Distributed Multi-link Operation (MLO) for Frame Replication in Wireless Time-Sensitive Networking

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***Abstract*—Wireless Time-Sensitive Networking (WTSN) faces challenges to ensure communication reliability without compromising communication latency. As communication in wireless link happens in the same channel, frame replication and elimination for reliability (FRER) in different bands or channels is not possible in the wireless part. However, with the new features like multi-link operation (MLO), FRER can be enabled in wireless links as well, improving the overall reliability of the communication. In this paper, we show how we achieve distributed MLO utilizing openwifi platform and wired TSN for synchronized transmission in multiple links. We show initial results of end-to-end reliability and latency when MLO is utilized under different traffic load levels on each operational link. We also show the effect of cross-node physical layer queue management for avoiding head-of-the-line queue blocking.**

***Index Terms*—wireless time-sensitive networking, MLO, FRER, openwifi, IEEE 802.11be.**

I. Introduction

Wireless Time-Sensitive Networking (WTSN) aims to bring the deterministic behavior of wired TSN to wireless networks, which inherently support flexibility and portability. While several challenges related to time synchronization and scheduling mechanisms in the shared medium have been tackled in the past by the research community [1], [2], achieving a high communication reliability remains still a hurdle. Traditionally, the reliability has always been addressed by enabling layer two re-transmissions, at a cost of increased communication latency. In case of scheduled transmission in WTSN, creating multiple additional dedicated time slots is another possibility to maintain reliability for highly time-sensitive traffic flows. In such a case, the network capacity is traded for reliability by reserving capacity beyond actual demand. Nevertheless, the issue with trading-off between reliability and increased communication latency persists, as the communication in different time slots must occur sequentially if the initial slot is missed or not used due to channel access procedure delays.

To improve the reliability in wired TSN, frame replication and elimination for reliability (FRER) is used. FRER is standardized as IEEE 802.11CB [3] and it is a mechanism to replicate packets in multiple disjoint paths between the source and destination. This allows for reception at the destination even if one of the links in a certain path fails.

In the WTSN domain, apart from over-provisioned scheduling and layer two re-transmissions, new Wi-Fi features can be utilized for improving end-to-end reliability. Multi-Link Operation (MLO) [4] was originally introduced in IEEE 802.11be to support load balancing in network nodes and stations, improving the overall throughput for applications. In the case of WTSN, MLO can be utilized to perform FRER over a wireless channel. To avoid adverse effects on latency, the schedules for highly time-sensitive flows must be aligned across all links to enable concurrent transmissions. If perfect alignment is not possible, then in the worst-case scenario, the time difference between scheduled slots on different links should stay within the maximum allowed packet waiting time on the wireless link. This is a new challenge for WTSN: not only must the channel access procedures in MLO be coordinated accordingly, but also time slots must be aligned across all links in MLO.

A multi-link capable device (MLD) is a device that supports communication via multiple wireless interfaces. The control of each wireless interface is performed by a separate lower MAC (L-MAC) sublayer and a unified upper MAC (U-MAC) sublayer. While the U-MAC layer is responsible for traffic steering in each link and link setup, the L-MAC manages the link-related parameters of each link and channel access mechanism. This two-tier architecture allows for transparent traffic handling at layer 2.

With the utilization of wired TSN, one can emulate a distributed MLD node architecture where U-MAC and L-MAC control are distributed among different locations. When there is a high traffic load on one link, packets might be delayed in physical layer buffers. Such packets can cause head-of-the-line (HOL) blocking on certain physical layer queues for other packets, even-though those packets have been transmitted correctly in the other link. To avoid HOL blocking, there is a need for coordination between L-MACs. In this paper, we show the design of a distributed MLD architecture for fast prototyping and testing of MLO in real test scenarios. As such, we utilized openwifi platform [5] together with Linux based TSN switches to enable end-to-end TSN communication with MLO in wireless links. In this paper, we show the following novelties:

- First MLO operational setup utilizing distributed MLD architecture employing openwifi with TSN backbone
- Time-based hash value packet elimination
- Cross-interface physical layer queue management for avoiding head-of-the-line (HOL) queue blocking

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The rest of the paper is structured as follows: in section II we give the related works and how this work differs from others, in section III we describe the system architecture of the distributed MLD backed by wired TSN, in section IV we describe the setup built for performing measurements in IDLab's industrial test-bed while section V reports achieved results in terms of communication reliability and latency, as well as the effects of cross-node physical layer queue management to avoid HOL blocking. Finally, section VI gives some observations on achieved results and future work, while section VII summarizes the findings of the paper.

II. Related Works

Operational in multiple bands at the same time is not something new for commercial devices. There exist APs that can operate in multiple bands simultaneously. What is new to IEEE 802.11be is the ability to steer different traffic flows from/to the same station on different channels. Such advancement aims to improve the throughput of devices while optimizing spectrum usage. Several studies have investigated the benefits of MLO in increased throughput [6].

In [7], the authors studied the impact of MLO on communication latency and throughput using experiments in a network-level simulator. Their findings indicate that in densely populated environments where multiple links are frequently occupied, MLO significantly outperforms Single-Link Operation (SLO) by leveraging intermittent transmission opportunities. However, in scenarios with asymmetrical link occupancy, MLO may increase latency due to suboptimal packet mapping, leading to interrupted backoff processes on busier links. Authors in [6] proposed a data-driven resource allocation algorithm for the IEEE 802.11be network to maximize throughput, ensuring fairness among MLDs. They evaluate the effectiveness of the proposed algorithm for multi-link multi-radio (MLMR) and simultaneous transmission and reception (STR) cases. In [4], authors explored traffic distribution strategies over multiple interfaces in MLO. Their research suggests that while congestion-aware policies generally enhance performance, distributing traffic flows across multiple links can make them more susceptible to interference from neighboring networks. Consequently, assigning new traffic flows entirely to the least congested interface often yields better results.

All the previous studies have been performed in network simulators. Having a test-bed setup to perform the MLO communication will help researchers to further investigate the benefits and challenges in realizing MLO in real life, as well as test different traffic steering algorithms on top. In [8], authors present a virtual MLD architecture utilizing multiple wireless interfaces, while in [9], authors present a testbed based on WiFi COTS devices for seamless redundancy. In our paper, we present a distributed MLD architecture. Due to utilization of openwifi platform, we go a step further by enabling cross-node physical layer queue management, which enables finer-grained management of packets in physical layer queues.

III. Distributed Multi-Link Operation Device Architecture

This section outlines the architecture of the distributed MLD and the overall system. It also explains the link and flow management mechanism, as well as the traffic steering method for FRER, which uses a time-based hash value mechanism.

A. Distributed MLD architecture

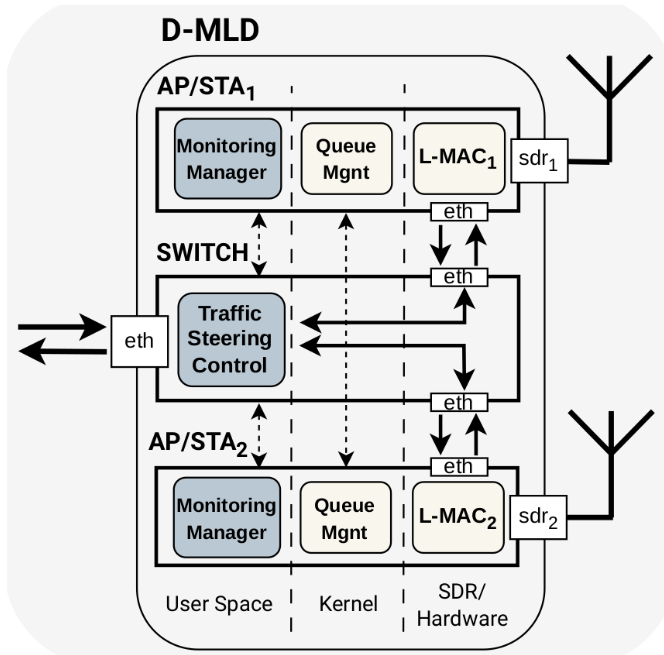

Fig. 1: Distributed MLD Architecture

To support MLO operation and end-to-end FRER, a distributed MLD (d-MLD) architecture is designed. The control functions are split among wireless nodes and the interconnected TSN switch. The *L-MAC* is implemented in FPGA in the openwifi platform and manages the low-level parameters such as channel access mechanism (back-off counter, layer two retransmissions), WTSN time-based scheduling, and over-the-air time synchronization [10]. Wireless nodes can operate either in access point (AP) or station (STA) mode. Each wireless device is managed and monitored by *device monitoring manager* logic implemented in user space utilizing *netlink* communication with the driver. The monitoring information that is collected in each operational link is: channel state information (CSI), packet error rate (PER), and signal-to-noise and interference ratio (SINR). Further, this information is shared with the *traffic steering control* in the TSN switch for performing traffic steering based on real-time monitoring information.

Distributed nodes are tightly time-synchronized via Ethernet. When the wireless nodes operate in AP mode, they are time-synchronized to the TSN switch. When the wireless nodes operate in STA mode, they are time-synchronized over wireless to their respective APs. In such a case, the TSN switch time is subordinated to the STA(s) time. The time synchronization master clock always resides in the wired network connected to the d-MLD operating in AP mode.

The proposed d-MLD architecture can support simultaneous transmit and receive (STR) on both links without any self-interference issues. Self-interference happens due to simultaneous reception and transmission in closely spaced frequencies or cross-talk between antennas in the same radio frequency front-end.

Figure 1 shows the interconnection between wireless devices and their building blocks to perform MLO, while Figure 2 shows the system perspective of the testbed setup. The d-MLD is interconnected with the central network controller (CNC) to retrieve information on e.g., WTSN scheduling and bootstrapping time synchronization. End devices that are connected to the central user controller (CUC) support application requirement sharing with the controller to enable automatic scheduling and management.

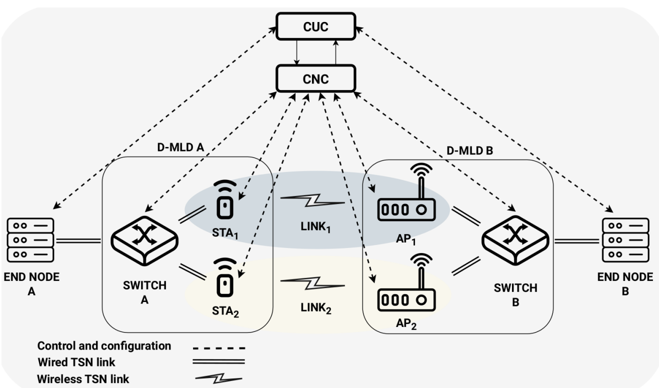

Fig. 2: Multi-link Operation System Perspectives

B. Link and Flow Management

Traffic steering is performed by *traffic steering control* in the TSN switch by allowing traffic duplication on both links or the selection of certain links based on wireless channel measurements. As the decision happens at the TSN switch, the TSN switch should be aware of the monitored information on each link: channel state information (CSI), packet error rate (PER), and signal-to-noise ratio (SNR) at fixed time intervals. Link management is handled independently for each link. This means that each wireless device, when in STA mode, independently associates with the corresponding AP device. Similarly, each wireless device when in AP mode broadcasts the same Service Set Identifier (SSID). *Device monitoring manager* tracks the established connections of the wireless devices and informs *traffic steering control* logic. As such, *traffic steering control* receives the list of all associated stations to the wireless device operating in AP mode, or it receives information if link is active for the wireless device operating in STA mode. If a link is not fully established with the AP or does not have a specific STA connected, the *traffic steering control* disables that link.

Next to link management, traffic flow management must be performed in real-time to achieve FRER similar to wired networks. Currently, flow management for MLO is performed on per-traffic identifiers (TID), by mapping certain TIDs at certain links, or dynamically shifting different TIDs between links based on specific parameters (e.g., link load). As the wireless link can change fast over time, to enable FRER utilizing MLO, traffic steering is performed on a per-packet level. Different packets can be steered on different links or can be duplicated in multiple links based on the latest link information. By enabling traffic flow management on a per-packet basis, wireless channel dynamics can be considereds.

C. Frame Replication and Elimination for Reliability (FRER)

To be able to detect duplicates and eliminate them at the endpoint, IEEE 802.11CB [3] specifies a redundancy tag (R-Tag) that utilizes a 16-bit sequence number that is placed in the Ethernet header similar to a VLAN tag. In wireless links, such sequence numbers should be mapped to a sequence number part of the IEEE 802.11 layer two header. This requires a dedicated mapping function when the packet switches from the wired network to the wireless and back, increasing the processing time for each packet. In addition, it will require a new information element on the IEEE 802.11 layer two header.

To streamline the process, we utilize an elimination mechanism based on hash values. When the packet is received at the endpoint, the elimination function produces the hash value of the packet and saves it in a register, adding a timer. Once the duplicates are received, their hash values are calculated and compared with the values saved in the register. If the hash value is the same and still active in the register, the packet is eliminated. To avoid any negative impact of the in-band network telemetry (INT) information on the hash value, the hash value is calculated over layer 2 and the IP payload of the packet only, excluding the IP header. The INT monitoring collects monitoring data on each network hope and adds them as an extension header in the layer three header. As such, the INT monitoring [11] makes the IP header of packet replicas different due to the monitored information on different paths.

D. Cross-node Queue Management

For real-time cross-node physical layer queue management, a *queue management* logic is implemented in openwifi driver. openwifi driver has one ring buffer for each hardware queue implemented in physical layer. Everytime a packet is transmitted from the physical layer queue, and *openwifi_tx_interrupt()* function will be called to clear the packet from the actual ring buffer. The driver tracks the ring buffer fillings and determines in real-time how many packets are causing HOL blockage of the physical layer queue. To avoid HOL driver need to be able to clear packets form the physical layer queue before they are transmitted. Such operation is different from the normal operation, where packets are cleared only once they are transmitted.

To this end, we have implemented a new function *openwifi_flush_tx_queue(struct ieee80211_hw *dev, u8 queue, u8 num_packets)* that can flush a certain number of packets from a certain hardware queue to avoid HOL blocking. The function is flagged and the flag to enable/disable the function is set from user space via *netlink* sockets. When enabled, the function is called at every *openwifi_tx_interrupt()* function given a certain threshold of packets residing in the queue is fulfilled. The threshold is set dynamically from the user space logic.

A logical communication between *queue management* logic in both devices, sharing information in real-time about which packets have been transmitted in the other link, allows for avoiding long delays in transmissions in certain links due to HOL queue blocking. Such interrupt-based communication can be implemented via a General Purpose Input/Output (GPIO) based communication between the drivers of both wireless interfaces.

IV. Measurement Test-Bed and Setup Implementation

The measurement setup is shown in Figure 2 and is composed of two openwifi APs running on ZCU102 boards and two openwifi stations running on ZedBoard. All the wireless nodes use FMCOMMS3 radio frontends that can operate between 70 MHz and 6 GHz. Both APs and STAs are connected to their respective Linux-enabled TSN switches utilizing a 10 Gbps link. Two end devices running NUCs are connected to the TSN switches. All the network devices are controlled by a centralized network controller (CNC), which collects the telemetry information and plots the monitored information in real time on a dashboard. The setup operates two links, one at 5 GHz and the other at the 2.4 GHz band.

A. Traffic steering

We follow an agent-based architecture [12], similar to the one used for communication between CNC and network nodes. However, for local information sharing we support direct communication between agents and modules inside the d-MLD. The *device monitoring manager* monitors information regarding the link statistics: CSI and PER on fixed intervals and shares this periodically with *traffic steering control* agent in the TSN switch. In addition, information regarding the link activity are shared, e.g. if the STA node is associated with AP or not. Such information are collected from *wpa_supplicant cli* and *hostapd cli*, respectively. Based on monitored information, *traffic steering control* decide to enable/disable certain paths

Bridges between certain interfaces in the TSN switch are implemented using the click router framework [13]. Packets are *colored* with a tag value based on which link(s) they are allowed to follow. Such *color* depends on the Differentiated Services Code Point (DSCP) value of the packet, and *traffic steering control* decides which packets can be steered/duplicated on each link based on DSCP value selection. As such, each packet can be dynamically steered on each link based on its *color*. Similarly, CNC can have full control over such traffic steering, by installing certain mapping in *traffic steering control* remotely.

B. Scenarios

To demonstrate the benefits of MLO in enabling FRER in WTSN, we conducted initial measurements to assess the achieved latency and reliability of time-sensitive applications under different levels of traffic load on dedicated links. In these measurements, packet duplication was performed at the TSN switches, while duplicate elimination was handled by the other TSN switch. We evaluated end-to-end traffic flow performance in terms of reliability, latency, and packet loss rate for each communication link separately.

Table I summarizes the test scenarios. Traffic load on each link was introduced by injecting UDP traffic from another station. First, we measure the maximum achievable UDP throughput for a single station connected to the AP on the respective link. Based on this, traffic load levels are set as fraction of the maximum achievable throughput. All traffic load level [0%, 25%, 50%, 75%] combinations at both links are tested. The time-sensitive traffic flow (the main traffic flow in the system) is represented as periodic traffic with a period of 50 ms and is transmitted from the end device connected to the d-MLD operating as AP to the end device connected to the d-MLD operating as a STA.

TABLE I: Scenarios and introduced traffic load on each link

Scenario ID	**Links**	**Traffic load**
1		0% - 0%
2		25% - 0%
3		50% - 0%
4		75% - 0%
5		0% - 25%
6		25% - 25%
7		50% - 25%
8	2.4 GHz	75% - 25%
9	- 5 GHz	0% - 50%
10		25% - 50%
11		50% - 50%
12		75% - 50%
13		0% - 75%
14		25% - 75%
15		50% - 75%
16		75% - 75%

C. Simultaneous load scenario

To assess the impact of simultaneous traffic loads on both links, we designed a WTSN MLO communication with scheduled transmissions between all the nodes. In this case, we add two additional interfering stations each operating in one of the MLO links at 2.4 GHz and 5 GHz, respectively. They connect to the respective APs of the d-MLD AP. All devices are time-synchronized and follow the same WTSN communication schedule, including the interfering stations, the d-MLD station, and the d-MLD AP. Each device is assigned a 256μs time slot within a recurring 16.384 ms cycle. The WTSN schedule is implemented in the physical layer of openwifi devices and supports cyclical scheduling similar to IEEE 802.1qbv in wired networks.

V. Results

In this section, we will present the achieved results. In subsection V-A, we show communication latency achieved for time-sensitive traffic flow under different traffic loads on each communication link. In addition, we also show the reliability of time-sensitive traffic flow as well as the achieved reliability of each link separately. In subsection V-B, we show the impact of simultaneous interference in both links on communication latency due to the HOL blockage effect. Next to this, we show the overcoming of HOL blockage with cross-node hardware queue management.

A. Traffic load impact

Achieved communication latency for the time-sensitive traffic flow is shown in Figure 3. Due to FRER enabled by MLO, the end-to-end median latency is below ∼5 ms for all scenarios, except scenario 16 where the traffic load on both links is 75%. What can be noticed is that the latency is impacted by the traffic load on the 5 GHz link. When the traffic load on that link is increased on average, the latency is increased as well (cfr. scenarios 13 to 16). The presence of outliers come from the fact that there is also traffic load not coordinated from the measurement setup. So even in case of scenario 0, there exists certain channel load due to presence of other APs in the environment.

Communication reliability is shown in Figure 4 for all measured scenarios. In all scenarios, the reliability is above 99% except for scenario 16 (scenario with the highest traffic load on both links), where the reliability dropped down to 98.25%. To compare the reliability of the time-sensitive flow with the actual reliability provided on each link, we also collected the packet loss rate every second on each link utilizing *device monitoring manager*. For the 5 GHz link (Figure 5), we see that the average reliability decreases with an increase in traffic load, and drops down to below 85% for scenarios 13 to 16. Similarly, for the 2.4 GHz link (Figure 6), the reliability drops below 95% (cfr. scenario 8 and 12) or even below 90% (cfr. scenario 4 and 16).

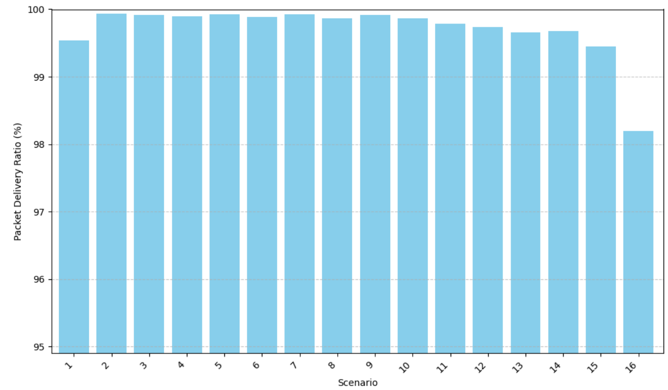

Fig. 4: Communication reliability for different scenarios

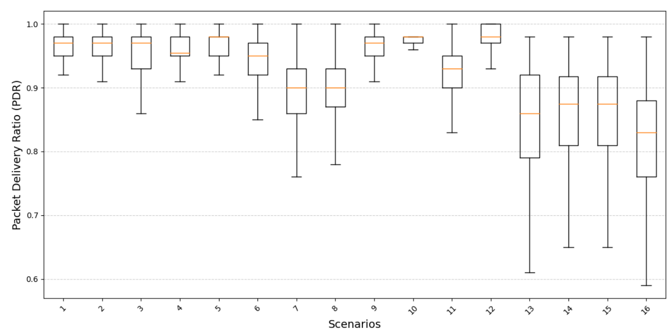

Fig. 5: Link reliability at 5 GHz

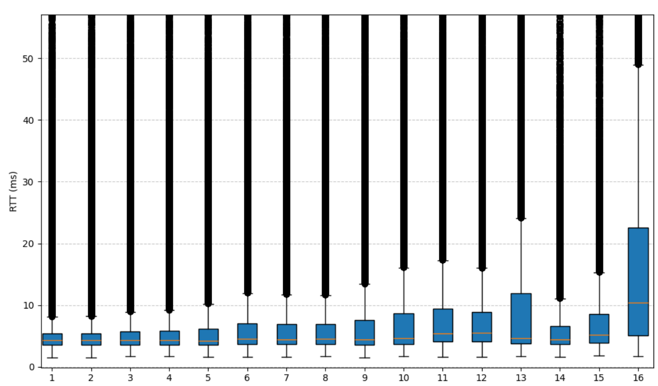

Fig. 3: Communication latency for different scenarios

B. Simultaneousness load impact

Figure 7 shows the communication latency over time for each duplicated packet of time-sensitive flow over both links. The traffic load is applied in three stages. Initially, both links are load-free, meaning that only time-sensitive traffic flow is present in the link, resulting in low and stable latency. During this the time-based hash value elimination mechanism works correctly as the delay between duplicates is small (in terms of μs). At second 25, traffic load is introduced in the first link, causing an increase in latency for the packet replica in that link. As such, due to increased load in the link, the channel access mechanism gets delayed. Consequently, packets experience longer buffering in the physical layer queues, leading to increased latency. As a result, duplicates may go undetected by the time-based hash value mechanism (red points between seconds 25 and 50). During this time, the d-MLD STA relies only on the second link for low-latency communication (green points between the second 25 and 50). At second 50, the traffic load is introduced in the second link as well. Due to the heavy load the packets are also buffered in the second link, resulting in some time when there will be no transmission from the d-MLD STA. At second 60, the interferer on the first link is stopped. Due to HOL blocking caused by delayed duplicates (red packets between seconds 60 and 65), the initial duplicates transmitted on the first link (green dots after second 60) are also delayed. Once the load on the first link ceases, the link flushes its buffer, transmitting all queued packets—including older and initial duplicates. Similarly, the load on the second link is stopped at second 70. The impact of HOL blocking on this link becomes evident with the red packets (second duplicates after second 70), which are only transmitted once the load is stopped.

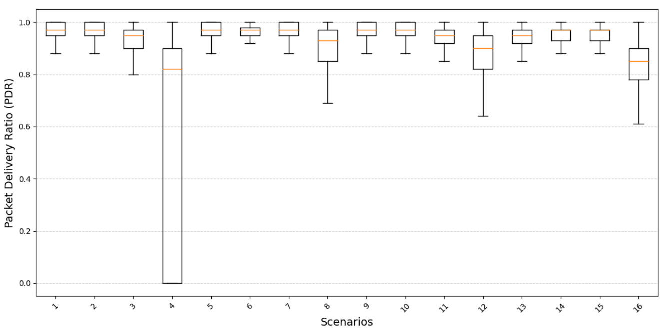

Fig. 6: Link reliability at 2 GHz

To mitigate delays caused by HOL blocking, a cross-node queue management mechanism is implemented. Figure 8 illustrates the latency over time with this mechanism enabled. Compared to the scenario in Figure 7, all packets are successfully received on the first attempt, and no duplicates are observed later. This improvement results from clearing a duplicate from the alternate link as soon as the packet is received through one link. Between seconds 50 and 60, when both links are under load, some latency is still present—these correspond to the first duplicates. Outside this interval, communication proceeds without noticeable delay.

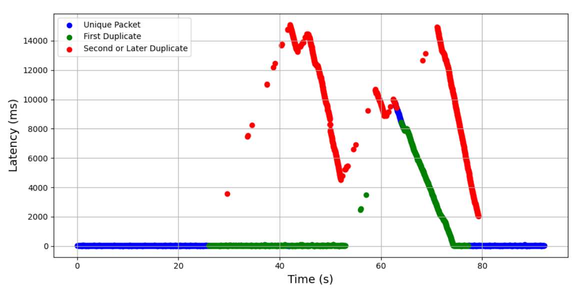

Fig. 7: Communication latency under simultaneous traffic load

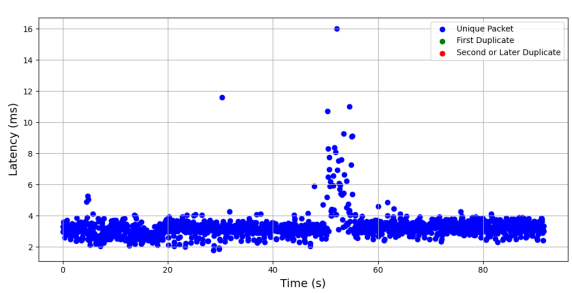

Fig. 8: Communication latency under simultaneous traffic load with cross-node queue management mechanism

VI. Observation and Future Work

It is obvious that concurrent load in multiple communication links increases the possibility of HOL blocking. To make the HOL blocking avoidance mechanisms even more agile, the traffic steering logic should be performed based on predictive queue management utilizing CSI modeling of each link. In addition to this, the utilization of CSI modeling on link bases, will offer dynamic channel selection possibilities in real-time, avoiding unnecessery spectrum usage by duplicated packets, when one of the links is underutilized.

Future directions to improve the current work related to triggering the channel access mechanism in one device by the events in the other device. This can assure continuous channel access in multiple links without the need for packet-based trigger event at physical layer.

VII. Conclusion

In this paper, we evaluate the impact of MLO on FRER and demonstrate how the reliability of time-sensitive flows improves through packet replication across multiple distinct links. We designed a distributed MLD architecture and created a test-bed setup using two openwifi boards per d-MLD. All the modules for distributed device monitoring, sharing collected information, as well as deciding on traffic steering based on that information are implemented. Additionally, we implement a low-overhead frame elimination mechanism based on hash values. To further prevent HOL blocking in hardware queues, a cross-node queue management function is introduced to eliminate delays on one link when a packet has already been successfully transmitted on the other.

Our results show that reliability above 99% can be maintained for time-sensitive traffic flows without affecting communication latency. This level of reliability was achieved even when the average reliability of individual links dropped below 90%. Also, we show that the communication latency is not impacted by HOL blockage in hardware queues.

Acknowledgment

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