Wi-Fi 7

Multi-Link Operation (MLO)

White Paper

Key Insights

Wi-Fi 7's Multi-Link Operation (MLO) has the following advantages:

- MLO multiplies throughput via link aggregation compared with Wi-Fi 6 single link operation
- MLO allows for band-switching and load-balancing
- MLO EMLSR delivers 80% throughput enhancement in dense environment
- MLO EMLSR achieve 85% average latency reductions in high network loading conditions

Overview

The IEEE 802.11be Extremely High Throughput (EHT) task group is currently developing the next generation Wi-Fi standard to achieve higher data rate, lower latency, and more reliable connection to enhance user experience. The final version of the IEEE 802.11be specification is expected to be published by late 2023, and ratified in mid-2024. In the meanwhile, the Wi-Fi Alliance (WFA) has kicked off associated development toward Wi-Fi 7 certification based on the IEEE 802.11be draft specification.

One of the key features of Wi-Fi 7 is Multi-Link Operation (MLO). As most current APs and stations incorporate dual-band or tri-band capabilities, the newly developed MLO feature enables packet-level link aggregation in the MAC layer across different PHY links. By performing load balancing according to traffic requirements, MLO achieves significantly higher throughput and lower latency for enhanced reliability in a heavily loaded network.

With MLO capability, a Multi-Link Device (MLD) consists of multiple "affiliated" devices to the upper logical link control (LLC) layer, allowing concurrent data transmission and reception in multiple channels across a single or multiple frequency bands in 2.4GHz, 5GHz and 6GHz. Figure 1 exemplifies the MLO operation with two links.

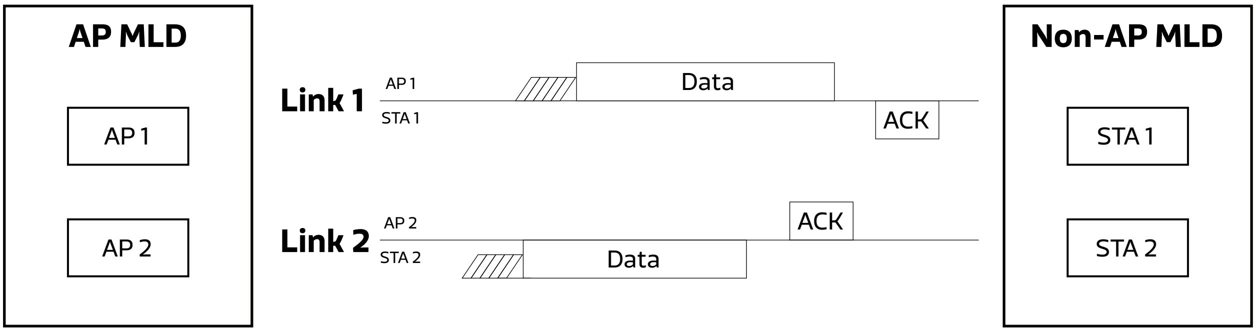

Figure 1. An Example of MLO Operation with Two Links

There exists Wi-Fi technologies that allow a device to connect to a single link and is capable of switching among 2.4GHz, 5GHz and 6GHz bands. However, such Wi-Fi devices typically have a switching overhead or delay of up to 100ms. Therefore, MLO is highly desirable for real-time applications like video calls, wireless VR headsets, cloud gaming and other latency-sensitive applications.

Multi-Link Operations

In our previous white paper "Key Advantages of Wi-Fi 7", we have shown that Wi-Fi 7 MLO STA can achieve 300% throughput enhancement from bandwidth aggregation in an ideal environment. In this white paper we focus on analysis of the various types of MLO.

The IEEE 802.11be draft spec defines different channel access methods according to two transmission modes: asynchronous and synchronous modes. Under asynchronous transmission mode, a MLD transmits frames asynchronously across multiple links without aligning the starting time. In contrast, in synchronous transmission mode the starting time are aligned across the links. In either mode, the links can have their own primary channel and parameters, including Packet Protocol Data Unit (PPDU), Modulation and Coding Scheme (MCS), Enhanced Distributed Channel Access (EDCA), etc.

Figure 2 illustrates examples of the asynchronous and synchronous multi-link transmissions. In asynchronous transmission mode the transmission starting time on the multiple links does not need to be aligned. However, in synchronous transmission mode, transmission starting time needs to be aligned to allow a device to transmit and receive frames simultaneously on multiple links.

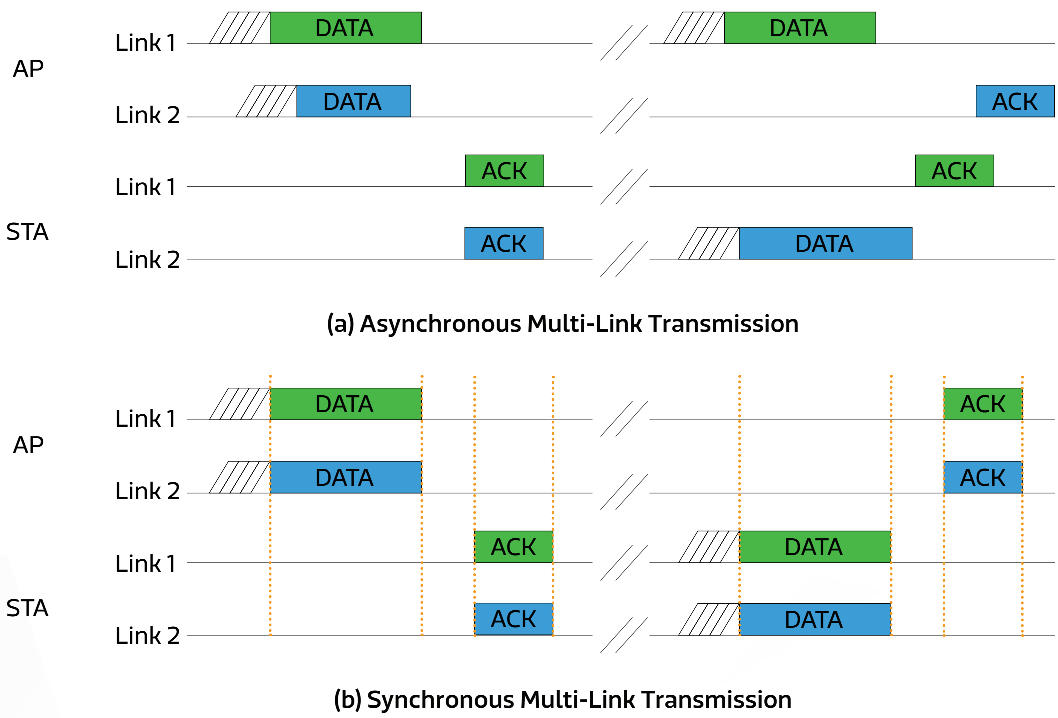

Figure 2. Multi-Link Transmission: Asynchronous and Synchronous Modes

In a system where the radios between the two links are not well isolated, transmission in one link may cause significant in-device coexistence (IDC) interference to the other link. To avoid this problem, a Non-STR (NSTR) mode is defined to coordinate across the links to achieve synchronous transmission. In contrast, if there is sufficient isolation that links can operate independently without loss from IDC interference, simultaneous Transmit & Reception can be attained, and is defined as Simultaneous Transmit and Receive (STR) mode.

All aforementioned modes are called multi-link multi-radio (MLMR), in which links are statically assigned and cannot switch to other frequencies dynamically. Alternatively, to further enhance NSTR system throughput in a busy environment, Enhanced Multi-Link Single Radio (EMLSR) mode is defined to dynamically switch all multi-link capable radios and antennas to a single link. More details are explained below, from the perspective of AP and STA both equipped with two links, respectively.

- **STR**
  As shown in Figure 3, the signal isolation between different links is sufficient so that the links can operate independently and are capable to transmit and receive simultaneously in different links. STR is different from legacy single link (SL) STA and legacy dual band dual concurrent (DBDC) STA, STAs affiliated with a STA MLD share a common transmitter sequence number (SN) and a common space for data transmission allocated to different links if multiple link's transmission have the same access category (AC). This property allows MLD to more quickly transmit an application's data packets among different links and naturally reduces latency performance.

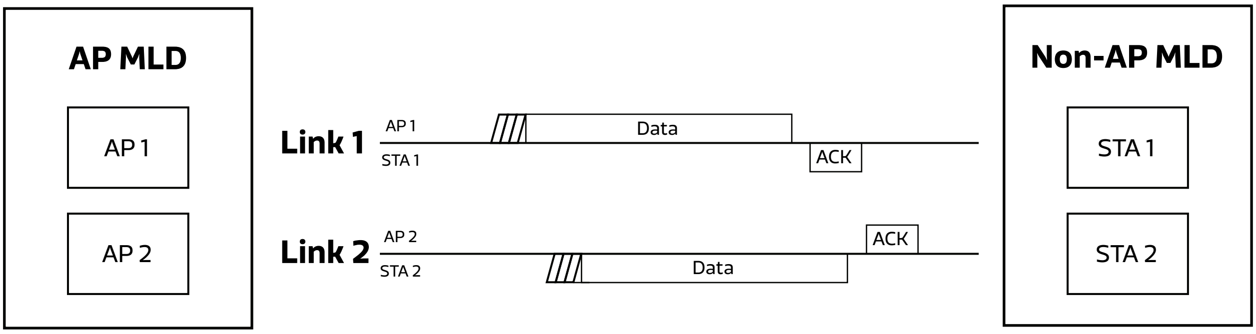

Figure 3. STR

- **NSTR**
  Contrary to STR, NSTR is not capable of transmitting and receiving simultaneously in different links. In other words, overlapping transmission and reception between links are not allowed. To facilitate multi-link operation, NSTR aligns or synchronizes transmission to avoid IDC interference. As shown in Figure 4, two links exist for downlink transmission from STR AP to NSTR STA. Link 1 can send data frames first, and when backoff countdown counters reaches 0 in Link 2, data frames can be sent in Link 2. However, the end time of this frame must be aligned with the frame sent earlier on Link 1 to avoid the response ACK frame from overlapping with the downstream data. Figure 5 illustrates two links for MLO uplink transmission from NSTR STA to STR AP. Because STA's will be de-sensed by other IDC interference, STA affiliated with an NSTR STA MLD cannot transmit the two overlapping PPDU's asynchronously. As a result, simultaneous Tx & Rx is required for overlapping PPDU's with almost the same start time and end time. If backoff counter of STA 1 is counted down to 0 while STA 2 backoff counter is not 0, STA 1 must wait until the backoff counter of STA 2 reaches 0. Only at this time can both PPDUs be transmitted at the same time (synchronize the start time) for both STAs affiliated with same STA MLD. Moreover, the end time of the frames must be also aligned as mentioned above.

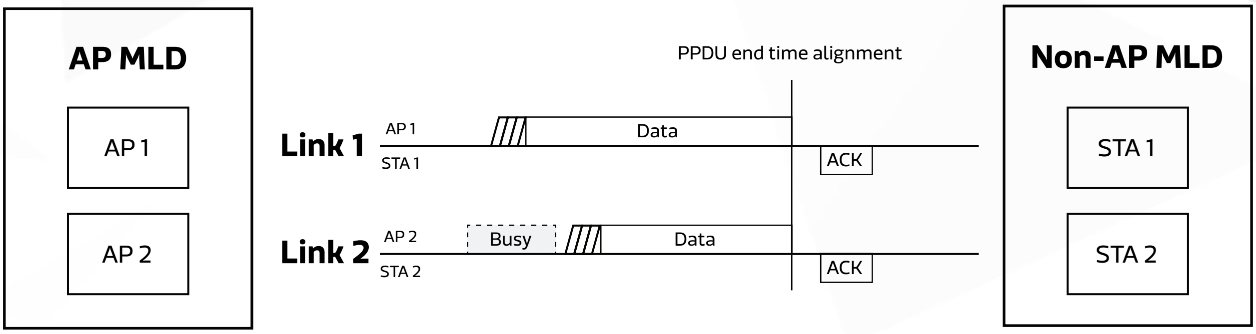

Figure 4. Downlink Transmission from STR AP to NSTR STA

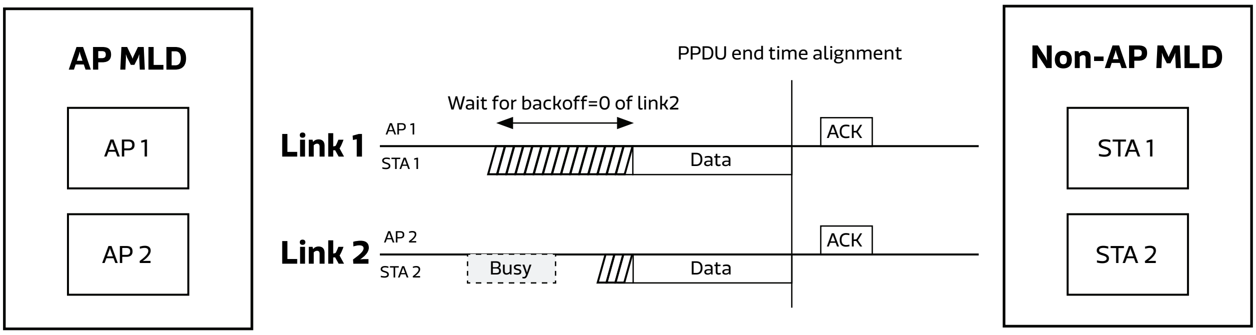

Figure 5. Uplink Transmission to STR AP from NSTR STA

- **EMLSR**

  An EMLSR device initially listens to both links with one or two spatial streams in each link. Upon proper RTS/CTS or BSRP triggering, the EMLSR device aggregates multiple links into a single MIMO radio, and communicates in combined number of spatial streams (NSS) in the first available link. As shown in Figure 6, after STA receives a specific control frame (MU-RTS[1]) from Link 1, it switches all NSS from Link 2 to Link 1 to enhance throughput in Link 1. Meanwhile, STA 2 cannot receive or transmit any PPDU from AP2 in Link2 temporarily because NSS of STA 2 becomes 0 (i.e., Link 2 is in a state of blindness[2] during this period). Figure 7 illustrates a similar mechanism for Uplink. The only difference is that STA does not need to use the initial frame of EMLSR frame to notify AP because AP has enough NSS to receive UL PPDU from the STA affiliated with EMLSR STA MLD. The uplink RTS/CTS procedure is to prevent hidden node problems.

  Note 1: Either MU-RTS or BSRP frame can be the initial frame of EMLSR frame exchange sequence in IEEE 802.11be specification.
  Note 2: The IEEE 802.11be specification also define some medium synchronization delay/ recovery procedures to handle such blindness issue.

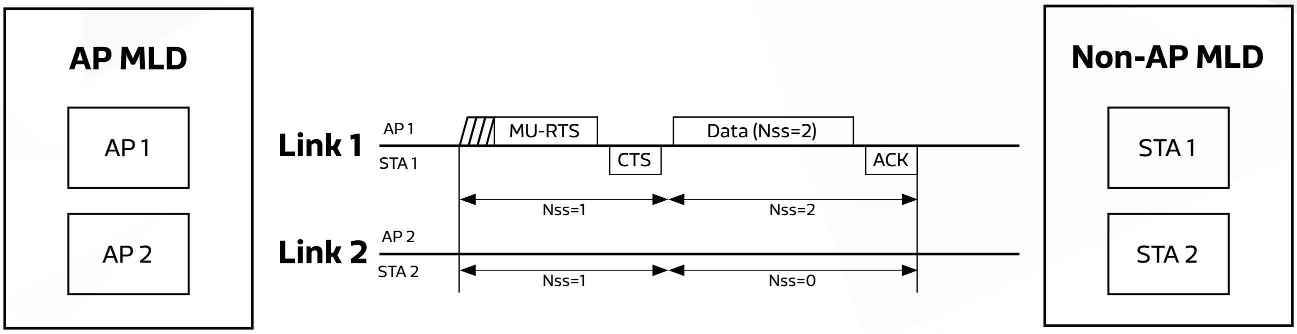

Figure 6. Downlink Transmission from STR AP to EMLSR STA (Max. NSS=2)

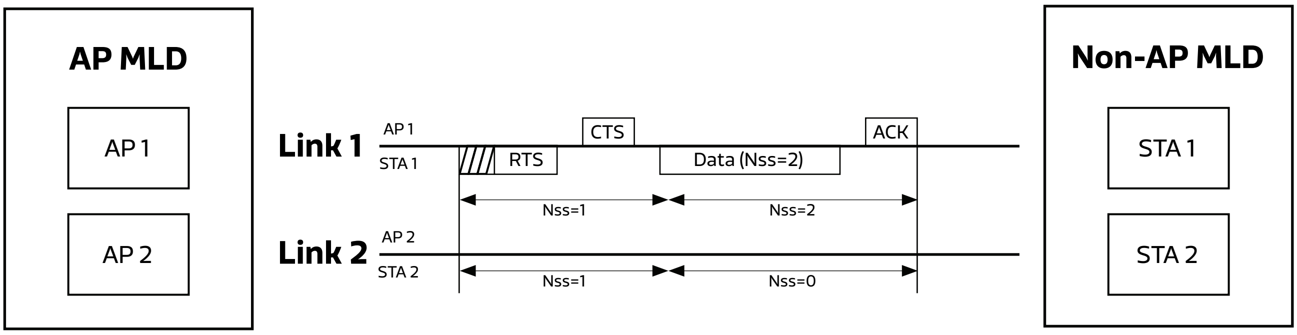

Figure 7. Uplink Transmission from EMLSR STA to STR AP (Max. NSS=2)

Simulations

To evaluate performance of different types of MLO, we assume all MLDs have the same parameters with respect to the number of spatial streams (NSS), data bandwidth (DBW) and Tx modulation and coding scheme (MCS). Detailed configuration and results are shown below:

- **Network Topology**
  Figure 8 illustrates the network topology for the simulations. The network elements include an AP MLD that supports two links, one Non-MLD STA for each link, and one MLD STA supports two links. The two Non-MLD STA in each link with AP MLD is used to generate background Uplink (UL) UDP traffic with more than 50% network loading. As for STA MLD, different traffic types are generated for different test scenarios:
    - For throughput test: Downlink (DL) FTP TCP traffic
    - For latency test: Bi-directional video conference UDP traffic

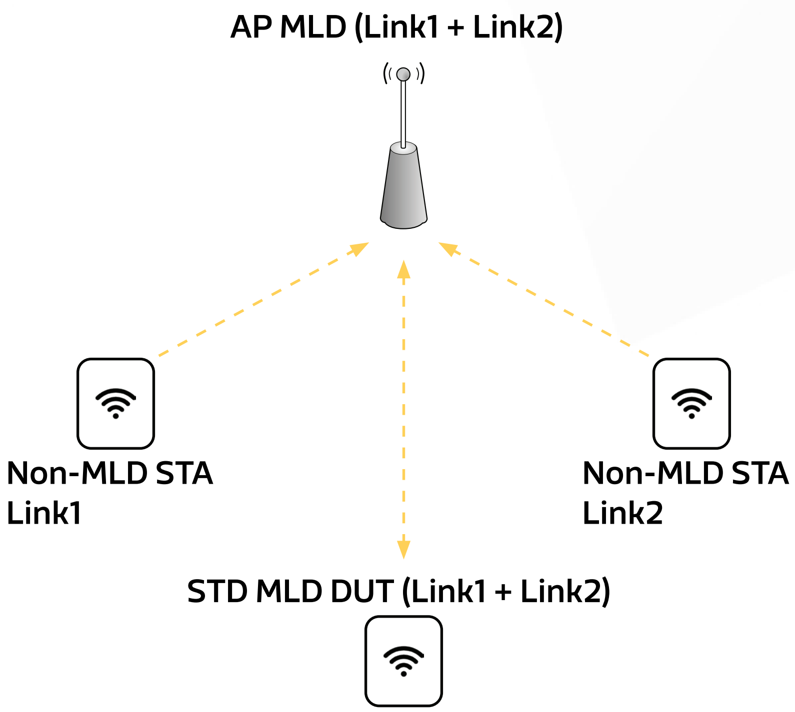

Figure 8. Network Topology for Simulations

- **Operation Mode and Configurations**
  - Configuration 1: Single-Link STA
    - Link1: DBW=80MHz, 2NSS
    - PHY rate: 1200 Mbps (MCS11)
  - Configuration 2: NSTR STA MLD
    - Link1: DBW=80MHz, 1NSS
    - Link2: DBW=80MHz, 1NSS
    - PHY rate: 600 Mbps (MCS11) for each link
  - Configuration 3: STR STA MLD
    - Link1: DBW=80MHz, 1NSS
    - Link2: DBW=80MHz, 1NSS
    - PHY rate: 600 Mbps (MCS11) for each link
  - Configuration 4: EMLSR STA MLD
    - Link1: DBW=80MHz, 1NSS
    - Link2: DBW=80MHz, 1NSS ➔ 2NSS Tx after EMLSR
    - PHY rate: 1200 Mbps (MCS11) for each link

It is important to note that each AP affiliated with AP MLD can fully support 2NSS Tx and 2NSS Rx (i.e., there is no need to perform NSS switching when the peer STA affiliated with STA MLD operates in EMLSR mode)

Frontend Architecture

In what follows, we describe system implementations of a Quad-Antenna STA for different MLO types. Figure 9 exemplifies an NSTR (or EMLSR) STA with 5/6GHz 2NSS + 5/6GHz 2NSS, and Figure 10 exemplifies an STR STA with 5GHz-High 2NSS + 5GHz-Low 2NSS. For small form factor STA, such as mobile phones, option in Figure 9 may be preferred due to frontend complexity consideration.

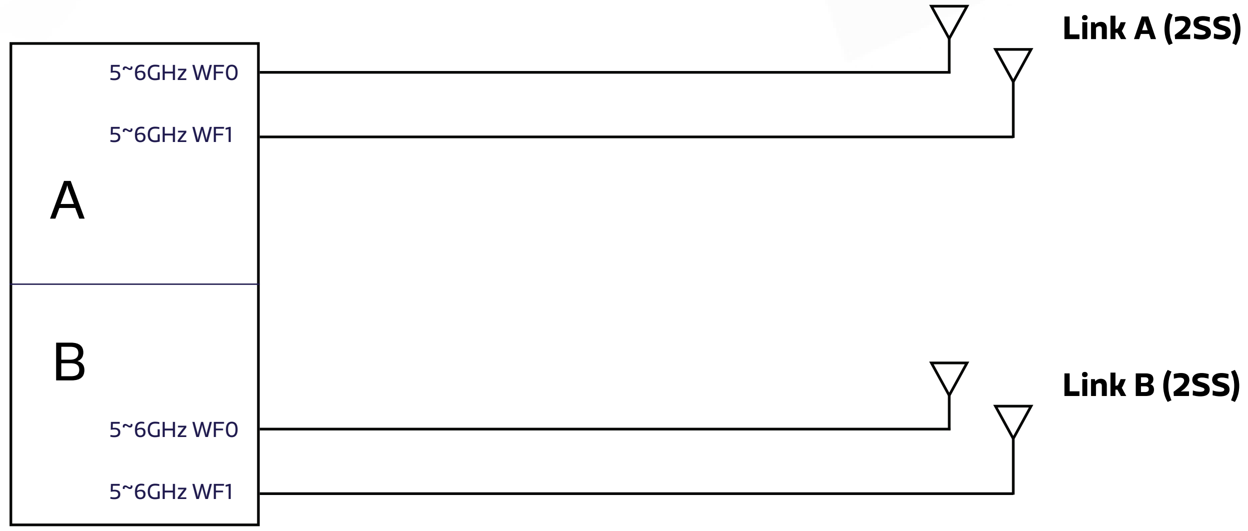

Figure 9. A Quad-Antenna NSTR (or EMLSR) STA with 5/6GHz 2NSS + 5/6GHz 2NSS

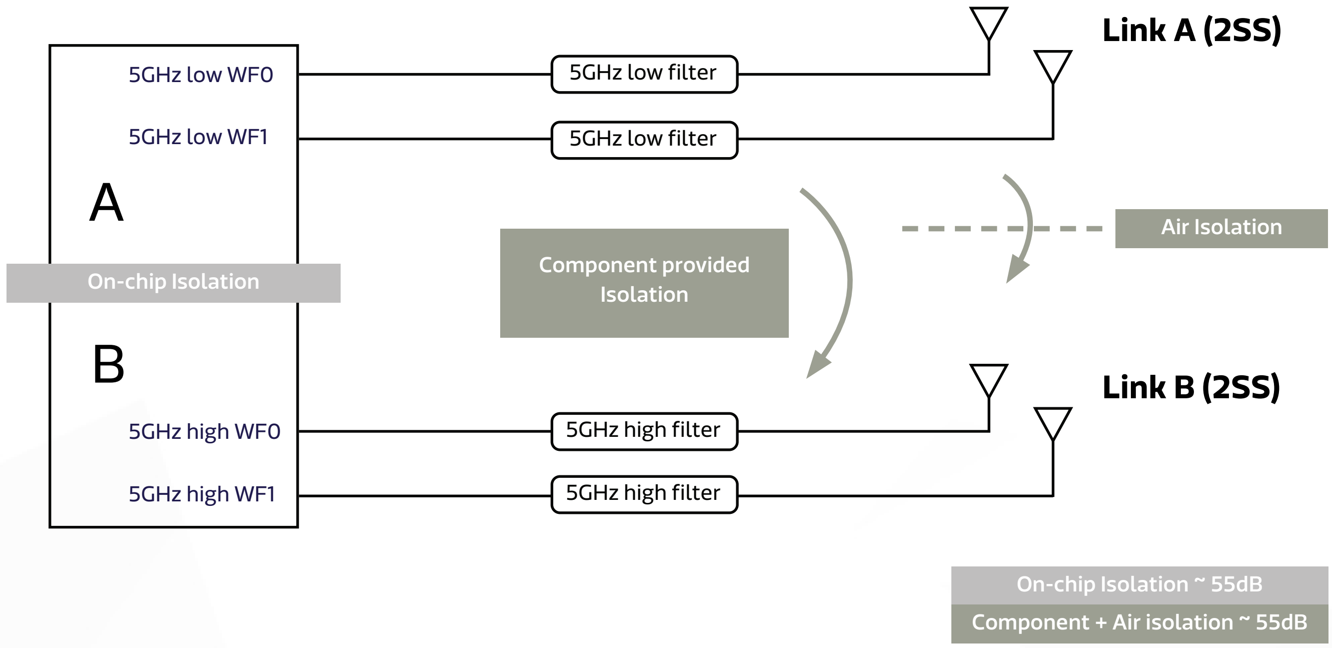

Figure 10. A Quad-Antenna STR STA with 5GHz-High 2NSS + 5GHz-Low 2NSS

Results & Analysis

Figure 11 illustrates throughput results with different network loading conditions. We can see that EMLSR has the best performance when a network becomes more congested (i.e., loading over 10%) and can even improve from 210Mbps to 380Mbps (80% improvement) when the network loading is 70%. This is because EMLSR can utilize all NSS for transmission using the link with the least wireless contention. The result also shows that NSTR has the worse throughput than others as it is difficult to perform simultaneous transmission in the UL direction on both links when one of the MLO link is busy.

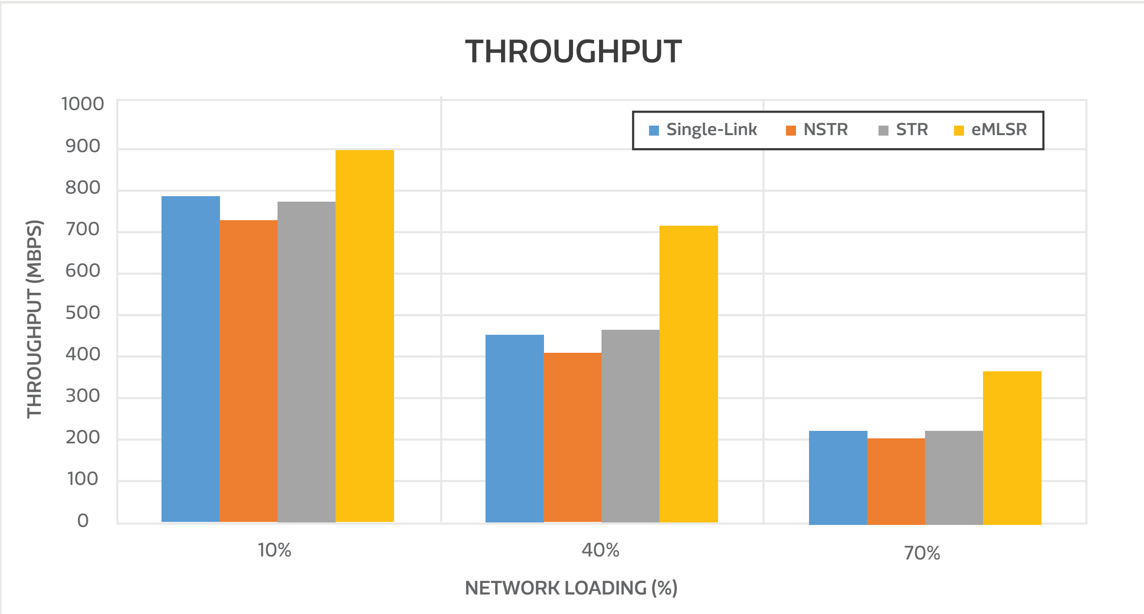

Figure 11. Comparison of Throughput

Figure 12 demonstrates latency benefits of MLO when subjected to different network loading. Measurement is done with 95% CDF. The result shows the latency of a Wi-Fi 7 MLO STA can be improved from 145ms to 18ms (more than 85% improvement) when compared to a Wi-Fi 6 Single STA when network loading is 70%. It also shows that STR has the lowest latency because the two links do not interfere with each other. That also explains why NSTR or EMLSR have higher latencies as its transmission may be blocked by IDC interference or running out of spatial streams.

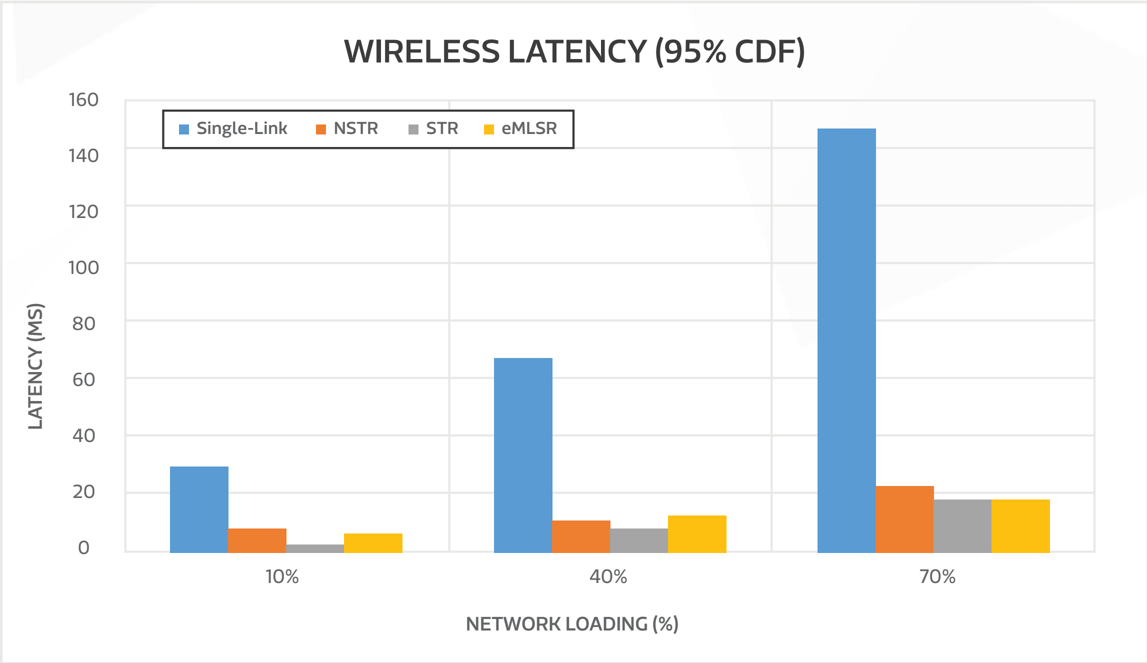

Figure 12. Comparison of Latency

System Architectures

MLO is a MAC-layer carrier aggregation solution. The MAC sub-layer can be divided into two parts: upper MAC (UMAC) and lower MAC (LMAC). The two-tier MAC implementation enables frames to be transmitted simultaneously over multiple links. UMAC is the common part for all interfaces, which performs link operations. It buffers the traffic from the host before it is assigned to a specific interface to be transmitted. It also buffers the traffic from the interface before passing it onto the host until the traffic can be arranged in sequence. The UMAC also enables seamless transition between links to minimize the access latency for efficient load balancing. On the other hand, LMAC is an individual part for each interface that performs link specific functionalities with its own channel access method and parameters.

MLO architecture could be implemented with different partitions as shown in Figure 13. Overall, the architectures are divided into two categories: single MAC MLO (Arch#1) and multiple MAC MLO (Arch#2, Arch#3, and Arch#4). Detailed implementations and major differences with benefits are explained as below:

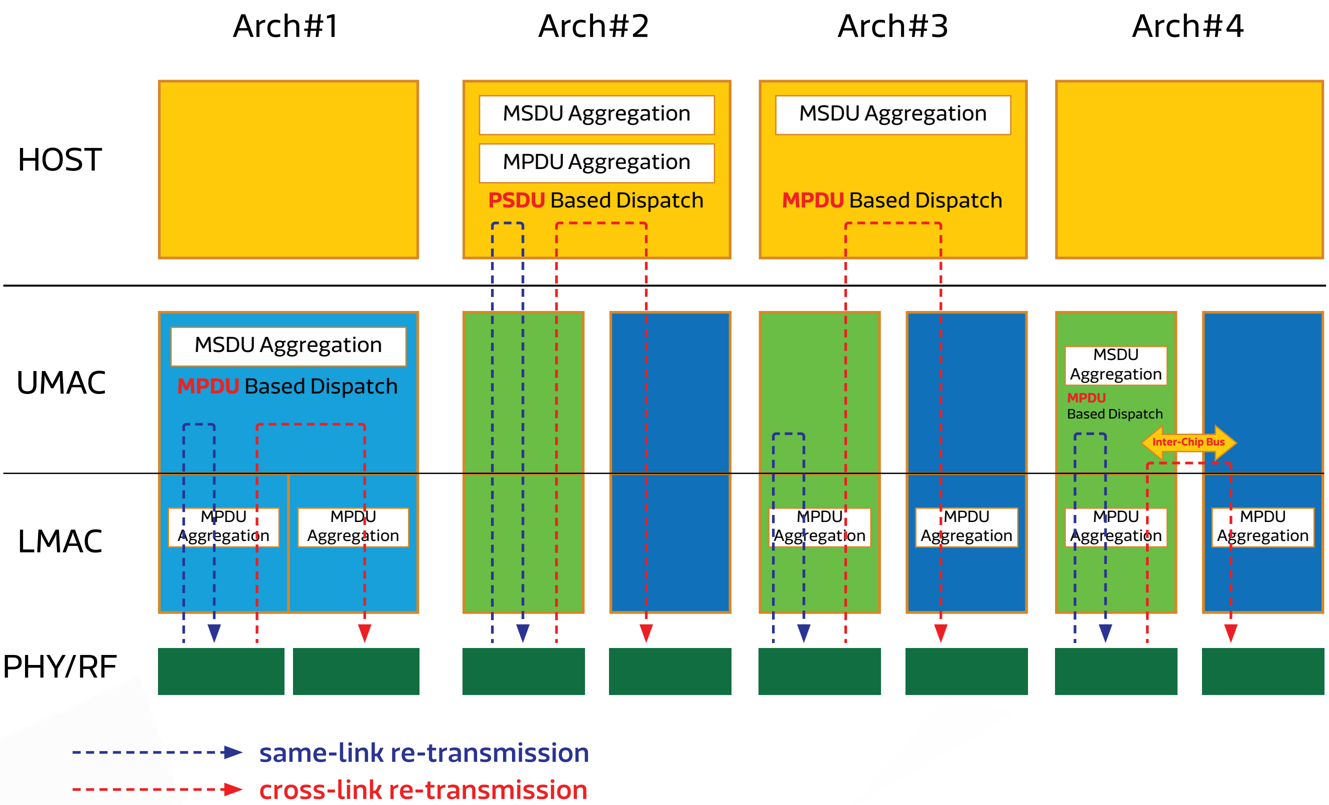

Figure 13. Implementation of Different MLO Architectures

In Arch#1, an MLD is implemented with single MAC. Each affiliated device of an MLD is composed of PHY and LMAC components. On top of the set of affiliated devices, only one UMAC component to aggregate its set of affiliated devices and provide LLC layer in HOST with a single HOST interface. UMAC support MAC operations like MSDU aggregation/de-aggregation and MPDU dispatch among multiple links, while LMAC supports a small number of operations including MPDU aggregation/de-aggregation. In Arch#2, different MAC HOST interfaces are presented to upper layers, and HOST layer is responsible for MSDU aggregation/de-aggregation, MPDU aggregation/de-aggregation and manages the session transfer to balance traffic between different bands/channels based on PSDU information. Arch#3 also contains different HOST interfaces as Arch#2. However, the difference between Arch#3 and Arch#2 is that MSDU aggregation/de-aggregation and MPDU dispatch are handled in HOST layer and MPDU aggregation/de-aggregation is done in LMAC. Arch#4 is more like a “distributed” solution. Only one MAC is presented to the HOST layer with HOST interface, making upper layers unaware of the session transfer between different bands/channels. The UMAC of the presented MAC is responsible for MSDU aggregation/de-aggregation and MPDU dispatch among multiple links. As the links might switch between different MACs, inter-chip bus need to be implemented. In this case, the performance might be bounded by the speed capability of the inter-chip bus.

Arch#1 is the preferred implementation for MLO as it provides the lowest latency and the least implementation complexity. Key summary of different architectures is listed in Table 1.

Item	Arch#1	Arch#2	Arch#3	Arch#4
Same-Link Re-transmission Latency	= baseline*	= baseline* + 10 ms**	= baseline*	= baseline*
Cross-Link Re-transmission Latency	= baseline*	= baseline* + 10 ms**	= baseline* + 10 ms**	= baseline*
MAC memory for Tx Descriptor	compact	compact	compact	3x compact
Board-level and system integration	Normal	Normal	Normal	Complicated routing for cross-chip highspeed link requests high layer stack
Host Interface (HIF)	Simple HIF configuration	Multiple and complicated HIF configuration impact power consumption and cost	Multiple and complicated HIF configuration impact power consumption and cost	Multiple and complicated HIF configuration impact power consumption and cost

*Average 110us for backoff ** Depends on PSDU or MPDU numbers in HOST queue, take 2 x 5ms as reference value

Table 1. Key Summary of Different MLO Architectures

Conclusions

The MLO is one of the key innovations in Wi-Fi 7. This paper introduces the basic architecture of MLO, its different modes of operation, and analyses its performance in simulations under multiple network loading conditions. One of the highlights is MLO in EMLSR mode, where significant throughput improvement in heavily loaded environments can be realized while still providing low network latencies. For example, in a 70% loaded network, EMLSR achieves 80% throughput improvement and 85% average latency reduction compared to a single link. These MLO enhancements are major reason why Wi-Fi 7 can achieve and maintain 1ms latency requirements for next generation use cases.

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MediaTek in the Wi-Fi Industry

MediaTek is the world's largest supplier of Wi-Fi solutions, including standalone networking products such as routers, repeaters and mesh access points, as well as devices with embedded Wi-Fi connectivity such as smartphones, tablets, TVs, IoT, smart home devices, PCs and laptops, games consoles, and others.

Besides delivering high performance and low power integrated solutions to these platforms, MediaTek has been actively participating in IEEE and Wi-Fi Alliance certification development to ensure the utmost performance and industry interoperability. Some recent examples include selection of MediaTek's Filogic platforms as Wi-Fi 6E and Wi-Fi 6 R2 test bed devices. For Wi-Fi 7, MediaTek has and will continue to contribute its technical know-how and knowledge of different market segment requirements to improve Wi-Fi performance for everyday use.