Study of Band Allocation Policies in IEEE 802.11be Networks with Devices of Different Capabilities

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***Abstract*—The upcoming IEEE 802.11be standard aims to provide extremely high bitrates to support next generation use cases. Among the proposed features, multi-link operation (MLO) is probably the one contributing most towards this goal. MLO enables new types of devices, i.e., multi-link devices (MLDs), to transmit simultaneously over multiple frequency bands to achieve massive bitrates (reaching 40 Gbps) and, consequently, lower latency. However, the coexistence of MLDs with legacy devices in existing and future wireless local area network (WLAN) deployments has not yet been explicitly investigated. In this work, we investigate different band management policies over a three-band densely populated WLAN, allowing MLDs to use one or more bands for the access procedure and data transfer. We evaluate, via extensive simulations, the access delay of the devices and the network throughput with respect to the ratio of legacy devices and MLDs. We show that by using different band allocation policies for MLDs, several trade-offs regarding throughput and access delay arise that need careful consideration to avoid performance degradation.**

***Index Terms*—WiFi, IEEE 802.11be, multi-link operation, access delay, throughput**

I. INTRODUCTION

The IEEE 802.11be amendment, currently under development, is indeed entitled to play a significant role in wireless connectivity in the upcoming years. Evolving from IEEE 802.11ax's roots, it introduces several key features both on the physical (PHY) and medium access control (MAC) layers to reach the marketed 40 Gbps throughput. The physical layer is improved with the adoption of an extended 320 MHz channel bandwidth, the 4K-QAM modulation scheme as well as further multiple-input multiple-output (MIMO) enhancement. Regarding the MAC layer, the real key feature (which can be safely identified as the game changer of the standard) is the so-called multi-link operation (MLO) [1]. In this newly introduced operation, the communication between two multi-link enabled devices (MLDs) in a network, e.g., an access point (AP) and a station (STA), can be carried out over different frequency bands, i.e., 2.4 GHz, 5 GHz and 6 GHz. Usually the employed operation is the non-simultaneous transmission and reception (NSTR), although the simultaneous mode is indeed possible but discouraged because of in-device coexistence interference [2].

As it always occurs when introducing a new wireless technology, retro compatibility and coexistence related issues arise, which usually degrade the performance both from the network and the single device points of view. Despite the fact that IEEE 802.11be is an amendment aiming to increase the obtained throughput, another key performance indicator is the achieved access delay. This is significant especially since the killer use cases for the standard are immersive multimedia (virtual, augmented, and extended reality) and Industry 4.0 (as a side assistance for wireless sensor networks), which typically have tight requirements in terms of latency [3]. The multi-link operation is currently a hot topic in the research community and numerous works have been already published. In [4] we have studied the impact of different mixed legacy/MLDs deployment cases on throughput and fairness. Authors in [5] studied experimentally the overall delay performance of multi-link operation and compared it to the one of legacy operation. In [6] authors provided an analytical model to determine throughput performance of heterogeneous networks containing both legacy and multi-link devices. Authors in [7] studied the possibility of using multi-link operation in homogeneous deployments to enable real-time applications. Lastly, authors in [8] analyzed throughput performance for both symmetric and asymmetric scenarios employing legacy and MLD devices.

Differently from the research efforts abovementioned, the aim of this work is to investigate the impact of different band management methodologies on the access delay performance of IEEE 802.11be future networks that also provide services to legacy devices (operating both in the 2.4 and 5 GHz bands). In this context, we analyse, through simulations, the access delay and the network throughput of both legacy devices and MLDs in four different band allocation policies complemented by deliberate split of legacy devices in the two lower bands. We find out several trade-offs that can be exploited to carry out a better management of the network in order to obtain superior performance both from the device and the general network points of view. In addition, we show the potential of distributing legacy devices appropriately over the bands to improve the network balance (in terms of access delay per device type), despite being made of heterogeneous devices. To our knowledge, this is the first work that studies such as a concept.

The rest of the paper is organized as follows: Section II provides the system model and the assumptions taken into

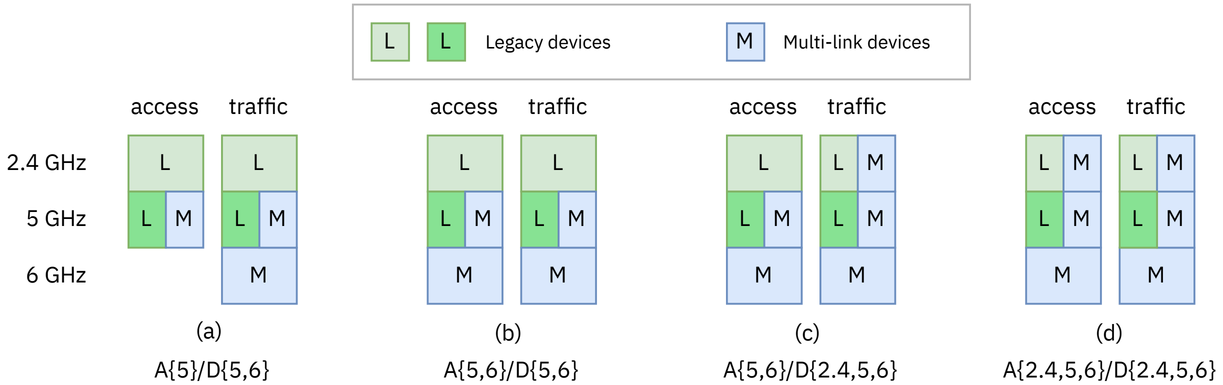


Fig. 1: Considered channel access and transmission band allocation policies. a) MLDs using the 5 GHz band for access, 5 and 6 GHz bands for data; b) MLDs using the 5 and 6 GHz bands for access and data; c) MLDs using the 5 and 6 GHz bands for access and 2.4, 5 and 6 GHz bands for data; d) MLDs using the 2.4, 5 and 6 GHz bands for both access and data.

consideration. Section III describes how the simulation environment was set up and the considered experimental methodology. The results obtained are provided and discussed in Section IV. Finally, Section V concludes the paper with the final considerations and further directions for future work.

II. SYSTEM MODEL

Let us consider a wireless local area network (WLAN) in a dense scenario with a density of 30 or 50 devices over an area equal to 15 × 15 m^2. Such a scenario is akin to common enterprise deployments in actual offices with working cubicles of 5 - 7 m^2. The WLAN is composed of an IEEE 802.11be compliant access point and 30 or 50 stations. All stations operate using the request-to-send/clear-to-send (RTS/CTS) reservation mechanism, to reduce the collision time. The access point can accept only a single RTS request at the time (regardless of the frequency band), with no device priority. This means that, in case that two or more stations send an RTS frame at the same time (even if they utilize different bands), the access point will consider this as a collision and will not accept any of them nor send any CTS reply. Each station can either be a legacy device or an MLD. The legacy devices are compliant to the IEEE 802.11ac standard, and therefore can operate either in the 2.4 GHz or 5 GHz bands. Furthermore, we assume that the AP can allocate legacy devices in different bands, applying different legacy device splits over the two bands, e.g., 50% in the 2.4 GHz band and 50% in the 5 GHz or 75% in the 2.4 GHz band and 25% in the 5 GHz. On the other hand, each MLD has three enabled interfaces with MLO capabilities and may operate in any of the 2.4 GHz, 5 GHz, and 6 GHz bands or combinations of them. In addition, all MLDs employ a multi-link access methodology with shortest backoff counter priority (MLA-S) [9], [10]. This means that a different distributed coordination function (DCF) is executed for each interface to support the channel access procedure, and consequently a separate backoff counter is used for each band. The counter that first reaches the value of 0 identifies the primary link band. The other bands are used as auxiliary links provided that they were enabled and that they were sensed as idle during the previous DCF slot. It should be noted that if only a single band is selected for access, the MLA-S acts exactly as a single link access (SLA) method. The exchange of the control frames (RTS/CTS/ACK) between the AP and the STA occurs in the primary link.

In this study, we consider four different band allocation policies. The deployment of the legacy devices is the same for all cases, i.e., they use either the 2.4 GHz band or the 5 GHz band, using a single band only, both for channel access and data transfer. Thus, we identify each case solely by the behaviour of MLDs. This is done by indicating which bands are used for channel access (A) and which ones for traffic (D). In particular, we use the notation A/D, where A and D denote the set of bands used for channel access, and data transmission, respectively. In this context, Fig. 1a depicts the A{5}/D{5,6} case, that is, the case where channel access of MLDs takes place in the 5 GHz band while transmission of data takes place in both 5 GHz and 6 GHz bands. In addition, the 5 GHz band is shared between part of the legacy devices and MLDs. Case A{5,6}/D{5,6} is shown in Fig. 1b; in this setup, channel access is carried out both on the 5 and 6 GHz bands. Again, the 5 GHz band is shared between the MLDs and part of the legacy devices. Case A{5,6}/D{2.4,5,6} (Fig. 1c) is similar to the previous one, but in addition, the 2.4 GHz band is used for data transmission. Both the 2.4 and 5 GHz bands are shared for data transmission between legacy devices and MLDs in this case. Finally, in case A{2.4,5,6}/D{2.4,5,6} (Fig. 1d) channel access and data transmission is performed in all three bands by MLDs. To simplify further the notation, we use "*all*" when all three bands are used by MLDs, either for channel access or data transmission. Hence, the last case abovementioned is depicted as A{*all*}/D{*all*}.

The performance of the system, under the four band allocation policies aforementioned, is evaluated using the *access delay* metric, which is defined as the time required for a device to get access to the medium (i.e., the time difference between

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	2
OFDM symbol duration	12.8 µs
Channel BW	80 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 beginning of the DCF and the successful transmission of the RTS frame). In addition, we also evaluate the *aggregated throughput* of the network; first, because it is the most common performance metric of similar systems, and second, because it allows us to get a global picture of the cases under consideration.

III. SIMULATION SETUP

We set up the single access point in the center of the area, at a height equal to 4 m. The stations (STAs) are positioned within the area in a random fashion. Every station is considered to be operating in full buffer condition (i.e., there are always frames to be transmitted). We perform the simulations both for 50 and 30 total stations in the network. Since our goal was to investigate the access delay performance, we employed in all three bands the maximum value of the channel bandwidth that legacy and multi-link devices have in common. Given that legacy devices are considered IEEE 802.11ac compliant, the maximum bandwidth in common is equal to 80 MHz. Employing greater channel bandwidth for the MLDs and greater MIMO (multi-input multi-output) capabilities would provide both higher throughput and lower delay values, but the overall scenario would become more complex to analyse. We vary the legacy/new devices ratio in the range 1%-99%, in 10% steps. Moreover, as previously explained, the legacy devices are split between STAs operating on 2.4 GHz and 5 GHz, according to two different splits (50%-50% and 75%-25%).

The simulations were conducted using a custom-developed event-driven Python simulator, which provides a faithful implementation of the main PHY/MAC features proposed for IEEE 802.11be. Each simulation was repeated for 150 times, each time varying the STAs' positions, implying different channel realizations. The total simulated time per run was 1 minute.

The path loss model incorporated follows IEEE 802.11ax's enterprise model [11], given by

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

where f_{GHz} is the channel's carrier frequency in GHz, d_{bp} is the break-point distance, d is the STA-AP distance, W is the average number of walls between the STA and the AP, and

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

On top of the path loss we also add a Rayleigth fading model, which is updated every 100 ms. For each device, the modulation and coding scheme (MCS) is selected according to the value of the signal-to-noise ratio (SNR) that is necessary to attain a target packet error rate (PER) of 10%. The choice is done through a lookup table, in a genie fashion (i.e., a perfect channel estimation is employed), similarly to [12].

A summary of the most significant simulation parameters is provided in Table I.

IV. RESULTS AND DISCUSSION

As we described earlier, the performance metrics considered in this work are the aggregated throughput and the access delay. Due to the considered saturated buffer conditions, the unique RTS acceptance from the AP and the fact that each MLD actually can be considered acting as multiple legacy stations, the throughput performance difference between 50 and 30 devices in total, is small. Therefore, only the system

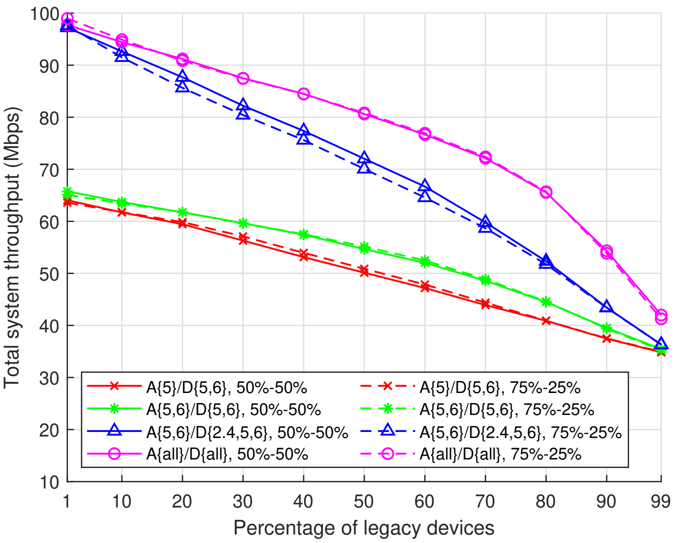
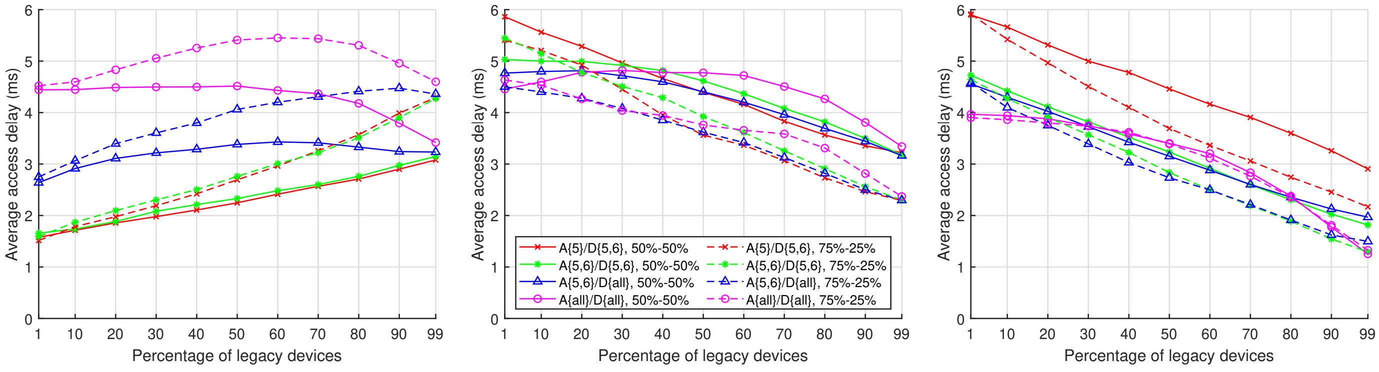


Fig. 2: Aggregated system throughput for the different channel access and transmission band allocation policies under consideration, for a network of 50 devices.



(a) Legacies on 2.4 GHz.

(b) Legacies on 5 GHz.

(c) Multi-link devices.

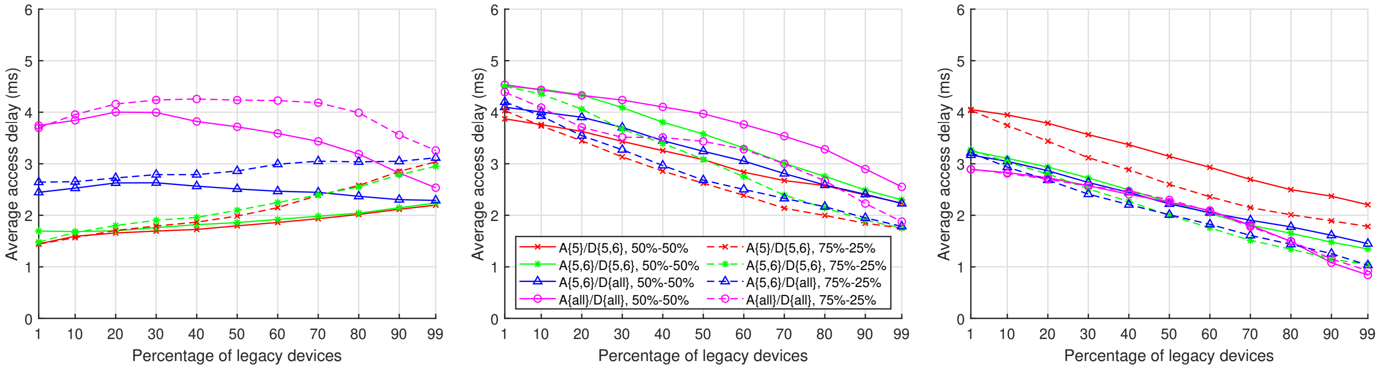
Fig. 3: Average delay performance for the different channel access and transmission band allocation policies under consideration, for a network of 50 devices.

throughput performance for 50 total devices is shown in Fig. 2. We can see that the difference between the 50%-50% and 75%-25% legacy devices splits over the two lower bands is not significant. The best throughput is achieved for the A$\{\mathit{all}\}$/D$\{\mathit{all}\}$ and A$\{5,6\}$/D$\{\mathit{all}\}$ cases, where all three bands are used by the MLDs for data transfer simultaneously. In addition, in the former case, all three bands are used for channel access as well, providing more opportunities to MLDs to prevail over legacy devices. Overall, when the MLDs take advantage of all their capabilities (transmission over all three bands), the network throughput increases. On the other hand, the worst throughput performance is attained in the A$\{5\}$/D$\{5,6\}$ case, where MLDs share the 5 GHz band for channel access with legacies and transmit data over two bands only.

On the other side, Fig. 3 shows the delay performance for the three types of devices, i.e., legacies in the 2.4 GHz band, legacies in 5 GHz band, and MLDs. Starting from Fig. 3a, we notice that when MLDs do not use the 2.4 GHz band (cases A$\{5\}$/D$\{5,6\}$ and A$\{5,6\}$/D$\{5,6\}$), the access delay results are very similar for both legacy devices splits, i.e., 50%-50% and 75%-25% legacy devices on 2.4 and 5 GHz, respectively. As expected, the 50%-50% split results in better performance in the 2.4 GHz band while the 75%-25% split favors the 5 GHz band, as illustrated in Fig. 3b.

It should be noted that the curves trend in Fig. 3b may look counter intuitive, since the access delay decreases as the number of legacy devices increases. This is easily explainable by noticing that, although the number of legacy devices increases, the overall number of devices trying to access the 5 GHz band actually decreases. For example, let us consider the A$\{5\}$/D$\{5,6\}$, 50%-50% case: at 30% of legacy devices, the overall number of nodes accessing the 5 GHz band is 42 (8 legacies on 5 GHz and 34 MLDs); at 60%, the nodes accessing the same band decreases to 35 (15 legacies on 5 GHz and 20 MLDs). This means that the final average access delay will be lower in the latter case.

On the other hand, when the 2.4 GHz band is used by MLDs as well, i.e., the cases A$\{5,6\}$/D$\{\mathit{all}\}$ and A$\{\mathit{all}\}$/D$\{\mathit{all}\}$, the access delay of legacies in 2.4 GHz band increases twice and thrice, respectively. Notice how the delay has a tendency of converging on a single value at 99% of legacy devices (around 3.2 ms for the 50%-50% split and 4.5 ms for 75%-25% split), due to the network being composed almost entirely



(a) Legacies on 2.4 GHz.

(b) Legacies on 5 GHz.

(c) Multi-link devices.

Fig. 4: Average delay performance for the different channel access and transmission band allocation policies under consideration, for a network of 30 devices.

of legacy devices. Finally, Fig. 3c illustrates the performance of MLDs. The cases with two access bands utilized by MLDs, that is, A$\{5{,}6\}$/D$\{5{,}6\}$ and A$\{5{,}6\}$/D$\{all\}$ provide similar performance, in contrast to legacies in the 2.4 GHz band. Furthermore, for low or high percentages of MLDs, the utilization of all bands both for channel access and traffic (case A$\{all\}$/D$\{all\}$) leads to good results; however this comes at the cost of higher access delay values for the legacies in 2.4 GHz band. Finally, the A$\{5\}$/D$\{5{,}6\}$ case (best for legacies) obtains far worse delay for MLDs (about 1.2 ms more than the previous three cases). Overall, taking into account both throughput and access delay of different device types and bands, the following trade-offs can be identified:

- Lowest access delay for legacy stations operating in 2.4 GHz band is achieved when MLDs do not use this band at all. Though, the system throughput is severely affected ($\leq$ 67 Mbps);
- Lower access delay for legacy stations operating on 5 GHz is achieved in the A$\{5{,}6\}$/D$\{all\}$ case. Moreover, a satisfactory system throughput can be viewed;
- Lowest access delay for MLDs is achieved in the A$\{5{,}6\}$/D$\{all\}$ case. A satisfactory system throughput is also achieved for this case, however legacies on 2.4 GHz can perform better in other cases;
- Network-wise low access delay trade-off. If a deployment case must be chosen to obtain low access delay for all device types, the best compromise seems to be case A$\{5{,}6\}$/D$\{all\}$. Indeed, the legacy devices operating on 2.4 GHz will suffer a higher delay compared to MLDs and the legacies on 5 GHz. However, the next generation use cases requiring low latency and operating only on the 2.4 GHz frequency band are very little. Therefore, the delay increase will not be easily noticeable by the common final user;
- Splitting legacy devices in the two lower bands is important as well. It can be used to balance the gain (loss) of 5 and 6 GHz devices with respect to 2.4 GHz legacy devices, while preserving network throughput practically unaffected.

Finally, comparing the results for 50 devices (Fig. 3) against the ones obtained for 30 devices (Fig. 4) we notice that, the overall access delay values are, as expected, always lower for 30 devices in all cases under consideration. On the other hand, our previous observations are confirmed with small deviations and somewhat smaller absolute differences due to the lower number of devices.

V. CONCLUSIONS

In this work we studied the impact of different band management policies on the access delay for IEEE 802.11be networks. We defined four separate cases with different band allocation policies that are expected to be employed in real-world deployments. Through extensive simulations, we obtained numerous results mainly in terms of access delay and aggregated throughput. By analysing the results, we were able to identify several trade-offs that are valid both for very dense scenarios (50 devices) and less dense ones (30 devices). In this context, we showed that band allocation management and device splitting are significant in attaining enhanced performance in different mixtures of legacy devices and MLDs. Future work includes the development of algorithms that exploit the trade-offs observed in this work, so that to improve the network balance in terms of average device delay, throughput and fairness. Finally, an additional step will be to bring into the game multiple RTS messages acceptance by the access point, which is expected to be implemented in off-the-self devices in the near future.

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.

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