network, so the STR ability mainly depends on the device properties only. Hence, we will refer to MLDs as STR or NSTR for shortness.

NSTR MLDs, a focus of this paper, cannot independently access the channel on different links because their transmission in one link can affect the reception in the other link. In spite of such a limitation, the multi-link operation can provide some gain but requires proper channel access rules. On the one hand, these rules shall maximize the
NSTR MLD performance. On the other hand, in a heterogeneous environment with both multi-link and legacy single-link devices, the rules shall provide fair resource allocation. This paper addresses the problem by examining channel access rules specified in the current standard, as well as other rules proposed in the literature and various submissions to IEEE 802.11.

The multi-link channel access for NSTR MLDs has raised much discussion within TGbe. The earliest approaches to synchronous channel access in Wi-Fi were proposed in [7], [8], and [9]. The first one inherited the wideband operation of 802.11 and introduced one primary link and several secondary links, which can be involved in the transmission only together with the primary link. According to the proposed approach, the MLD performs EDCA on the primary link. If it wins the contention, it can additionally transmit in those secondary channels that have been idle for a certain period, namely Point coordination function InterFrame Space (PIFS). This approach is further described in Section III-A1.b.

Another approach was to run EDCA on all links separately [8], [9], [10]. When the backoff counter reaches zero on at least one link, the MLD may transmit on all links, the channels of which are idle for at least PIFS, despite their backoff values. This approach is rather aggressive and potentially unfair: MLDs gain channel access considerably more often than single-link devices in the same network. See Section III-A2.b for more information.

An opposite approach [7] makes MLD wait until backoff procedures are finished for all links. Only after that the MLD starts a synchronous transmission. See details in Section III-A2.c. This approach has been improved by the current version of the standard that allows the MLD to choose whether to wait until the backoff counters reach zero on the other links when it reaches zero at least on one link. Apart from that, submission [10] suggests truncating the remaining backoff on the other links. Specifically, when the backoff reaches zero on one link, the MLD can transmit on those links where the backoff is below some predefined threshold.

Asynchronous transmission by NSTR MLD causes the blindness issue. When an NSTR MLD transmits on one link, it becomes blind and cannot track the state of the other links. So, in all the schemes, MLDs should suspend backoff on these links for the transmission time. Moreover, even after the transmission ends, the NSTR MLD remains blind on the other links. As the MLD may miss a frame preamble, it considers the channel on these links as busy only if the signal is above the energy detection threshold. To rediscover the actual channel state, the MLD can temporarily reduce the energy detection threshold [11], [12]. Another approach is to wait for a maximal frame duration or until a new frame is detected, whichever happens earlier. An access point (AP) could also assist the NSTR MLD: after successful transmission, the AP can respond with an ACK that contains information about the channel state in all other links. However, this approach requires more sophisticated MAC protocol modifications.

Unfortunately, even with the discussed improvements, asynchronous transmissions by NSTR MLD reduce the gain of the multi-link operation compared to STR, especially in highly loaded networks [13]. Many proposals suggest new mechanisms that can help to organize synchronous channel access. For example, submissions [14], [15], [16], [17] propose various schemes of using trigger frames to initiate uplink multi-link transmission.

C. LITERATURE REVIEW

In addition to the intensive discussion within TGbe, the multi-link operation has attracted much interest in the academic community.

The research on multi-link operation originates from the improvement of wideband operation. The paper [18] describes an analytical model of an 802.11ac/ax network, where the STAs can simultaneously transmit on those 20 MHz wide channels that are idle. The paper also proposes a simple method to select a near-optimal primary channel to maximize the total throughput. However, the designed model cannot be directly applied to evaluate the performance of the multi-link operation.

The paper [19] proposes an extension to the wideband operation scheme where a device switches its primary channel if it is busy for a long time. For that, the STAs contain independent radios that monitor various primary channels. Also, the devices run different backoff procedures in various primary channels. The authors use simulation in the Residential Scenario (SS1) of IEEE 802.11 TGax to show how the throughput and delays are improved with the proposed approach. Unfortunately, such a mechanism is impractical because the power-saving devices can lose connectivity.

Several papers study the multi-link operation by studying multi-connectivity in Wi-Fi networks, i.e., the ability of a STA to be associated with multiple APs. At the time of the paper being written, this feature is beyond the standard.

The authors of the paper [20] exploit multi-band connectivity for a control plane and data plane separation. They achieve more efficient resource management and improve throughput and reliability. However, control and data plane separation is not crucial for typical Wi-Fi networks.

The paper [21] models multi-connectivity in 802.11ax networks, assuming the absence of cross-interference between different links. They consider that client STAs are connected to multiple APs and transmit the same information to many APs to improve reliability. Because of the made assumptions, the results of the paper are inapplicable to NSTR MLDs that follow the standard.

In work [22], the authors demonstrate a prototype of an STR multi-AP multi-link system, where the STA operates in two channels to reduce latency for packets from real-time applications (RTA).

Some recent papers evaluate the performance of STR multi-link operation of 802.11be. The authors [23] use a custom MATLAB-based simulator to demonstrate that STR multi-link operation in Wi-Fi can reduce the worst-case
latency by order of magnitude and satisfy stringent worst-case latency requirements in dense traffic conditions, which is especially helpful for RTA. However, the authors analyze only how STR MLDS reduce latencies. In contrast to our work, the study does not consider channel access approaches in the case of cross-link interference, i.e., the NSTR operation.

The performance of NSTR multi-link operation is studied in the papers [5], [6], [24], [25], [26]. The paper [5] compares various two-link channel access schemes, where the device accesses channels in both links synchronously when

1) the backoff counter on a primary link reaches zero;
2) at least one backoff counter reaches zero;
3) both backoff counters reach zero.

Also, they consider a scheme where the device accesses channels independently but aligns transmission ends. The authors extend Bianchi model [27] to analytically calculate the throughput of the network. The analytical model is verified through a self-developed MATLAB model. The main assumption of the model is that all transmissions are synchronized, which is not held if at least one single-link (or legacy) device is present in the network (in our paper, we provide many results confirming this statement). Moreover, transmissions may have different durations, so slot boundaries may not be synchronous on different links. Our study corrects this limitation and includes more channel access schemes, including those which are similar to the schemes from [5] (see Sections III-A1.b, III-A2.a and III-A2.b).

The paper [6] studies downlink transmissions for MLDS. It considers a case when an STR AP tries to align the ends of transmissions on different links if it sends data to an NSTR MLD. As for channel access, the paper analyses two solutions. The first one synchronizes backoff counter on two links by suspending it when the channel is busy on at least one link (a similar scheme is considered in Section III-A1.a). The second solution allows starting transmissions asynchronously but forces frame end alignment by cutting one of the transmissions. As this solution can be applied to various schemes, we consider it as an option in Section III-B2. The authors implement their solutions using the widely used ns-3 platform and consider the presence of overlapping networks. The results show that the approaches work efficiently only when single-link devices generate a light load. Unfortunately, these solutions do not apply for uplink transmissions and a higher number of contending devices. The paper [24] by the same authors presents a set of advanced techniques for an asynchronous channel access scheme: opportunistic backoff procedure resumption and an additional multi-channel busy status indication from the AP. These studies focus only on a case of asynchronous channel access without considering other options from the literature. In [25], the authors evaluate the performance of STR and NSTR using a dataset with real spectrum occupancy measurements of the 5 GHz band. The results of the trace-based simulation model show that while STR generally outperforms NSTR in terms of latency reduction in asymmetrically occupied channels, the use of STR may be detrimental and increase the latency compared to default single link operation. Our previous conference paper [26] studies the performance of the standardized channel access scheme for NSTR MLDS. We have shown that the presence of legacy single-link devices may significantly reduce the gain of the multi-link feature, i.e., the two-link NSTR device obtains throughput well below the expected doubled throughput of a single-link device.

This paper extends our previous work by comparing many more channel access schemes in a vast range of scenarios. We consider the channel access strategies not present in the 802.11be standard amendment draft and study how RTS/CTS mechanism influences the behavior of MLDS. We also compare the strategies using both per-device throughput and fairness metrics.

III. CHANNEL ACCESS SCHEMES

In Section III-A, we propose a basic classification of EDCA-based channel access schemes for NSTR multi-link operation described in the literature (see Section II-C). The classification is illustrated in Fig. 1. In Section III-B, we elaborate on the extensions of the schemes: RTS/CTS mechanism and the frame duration alignment approach considered in [6] and [26].

A. CHANNEL ACCESS SCHEMES CLASSIFICATION

To simplify the description of the considered channel access schemes, we define an EDCA function as a procedure that determines when a frame is permitted to be transmitted. Depending on the scheme, an MLD can run a single EDCA function or multiple EDCA functions, each of which is assigned to a specific STA of the MLD. Let us consider these two types separately.

1) SCHEMES WITH A SINGLE EDCA FUNCTION

a: COMMON EDCA

The schemes with a single EDCA function can be realized in two ways. First, called Common EDCA (C-EDCA) means that the MLD counts down the backoff when the channels of all of its links are idle and suspends backoff when at least one of the links is busy. A similar approach was considered in the early development of IEEE 802.11n in the context
of 40 MHz operation [28], [29]. It was discussed that a station could decrement backoff only when all subchannels are idle and pause when at least one is busy — C-EDCA acts likewise, substituting subchannels with links. When the backoff becomes zero, the MLD transmits on all links in parallel. For clarity, we define that the contention window doubles if all transmissions fail, and the contention window resets to $W_{\text{min}}$ if at least one transmission is successful or if the retry counter reaches Retry Limit.

**b: PRIMARY EDCA**

With Primary EDCA (P-EDCA), the MLD selects a primary link, while all the other links are called secondary ones. The MLD counts down the backoff on the primary link when its channel is idle. When the backoff timer expires, the MLD transmits on the primary link and on those secondary links where the channel is idle for at least PIFS. The P-EDCA scheme is an evolution of 11ac/ax wideband operation because it uses very similar rules. This scheme has first been considered in [7], [8], [9] and also in paper [5].

**2) SCHEMES WITH MULTIPLE EDCA FUNCTIONS**

In the schemes with multiple EDCA functions, each STA affectionated with an MLD (MLD-STA) runs its own EDCA function. All these schemes can be summarized as follows.

1) When a backoff of an MLD-STA expires, the MLD-STA becomes an inviting MLD-STA.

2) The inviting MLD-STA waits until at least $M$ other MLD-STA(i) have backoff equal or less than some threshold $B_{th}$, or (ii) are transmitting, or (iii) sense the channel as busy.

3) After condition 2) is satisfied, all MLD-STA that are contending with backoff $\leq B_{th}$ become invited MLD-STA, and the MLD starts a parallel transmission on the links of invited and invited MLD-STAs.

4) The rest of the contending MLD-STAs suspend their backoff for the transmission duration.

5) If the link of the inviting MLD-STA becomes busy, the MLD-STA does not transmit and restarts its backoff for the next attempt (the contention window is unchanged). Note that $B_{th}$ can vary from 0 to the maximum backoff, and $M$ cannot exceed the total number of MLD-STAs on MLD.

Below, we consider several schemes that use multiple EDCA functions.

**a: INDEPENDENT EDCA**

In the Independent EDCA (I-EDCA) scheme, $M = 0$ and $B_{th} = 0$. Thus, the inviting MLD-STA does not wait for other STAs but transmits with only those STAs that have zero backoff, i.e., they win the contention at the same time. Although the scheme has much in common with the STR operation, in contrast to the STR operation, with I-EDCA, each MLD-STA suspends its backoff if another MLD-STA initiates the transmission. Note that 802.11be specification will support I-EDCA. An idea similar to I-EDCA is considered in [6].

**b: MULTI-EDCA**

In the Multi-EDCA (M-EDCA) scheme, $B_{th} = 1023$, i.e., the maximum backoff value. The STA that finishes backoff first invites all other STAs with idle channels for a synchronized transmission. M-EDCA has been considered in [8], [9], and [10].

**c: STANDARDIZED EXTENSION OF EDCA**

The current 802.11be standard describes a channel access scheme that corresponds to $B_{th} = 0$ and any $M$ that can be selected by the developers. If $M = 0$, we obtain I-EDCA. Otherwise, we obtain a scheme referred to as the Standardized Extension of EDCA (S-EDCA). With S-EDCA, the MLD-STAs have to finish the backoff to become invited. Hence, the MLD waits for a maximum backoff time among $M$ smallest backoff timers. S-EDCA concept has also been described in [7].

**B. EXTENSIONS OF THE SCHEMES**

1) RTS/CTS

All the described schemes can also adopt the synchronous RTS/CTS handshake. An MLD using a scheme with a single EDCA function can send RTS frames synchronously in multiple links. Then the MLD transmits data frames on those links where the handshake was successful, i.e., a CTS frame was received. An MLD using a scheme with multiple EDCA functions uses the RTS/CTS mechanism similarly: the MLD sends RTS frames concurrently for a synchronous transmission attempt; or independently otherwise. On top of that, an MLD can choose different rules to manage backoff and the contention window on invited MLD-STAs. In our simulations, MLDs update the backoff and contention window on the invited MLD-STAs after any of their transmission attempts.

2) FRAME ALIGNMENT EXTENSION

On top of the considered simple channel access schemes, we analyze the effect of frame alignment extension. With this extension, an MLD attempts to transmit a frame, which aligns with the ongoing transmission on another link. The motivation is to provide more opportunities for all NSTR MLDs to perform a synchronized transmission in two links.

For example, in Fig. 2, MLD A starts transmission on Link 1, and MLD B operating on Link 1 and Link 2, finds the frame duration from its preamble. In IEEE 802.11, the duration can be deduced from the modulation and coding.
scheme and the frame payload length in bytes, both contained in an L-SIG field of the PHY preamble. Given the frame duration and the remaining contention time in Link 2, MLD B can manipulate the duration of its own frame so that both frames end almost simultaneously (within a margin of 4–8 µs). So, the channels become free at the same time in both links, which allows any NSTR MLD, such as MLD C, to perform simultaneous transmission.

In the following sections, we use simulation to study the performance of the five aforementioned channel access schemes.

IV. SCENARIOS

In the considered scenarios, many legacy devices and MLDs are connected to a single AP MLD, see Fig. 3. All MLDs support two links connectivity. The AP is STR, and the non-AP MLDs are NSTR. We consider such a scenario as we expect that AP MLDs will have sufficient size and special technical solutions to combat inter-channel interference, while small user devices may not be able to do that. Let \( N_1 \) legacy devices operate on Link 1, \( N_2 \) legacy devices operate on Link 2, and \( N_3 \) MLDs operate on both links. We consider two scenarios:

- Scenario 1 — symmetric scenario. The numbers of legacy devices on both links are the same: \( N_1 = N_2 \).
- Scenario 2 — asymmetric scenario. Legacy devices operate only on Link 2, \( N_1 = 0 \).

We consider an ideal channel between the devices (i.e., no fading, fixed transmission parameters). All stations have saturated uplink traffic (for each link) of the same access category, and there is no downlink traffic from AP MLD. The AP acknowledges the successfully received data with ACK/BlockAck frames and answers to RTS frames with CTS frames. The NSTR blindness problem mentioned in Section II-B is addressed by assuming that after the MLD finishes its transmission, its MLD-STAs can detect the ongoing transmissions from other devices by the energy level, even if the preamble is missed. So, the MLD-STAs consider the corresponding links as occupied and suspend EDCA. When the occupying signal ends, the MLD-STA on that link will wait for an Extended InterFrame Space (EIFS).

We model the described scenario using an ns-3-based simulation tool. Let all devices be in the range of each other. Also, in an ideal channel, an RTS or A-MPDU frame can be lost only due to a collision because, in all access schemes, self-interference is avoided. MIMO is not used in the analyses, as it would simply result in the multiplied throughput by the number of spatial streams.

Table 1 summarizes the simulation parameters. The devices transmit data in uplink using A-MPDUs. Each MPDU carries \( L = 1500 \) bytes of payload. Typically, each A-MPDU contains a number of MPDUs uniformly distributed between 50 and 64 unless stated otherwise. Notably, if an MLD synchronously transmits two A-MPDUs on two links, the shortest A-MPDU is padded to match the duration of the longest one.

In every scenario, we study the access scheme with and without RTS/CTS handshakes. In our scenarios, the MLDs can use one of the five uplink channel access schemes described in Section III: C-EDCA, P-EDCA, S-EDCA, M-EDCA, and I-EDCA.

| TABLE 1. Simulation parameters. |
|-----------------------------------|
| Total number of devices | 8 |
| MPDU payload | 1500 bytes |
| MCS | 4 |
| Bandwidth | 80 MHz |
| Number of spatial streams | 1 |
| AIFS | 34 µs |
| \( W_{\text{min}} \) | 15 |
| \( W_{\text{max}} \) | 1023 |
| Max retries | 7 |
| Modeled time | 100 s |

V. NUMERICAL RESULTS

A. SCHEMES WITH SINGLE EDCA FUNCTION

We start with the Common EDCA channel access scheme, described in Section III-A1. Figure 4 shows the per-device throughput for legacy devices and MLDs. The numbers in square brackets in figures \([N_1, N_2, N_3]\) indicate the number of devices of each type. In Scenario 1 (Fig. 4a,b), legacy stations in both links have the same throughput because of the behavior of MLDs in the C-EDCA case is symmetrical. For MLDs, the bar graph shows the aggregated throughput over both links.

As Fig. 4 shows, the MLDs employing C-EDCA obtain negligibly small throughput (less than 5% of legacy devices’ throughput). The MLDs can rarely transmit in these scenarios because the traffic at all devices is saturated, and the legacy stations occupy the links asynchronously. Hence, both links are rarely free simultaneously, so MLDs have a small opportunity to count down the backoff and then transmit. With the use of the RTS/CTS handshake, the performance of MLDs does not improve significantly, but it maximizes the total throughput to up to 327 Mbps. Because the RTS/CTS handshake further reduces the collision time for all stations, the channel time is mostly occupied by successful transmissions.

In Scenario 2, the situation changes radically for MLDs. With RTS/CTS off (Fig. 4c), the throughput per MLD is 2–6 times greater than that per legacy device. The MLDs in these scenarios contend in the second link together with the legacy devices transmits data in Link 2, which allows any NSTR MLD, such as MLD C, to perform simultaneous transmission.
station, but they transmit frames in two links simultaneously instead of one. The gain for MLDs is much higher than 100% because, in the case of collision between an MLD and a legacy station, the latter loses its single frame and increases the backoff stage, whereas the MLD loses just one of the two and does not increase the backoff stage (see description of C-EDCA). For example, in the [0, 6, 2] case, the average backoff duration for legacy devices is 17.8 slots, whereas it is just 8.4 slots for MLDs; in the [0, 1, 7] case, values are 17.1 slots and 14.0 slots for legacy devices and MLDs, respectively.

In Scenario 2, RTS/CTS increases throughput for every STA, retaining a similar behavior (see Fig. 4d). However, when the quantity of legacy stations decreases, their throughput rises rapidly. The reason is as follows. When a legacy device falls into collision with an MLD on Link 2, the MLD transmits only on a non-collided Link 1. All other MLDs with C-EDCA sense this transmission and suspend their backoff. Contrary, the legacy stations are not listening to Link 1 and can access the channel on Link 2, free of MLDs.

To measure the fairness of channel resource distribution, we use Jain’s index, displayed in Fig. 5. Jain’s fairness index [30] is a fairness measure widely used in the literature, and it is calculated as follows.

\[ J(x_1, \ldots, x_n) = \frac{\left(\sum_{i=1}^n x_i\right)^2}{n \cdot \sum_{i=1}^n x_i^2} \]

We use the “per-interface” throughput of devices at each specific link as arguments for the measure. That means Jain’s index will max out when all interfaces of legacy devices or MLDs will have the same opportunity to transmit on a link. Note that in Scenario 1, Jain’s index is equal in both links, whereas, in Scenario 2, Jain’s index in Link 1 always equals one because MLDs share their resources equally. Hence, we always plot only Jain’s index for Link 2.
In Scenario 1 (Fig. 5a), the poor performance of MLDs leads to a drop in Jain’s index because the majority of resources are obtained only by legacy devices. The fewer devices obtain the most resources, the smaller becomes the Jain’s index. In Scenario 2 (Fig. 5b), when there are few of MLDs, they additionally gain channel time on Link 2, more than legacy devices, hence reducing Jain’s index by up to 0.17. However, when the portion of MLDs becomes larger, legacy devices get more channel time than MLDs in Link 2, taking advantage of collisions between MLDs, as described previously.

As an intermediate summary, C-EDCA is inapplicable for MLDs if legacy devices occupy two links and have a high traffic load. If only one link serves legacy devices, C-EDCA shows good performance. However, there is a high imbalance in channel distribution between device types when the numbers of devices of each type differ significantly.

We continue with the P-EDCA scheme, which, unlike C-EDCA, has an additional degree of freedom, i.e., the location of the primary link. Here we study Scenarios 1 and 2, where all MLDs set their primary link on either the first or the second link, as would be stated in the further text.

We start with MLDs having Link 1 as their primary link. For P-EDCA in Scenario 1 (Fig. 6a), we illustrate throughput per legacy device separately for Link 1 and Link 2. One can see that legacy devices on Link 2 are essentially unaffected by MLDs because the latter rarely transmit on secondary Link 2 in sync with Link 1. As with C-EDCA, this is the problem of misaligned legacy transmissions on both links. This leads to a situation where MLDs perform similarly to legacy devices on Link 1.

In Scenario 2 (Fig. 6b), again, we notice that MLDs on Link 1 operate independently of legacy devices on Link 2. The throughput per device depends mainly on the number of stations on a link. The introduction of multi-link operation leads to rare simultaneous transmissions in two links. This explains the slightly increased throughput of MLDs (by 3–16%) in [0, x; 8 − x] cases compared to legacy devices in [0, 8 − x; x] cases.

The case of primary Link 2 is trivial and is not shown in the paper. Because of the symmetry of Scenario 1, the behavior is identical to a former case in Fig. 6a. In Scenario 2, MLDs contend in Link 2 together with the legacy devices, but MLDs’ throughput is twice as high because of an additional transmission on Link 1. For Scenario 2, the performance for MLDs and legacy devices stays constant at 35 Mbps and 17.5 Mbps, respectively.

To summarize, MLDs employing P-EDCA have a marginal advantage over legacy stations. MLDs cannot access the channel on the secondary link if there are legacy devices...
B. SCHEMES WITH MULTIPLE EDCA FUNCTIONS

Next, we study the throughput per device (MLD and legacy devices separately) when MLDs use channel access schemes with multiple EDCA functions (see Section III-A2): I-EDCA, M-EDCA, and S-EDCA. We plot the throughput values for the three schemes in Fig. 7, 8. On top of that, we added the frame alignment extension to these schemes.

The first observation is that the performance of these schemes does not differ much without frame alignment. As with previous schemes, MLDs can rarely access channels in two links at the same time when legacy devices occupy both of them and their load is high. The time portion of synchronous transmissions is negligibly small (<5%). The major gain for MLDs is due to the ability to access the channel on either link independently.

Notably, Frame alignment does not change the performance of I-EDCA (not shown in Fig. 7, 8) but changes the performance of S-EDCA and M-EDCA significantly and differently. After the frames in the two links are aligned, a device with a more aggressive EDCA function will likely capture the channel first. The M-EDCA scheme with frame alignment is the most aggressive one among the considered. It prioritizes MLDs because their expected backoff is less than that of legacy devices. Hence, M-EDCA devices often transmit synchronously in two links, which results in the highest throughput for MLDs but at the cost of the reduced performance of legacy devices. Moreover, M-EDCA MLDs’ gain is at most 30%, whereas legacy devices can lose up to 65% of their performance. This leads to 2–5-fold throughput dominance of MLDs over legacy devices, and it naturally raises fairness concerns. Figure 9b,e confirms that M-EDCA has the lowest fairness in terms of Jain’s index. Each M-EDCA MLD captures more channel time than a legacy device in the same link.

Conversely, S-EDCA is the least aggressive scheme. It reduces the performance of MLDs, allowing legacy devices to capture more channel time, up to twice as much in the considered scenarios. Figure 9c,f depicts this relatively unfair resource distribution: Jain’s index per every channel with legacy devices drops by up to 12% from the maximal value. Since, with the S-EDCA scheme, the expected backoff of MLDs is larger than that of legacy devices, MLDs get less priority. Moreover, MLDs shorten their frames to perform alignment, which makes their gain from frame alignment negative. Apparently, both effects are an unwanted behavior, so frame alignment, though it seems useful, is inappropriate for the S-EDCA scheme.

From Fig. 7 and 8, we observe that the described effects remain for both Scenario 1 and 2, different distributions of the A-MPDU size (i.e., the number of MPDUs in each
Throughput per device for S-EDCA, M-EDCA, and I-EDCA, Scenario 1, RTS/CTS off. Left: MLDs, right: legacy devices, top: MPDUs per A-MPDU ~ $U[50, 64]$ bottom: MPDUs per A-MPDU ~ $U[1, 64]$. \([N_1, N_2, N_3]\) denote the number of legacy device on Link 1, on Link 2, and the number of MLDs, respectively.

Jain's index for networks with MLDs using multiple EDCA functions, frame alignment on. Left: I-EDCA, center: M-EDCA, right: S-EDCA, top: Scenario 1, bottom: Scenario 2. \([N_1, N_2, N_3]\) denote number of legacy device on Link 1, on Link 2, and number of MLDs, respectively.
A-MPDU: $U[50, 64]$ and $U[1, 64]$), and both with and without the RTS/CTS mechanism.

Specifically, in Scenario 1, legacy devices are distributed equally among the links, and MLDs without alignment obtain a 50–60% throughput increase compared with legacy devices. It is a reasonable gain, but still far from the expected 100% gain of STR MLDs. M-EDCA with frame alignment even surpasses it, but at the cost of performance reduction of legacy devices. In Scenario 2 (see Fig. 7c,d), MLDs fully use less congested Link 1, obtaining maximum gain over legacy devices.

The RTS/CTS mechanism only reduces collision time. Consequently, the throughput bars in Fig. 7a,b are higher than the corresponding bars in Fig. 8a,b by 7–12% for legacy devices and 14–30% for MLDs. However, RTS/CTS does not significantly change the behavior of multi-link channel access schemes, and the qualitative effects are similar.

The A-MPDU length distribution does not notably influence this behavior either. Indeed, the bars in Fig. 8a,b are only slightly higher than in Fig. 8c,d because, on the one hand, larger A-MPDU sizes result in more efficient transmissions; on the other hand, they also cause longer collisions without RTS/CTS.

To summarize, the schemes with multiple EDCA functions without any modification perform similarly to each other in all the considered scenarios. All MLDs outperform legacy devices in terms of throughput because they have an additional option of which link to use. When the same number of legacy devices occupy both links, MLDs enjoy a gain from 40% to 85% as the relative number of MLDs grows. When legacy devices operate only on one link, MLDs get full access to the other link and share its resources equally. The schemes start to differ when frame alignment is introduced. When two links become free simultaneously, with M-EDCA, MLDs capture more channel resources, as they behave more aggressively than legacy devices. Moreover, we observe an increase in the number of collisions and a total network throughput drop. At the same time, with S-EDCA, MLDs access the channel less frequently than legacy devices. Therefore, the scheme described in the 802.11be draft needs modification for frame alignment to introduce gain for NSTR MLDs in congested scenarios.

The remaining challenge is to design a multi-link channel access scheme with simple rules that would enable a higher gain. Ideally, the NSTR scheme should perform similarly to STR, i.e., close to 100% gain of throughput per device while yielding the maximum total network throughput and keeping Jain’s index at each link close to 1.0.

### VI. CONCLUSION

Multi-link is one of the key features of the upcoming Wi-Fi 7 technology. It is expected to be especially beneficial for total throughput, latency, and reliability. However, the links used by MLDs may experience cross-interference, which induces a prohibition of STR. Such a constrained multi-link operation can still be beneficial, but it requires a special channel access protocol to prevent STR in the network with NSTR devices.

In this paper, we have first derived a classification of EDCA-like channel access schemes. As our main contribution, we have picked up the most debatable schemes and put them to the test using computer simulation. We have checked their throughput and fairness performance in two congested scenarios. We observe that channel access schemes with a single EDCA function are impractical in scenarios where all links are occupied by legacy devices with high traffic loads. If one link is free of legacy devices, these schemes can reach high gain, but a substantial portion of that link’s resources is wasted. Schemes with multiple EDCA functions perform similarly and significantly better than those with a single EDCA function across numerous cases. The synchronous transmissions constitute only a marginal portion, so the frame alignment extension is proposed to solve this problem. It causes high throughput of M-EDCA MLDs, sacrificing that of legacy devices, whereas S-EDCA MLDs underperform considerably. Thus, we expect that a simple I-EDCA scheme will be a viable solution for the first Wi-Fi 7 devices. To achieve higher performance, the M-EDCA scheme can be used, but it should be modified for a better tradeoff between throughput and fairness. Alternatively, an open challenge is to design a new NSTR channel access scheme that would perform closer to STR operation.

We notice that NSTR MLDs do not excel in the congested scenarios studied in this paper, and more work is required to study NSTR performance in non-full-buffer cases as well as for real-time applications. Hence, we plan to continue this work in the future.

We expect that these results will encourage the industry and academia to pay attention to the mentioned channel access schemes. These schemes can serve as a good basement for further investigation and protocol implementation in real NSTR devices.

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