Investigating Inclusiveness and Backward Compatibility of IEEE 802.11be Multi-link Operation

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Abstract—**Nowadays is not possible to avoid considering the coexistence and the fusion of different wireless technologies as completely separated entities. The ever-growing number of devices employing multi-RATs (Radio Access Technologies) that require continuous wireless connectivity is posing great challenges. Furthermore, the requirements in terms of both throughput and latency originated by the use cases, are pushing the current technologies to their limits, especially for indoor dense deployments that are usually covered by Wi-Fi. The IEEE 802.11 Working Group is currently tackling such challenges by working on a new amendment of the standard (namely 802.11be), which introduces, among other novelties, the multi-link operation (MLO). Through MLO, the target is to achieve simultaneous transmission over multiple bands to obtain massive bitrate up to 40 Gbps. The introduction of MLO poses challenges on the coexistence with older legacy devices in mixed networks. This contribution explores how the coexistence of legacy IEEE 802.11 devices and new IEEE 802.11be devices realizing the proposed multi-link feature can be improved by using an appropriate static band assignment policy. Another issue is how the overall network behaves when varying the number of devices and the legacy/new nodes ratio. Simulations for three different band allocation cases close to reality are developed. Performance results in terms of aggregated, average throughput and fairness are derived for different conditions.**

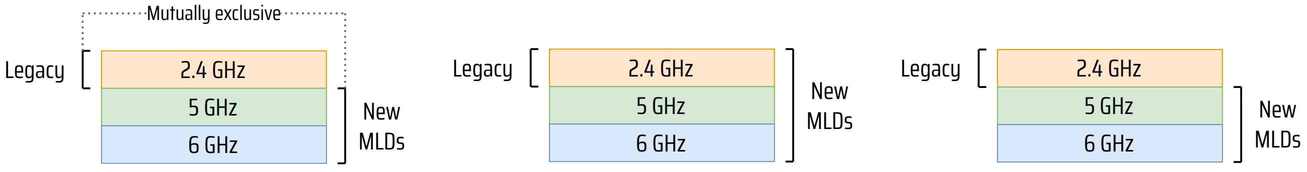
Index Terms—**WiFi, IEEE 802.11be, multi-link operation, legacy devices, throughput, fairness**

I. INTRODUCTION

The constantly growing requirements from state-of-the-art applications and use cases, especially in terms of quality of service (QoS), have been the pushing force behind the Wi-Fi technology advances practically from its very inception in 1997. This resulted in the development of several amendments of standards under the IEEE 802.11 name. The last approved version of the standard (IEEE 802.11ax) has put Wi-Fi networks closer to cellular networks, with the introduction of orthogonal frequency-division multiple access (OFDMA) and specific techniques to improve the spatial reuse [1], which allows reaching data rates up to 10 Gbps. Currently, the IEEE 802.11 Working Group is in the process of defining the next standard, namely IEEE 802.11be. One of the most relevant key features of the new upcoming standard is the so-called multi-link operation (MLO). 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 bands. The operation usually follows a half-duplex fashion (a device can either transmit or receive but not simultaneously). The radio interfaces can either function independently or be synchronized [2], [3]. On a side note, although simultaneous transmission and reception are allowed, it is greatly discouraged due to in-device coexistence interference related issues [4], [5].

Naturally, such a new concept requires a partial redesign of the medium access control (MAC) sub-layer, since it needs to deal with multiple radio interfaces simultaneously. Briefly, the new MAC sub-layer is split into upper and lower layers: the upper one performs all the link agnostic tasks, while the lower layer contains the transmission/reception buffers and deals with the actual frames exchange using the radio interfaces. This means that the frames originated from the upper layers can be spread over the different radio interfaces. Such changes led to define a device (either an access point or a station) that employs multi-link operation as a multi-link device (MLD) [5].

Since devices' life spans several years, it is highly improbable to have homogeneous networks (i.e., all devices complying with the same IEEE standard), unless it is a special designed deployment (e.g., Industry 4.0 scenarios) [6]. Therefore, most networks are composed of legacy and new MLDs, operating according to different IEEE 802.11 amendments. This usually leads to coexistence issues, which affect all performance indicators both from the single device and the entire network points of view (e.g., throughput and fairness). It is then essential to establish an appropriate way of mitigating the coexistence-related effects. Being a hot topic in communications, several works have been already published in the past focusing on multi-link operation. Authors in [7] provided a general view of the coexistence challenges in mixed networks due to the different employed channel access method, proposing additional techniques to address those challenges for the considered cases. Authors in [8] studied the performance for three different scenarios by means of simulation; however, the



(a) (b) (c)

Fig. 1: Considered cases. a) Two access bands with single RTS acceptance; b) Single access band with single RTS acceptance; c) Two access bands with multiple RTS acceptance.

considered assumptions make the study quite far from the real-word case. Finally, authors in [9] discussed the MLO performance in the presence of legacy devices but with a focus on non-synchronized non-simultaneous transmission and reception.

In this work, we focus on investigating how employing different band assignment policies can affect the coexistence of legacy devices (operating solely in the $2.4\,\text{GHz}$ band) and MLDs (operating simultaneously in two or more different bands). It should be also pointed out that this work is more oriented towards the channel access, as it is the only element in our abstraction that is affected by coexistence-related issues. The remaining of the paper has the following structure: Section II describes the problem and the considered assumptions; Section III provides details regarding the simulation environment and how the study is carried out; Section IV shows the obtained simulation results and discusses additional considerations; finally, Section V contains the final considerations of our work.

II. Problem Statement and Assumptions

As explained previously, we focus on evaluating the effects of simple static band assignment policies. We consider that all devices are operating using the Request-To-Send/Clear-To-Send (RTS/CTS) reservation mechanism, in order to minimize the collision effects. Consequently, a collision can occur only when two or more devices transmit an RTS frame simultaneously. Moreover, we should point out that we take into consideration only the single-user (SU) transmission mode. Therefore, all OFDMA sub-carriers are reserved by a single user, contrary to the multi-user (MU) case in which they are grouped into resource blocks and then are assigned to different users.

We consider three band allocation strategies that are very close to reality. In particular, Fig. 1a shows a deployment in which legacy devices operate on the $2.4\,\text{GHz}$ band, while the new MLDs operate on the 5 and $6\,\text{GHz}$. In this case, the access point can handle a single access request at a time. This means that a legacy device transmitting on the $2.4\,\text{GHz}$ band will "lock" the access point operation, and prevent it to accept access requests from other bands. Fig. 1b shows the deployment that is expected to be used in general purpose mixed networks; no separation exists between the two types of devices, so new MLDs will operate on all three bands, sharing the access band with the legacy nodes. Finally, Fig. 1c shows a case in which, similarly to Fig. 1a, a complete separation between the two device types is employed. However, in this case an advanced access point, capable of handling multiple simultaneous access requests over different bands, is used. It should be pointed out that, in real-world scenarios, a similar access point behaviour will cause an increase of self-interference related issues. Therefore, additional considerations would be needed in order to transpose this case to the real-world [10].

Additional considerations are needed for the MAC operation. For Cases A and B, no device priority is considered in collision cases. This means that if two or more frames coming from different devices collide (in our case, RTS frames) the AP will recognize the collision and will reject both requests. A CTS frame will not be sent, and the STAs' internal timeout will expire, resulting in both transmitted RTS frames to be discarded. For Case C, it is assumed that the AP is capable of handling simultaneous access requests over different bands at the same time.

Furthermore, it is considered that all MLDs employ a single link access (SLA) methodology [3]. Therefore, the distributed coordination function (DCF) will be performed on a single link (called primary link); the availability of the additional links (auxiliary links) is simply evaluated through channel sensing when the backoff counter of the primary link reaches a value of zero. The control frames exchange (RTS/CTS/ACK) takes place in the primary link. Additionally, we consider the primary link to be always the one with the lowest carrier frequency.

In order to evaluate the behaviour for each case depicted in Fig. 1, we consider two metrics: throughput and fairness. We computed three kinds of throughput: aggregated system-wise, aggregated per device type and average per device type. While the first is straightforward and well known, we need to clarify the two per-device ones. We define the aggregated throughput per device type as the total throughput related to a single class of devices (either legacy or MLDs). Similarly, the average throughput per device type is defined as the average throughput provided to a single device class. The two metrics are summarized as

$$S_{\text{TOT},c} = \sum_{i=1}^{u_c} s_i \qquad S_{\text{AVG},c} = \frac{1}{u_c}\sum_{i=1}^{u_c} s_i \ , \tag{1}$$

where c is the device type (legacy or MLD), u_c is the number of stations in c, and s_i is the uplink throughput for the i-th

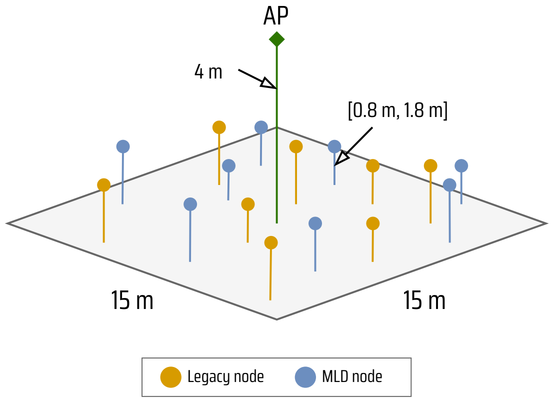


Fig. 2: Depiction of the employed scenario (for viewing purposes, only 16 of the 50 total devices are shown).

station. Clearly, the network-wise aggregated throughput is given by

$$S_{\text{network-wise}} = \sum S_{\text{TOT},c} \tag{2}$$

Finally, fairness is computed through the Jain's Fairness Index

$$JFI = \frac{\left[\sum_{j=1}^{n} s_j\right]^2}{n\sum_{j=1}^{n} s_j^2} \;, \tag{3}$$

where n is the number of transmitting devices under consideration and s_j is the uplink throughput for the j-th station [11].

III. SIMULATION SETUP AND PARAMETERS

We consider a simple scenario over a 15×15 m^2 squared area, with a single AP placed in the centre of the area, at a height of 4 m. The stations are randomly placed inside the area, at a height between 0.8 m (as if it is a laptop placed on top of a desk) and 1.8 m (as if it is a smartphone during a call), similarly to the topology employed in [12]. All devices are operating with full buffers (always having available frames for transmission) and all three bands have the same channel bandwidth (20 MHz), in order to avoid greater differences in terms of employed data rate. Note that aiming to investigate inclusiveness of different device types and backward compatibility we employed a simple transmission scheme over the minimum available channel bandwidth. Extending the model to greater bandwidths and full MIMO capabilities would increase bit rates substantially (in the order of Gbps). The legacy/new devices ratio is varied from 10 to 90%, in 10% steps. An example of such a scenario is depicted in Fig. 2.

Simulations are performed on a custom developed event-driven Python simulator that provides a complete implementation of IEEE 802.11be PHY/MAC key features, with a particular focus on multi-link operation. The simulation tool follows closely the methodology for system-level simulators described in [13]. Each simulation is repeated 150 times, varying the STAs' position within the area above mentioned (leading to different channel realizations). The simulated time is 1 minute.

TABLE I: Simulation parameters.

PHY	
P_{TX}	15 dBm
Antenna TX/RX gain	0/0 dBi
Break-point distance d_{bp}	5 m
Average number of walls W	3
OFDM symbol duration	12.8 µs
Channel BW	20 MHz
Clear channel assessment (CCA) threshold	-82 dBm
Spatial streams	2
T_{preamble}	160 µs
T_{preamble}(legacy)	40 µs
Noise Figure	7 dB
Guard Interval	0.8 µs

MAC	
DCF Slot	9 µs
CW_{min}	16
Max retrials per frame (retry limit)	7
DIFS	20 µs
SIFS	10 µs
MAC header	320 bits
CTS/ACK frame size	112 bits
RTS frame size	160 bits
Control frames rate (MCS 0)	17.2 Mbps
Payload size	12000 bits

The path loss model employed for the channel characterization is given by

$$\begin{aligned} PL(\text{dB}) = 40.05 + 20\log_{10}\left(\frac{f_{\text{GHz}}}{2.4}\right) + \\ + 20\log_{10}[\min(d_{bp}, d)] + K + 7W \;, \end{aligned}$$

which corresponds to the enterprise model, defined for IEEE 802.11ax in [14] by the related Task Group. In particular, f_{GHz} is the channel's carrier frequency in GHz, d_{bp} is the break-point distance, d is the distance in between the STA and the AP, and W is the average number of walls between the STA and the AP. The parameter k is related to the break-point distance effect on the path loss, given by

$$K = \begin{cases} 35\log_{10}\left(\frac{d}{d_{bp}}\right) & \text{if } d \geq d_{bp} \\ 0 & \text{if } d < d_{bp} \end{cases} \;.$$

On top of the path loss, a Rayleigh fading model is considered. Finally, for each device, the modulation and coding scheme (MCS) is selected according to the signal-to-noise ratio (SNR) by the means of a lookup table, in a genie fashion aiming for a target packet error rate (PER) equal to 10% [15], [16]. A summary of the simulation parameters is provided in Table I.

IV. RESULTS

As explained previously, we considered throughput (in three different flavours) and fairness as metrics to evaluate the performance of the different cases. Fig. 3 shows the total, network-wise aggregated throughput for the three cases. For Case A, it is clearly visible the effect of the access point lock,

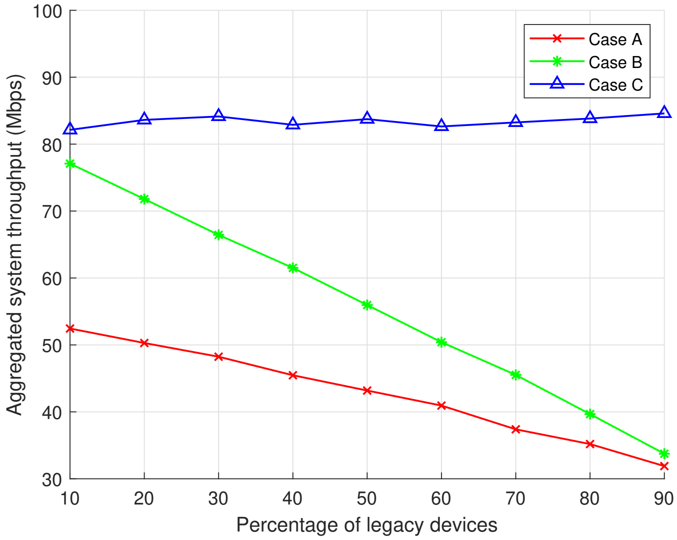


Fig. 3: Aggregated network-wise throughput for the three cases.

even if the curve steepness is quite moderate, especially if it is compared against Case B. Case B shows a clear performance gain due to the additional frequency band used by MLDs. However, the access channel sharing between the legacy and new devices increased the steepness considerably; at 90% of legacy devices, Case A and B obtain almost the same aggregate throughput. Concerning Case C, the achieved performance is almost constant, since the variation of the percentage of legacy devices implies very little change in the aggregated network-wise throughput, due to the absence of any kind of lock at the access point level.

Fig. 4 depicts the aggregated throughput per device type. It is clearly visible how the network-wise throughput is split between legacy and new devices. We can state that, from the MLDs point of view, Case B provides better performance up to 35% of legacy devices, afterwards Case C becomes predominant. It should be noted that such information is not provided by the network-wise throughput of Fig. 3. From the legacy devices' point of view, no significant difference exists between Cases A and B, since their operation remains unaffected between the two cases. Analogously to the previous figure, for Case C the throughput is almost constant for both legacy and new MLDs, which is around 29 Mbps and 54 Mbps, respectively.

Lessons can also be learned by observing Fig. 5, which shows the average throughput per device type for all three cases. Differently from the previous figures, for Cases A and B, the average throughput is basically constant for all different percentages (between 0.50 and 1.65 Mbps). On the other hand, for Case C, we have curves in $1/N$ fashion for both legacy and new devices, with peaking throughputs of 5.70 and 11.20 Mbps for legacy and new MLDs, respectively. Similarly to Fig. 4, from the MLDs' point of view, the best choice up to 35% of legacy devices is Case B, even if the difference is not significant. It is clear that Case A provides the worst performance of all.

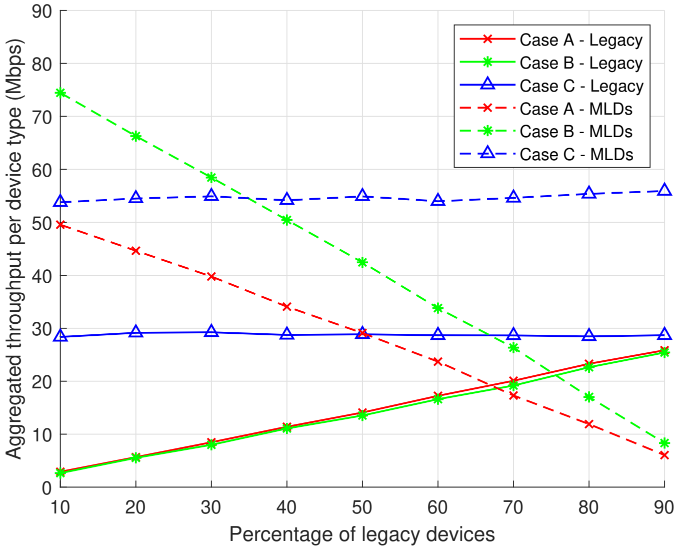


Fig. 4: Aggregated throughput for each device type for the three cases.

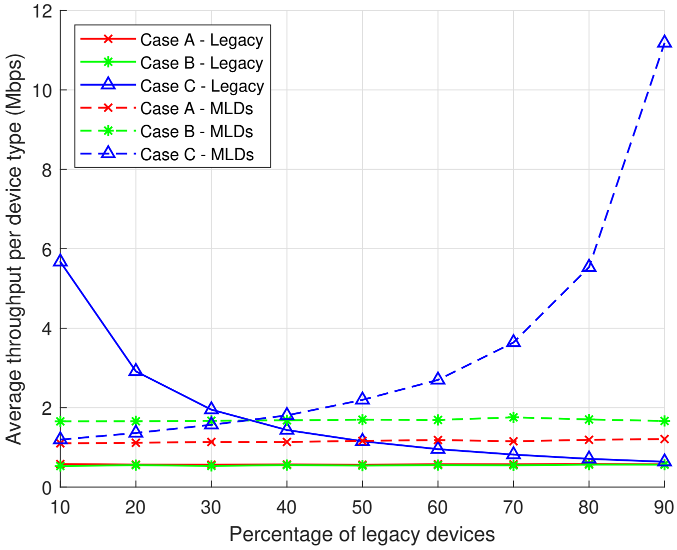


Fig. 5: Average throughput for each device type for the three cases.

Finally, the performance in terms of fairness is shown in Fig. 6, both for the overall network and for each device type. Starting with the total network fairness, we can easily notice how it is affected by the legacy/MLDs ratio. For Case A and B, a U-shaped trend is visible, with minimums on 60% and 70% for Cases A and B, respectively. Thus, a 10% right-shift is present. We can state that the higher the number of employed parallel links, the greater the curve shift towards the right. This can be easily explained by noticing that, on average, MLDs will deliver more frames than the legacy devices. Since Jain's fairness index is based on the average

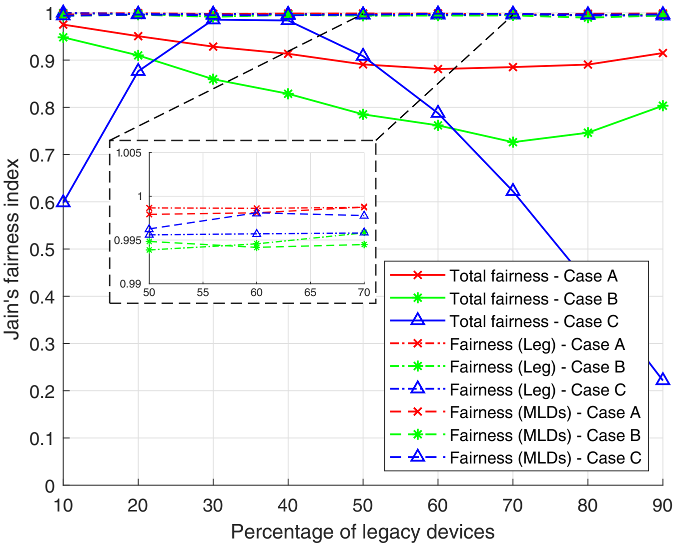


Fig. 6: Network-wise and devicetype-wise fairness for the three cases.

aggregated throughput per network node, a kind of balancing effect shows up when the legacy devices become prevalent (see [11] for more details). About Case C, the trend has a completely reversed behaviour, with a maximum around 35% of legacy devices. Again, such conduct is because of the fairness indicator formulation. Since in Case C we allow the acceptance of multiple RTS requests, MLDs and legacy devices act as if they belong to two separate WLANs. It is clear that, in this case, the sole total fairness does not provide a full picture. Consequently, we computed the fairness separately for each device type, as shown in the zoomed view chart in Fig. 6. It is visible that it remains always above 0.99, regardless of the percentage of legacy devices. Although the differences between the three cases are very small (around 0.5%), we notice that Case A achieves a slightly higher fairness, followed by Case C and B.

V. CONCLUSIONS AND FUTURE WORK

In this work we studied and assessed the effects of coexistence of new IEEE 802.11be MLDs with legacy devices. In order to investigate which one achieves higher performance when deploying dense networks, three different cases are considered as typical evaluation scenarios. By evaluating the throughput and fairness with respect to the percentage of legacy devices, we identified the importance of choosing the correct point of view (from the network or the device type) when deciding about the channel access in dense deployments (e.g., 50 STAs per AP). This last point may be addressed by means artificial intelligence techniques (e.g., reinforcement learning, federated learning). Future work includes the employment of a more realistic access point model that will definitely provide additional insights on the peak achievable performance for Case C in real-world scenarios. In addition, bringing packet aggregation, enhanced multiple-input multiple-output (MIMO) to the game will certainly allow further enhance performance, both in terms of throughput and total service delay [8].

ACKNOWLEDGMENT

This work has received funding from the European Union (EU) Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie ETN TeamUp5G, grant agreement No. 813391. This work was also supported by Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions (INTERACT) through COST Action under Grant CA20120, FCT/MCTES UIDB/50008/2020 and SNF Scientific Exchange-AISpectrum (project 205842).

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