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Queue Simulation Study for Multi-Link Operation in IEEE802.11be Networks

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***Abstract*—Multi-Link Operation allows simultaneous data transmission and reception over multiple frequency bands and it is one of the most relevant key features of the IEEE 802.11be standard. In some cases, this parallel communication is not possible, due to the cross-link interference and device properties. So, the devices have to operate in synchronous mode using, for example, start and end alignment mechanisms. Wireless networks can take advantage of multi-link presence to improve throughput and reduce latency. Indeed, to get the most out of this feature, particular emphasis is reserved not only on how to access the channels and do contention but also on how to manage packet flows over the different links. The packets could have different priorities and proprieties and, in some cases, it's necessary to assign them to a specific interface or modify it dynamically. Firstly, in this paper, a study of this standard and literature works is conducted. Then, the *OMNet++* simulation environment is analysed, examining the architectural model. As far as we know, no work in the literature uses it for this purpose, so we investigate it to be suitable for Wi-Fi 7 networks, highlighting the capabilities of this framework with the described needs. Several simulations are conducted, considering different scenarios and features in physical and MAC layers. Two types of packets are generated at the application level, so queues for multi-interfaces, contention and frame aggregation mechanisms are evaluated.**

***Index Terms*—IEEE 802.11be, Wi-Fi 7, Multi-Link Operation, OMNet++**

I. Introduction

Wireless Fidelity (Wi-Fi), based on the family of IEEE 802.11 standards, has become one of the most popular wireless technologies for data transmission [1]. From 2019, the IEEE Task Group BE (TGbe) has started working on a new amendment, called IEEE 802.11be or Wi-Fi 7. Different technical features have been suggested in PHYsical (PHY) and Medium Access Control (MAC) layers [2]. One of this standard's most relevant key features is the so-called Multi-Link Operation (MLO), which concerns the MAC layer. In MLO, the communication between two devices, which can be an Access Point (AP) and a station (STA), can be performed over multiple frequency bands, i.e., 2.4 GHz, 5 GHz and 6 GHz [3]. The device with multiple wireless PHY interfaces and a unique MAC address is called Multi-Link Device (MLD). The standard defines two different transmission modes: asynchronous and synchronous. The first one allows the Simultaneous Transmission and Reception (STR) capability over multiple links, which means that the MLD can transmit or receive asynchronously on multiple links [2]. In some cases, if the links operate on channels close to each other, especially in 5 GHz and 6 GHz bands, the transmission on one link impairs the ongoing reception on another link. Such inability to enable concurrent UpLink (UL) and DownLink (DL) transmissions and receptions on multiple links is a critical problem [4]. These devices are called non-STR or Non Simultaneous Transmission and Reception (NSTR). NSTR has two variants [5]: start-unaligned and start-aligned. In the first case, the transmissions are end-aligned but not start-aligned. In the second case, they are both start and end aligned. Furthermore, it is possible to use only one link at once. This modality is known as Single Link Operation (SLO).

The standard divides the MAC sub-layer into two parts. First, there is the Upper MAC (U-MAC), which is a common part of the MAC sub-layer for all the interfaces. Traffic awaits in the U-MAC before it is assigned to a specific interface to be transmitted [2]. Below the U-MAC, there is the Lower MAC (L-MAC). This level is independent and has its parameters for each interface [6]. This structure allows to design of a traffic manager on top of MLO framework to apply different traffic policies to allocate new incoming packets across the interfaces, ensuring a more balanced use of the network resources [7]. The intended purpose of MLO is to provide parallel channels to either increase the data rate or to enhance the latency [8]. This is a problem for the NSTR devices. Typically, AP are many-antenna systems and have the hardware requisite to select channels to provide isolation between the links and be STR [9]. Otherwise, this capability is often not present in the non-AP devices, e.g. the most popular and cheaper end-user devices. Designing a NSTR channel access strategy to improve performance, also considering how to properly handle traffic and packet queues at upper and lower MAC levels and manage the different links is still an open question.

Firstly, in this paper, we describe the IEEE802.11be features analyzing the literature state of the art. We focus on *OMNet++* simulator tools. Then, we try to implement a simulator architecture model to investigate the Wi-Fi 7 requirements with a focus on the queue of each wireless interface at U-MAC and L-MAC. This could be the starting point for designing a strategy related to traffic allocation, which can address the shortfall of NSTR mode. The rest of the paper is organized as follows. Section II introduces the current state of the standard with a brief literature review. Section III describes the simulation environment. Section IV explains the assumptions taken into

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consideration and shows the obtained results in the different scenarios. Finally, section V concludes the paper, highlights research open issues and describes future works.

II. Related Works

In recent years, different studies of the STR and NSTR MLO implementations have been conducted to compare the feasibility and the performance with respect to the SLO, especially in terms of throughput, latency and packet delay [5] [10] [11] [12]. For the reasons mentioned earlier, evaluation and comparison of different channel access schemes for NSTR operation have raised much attention and discussion in literature [4] [13]. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is applied in Wi-Fi devices to access the channel, operating in unlicensed bands. It is among the most prevalent techniques due to its intrinsic capability to cope with the high level of dynamism and heterogeneity of modern wireless networks in a very simple low-cost way [14]. In reality, channel availability cannot be guaranteed with different links [15]. MLD devices run separate back-off counters on each link. Specifically, for NSTR devices, when a back-off counter reaches zero on one link, the device can decide to start the transmission immediately or it can decide to postpone it, keeping its back-off value equal to zero, waiting until the other links finish their back-off procedure. As soon as the back-off of all links reaches zero, the device begins synchronized simultaneous transmissions on all links [4]. During the waiting period, the link may lose the channel access opportunity because other stations may also contend the channel access on that link. The NSTR device has also the possibility to choose to not transmit and keep its back-off counter at zero [16]. As said in the previous chapter, to transmit simultaneously, the MLD can use various techniques to align the ends of the transmission such as packet aggregation, fragmentation, padding and etc. [4]. Different standard channel access schemes with start and end alignment mechanisms are summarized in paper [12]. Paper [9] analyses the case in which the acknowledgement transmission in the UL on one link can overlap with the DL reception from AP on another channel. AP has precise knowledge of the start and end of potential acknowledgement (ACK) response from STA on different channels, so based on the entity of collision, the decision to align the end of data transmission on the links is taken. All these works focus on multi-link channel access rules at MAC level.

Another much-discussed aspect in literature is how to distribute the traffic over multiple links or which link can be used to guarantee the Quality of Service (QoS) requirements. In [7] different high-level traffic-to-link allocation policies to distribute the incoming traffic over the set of enabled interfaces are proposed. The traffic can be allocated to the emptiest interface or equally to all interfaces. It can also be distributed according to the observed channel occupancy. Taking these strategies as a reference, paper [17] proposes a new dynamic approach which considers channel occupancy and also the link rate on each interface. Other widely used techniques are based on packet splitting or packet duplication. In the first case, the payload is split into multiple fragments, and each is sent on one link. In the other, the payload is replicated and a copy is sent on every link. This redundant transmission is helpful to enhance reliability and reduce the worst-case latency [16]. Paper [18] proposes a new adaptive multi-connectivity scheme. The scheduler has to choose between load balancing, packet splitting or duplication based on the queue length and the Contention Window (CW) of each interface, but also on the effective load currently experienced by the network and so on.

The channel resources in a Wi-Fi network usually need to be used to support different types of traffic. The 802.11be amendment defines a Traffic Identifier (TID) mapping mechanism to classify data according to the QoS requirements, which are mapped to available channels for UL and DL traffic [19]. Paper [19] prioritises Real Time Traffic (RTA) by changing standard access parameters and allocating separate channels. Although wider bands are primarily dedicated to high-priority traffic, the paper [20] proposes to share faster links with the lower class to reduce their latency using an optimal routing strategy. While paper [15] assigns an exclusive logical queue with low latency to RTA traffic, exploiting a back-off mechanism based on the expected arrival time.

Most of them do not specify the simulator used or others use custom *Python* code [3] or *ns-3* simulator [4] [18]. Starting from the analyzed papers we concentrate on a simulator environment in *OMNet++* to manage packet queues in case different types of packets are generated from the application level, following a Poisson process. We implement a contention model, based on CSMA/CA policy, and we focus our attention also on the frame aggregation procedure to improve the flows and reduce the 802.11 protocol overhead. To the best of our knowledge, this is the first time that this kind of simulator is used to explore the Wi-Fi 7 features. Paper [21] describes the two network simulators, *ns-3* and *OMNet++*, which are compared in terms of their capabilities of simulating the Wi-Fi networks. Unlike *ns-3*, *OMNet++* provides a graphical user interface and many integrated visualization tools. It offers debugging tools to investigate interference, which can be essential, especially for the study of random access techniques.

III. Designed Network Structure

As said in the previous chapter, simulations are performed using *OMNet++* which is a modular discrete event simulator for different kinds of networks. It is open-source for non-commercial purposes [22]. In particular, the *INET* framework, an open-source model library for this simulation environment, contains models for the Internet stack, wired and wireless link-layer protocols (Ethernet, IEEE 802.11, etc.), mobility support, several application models, and many other components. [23].

The main element of the simulated network is the *StandardHost*. This template includes the most common Internet protocols, such as User Data Protocol (UDP), Ethernet, IEEE 802.11, slots for application models and various Network Interfaces (NICs) modules, which are the primary means of communication between network nodes. Wireless NICs contain a radio model component, which is responsible for modelling the PHY. The radio model describes the physical device that is capable of transmitting and receiving signals on the medium. It includes the antenna, receiver, transmitter, error model and etc. There are various radio modules, which must be compatible with the medium module. In *INET*, all wireless simulations require a transmission medium module. This module represents the shared physical medium where communication occurs, taking into account signal propagation, attenuation, interference, and etc. NICs modules also contain an L2 protocol with configurable MAC protocols. For our purposes, we utilize the standard *CsmaCaMac* that implements an imaginary CSMA/CA based MAC protocol with optional acknowledgements and a retry mechanism. In general, the simulation might also not require a detailed setting of the lower layers. We use the *WirelessHost*, which is an extension of the *StandardHost* and it provides a network node with one (default) IEEE 802.11 network interface in infrastructure mode. A configurator submodule of the network, the *Ipv4NetworkConfigurator*, is responsible for assigning Internet Protocol (IP) addresses to hosts to communicate with one another. *OMNet++* supports packet drops and retransmissions and frame aggregation features [23].

Authors in [24] extend and modify (at the physical layer) the default features provided by this simulator to emulate the latest massive Multiple Input Multiple Output (MIMO) technologies, with the design of new modules, and make it compatible with the 802.11ac standard, which is available in the framework.

To the best of our knowledge, the current tool's latest release does not support the IEEE 802.11be standard. All built-in wireless network nodes support multiple wireless interfaces, but only one is enabled by default. Due to this, we started exploring the simulator features at various network stack levels to manage different types of packets and be suitable for our purposes. The architecture of our network model is illustrated in Figure 1. In particular, in our model, we consider only two hosts: the first one generates and sends UDP packets

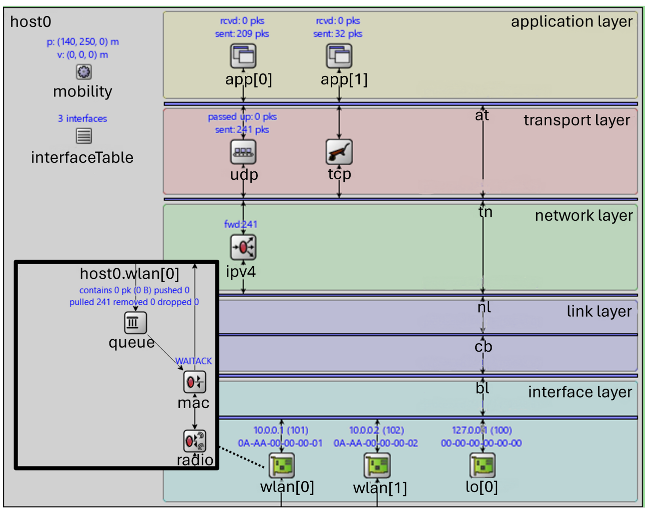

Fig. 1. OMNet++ simulation network architecture.

to the other one, which behaves like a sink. Each host is configured with two application modules: *app[0]* and *app[1]* which packets are sent via different ports. The first application produces audio messages with a length of 100B, while the second one produces video data with a length of 1000B. UDP messages are generated at intervals that follow an exponential distribution with a respective mean of 10 ms and 50 ms. To simulate MLO feature, each host is set up with two wireless interfaces, *wlan[0]* and *wlan[1]*. Each of the two interfaces has a local address and therefore, the transmission of voice and video information is carried out from different local addresses to different recipient addresses. The *wlan* module includes different sub-modules such as queue, MAC, radio, clock and etc. The *MassiveMIMOUCPA* radio module is chosen, whose open-source implementation is taken from paper [24].

IV. Implementation and Simulation Results

We aim to assess whether there are any opportunities to model IEEE802.11be multi-link and queue management features within this framework. To accomplish this, we examine simplified network configurations, using the available simulator modules, that share common properties and functionalities with the Wi-Fi 7 standard. Based on our previous considerations, we build two different models. The first is a *csma* model with contention medium access to represent the real network behaviour. The second is a packet *aggregation* model that allows the reduction of the network load in case packets are collected due to collisions or intensive traffic. For both, we consider the simplest network interface operating with IEEE802.11a standard that allows iterating over the different bitrate values: 6, 9, 12, 18, 24, and 36 Mbps. We use a simple disk signal propagation model with a communication range of 200 m. Aggregation with a size of 4065B is enabled by default for the *WirelessHost*. Our *aggregation* model sets the aggregated frame size to 1000B so that small packets are aggregated into a frame of this dimension. For the *csma* model, *ackTimeout* is set to 300us and *headerLength* to 25B.

To compare the results we use end-to-end delay, throughput, and the number of received packets as metrics, as shown in Figure 2 where the graphs on the right are referred to the *csma* model, while the others on the left to the *aggregation* model. In Figure 2a, data segmentation is observed for the *csma* model. It is related to the type and, consequently, to the size of the transmitted data. For the *aggregation* model, in Figure 2b, data segmentation depends also on the specified bitrate value. As shown in Figure 2d, the throughput of the model with packet aggregation is higher, but it depends on the size of the input packets. For this reason, the size of the aggregated packet must be adequately selected. The destination node has received the same number of packets at the end of all simulations (Figure 2e and 2f). Signal transmission errors are not considered.

Furthermore, we consider another model that returns Packet Error Rate (PER) and Signal to Noise plus Interference Ratio (SNIR) values. To achieve this, *Ieee80211NistErrorModel* is adopted as the default error model. It describes how the SNIR affects the amount of errors at the receiver. We work with the

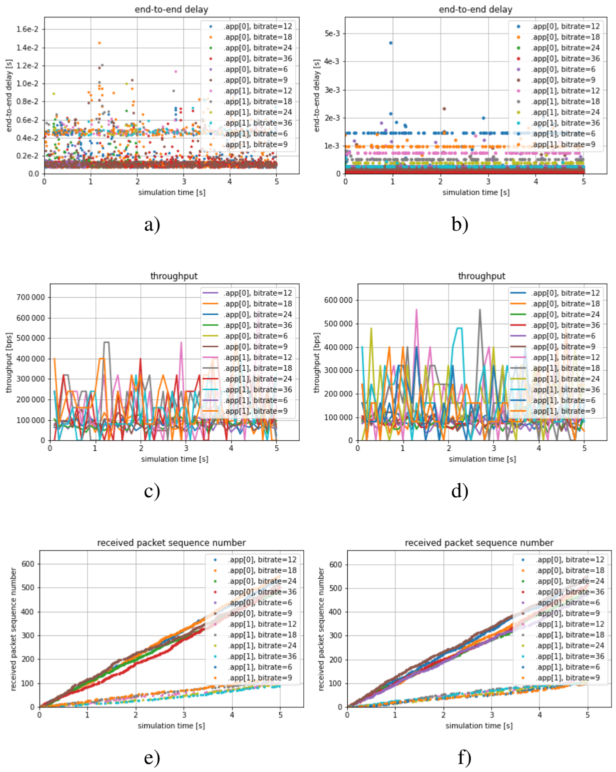

Fig. 2. Simulation results of the two models: csma and aggregation.

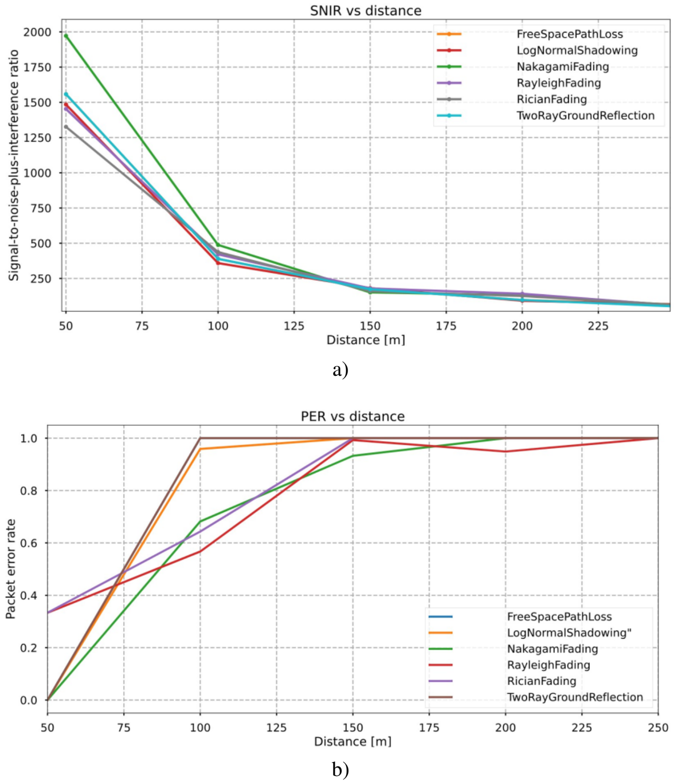

Fig. 3. SNIR and PER simulation results.

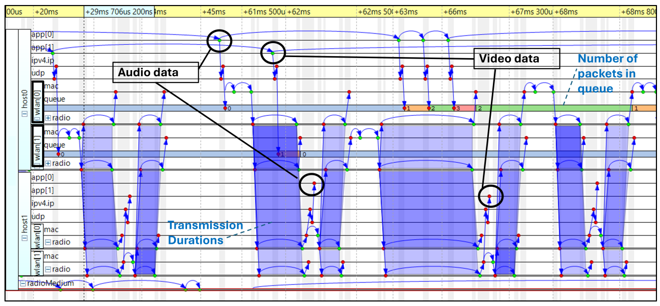

Fig. 4. Log file: packet transmission at various network levels.

IEEE802.11ac standard. In this case, the model automatically selects the highest possible bitrate value. This value depends on protocol, standard specifications, network configuration and available speeds. In *OMNet++*, the default medium model uses the free-space path loss model. Additionally, multipath propagation is taken into account to model real-time traffic. The above simulation structure is analyzed on a model considering different path loss models, such as TwoRayGroundReflection, LogNormalShadowing, Nakagami, Rician and Rayleigh fading (which are already well described in the literature).

The graphs in Figure 3 show the results of calculating the PER and the SNIR. The first is calculated from Bit Error Rate (BER), which is derived from SNIR. Based on the results, the Modulation and Coding Scheme (MCS) used by the station or the AP can be selected according to the SNIR by the means of lookup table [3]. The error model calculations are associated with different modulation schemes, like Amplitude and Phase Shift Keying (APSK), 256/512/1024 Quadrature Amplitude Modulation (QAM) and etc. There are no evident differences between the various models, but PER value increases with the communication range.

Mainly, these experiments were carried out to manage the various packet queues at both application and network interface levels. Despite the modelling of the data transmission between two nodes using two independent channels, all transmission requests were directed to both interfaces that do not work independently, as highlighted in the simulation log file in Figure 4. *OMNet++* current implementation does not allow independent simultaneous transmission and reception on multiple interfaces: information from a single network node is transmitted sequentially. This is for us an open point and the result of the tools analysis. As mentioned previously, the simulator instrument and the analyzed modules need to be modified to include the MLO IEEE 802.11be feature.

V. Conclusions and Future Works

Different simulations, examining several *OMNet++* features, were conducted. From a simulation point of view, in *OMNet++* we are able to manage different types of packets and queues only at the application level. This is not possible at a lower level. Starting from the studied configurations, our future aim is to model devices as a queueing system with separate parallel queues also at L-MAC [18], one for each interface with a traffic scheduler and a common queue at

U-MAC level: each packet has to be assigned to a specific interface. Each MLD can be seen as an M/M/1 queueing system [20] [25], with different inter-arrival and service times, exponentially distributed, and only one available processor. All interfaces have to be enabled at the same time, each with its MAC and PHY layer. So, it is necessary to adapt the current features of the framework to our purposes, reviewing the flowchart and the packet transmission principle in the software system. We think about two possible solutions:

1) modification of *csmaca* module by adding a submodule for the queue and radio. This may lead to errors in the identification of the transmission channel from other system modules. It should be expected.
2) implementation of a sniffer algorithm that identifies the packet's source or other information necessary for transmission from the node's upper to lower level. It is crucial to maintain the packet structure to avoid subsequent identification errors.

The *csma* model allows contention between multiple transmissions and receptions on the same channel. This has to be tuned in a more sophisticated way to work with MLO because the multiple back-off instances have to run in parallel. The *aggregation* model can be used with the supervised action of the traffic manager, for example, when an interface is saturated and packets have to be sent also to the other interface as well. So, for the future model, we have to put them together to improve the throughput performance and reduce delay. With the aggregation, the contention periods, the interframe spaces and ACKs are also reduced [23].

VI. Acnowledgement

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