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Research Article

Enhanced Multilink Single-Radio Operation for the Next-Generation IEEE 802.11 BE Wi-Fi Systems

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For the next-generation Wi-Fi systems, the Enhanced Multilink Single-Radio (EMLSR) operation has become a promising feature to improve the Wi-Fi system performance. The EMLSR enables dynamic switching among multiple bands with low-cost implementation and efficient power consumption. However, with realistic channelization of multiple links with 320 MHz bandwidth on 6 GHz and 160 MHz bandwidth on 5 GHz, the performance of EMLSR is jeopardized due to the crowded 5 GHz band with existing Wi-Fi systems. In addition, the unbalanced bandwidth configuration between an access point (AP) and stations (STAs) multilink devices (MLDs) may result in wasted secondary channels when STAs supporting smaller bandwidth stay on the primary channel only. We proposed the further enhanced EMLSR with a new MAC protocol and link selection mechanism, where a primary link (PL) is selected between AP and STA with the unbalanced Link/Band and one or multiple secondary links (SLs) with balanced Link/Band. The STA tunes the main radio on the PL and the scan radio to one of the SLs. The PL will be more prioritized than the SL based on the link selection algorithm to maximize the channel utilization. Compared with legacy EMLSR, the enhanced EMLSR can improve the utilization of the secondary channel. Even under heavy OBSS load on SL or both PL and SL, the further enhanced EMLSR can achieve 50% to 70% throughput gain.

1. Introduction

The development of IEEE 802.11 standards has been moving quickly in the past few years. With an ever-growing number of devices using Wi-Fi, the next-generation Wi-Fi systems are required to be capable of managing dense scenarios, increased data traffic, and a diverse mix of applications and services with differing requirements. Up to IEEE 802.11ac [1], the evolution of Wi-Fi standards and technologies was focused primarily on achieving successively higher throughput [2]. However, in the real deployments, with lots of users with varying application requirements, the next-generation Wi-Fi system is designed to deliver a satisfactory experience to all the users that are operating in the system [3–7]. The problem is not how high the throughput can be achieved but whether the Wi-Fi system has enough capacity to handle the growing demand for many users with different application requirements.

The latest Wi-Fi standard IEEE 802.11ax [8] or Wi-Fi 6 is designed to improve system performance by introducing several multiuser (MU) technologies, including orthogonal frequency-division multiple access (OFDMA) [9] and target wake time (TWT) [10]. In addition, the 802.11ax standard has enhanced the multiuser multiple input, multiple output (MU-MIMO) mechanism that was firstly introduced by the 802.11ac standard. By using the OFDMA mechanism, an AP can distribute the data transmissions to multiple users into multiple resource units (RUs) and simultaneously transmits data in the RUs to these users. Compared with the single-user transmission mechanism, OFDMA reduces the overhead of channel access to transmit data to the multiple users one by one. With the help of OFDMA, the performance of Wi-Fi systems under dense environment is dramatically improved [11]. The MU-MIMO mechanism is enhanced as well in the 802.11ax standard to support more spatial streams. Furthermore, MU-MIMO mechanism can be used together with OFDMA to increase the number of users simultaneously in the MU transmissions. One of the existing issues of Wi-Fi system is the overhead associated with the channel access. In order to handle the negative effects of channel contention, the TWT mechanism was introduced in the IEEE 802.11ax amendment. It provides a simple but efficient solution to schedule frame transmissions to different user groups in different time period so the channel contention is limited inside the scheduled time period. In addition to the contention reductions, TWT mechanism can also contribute to the advantage of other transmission mechanisms such as MU transmissions, spatial reuse [12], and coexistence in high-density WLAN networks.

After the IEEE 802.11ax standard was recently concluded, IEEE 802.11 Working Group (WG) [13] has been established for the development of the next-generation Wi-Fi standard named as IEEE 802.11be or Wi-Fi 7. Compared with IEEE 802.11ax [14] that focused on the development of the new DL/UL MU (OFDMA and MU-MIMO) mechanisms to improve the spectrum efficiency, 802.11be spends more efforts on the wider bandwidth operation to improve the throughput and reduce latency, especially considering the limitations from the regulations that prevent Wi-Fi system from using more bandwidth. For example, according to the FCC [15], the current bandwidth on the 6 GHz band for Wi-Fi system is up to 320 MHz. In addition, there are other issues which may not enable wider bandwidth on single band. According to the existing EDCA procedure [16] of the Wi-Fi system, the transmission opportunity (TXOP) is initiated with the backoff procedure running on the primary 20 MHz channel. The channel is determined as busy if the primary 20 MHz subchannel is busy even if the rest of the other 20 MHz channels are idle. Further, the channel with broad bandwidth is determined as busy if any of the 20 MHz channels within the operating bandwidth is busy. In other words, the broader the operating bandwidth is, the less likely the broad bandwidth of channel may be available for data transmissions. Furthermore, the operation in a channel with wider bandwidth consumes more power in a single band. The power consumption behavior is crucial for mobile devices such as phones or tables. IEEE 802.11be has changed the direction of pursing more bandwidth in a single band for maximizing the spectrum utilization. The task group has defined a mechanism named multilink operation (MLO) to explore the benefits of available bandwidth from multiple bands.

Currently, the 802.11be standard is still under development. There are no Wi-Fi products following the 802.11be specification available on the market. Most of the previous studies focused on the performance of the traditional single-link Wi-Fi systems. The IEEE 802.11be task group's technical contributions [17–19] are the building blocks for MLO operation. The contribution in [17] introduces the basic MLO architecture and necessary changes from the exiting Wi-Fi system to the next-generation MLO-based Wi-Fi systems. The contribution in [18] discusses the potential performance gain that can be obtained using the multiradio-based MLO operation. The contribution in [19] introduces the concept of single-radio-based MLO operation and provides initial performance results of single-radio-based MLO system. In paper [20], the authors have studied the impact of MLO operation on the existing 802.11 channel access procedure and presented the throughput performance of a multiradio-based MLO system, where the multiradio system is assumed to support simultaneous transmitting and receiving (STR) capability. In paper [21], the authors have summarized the developing directions of 802.11 standard and discussed the benefits of both the single-radio-based and multiradio-based MLO systems. To the best of the authors' knowledge, the studies on the newly introduced MLO mechanism of 802.11be are still very limited. This contribution is to establish a system throughput model for the existing EMLSR mechanism for performance analysis and further propose the enhancement to improve the existing EMLSR mechanism.

Section 2 reviews the basic MLO mechanisms including multilink mutiradio (MLMR) mode and multilink single-radio (MLSR) mode defined in the IEEE 802.11be draft standard. Then, in Section 3, the existing EMLSR mode of the IEEE 802.11be is introduced and the related issues/problems are analyzed. In Section 4, a system throughput model of existing EMLSR mechanism is given for performance analysis. The further enhanced EMLS mode operation is proposed in Section 5 and performance evaluation based on NS3 simulator is shown to compare the enhanced EMLSR mechanism with the existing one in Section 6. Finally, the conclusion of this contribution is drawn in the last section.

2. 802.11BE Multilink Operation

Today, major AP vendors support the AP solutions with dual-band/triband operation. In these APs, the Wi-Fi MAC and PHY of multiple bands work almost independently and provide multiple independent links to Wi-Fi STAs. As shown in Figure 1, a dual-band AP may have both 5 GHz and 6 GHz enabled simultaneously. The AP may establish BSS1 with 160 MHz bandwidth on the 5 GHz band and BSS2 with 320 MHz bandwidth on the 6 GHz band. Because these two BSSs are operating independently and provide services to different STAs, the 160 MHz bandwidth on the 5 GHz band and the 320 MHz bandwidth on the 6 GHz band cannot be combined to achieve the optimal wider bandwidth operation of 160 + 320 MHz.

In order to optimize the system spectrum utilization and achieve better throughput performance, the IEEE 802.11be has defined the MLO to support sending data frames concurrently on multiple links. The MLO allows the users to enjoy the multilink benefits unavailable for a simple non-contiguous wide spectrum on a single link, such as asynchronous channel access and enhanced power save. As shown in Figure 1, the MLO can aggregate a various number of links of different widths, for example, 160 MHz + 40 MHz. The 802.11be has introduced a concept of a multilink device (MLD) [22] as illustrated on the right side of Figure 1 which

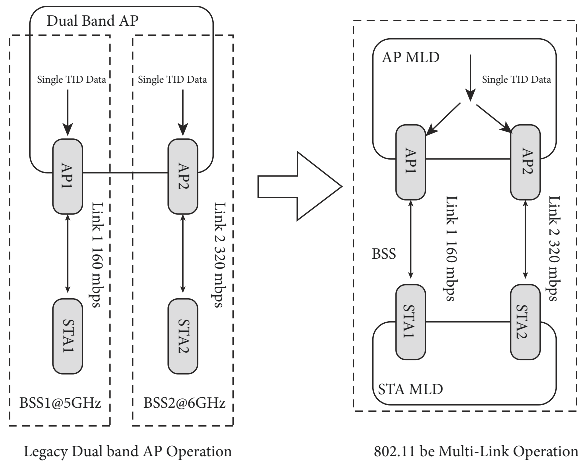

Figure 1: IEEE 802.11be MLO.

consists of multiple AP/STAs but with a single interface to the upper layer. The upper layer protocol takes the MLD as a single Wi-Fi device. Despite having multiple PHY/MAC interfaces, MLD has a single MAC address and uses this MAC address as its own identity. The sequence number space is shared by the AP/STAs within the same MLD. The MLO simplifies the procedures for frame fragmentations and frame reassembly, duplication detection, and dynamic link switching. It enables frame transmission and retransmission on any link regardless of the link of the initial transmission of the frame.

The IEEE 802.11be group has designed a new association procedure that allows AP MLD and STA MLD to establish a connection on any supported link [23]. The capabilities of all the links can be exchanged in any enabled link as well. 802.11be also enables two types of acknowledgment modes, referred to as restricted and dynamic link switch. In the restricted mode, data frames and ACKs are bound to one link [24]. Management exchanges transmitted over one link, such as relation to power save mode, security key negotiation, and Block ACK (BA) negotiation, apply only to this link. It is a simple scheme of multiple independent links with enabled aggregation. In the dynamic link switch mode, multiple links can be used for transmission of the same flow. Management information and negotiations sent over one link can apply to other links. This mode enables load balancing and congestion avoidance. It also improves peak throughput and reduces latency, overhead, and power consumption.

According the MLD types, there are different flavors [25] of MLO specified in the IEEE 802.11be draft standard. The MLD types are defined based on the capabilities of the MLD. If an MLD implements multiple radios and uses these multiple radios concurrently for the MLO, then these devices are defined as multilink multiradio (MLMR) MLD. If an MLD only implements single radio and still wants to operate multiple links, then these devices are called multilink single-radio (MLSR) MLD. After an MLSR STA MLD associates with AP MLD, it may establish MLO with the AP MLD. However, due to the limitation of having only one radio, the MLSR STA MLD cannot use multiple links concurrently. The single radio needs to switch back and forth between multiple bands in a time domain multiplex (TDM) fashion. Normally the band switch operations of a single radio require both time and extra signaling. Therefore, the MLSR operation only allows an MLSR STA MLD to switch the band in a static fashion; that is, the MLSR STA MLD may have to park the radio on one band for several minutes finishing a data transmission session and then switch to another band. To provide more flexibility, the IEEE 802.11be draft spec has defined an Enhanced Multilink Single-Radio (EMLSR) operation [26] to enable an MLSR MLD to dynamically switch band to improve both throughput and latency performance. The EMLSR provides flexibility for an EMLSR MLD STA to switch dynamically between bands to improve the opportunities to obtain a TXOP. We will discuss the details of EMLSR from the next section.

3. EMLSR Operation and Related Issues

Most of the MLSR STAs implement either a configurable radio that has the flexibility of switching between two 1×1 radios and one 2×2 radio or a scan radio in addition to the main radio to support the EMLSR operation. An example of using scan radio to support EMLSR operation is shown in Figure 2. Using the other architecture of configurable radio has a similar issue, so we skip it here to save some text. When an AP MLD intends to conduct EMLSR operation with an EMLSR STA MLD, each AP within the AP MLD tries to access the corresponding band/channel by running EDCA function independently. In this example, AP1 of the AP MLD is operating on the 6 GHz band and AP2 is operating on the 5 GHz band. If the EDCA function completes the backoff procedure, the corresponding AP starts frame exchange procedure by sending Initial Control Frame (ICF).

In this example, AP1 on the 6 GHz band completes backoff first, so AP1 sends an MU-RTS [27] frame to start EMLSR operation. MU-RTS is one of the ICF types. The STA MLD, in order to operate under the EMLSR mode, configures scan radio (STA1) on the 6 GHz band and main radio (STA2) on the 5 GHz band. When AP1 on the 6 GHz band sends out MU-RTS, the scan radio receives the MU-RTS and understands the following Downlink (DL) data transmission which will be carried out on the 6 GHz band. The scan radio has limited functionality and is not capable of receiving data frames with high MCS or NSS (e.g., above MCS4 or NSS = 2). Therefore, the main radio that stays on the 5 GHz band needs to be tuned to the 6 GHz band. The tuning procedure that involves a number of PHY/MAC operations (e.g., PLL settling, register configuration, etc.) consumes nonnegligible time. According to the IEEE 802.11be spec, the band switching time ranges from 16 μs to 256 μs depending on the implementation.

To accommodate this band switching delay and let the STA MLD be able to respond within the SIFS (16 mu s), it is defined that the MAC padding field is added to the ICF. Different from PHY padding or packet extension (PE) [28], the MAC padding is a MAC frame field with specific pattern and is added before the Frame Check Sequence (FCS). When the scan radio is in the process of receiving the ICF, it

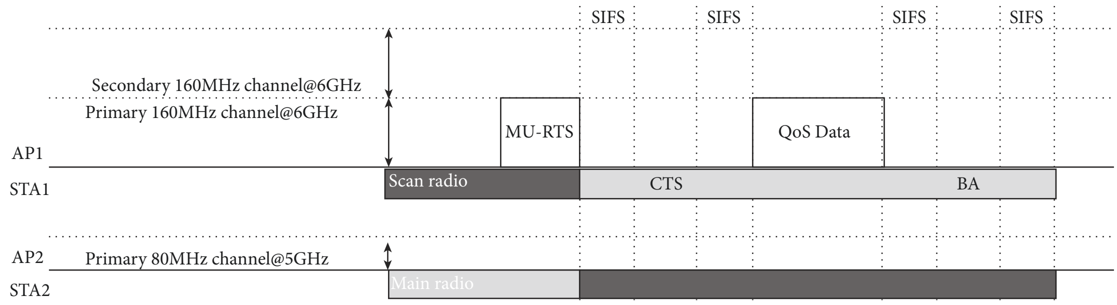

Figure 2: EMLSR operation frame sequence.

identifies the MAC padding field by matching the special pattern and starts the band switching operation before the FCS validation is conducted; that is, once the start of the MAC padding field is identified, the scan radio indicates the main radio to start the band switch procedure and the scan radio stays on the same band to complete the reception of the ICF. During this process, the scan radio performs CFO correction and other PHY related tasks and passes the obtained information to the main radio so that the main radio can get prepared to send out Trigger Based (TB) PPDU as the response. The STA when sending a TB PPDU as a response has a requirement that is more stringent than the requirement for the same STA sending out a regular Single User (SU) PPDU. It is because when an STA sends out a TB PPDU, other STAs at the same time might be triggered to send out TB PPDUs as well.

For the AP to be able to correctly decode frames in the TB PPDUs from multiple STAs, the TB PPDUs from multiple STAs are required to meet both timing and power accuracy requirements [29]. While the PHY of the scan radio is performing the above operations, the MAC of the scan radio reads the band switching information in the ICF assuming that the FCS check will pass later, as well as passing this information to main radio so that the main radio can start band switching operation. During the association procedure, the STA MLD indicates its required switching time, so when AP MLD sends out the ICF, MAC padding field with sufficient length is added to the ICF. When the scan radio in the process of the ICF reception, at the end of MAC frame, performs FCS check, if the FCS passes, then the scan radio indicates to the main radio that FCS is successful and the main radio may send out the response frame (e.g., a Clear to Send (CTS) or Buffer Status Report (BSR) frame) after SIFS. Otherwise, if the FCS check fails, then the scan radio shall indicate to the main radio to revoke the band switch operation.

Compared with other MLO options, the EMLSR has its advantages. Firstly, compared with the true MLMR MLO options, STA MLD with EMLSR does not need to implement multiple radios, so it is more cost and power consumption efficient, while it still allows end user to have the MLO operation with low-cost implementation; that is, during the EDCA procedure, both AP and STA have the flexibility of exploring multiple bands. Secondly, relative to the single-radio option, EMLSR does not compromise the capability of fast switching between multiple bands and achieves better system performance than MLSR.

As described in the above paragraphs, the EMLSR is a promising feature for the next-generation Wi-Fi systems. However, there are several issues that need to be solved to optimize the system performance. First, there is an issue caused by the bandwidth configuration of the 6 GHz and the 5 GHz BSS operation. According to the channelization [30], the 6 GHz band is cleaner and allows 320 MHz BSS operation. However, it is only allowed to operate a BSS up to 160 MHz in the 5 GHz band. In most of scenarios, it is really challenging to secure a 160 MHz PPDU transmission in the 5 GHz band due to the legacy Wi-Fi systems coexisting on the 5 GHz band. When an AP or an STA on the 5 GHz band intends to transmit a 160 MHz PPDU, it needs to complete the EDCA procedure on the whole 160 MHz channel, which means an STA needs to complete the backoff procedure on the primary 20 MHz channel and pass the ED check on the secondary 20 MHz, 40 MHz, and 80 MHz channels to finally be able to initiate the transmission. However, due to the legacy Wi-Fi systems that are already deployed, if any of the secondary channels within the 160 MHz channel is occupied by other 802.11be BSSs or a legacy BSS, the PPDU transmission is not allowed to be started. Therefore, in the crowded 5 GHz band, it is very unlikely that an AP or an STA can transmit 160 MHz PPDU in most of the typical Wi-Fi operation scenarios. As shown in Figure 3, when an AP MLD performs EMLSR operations on the 5 GHz and 6 GHz bands, each AP associated with the AP MLD runs EDCA operation on the 5 GHz and 6 GHz bands independently. Let us assume that both the 5 GHz and 6 GHz bands are equally busy and OBSSs only exist on the primary channels. Then the chance for an AP or an STA to be able to acquire the channel is almost the same. In other words, if the EDCA function is conducted independently, then the backoff on either band may be completed and the possibility of that is almost the same for either band. Now, as mentioned early, the 6 GHz is running on 320 MHz, while the 5 GHz can only run on 160 MHz or even 80 MHz. An EMLSR STA may end up with using the 6 GHz or the 5 GHz band with equal probability and switching back and forth between transmitting PPDUs with 320 MHz on 6 GHz and PPDU with 160 MHz or 80 MHz. Compared with an STA that does not support EMLSR and only operates on 6 GHz band, an EMLSR STA may have even worse performance due to the transmission spent on the narrow channel on the 5 GHz band.

Second, there is another issue caused by the bandwidth configuration difference between AP MLD and STA MLD. As shown in Figure 4, the spectrum regulation already allows

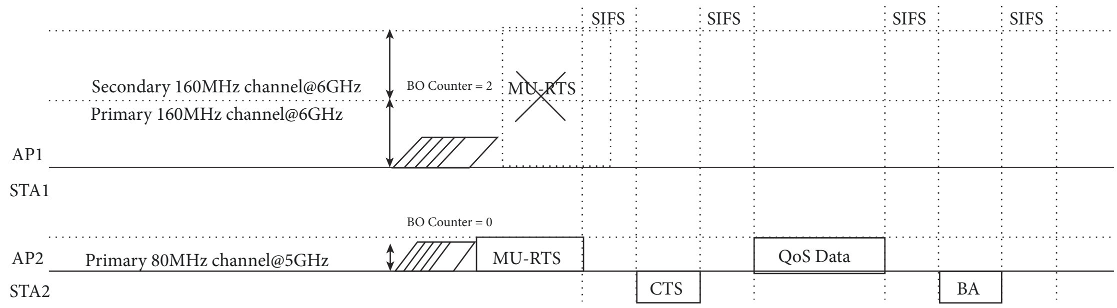

Figure 3: Unbalanced bandwidth issue of EMLSR.

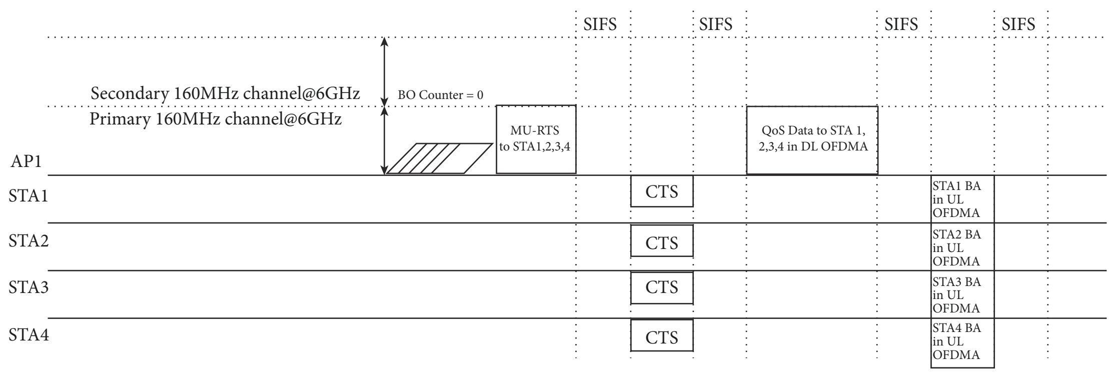

Figure 4: AP STA bandwidth configuration issue of EMLSR.

320 MHz operation in the 6 GHz band and 160 MHz operation in the 5 GHz band. So today almost all the AP implementation processes support 320 MHz BSS operation on the 6 GHz band and 160 MHz BSS operation on the 5 GHz band. On the other hand, due to the cost and power consumption consideration, most STA implementation processes support only 80 MHz in the 5 GHz band and 160 MHz in the 6 GHz band. It is because, according to the IEEE 802.11 specification, 80 MHz is mandatory for STA on the 5 GHz band and 160 MHz is mandatory for STA on the 6 GHz band. As shown in Figure 4, on the 6 GHz band, when an AP or an AP MLD has established an 320 MHz BSS, all the associated STAs need to stay on the primary channels. Only if the STAs are capable of 320 MHz operation, half of the bandwidth of the 320 MHz BSS will be wasted. Although EMLSR is a promising mechanism to improve the performance for the next-generation Wi-Fi systems, in reality there is a lack of the capabilities to utilize the secondary channels.

4. System Modeling

Let us assume that both AP MLD and STA MLD support the multilink operation MLO with only two enabled links. The concept can be extended to the multilink operation MLO with more than two links, where p_1 is the probability that link 1 is busy and p_2 is the probability that link 2 is busy. According to IEEE 802.11 specification, the Clear Channel Assessment (CCA) mechanism [1] is used to decide whether a channel is busy. On the primary 20 MHz channel of the system operating channels, the CCA checks the incoming energy by running Energy Detection (ED) and detects the incoming 802.11 packet by running Packet Detection (PD). On the other hand, on the secondary 20 MHz channels of the system operating channels, only ED is performed. Therefore, the probability that a primary 20 MHz channel is busy and the probability that a secondary 20 MHz channel is busy could be slightly different. In this paper, to simplify the analysis without loss of generality, we consider that the probability of a busy 20 MHz channel is assumed to be the same regardless of whether it is for the primary or secondary 20 MHz channels. Hereafter, we use p to represent the probability that a 20 MHz channel is busy. Then, the probability that link 1 is busy is expressed as follows:

$$p_1 = 1 - (1 - p)^m, \tag{1}$$

where m is number of 20 MHz channels of the system operating channels of link 1. If link 1 is operating on the 6 GHz band, the value of m is equal to 12 which enables 320 MHz operation. Similarly, the probability that link 2 is busy can be expressed as follows:

$$p_2 = 1 - (1 - p)^n, \tag{2}$$

where n is number of 20 MHz channels of the system operating channels of link 2. If link 2 is operating on the 5 GHz band, the value of n is equal to 6 which enables 160 MHz operation.

Now the maximum throughput c_1 that can be obtained on link 1 and the maximum throughput c_2 that can be obtained on link 2 can be calculated based on Shannon capacity. c_1 can be expressed as follows:

$$c_1 = 20m10^6 \log_2(1 + \mathrm{SINR}), \quad (3)$$

and c_2 can be expressed as follows:

$$c_2 = 20m10^6 \log_2(1 + \mathrm{SINR}). \quad (4)$$

The total maximum throughput of an MLMR system then can be expressed as follows:

$$T_{\mathrm{MLMR}} = (1 - p_1)c_1 + (1 - p_2)c_2. \quad (5)$$

By substituting p_1, p_2, c_2, c_2 in equation (5) with the results of equations (1)–(4), the maximum system throughput of an MLMR system with two enabled links can be derived as follows:

$$T_{\mathrm{MLMR}} = 20\left(m(1 - p)^m + n\left(1 - p^n\right)\right)10^6 \log_2(1 + \mathrm{SINR}). \quad (6)$$

For an EMLSR system, there is only one radio available for frame transmissions. Therefore, link 1 can be used for transmission under one of two conditions. The first condition is that link 1 is not busy while link 2 is busy. The second condition is that both links are not busy, and then we can assume that both links can be used for transmission with the same probability. Transmission on link 2 follows similar conditions. The maximum system throughput for the EMLSR system with two enabled links can be expressed as follows:

$$T_{\mathrm{EMLMR}} = (1 - p_1)p_2c_1 + (1 - p_2)p_1c_2 + \frac{(1 - p_1)(1 - p_2)(c_1 + c_2)}{2}. \quad (7)$$

Following the same way of deriving the maximum throughput of MLMR system in equation (7), the maximum system throughput of the EMLSR system can be expressed as follows:

$$T_{\mathrm{EMLMR}} = 20\left(\frac{(1 - p)^m\left(1 - (1 - p)^n\right)m + (1 - p)^n\left(1 - (1 - p)^m\right)n + (1 - p)^m(1 - p)^n(m + n)}{2}\right) \cdot 10^6 \log_2(1 + \mathrm{SINR}). \quad (8)$$

5. Further Enhanced EMSLR Operation

The following mechanism is proposed to further improve the EMLSR performance. The mechanism can be divided into two parts. In the first part, an enhanced protocol is proposed to solve the AP STA unbalanced bandwidth issue, and, in the second part, a link selection mechanism is proposed to solve the band unbalanced bandwidth issue.

As shown in Figure 5, we define the primary link (PL) and the secondary link (SL) for the EMLSR operation. The PL is the Link/Band where the AP STA unbalance issue occurs, and the SL is the Link/Band where AP STA unbalance issue does not exist. In this example, 6 GHz is defined as the PL where AP MLD on the 6 GHz band is operating on 320 MHz, while the STA MLD on the same band is operating on 160 MHz. In the other Link/Band (e.g., 5 GHz), both the AP MLD and the STA MLD are operating on 80 MHz. In this proposal, it is assumed that only one PL and one or more SLs are allowed. The reason is that, in a practical deployment, no AP MLD could support more than one 320 MHz link due to cost considerations.

When an STA MLD is under the procedure to associate with the AP MLD, AP MLD and STA MLD need to exchange per-band capabilities, for example, Operating Bandwidth Capabilities and MCSs. If the STA MLD figures out that, on the 6 GHz band, its own bandwidth capability is smaller than that of AP MLD on the same band, the STA MLD determines this link as the PL and conveys this information to the AP MLD. Other links are determined as SLs. Then STA MLD tunes the scan radio to one of the SLs and tunes the main radio to the PL. This example illustrates only the case in which STA MLD supports one PL and one SL. But the protocol can be extended to support the case of multiple SLs.

The two following scenarios are evaluated, respectively: (a) AP MLD completes the backoff procedure on the SL first; (b) AP MLD completes the backoff procedure on the PL first. Under scenario (a) where the backoff procedure is completed firstly on the SL, AP2 in the AP MLD sends out the MU-RTS with non-HT DUP PPDU of 80 MHz bandwidth on the 5 GHz band. Because both AP2 in the AP MLD and STA2 in the STA MLD are operating on 80 MHz, there is no need to explore the secondary channels. The main radio on STA2 of the STA MLD after receiving the MU-RTS from AP2 stays on the 5 GHz band and responds with a CTS after SIFS. AP2 after receiving CTS continues sending DL QoS Data to STA2. STA2 after receiving the DL QoS Data sends BlockAck back to AP2 to complete the current TXOP. Under scenario (b) where the backoff procedure is completed on the PL firstly, AP1 in the AP MLD sends out the MU-RTS in the same PHY PPDU format but with 320 MHz bandwidth

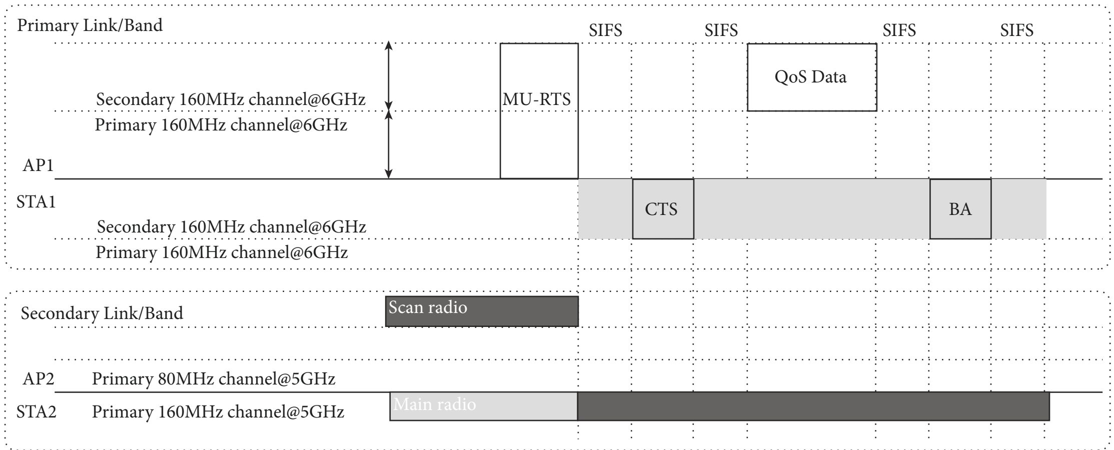

Figure 5: EMLSR optimization protocol.

on the 6 GHz band. STA1, different from STA2 in scenario (a), operates only on 160 MHz bandwidth, and, instead of the main radio, it is the scan radio that receives the MU-RTS.

Although the scan radio of STA1 is operating on 160 MHz while the MU-RTS is coming in with 320 MHz bandwidth, because the MU-RTS is sent out using the non-HT DUP PPDU format, the same information is repeated per 20 MHz channel so that the scan radio that operates on the partial bandwidth of full BSS bandwidth can still successfully receive the MU-RTS. When the scan radio is in the process of receiving the MU-RTS, following the regular EMLSR protocol, the scan radio detects the MAC padding field of the MU-RTS by matching the special pattern of the MAC padding field. Once the MAC padding field is detected, the scan radio indicates to the main radio who is staying on the SL to start the procedure of tuning to the secondary 160 MHz channel of the PL. During the reception of the MU-RTS, the scan radio collects PHY related information and passes this information to the main radio so that it can get ready to send CTS back to AP1 SIFS after the reception of the MU-RTS. The CTS is sent back using the non-HT DUP PPDU with 160 MHz bandwidth on the secondary 160 MHz channel of the 320 MHz BSS. Once the CTS is received, AP1 sends out QoS Data on the secondary 160 MHz channel of the 320 MHz BSS, and a BlockAck frame is sent out by STA1 after the QoS Data is successfully received to complete the current TXOP.

In general, the principle of the link selection algorithm is to prioritize the maximization of the broader bandwidth utilization. The SL will be used only when the PL is busy with its own transmission or occupied by transmissions from other STAs. Then the maximum system throughput of the enhanced EMLSR system with two enabled links can be expressed as follows:

$$T_{\text{EEMLMR}} = (1 - p_1)c_1 + p_1(1 - p_2)c_2, \tag{9}$$

and, following the same way through which equation (8) is derived, the maximum throughput of the enhanced EMLSR system can be expressed as follows:

$$T_{\text{EEMLMR}} = 20\left((1-p)^m m\right) + \left((1-p)^n\left(1-(1-p)^m\right)n\right) \cdot 10^6 \log_2(1 + \text{SINR}), \tag{10}$$

where p_1 is the possibility that the PL is busy and p_2 is the possibility that the SL is busy. ρ_1 is the PHY supported data rate for certain MCS when rate selection is enabled. ρ_2 is the corresponding PHY data rate of the SL. T is the instantaneous throughput given the busy possibility and selected MCSs. As mentioned earlier in the section, SL will be used only when PL is busy with its own transmission or occupied by transmissions from other STAs. Then the throughput upper bond can be defined as follows:

$$T = (1 - p_1)\rho_1 + p_1(1 - p_2)\rho_2. \tag{11}$$

In a real Wi-Fi system, the accurate ratio for a certain link to be busy is unknown. We can only estimate it based on the historical usage of certain channel. It requires long duration of sampling period to have accurate estimation, which is not suitable for TXOP-based EMLSR operation. In this paper, we propose the following link selection algorithm that is based on the cross-link signaling between PL and SL. Because EDCA function is running on both the PL and the SL, each of the PL and SL shall maintain its own backoff counters and NAV independently. We assume that there is a tunnel between the PL and SL so that the PL and SL can exchange their NAV information and backoff counter information at each slot boundary. Again, let us start with the two scenarios as we did in the previous section. But, this time, we will start with scenario (b), which is the scenario in which the PL finishes the backoff procedure firstly. Recall that the principle of the link selection algorithm is to maximize the use of the PL. So when PL finishes the backoff earlier, it will move forward to start the frame transmission without checking the NAV and backoff counter information on the SL. The EDCA function on the PL is exactly the same as that of a non-MLO operation. On the other hand, in scenario (a), which is the scenario in which the SL completes the backoff procedure firstly, as shown in Figure 6, at the boundary of the slot, SL checks the NAV of the PL through a special tunnel. If either the physical CS or the NAV on the PL indicates that the PL is busy, then the SL link can move forward to start the frame transmission. Otherwise, if both the physical CS and the NAV on the PL indicate that the PL is idle, then the PL is either in the idle state or in the process of the EDCA. Now the SL needs to compare the remaining backoff counter number with a predefined threshold. If the number is bigger than the threshold, meaning that the PL is far away from completing the backoff procedure, then the SL can move forward to start the frame transmission. On the other hand, if the remaining backoff number is smaller than the threshold, the SL shall redraw a new backoff counter number using the same AC [26] and restart the backoff process so that the TXOP can be given to the PL. The value of the threshold depends on the network deployment and can be optimized according to the channel status on both PL and SL.

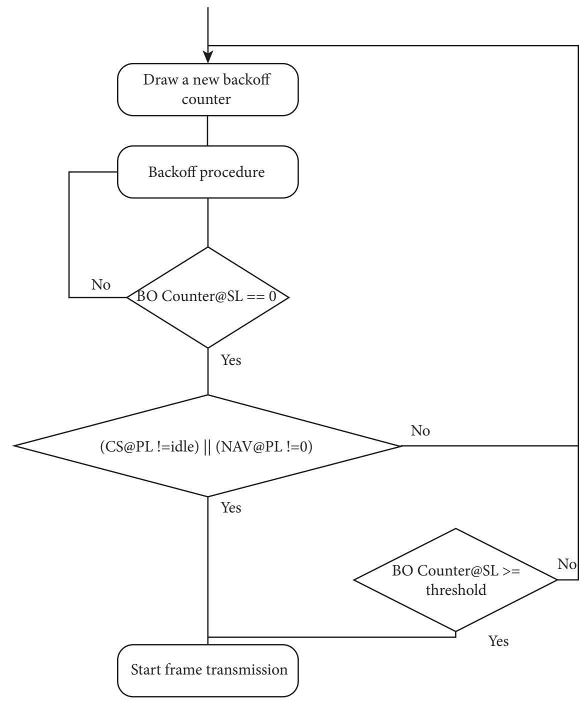

Figure 6: EMLSR link selection algorithm.

6. Performance Evaluation

The performance of further enhanced EMLSR is evaluated based on the NS3 simulator [32] with following assumptions. The simulation scenario is shown in Figure 7. It is a single floor apartment build scenario with each apartment with the size of 10 m × 10 m. In each apartment, there is one AP MLD configured and two STA MLDs associated with the AP MLD. The penetration loss of the wall between each apartment is 5 dB. After the association, AP MLDs start DL SU type of transmissions with their associated STA MLDs in a round robin fashion. There are no DL MU transmissions or UL transmissions configured in any of the apartments. All the STA MLDs are configured with stationary positions with no mobility. Both AP MLD and STA MLD support 5 GHz and 6 GHz EMLSR operations. The AP MLDs are configured to use two TX/RX antennas on both the 5 GHz and 6 GHz bands. The STA MLDs are configured to use only one TX/RX antenna under the EMLSR mode. HE MCS0 to MCS11 are enabled. Depending on the configuration, the rate selection is enabled/disabled. EDCA with default parameters per each traffic class is used. For operating channels, on 5 GHz, a random channel with 80 MHz bandwidth is selected, and, on 6 GHz, a random channel with 160 MHz bandwidth is selected. We only enabled AMPDU aggregate with 64 BA window. There is no AMSDU aggregation. There is no regular RTS configured. Only MU-RTS is enabled to start the EMLSR operation sequence. Each AP MLD is independently managed.

Table 1 summarizes the channel model and path loss configurations, where $PL(d) = 40.05 + 20 \times \log 10 \ (f_c/2.4) = 20 \times \log 10(\min(d, 5)) + (d > 5) \times 35 \times \log(d/5) + 18.3 \times F^{(F+2)/(F+1)-0.46} + 5W$, where $d = \max(3\text{D distance}[m], 1)$, f_c is frequency with unit GHz, F denotes number of floors traversed, and W denotes the number of walls traversed in x-direction plus number of walls traversed in y-direction.

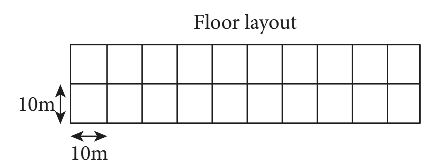

Figure 7: Simulation scenario.

We turn on the BSS in the first apartment and turn off the rest of the BSSs in the first set of experiment; that is, there are no OBSSs. Rate selection is turned off as well. As shown in Figure 8, the x-axis shows the MCSs variation and the y-axis shows the throughput of original EMLSR and our proposed enhanced EMLSR of the BSS under test. It is demonstrated that enhanced EMLSR provides better throughput performance on all the MCSs. With MCS0, which is the base rate for all the management frame and control frame transmission, the proposed enhanced EMLSR provides 30 Mbps more throughput on top of 26 Mbps that is achieved on the original EMLSR operation. Almost 100% throughput gain is achieved. With MCS11, we have similar observations. The throughput gain here comes from the capabilities of the enhanced EMLSR that can utilize the secondary channel of the broader bandwidth, while the original EMLSR can only utilize the primary 80 MHz channels.

Table 1: Channel model and path loss configurations.

Fading model	TGac channel D NLOS for all the links
Path loss model	PL(d)
Shadowing	Log-normal with 5 dB standard deviation, i.i.d. across all links

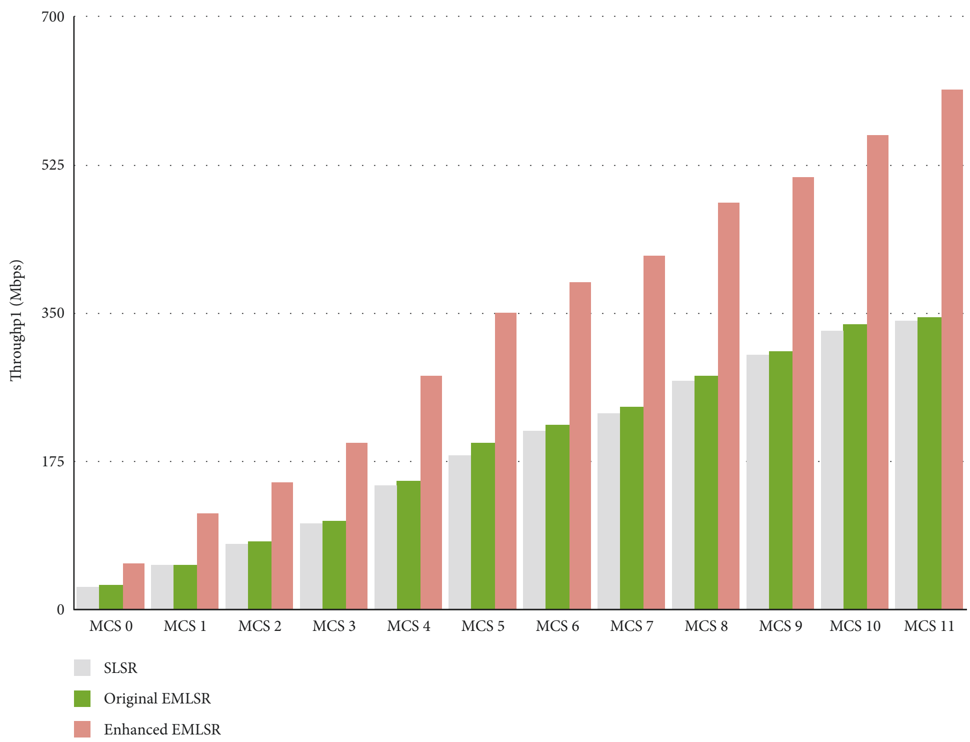

Figure 8: Throughput performance without OBSSs.

The performance is also evaluated in a scenario in which all BSSs are turned on. and, on top of that, one AP and one STA BSS in each apartment are added. The one BSS added will create OBSS traffic for each of the BSSs in the apartment. All the OBSSs added only run DL SU traffic and a global knob is implemented which can control ratio of the OBSS traffic against my BSS traffic. Assuming the same radio of OBSS traffic on both PL and SL, as shown in Figure 9, the x-axis shows the ratio of traffic of OBSS against that of my BSS and the same ratio applies to both PL and SL. With increasing of the OBSS traffic load, the average BSS throughput is decreased. However, the proposed further enhanced EMLSR still outperforms the original EMLSR. With the OBSS traffic load increased to 80%, as shown in Figure 10, the average BSS throughput using original EMLSR is 70 Mbps, while with the further enhanced EMLSR the average BSS throughput is increased to 120 Mbps. So, under heavy OBSS load on both PL and SL, the further enhanced EMLSR achieves 70% throughput gain.

Let us then look at a more practical scenario where the SL (5 GHz) is busier than the PL (6 GHz). Because the 6 GHz band has been recently opened by the regulation bodies, there are not many deployments on the 6 GHz band yet. The 5 GHz band, on the other hand, supports legacy Wi-Fi BSS down to 802.11ac or 802.11n. So, it is a reasonable assumption that the SL is busier than the PL in the real-world deployment. For simulation studies, the OBSS load on the PL stays the same at 20% and the OBSS load on the SL increases from 20% all the way up to 80%. Again, with increased OBSS traffic load, the average throughput performance is decreased. However, with the further enhanced EMLSR being adopted, the average BSS throughput is still better than that of the original EMLSR. Under the heavy BSS load of 80% on the SL, the original EMLSR provides 200 Mbps throughput, while the throughput of the further enhanced EMLSR reaches 300 MHz. The 50% throughput gain is achieved by adopting the further enhanced EMLSR. The main contribution of the throughput performance gain comes from the flexibility of the enhanced EMLSR. It distributed more TXOPs on the PL that is less busy tham the SL, and the bandwidth of the PL is broader than that of SL. It is interesting to observe that the original EMLSR has worse performance than the baseline SLSR system under heavy OBSS load on the SL. This is because the original EMLSR may try to use the smaller bandwidth of the 5 GHz band when the EDCA is completed on the 5 GHz band. But it is more efficient for the SLSR system to wait a bit long on the 6 GHz band to obtain a TXOP with bigger bandwidth.

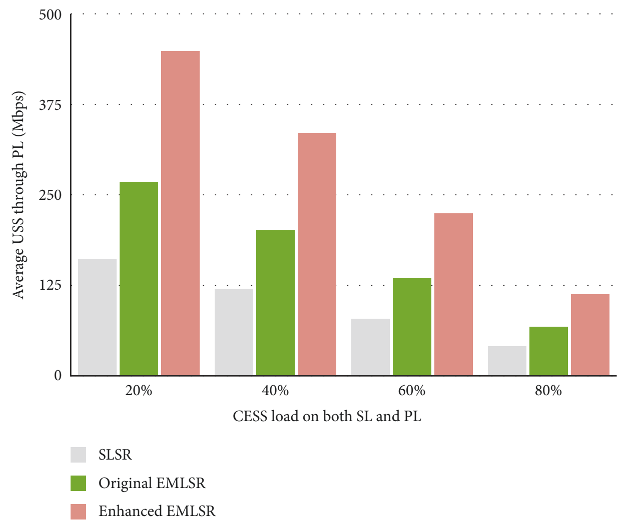

Figure 9: Throughput with OBSS on both PL and SL.

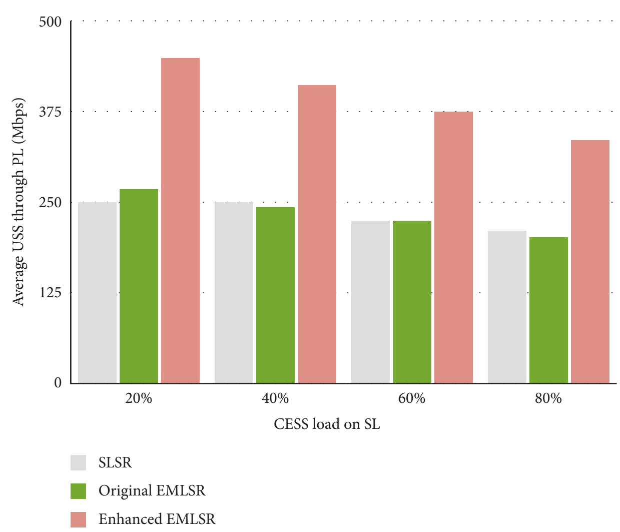

Figure 10: Throughput with OBSS on SL only.

7. Conclusion

The MLO is a new mechanism defined in the IEEE 802.11 draft specification. With the help of MLO, APs and STAs will be provided with the capabilities to transmit and receive data from the same traffic flow over multiple radio interfaces. The EMLSR is an enhanced feature of MLO enabling dynamic switching between multiple bands with low-cost implementation and efficient power consumption. In this paper, we proposed the further enhanced EMLSR with a new MAC protocol and link selection mechanism, where a primary link (PL) is selected between AP STA with the unbalanced Link/Band and one or multiple secondary links (SLs) with balanced Link/Band. The STA tunes the main radio on the PL and the scan radio to one of the SLs. The PL will be more prioritized than the SL based on the link selection algorithm to maximize the channel utilization. Compared with the legacy EMLSR, the further enhanced EMLSR can improve the utilization of the secondary channel. Even under heavy OBSS load on SL or both PL and SL, the enhanced EMLSR can achieve 50% to 70% throughput gain.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] in *Wireless LAN Medium Access Control and Physical layer Specification*IEEE, Piscataway, NJ, USA, 2013.
[2] F. Tian, Y. Yu, X. Yuan, B. Lyu, and G. Gui, “Predicted decoupling for coexistence between WiFi and LTE in unlicensed band,” *IEEE Transactions on Vehicular Technology*, vol. 69, no. 4, pp. 4130–4141, 2020.
[3] C. Chen, J. Jiang, Y. Zhou, N. Lv, X. Liang, and S. Wan, “An edge intelligence empowered flooding process prediction using internet of things in smart city,” *Journal of Parallel and Distributed Computing*, vol. 165, pp. 66–78, 2022.
[4] Y. Wang, L. Guo, Y. Zhao et al., “Distributed learning for automatic modulation classification in edge devices,” *IEEE Wireless Communications Letters*, vol. 9, no. 12, pp. 2177–2181, 2020.
[5] C. Chen, Y. Zhang, Z. Wang, S. Wan, and Q. Pei, “Distributed computation offloading method based on deep reinforcement learning in ICV,” *Applied Soft Computing*, vol. 103, Article ID 107108, 2021.
[6] X.-X. Zhang, H.-T. Zhao, Z. Hongbo, and A. Bamidele, “NAS-AMR: neural architecture search based automatic modulation recognition method for integrating sensing and communication system,” *IEEE Transactions on Cognitive Communications and Networking, early access*, vol. 8, no. 3, 2022.
[7] Y. Peng, P. Liu, Y. Wang, G. Gui, B. Adebisi, and H. Gacanin, “Radio frequency fingerprint identification based on slice integration cooperation and heat constellation trace figure,” *IEEE Wireless Communications Letters*, vol. 11, no. 3, pp. 543–547, Mar. 2022.
[8] IEEE, “Proposed TGax draft specification,” IEEE, IEEE P802.11ax/D2.0, Technical Report, 2017.
[9] G. Naik, S. Bhattarai, and J. Park, “Performance analysis of uplink multi-user OFDMA in IEEE 802.11ax,” in *Proceedings of the 2018 IEEE International Conference on Communications (ICC)*, pp. 1–6, Kansas City, MO, USA, May 2018.
[10] L. Sanabria-Russo and B. Bellalta, “Traffic Differentiation in Dense Collision-free WLANs Using CSMA/ECA,” *Ad-Hoc Networks*, vol. 75–76, pp. 333–351, 2018.
[11] B. Bellalta and K. Kosek-Szott, “AP-initiated multi-user transmissions in IEEE 802.11ax WLANs,” *Ad Hoc Networks*, vol. 85, pp. 145–159, March 2019.

[12] Z. Shen, B. Li, M. Yang, Z. Yan, X. Li, and Y. Jin, "Research and performance evaluation of spatial reuse technology for next generation WLAN," in *Proceedings of the International Wireless Internet Conference*, pp. 41–51, Springer, Cham, January 2019.

[13] IEEE 802.11TM Wireless Local Area Netwokrs, https://www.ieee802.org/11/.

[14] N. Korolev, I. Levitsky, and E. Khorov, "Analyses of NSTR multi-link operation in the presence of legacy devices in an IEEE 802.11 be network," in *IEEE Conference on Standards for Communications and Networking (CSCN)*, pp. 94–98, Thessaloniki, Greece, December 2021.

[15] Report and Order and Further Notice of Proposed Rulemaking, https://docs.fcc.gov/public/attachments/FCC-20-51A1_Rcd.pdf.

[16] J. Sandoval and S. Cespedes, "Performance evaluation of IEEE 802.11ax for residential networks," in *Proceedings of the 2021 IEEE Latin-American Conference on Communications (LATINCOM)*, pp. 1–7, Santo Domingo, November 2021.

[17] Y. Seok, J. Yee, J. Liu, and T. Pare, "Synchronous multi-link operation," *Doc IEEE*, vol. 11-19/130Sr4, April 2020.

[18] L. Chu, Y. H. Kwon, M. Kumar, H. Zhang, Y. Zhang, and R. Cao, "Multiple link operation follow up," *Anales de Documentación: IEEE*, vol. 11-20/04B7r5, April 2020.

[19] D. Akhmetov and L. Cariou, "Performance aspects of multi-link operations," *Anales de Documentación: IEEE*, vol. 11-19/1291r3, September 2019.

[20] Y. Li, Y. Guo, G. Huang, Y. Zhou, M. Gan, and D. Liang, "Channel access in multi-band operation," *Doc IEEE*, vol. 11-19/1116r5, January 2020.

[21] E. Khorov, I. Levitsky, and I. F. Akyildiz, "Current status and directions of IEEE 802.11be, the future wi-fi 7," *Current status and directions of ieee*, vol. 8, pp. 88664–88688, 2020.

[22] S. Chauhan, A. Sharma, S. Pandey, K. N. Rao, and P. Kumar, "11be: a review on Wi-Fi 7 use cases," in *Proceedings of the International Conference on Reliability, Infocom Technologies and Optimization (ICRITO)*, pp. 1–7, IEEE, Noida, India, September 2021.

[23] G. Naik, D. Ogbe, and J.-M. J. Park, Q. C. Montreal, Can Wi-Fi 7 support real-time applications? On the impact of multi link aggregation on latency," in *Proceedings of the IEEE International Conference on Communications (ICC)*, pp. 1–6, Canada, June 2021.

[24] J. Gomez-Ponce, D. Burghal, N. A. Abbasi et al., "Directional delay spread and interference quotient analysis in sub-7GHz Wi-Fi bands," in *Proceedings of the IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, Taipei, Taiwan, December 2020.

[25] I. Levitsky, Y. Okatev, and E. Khorov, "Study on simultaneous transmission and reception on multiple links in IEEE 802.11be networks," in *Proceedings of the International Conference Engineering and Telecommunication (En&T)*, pp. 1–4, Dolgoprudny, Russia, November 2020.

[26] STR AP Sync. PPDU Transmission, https://mentor.ieee.org/802.11/dcn/20/11-20-0638-00-00be-str-ap-sync-mlo-operation.pptx.

[27] MU-RTS/CTS PHY Format, https://mentor.ieee.org/802.11/dcn/16/11-16-0648-00-00ax-mu-rts-cts-phy-format.pptx.

[28] P. Angueira, I. Val, J. Montalban et al., "A survey of physical layer techniques for secure wireless communications in industry," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 810–838, Secondquarter 2022.

[29] A. S. Gvozdarev, A. Alischyuk, and M. Kazakova, "Impact of system correlation matrix bordering on the MU-MIMO ergodic sum-rate capacity in the presence of the multipath fading channel," in *Proceedings of the 4th International Conference On Advanced Communication Technologies And Networking (CommNet)*, pp. 1–6, Rabat, Morocco, December 2021.

[30] https://mentor.ieee.org/802.11/dcn/20/11-20-0479-00-00be-240-mhz-channelization.pptx.

[31] D. Nunez, F. Wilhelmi, S. Avallone, M. Smith, and B. Bellalta, "TXOP sharing with coordinated spatial reuse in multi-AP cooperative IEEE 802.11 be WLANs," in *Proceedings of the IEEE 19th Annual Consumer Communications & Networking Conference (CCNC)*, pp. 864–870, Las Vegas, NV, USA, January 2022.

[32] Network Simulator, https://www.nsnam.org/.