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Analysis of Latency and Reliability Improvement with Multi-Link Operation over 802.11

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***Abstract*—With the uprising of new fields such as robotics, IoT or Augmented Reality, one of the main objectives of industrial modernization is the incorporation of safe and secure wireless technologies in the factory floor. However, nowadays wireless protocols can not fulfill the communication requirements of industrial networks, among which reliability and bound guaranteed latency are probably the most stringent ones. The lack of guaranteed low latency and ultra-high reliability of wireless networks are mainly derived from the error-prone nature of wireless propagation. Multi-link techniques are expected to provide enhanced reliability, latency and also protection against external interference. In this work, we assess the reliability and latency enhancement of the Multi-Link technique proposed in 802.11be. The assessment is done through simulation means using realistic industrial propagation and interference models. The results shown in this paper prove that Multi-Link provides an enhancement in wireless reliability and latency.**

***Index Terms*—802.11, Factory Automation, Industry 4.0, Wireless Communications, Multi-Link, Reliability, Low Latency**

I. Introduction

Time Sensitive Networking (TSN) is a set of sub-standards compiled in IEEE 802.1 that allows for synchronized, deterministic and reliable communications. It is currently implemented over Ethernet, which dominates the wired world in Local Area Networks (LAN) communications and allows wired networks to support real-time communications, being the most extended implementation in today's industrial environments.

In recent years, there has been a growing interest in wireless communication technologies for industrial applications [1] [2]. The reasons behind this interest are the inherent advantages of wireless compared to wired technologies. Wireless systems are easy to install, scale and reconfigure. However, wireless, as opposed to wired, presents limitations to provide deterministic and reliable communications. The major limitation for traditional wireless architectures is related to the harsh nature of the industrial propagation channel and thus, no wireless protocol has been able to provide a reliable integration between TSN and non-wired networks so far. These deficiencies lay in the inherent limitations of the wireless media, such as reduced reliability due to the wireless channel propagation phenomena and limited radio resources. In addition to those, wireless networks deployed in unlicensed bands can also suffer from low reliability due to interference from nearby wireless devices.

Due to the growing interest in industrial wireless communications, there is a research trend of extending TSN to wireless technologies leading to the wireless TSN paradigm. This has caused an uprising of new techniques that have been adopted by most recent wireless standards such as IEEE 802.11ax and 3GPP 5G. These technologies have taken big steps towards the direction of more efficient and controlled networks and have settled the foundations for future amendments to provide the desired integration between the TSN wired backbone and a wireless architecture [3] [4].

The Task Group in the new IEEE 802.11be amendment (TGbe) [5], commercially labeled as Wi-Fi 7, has proposed a great deal of techniques, being Multi-Link one of the most promising ones. The intended purpose of Multi-Link is to provide parallel channels to either increase the data rate or to enhance the latency and reliability by transmitting redundant information using separate paths. From a industrial point of view the focus lays on latency and reliability enhancement, rather than increasing the throughput, emulating the 802.1CB procedure [6].

In this paper we perform a comprehensive analysis of the Multi-Link Operation (MLO) proposed in 802.11be in the context of wireless TSN operation. The presented simulations use parallel redundant links in order to enhance the probability of a successful transmission in a hard deadline bound, which is a major requirement in time-critical industrial applications. Obtained results show that significant gains in terms of latency and reliability can be achieved compared to conventional Wireless Local Area Networks (WLANs) with only one link, especially in controlled scenarios with limited interference.

The paper is organized as follows: Section II introduces the current state of the 802.11 standard along with new techniques being proposed in 802.11be to enhance the deterministic behavior of 802.11. Section III presents an overview of MLO proposed in 802.11be. Section IV describes the methodology followed in this work in order to evaluate the Multi-Link performance gains. Section V compiles the results and describes the rationale behind them. Finally, Section VI presents a summary of the work done along with the conclusions reached through it.

II. Current state and future of 802.11

802.11ax [7] has been released in 2020 being the latest operative 802.11 amendment. The final version of its successor, 802.11be, is expected to be completed by early 2024. This future amendment will try to tackle the inherent problems of 802.11 towards achieving reliable and real time communications. Some of the 802.11be proposals are focused into improving existing techniques and methods that are currently implemented in the 802.11ax standard. However, the most compelling ones are the novel ideas that attempt to accomplish a more controlled and deterministic behaviour of the network.

Instead of merely focusing on increasing the throughput, the main objective of 802.11ax was to improve the efficiency of WLANs to support crowded scenarios such as stadiums or industrial facilities [8]. In previous 802.11 amendments each device had to access the channel by their own with no network planning. This led to an increased number of collisions and downtimes. In order to create a more efficient schedule for the network, 802.11ax has included diverse techniques and methods. The principal novelties are the Orthogonal Frequency Division Multiple Access (OFDMA) and the Trigger Frame (TF).

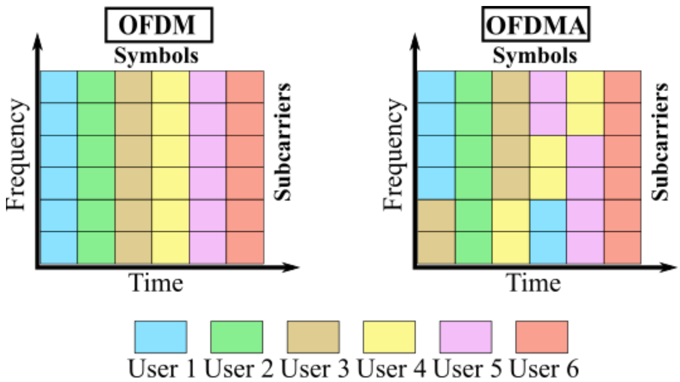


Fig. 1: OFDMA scheduling.

802.11ax-capable devices have now the option to use OFDMA Multi-User transmission by allocating its information into specified Resource Units (RU). These RU are made up of sets of subcarriers within an OFDMA frame that are assigned to specific users, RU are represented by colored squares in Figure 1. The exact allocation and amount of subcarriers for each RU depends on the number of devices that the Access Point (AP) will serve in that transmission. The amount of subcarriers that comprises an RUs may vary between transmissions since RUs' size depends on the number of connected users. The assignment of the RU is specified by the TF, a downlink frame whose information proceeds from a previous exchange called Buffer Status Report/Request (BSR).

The BSR exchange comprises two frames, the Buffer Status Request (downlink) and the Buffer Status Report (uplink). This exchange is depicted in Figure 2, first, the AP gathers information asking about the amount of data that the connected devices have stored and have ready to be delivered, after which the stations respond specifying their needs. The BSR information is used by the AP to make a decision and allocate resources for the users. The current BSR specification only provides the amount of data waiting to be transmitted by the STAs. From a wireless TSN perspective, knowing the priority and the periodicity of such data is a compelling field of study, since it can improve the performance of the system [9].

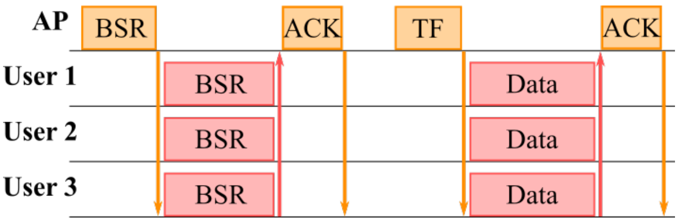


Fig. 2: 802.11ax frames exchange.

Despite the fact that OFDMA and TF allow scheduled operations over 802.11, the transmissions are still based on non-deterministic Medium Access Control (MAC), namely the Distributed Coordination Function (DCF). The DCF employs a Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) with binary exponential backoff algorithm, which means that the devices are forced to wait for a period of time before trying to access the medium. If collisions occur, this period may be exponentially increased, which drastically impacts the latency of the communication [10].

OFDMA in 802.11ax addresses this problem from an Uplink perspective with trigger-based communications. Nevertheless, the AP must still access the channel to transmit the TF using the DCF. In addition, 802.11 standard is defined to be backwards compatible, therefore older non 11ax devices may still be attached to the network and may attempt to transmit their own information using the DCF.

As seen, any future 802.11 improvement is tied up to the inherent operations over unlicensed bands and the backwards compatibility of the standard. 802.11be attempts to tackle these limitations with techniques such as MLO, AP Coordination or Enhanced TF [11]. In addition, some countries are opening the 6 GHz band for Wi-Fi operation, as is the case of USA [12], where this band will only be accessible for 802.11ax and newer devices. The combination of these techniques along with a new operative band inaccessible for old Wi-Fi devices constitute a first step towards achieving Wireless TSN.

III. Multi-Link Operation

This section overviews the MLO proposed for the 802.11be standard, and how these techniques can enhance the reliability and latency over open access bands.

The 802.11 operation over unlicensed bands constitutes an issue towards achieving deterministic communications. Many nodes might access the radio channel simultaneously which translates into collisions and higher delivery time. The latency of the communications is a fundamental factor in certain industrial scenarios such as control loops or alarms, where exceeding a timing deadline not only translates into useless information but might also have catastrophic human and economic consequences.

Reliability and latency, two of the most representative Key Performance Indicators (KPI) for industry applications [13], are clear targets of improvement thanks to these techniques.

MLO allows to transmit the same information through multiple channels. This increases the probability that such information arrives at the receiver, which reduces the number of re-transmissions and, therefore the latency of the operation.

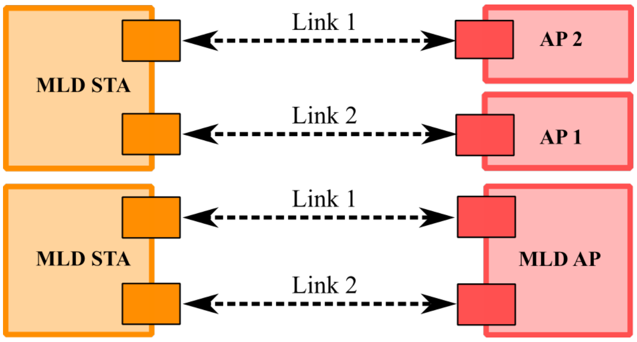


Fig. 3: Multi-Link Operation.

Multi-Link might be achieved either through one single frequency band or by using parallel channels between different bands. Besides, those links may be connected to the same AP or not, using different Basic Set Services (BSS) for each. Simulations ran in this study have taken into consideration both of these possible scenarios as depicted in Figure 3.

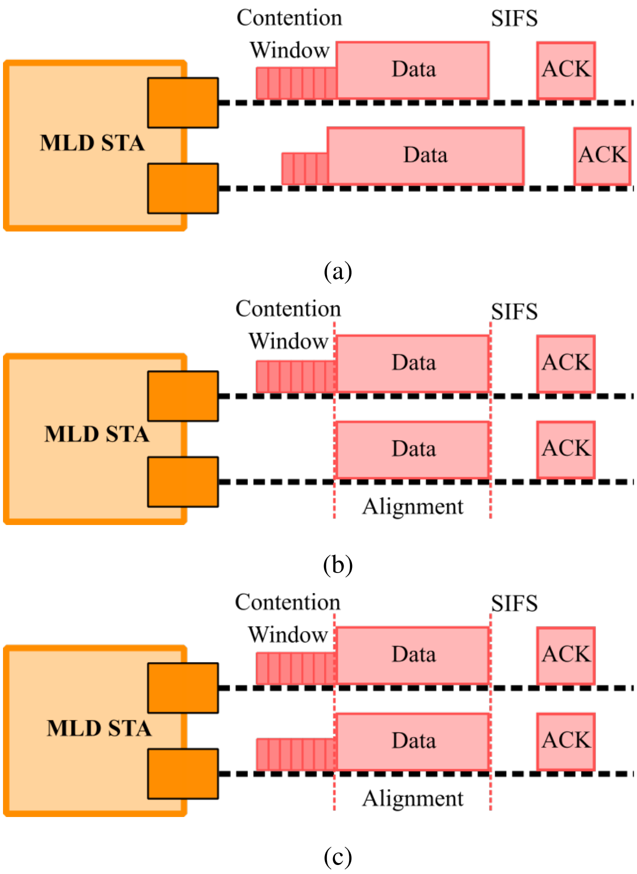


Fig. 4: Multi-Link channel access proposals [14].

Related to the 802.11 CSMA/CA and DCF inherent operation, devices may access each channel independently or they can wait and align every transmission using one or more backoff counters [15]. For the simulations used in this study we have considered that each link accesses the channel independently, i.e., with its own backoff counter.

TGbe has defined two modes of operation, Simultaneously Transmit and Receive (STR) and non-STR [16]. The nature of this classification relies on the possible interference between the radio modules comprising the Multi-Link Device (MLD) if the carrier frequencies are too close to each other. Indirectly, this relates to a synchronous or asynchronous behaviour between the links. If non-STR is needed, all links must align its transmission and share a channel access contest as depicted in Figure 4 (b) & (c). Simulation ran in this study have only considered asynchronous transmissions represented in Figure 4 (a).

Finally, an important factor for MLO, in order to provide reliable redundant channels, is the level of correlation between the links conforming the technique. The higher the correlation is, the lower the improvement of the global communication. For an static capture of the radio medium, the state of the parallel links will be similar, either all prone to failure or all allowing a correct reception. The uncorrelation of the links grants the possibility of facing parallel bad state channels with good performance ones. This variety provides a higher probability for the information to be delivered and improves the reliability of the communication.

IV. Methodology

The ultimate objective of this study is to evaluate the improvement over the communication latency using MLO through different radio channels. For this task we have set two types of wireless networks in which we vary certain parameters through the course of multiple simulations. The radio channels used for these simulations have been generated from the data compiled in a radio measurement campaign carried out by the National Institute of Standards and Technology (NIST) [17] in factory plants. In order to evaluate such channels, we have calculated their Packet Error Rate (PER) along with Rayleigh and Rician fading channels for the sake of comparison.

Every simulation uses owned MATLAB code supported by the WLAN MathWorks Toolbox. Every transmission employs Modulation and Coding Scheme (MCS) of 0, which translates into a BPSK modulation with 1/2 of Code Rate.

For latency measurement we have set the timer right after the AP sends the Buffer Status Request message, counting the time until the AP correctly receives the Uplink data from the targeted STA. Consequently for each latency value the following messages would have been exchanged:

1) Buffer Status Request.
2) Buffer Status Report.
3) Trigger Frame.
4) Uplink Data.

For characterizing the aforementioned channels, we have selected a target PER of 10^{-5}. In order to have enough precision while maintaining feasible simulation times, 10^6

packets have been simulated for each setup. An initial average SNR has been set to 0 dB which increases by 2dB every time one of the following conditions are met:

- The number of packet errors reaches 100.
- All 10^6 packets have been simulated.

Finally, simulation ends when the target 10^{-5} PER is obtained.

A. Latency Scenarios

We have labeled the first wireless network as "Legacy Scenario", which is represented in Figure 5. Three devices comprise this network: the AP, the 802.11be STA under measurement and the legacy STAs. These last devices independently desire to transmit information, which can result in interference. The number of legacy devices and its transmission probability is depicted in Table I for the four proposed setups.

Each of these setups has been simulated using both single link transmission and MLO with two parallel links. The objective of using this network is to analyze the Multi-Link improvement over different levels of interference. Therefore, the radio channels used for every simulation have been fixed to 6 dB of average SNR. As seen in Figure 9 (c) this is the first value of average SNR that achieves the desired PER when certain MLO is used.

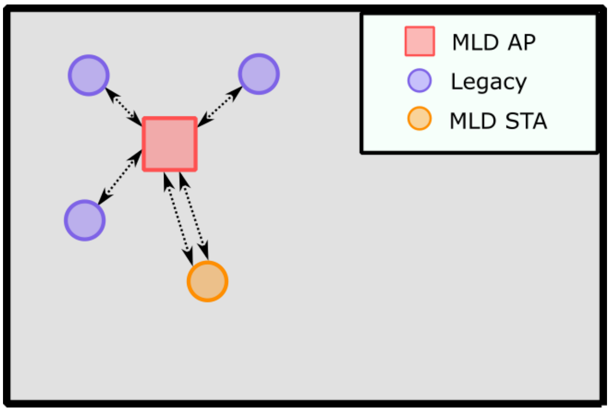


Fig. 5: Legacy Scenario, La & Lb setup cases.

TABLE I: Legacy Scenario setups.

Legacy Setup	Nº Legacy STA	Transmission Probability
La	3	10%
Lb	3	30%
Lc	7	10%
Ld	7	30%

The second wireless network, which has been labeled as "Industrial Scenario", attempts to resemble an industrial environment. We consider an scenario where every connected device is managed and scheduled, where the only possible interference is due to Probe Request messages from external nodes and from disconnected devices attempting to reconnect.

Three types of simulation setups have been proposed, each of which comprises:

- An STA under measure.
- One or more APs, each of which conforms a BSS.
- Multi User STAs that share the available bandwidth with the targeted STA.
- Non connected STAs that interfere in the network due Probe Request signals.

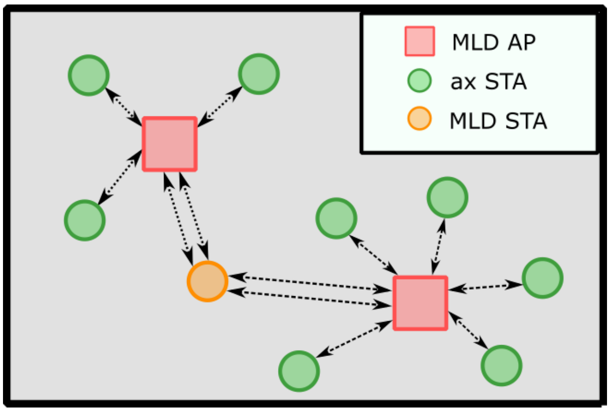


Fig. 6: Industrial Scenario, Ic_2links setup case.

TABLE II: Proposed industrial scenarios for latency simulations.

Industrial Setup	2.4 GHz band Average SNR	Interference	Available RU
Ia_1link Ia_2links	L1 - 6 dB L1 - 6 dB | L2 - 4 dB	L1 - 2% L1 - 2% | L2 - 2%	L1 - 106 L1 - 106 | L2 - 106
Ib_1link Ib_2links	L1 - 3 dB L1 - 3 dB | L2 - 3 dB	L1 - 15% L1 - 15% | L2 - 10%	L1 - 106 L1 - 106 | L2 - 52
Ic_1link Ic_2links	L1 - 3 dB L1 - 3 dB | L2 - 4 dB	L1 - 15% L1 - 15% | L2 - 20%	L1 - 106 L1 - 106 | L2 - 26

(a)

Industrial Setup	5 GHz band Average SNR	Interference	Available RU
Ia_1link Ia_2links	- -	- -	- -
Ib_1link Ib_2links	- -	- -	- -
Ic_1link Ic_2links	L1 - 4 dB L1 - 4 dB | L2 - 3 dB	L1 - 5% L1 - 5% | L2 - 10%	L1 - 52 L1 - 52 | L2 - 52

(b)

Table II indicates the three setups used in the industrial simulations: Scenario Ia, Scenario Ib and Scenario Ic. Table II (a) specifies the characteristics of the links in the 2.4 GHz band along with its noise and interference. Table III (b) illustrates the links deployed for the 5 GHz band, which is only used when two BSS are present. For each setup, we consider one link (L1) or Multi-Link (L1 and L2). This wireless network is depicted in Figure 6 representing the Ic setup.

B. Radio Channels

In order to simulate channels that resemble real communications in industrial scenarios we have used the radio frequency (RF) measurements gathered by the NIST campaign for some selected industrial environments:

- Automotive Assembly Plant.
- Boulder Steam Plant.
- Machine Shop.
- Open Area Test Site.

The Automotive Assembly Plant is the chosen location for this study since it is a good representation of a dense factory floor with strong multipath and fading components. Two distinct routes were chosen for the measurements, an outer route through the more open and wider areas, and an inner route tracing a path across enclosed spaces with higher density of machines and tools.

Both routes have been followed for several runs in a three day campaign span. Runs were composed by acquisitions which are then divided into records, meaning each run results in multiple acquisitions and each acquisition contains multiple records. For each acquisition 300 records have been captured, which are complex Channels Impulse Responses (CIRs) of the associated way point of the acquisition.

A Power Delay Profile (PDP) for both 2.4GHz and 5GHz bands has been obtained by the cumulative measured CIRs of the Automotive Assembly Plant. Both PDP are depicted in Figure 7.

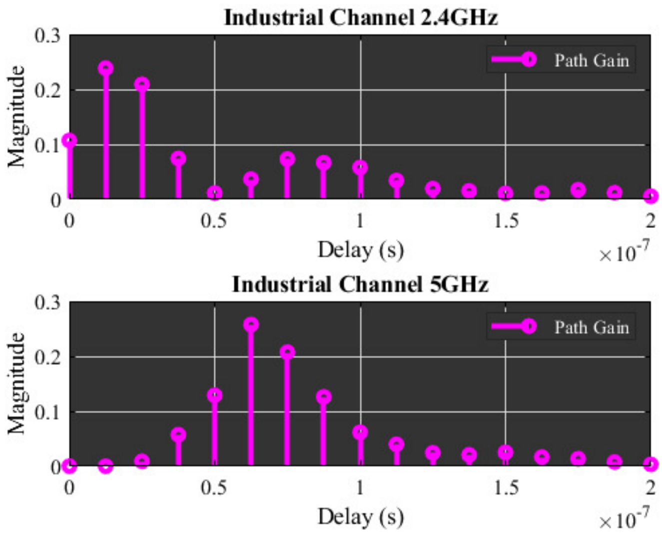


Fig. 7: Industrial PDPs for 2.4 and 5 GHz bands.

Finally, for the sake of comparison, two channels with Rician and Rayleigh statistic behaviour have been used. Rayleigh and Rician fading channels have been studied for a long time and its inclusion in this paper provides a good starting point to evaluate and compare the obtained results for the industrial channel. They are useful models of real-world phenomena in wireless communications, including multi-path scattering effects, time dispersion, and Doppler shifts. Figure 8 shows a typical wireless scenario with one direct and two reflected paths.

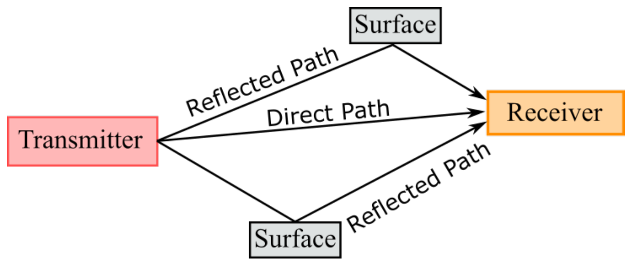


Fig. 8: Typical wireless scenario.

As depicted in Figure 8 the major paths result in the arrival of delayed versions of the signal at the receiver. In addition, the radio signal suffers from scattering for each major path. Such scattering typically results from reflections off objects near the nodes. These components combine at the receiver and cause multipath fading. The fading process is characterized by a Rayleigh distribution when there is no dominant line-of-sight propagation. Whereas a Rician distribution resembles the sum of two or more signals such as line-of-sight and reflected contributions.

V. Results

This section shows, on the one hand, the reliability performance that could be obtained with MLO by using redundant channels, and, on the other hand, the latency performance provided by the reduced number of re-transmissions.

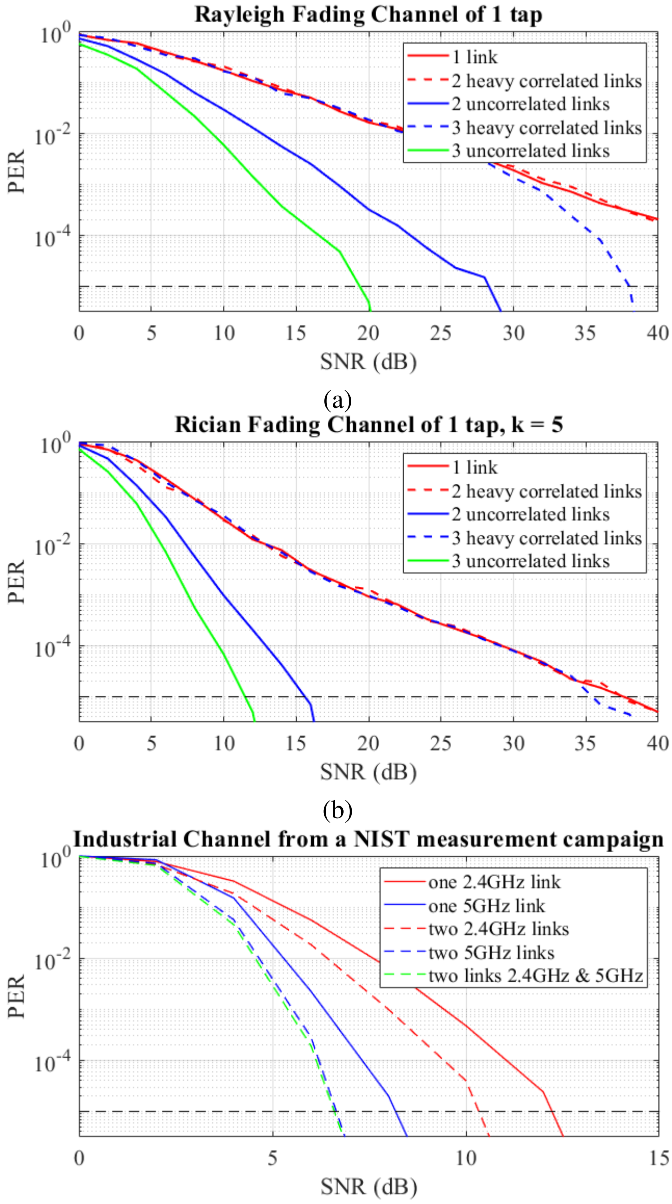
A. Packet Error Rate

PER Curves obtained for Rayleigh and Rician fading channels in Figure 9 compare the reliability of the communication for different levels of correlation between the channels, whereas the results for the industrial channel compare the reliability varying the frequency band of operation. Note that PER results have been obtained on the physical layer and no retransmissions are considered.

The average SNR needed to achieve a 10^{-5} PER is higher for the Rayleigh channel since it is the most aggressive statistical distribution. As seen in Figure 9 (a), when using one single link or two high correlated links the average SNR needed to obtain the targeted PER ramps up to 60 dB. Adding a third correlated link improves the transmission and reduces the required average SNR to 37 dB. Both of these values are way too high to be feasible in real WLAN communications.

The reliability of the communication increases substantially when using uncorrelated links. By employing two and three uncorrelated channels the average SNR needed is reduced to 26 dB and 19 dB ,respectively. This results highlight the importance of achieving uncorrelated channels when MLO is applied.

Rician PER curves in Figure 9 (b) follow the same tendency as Rayleigh ones. However, since a Rician distribution suffers from softer variations, the average SNR values needed to obtain the targeted PER are inferior. It is important to notice that



(c)

Fig. 9: Packet Error Rates for (a) Rayleigh Channel (b), Rician Channel of K = 5 & (c) NIST Industrial Channel.

the relative improvement by adding a third uncorrelated link differs between each distribution. For the Rayleigh channel there is an improvement of around 10 dB whereas for the Rician case such improvement is reduced to approximately 5 dB. This behaviour describes how MLO improvement decays when the wireless channels improve.

In the case of the results obtained simulating industrial setting, the results differ slighly. Now channels are not compared according to their correlation but to the frequency band they work in. It is important to note that results are depicted for the same average SNR value at the receiver. For the same distance, in a real implementation the link located at the 5 GHz band would be received with lower SNR compared to one at the 2.4 GHz band since the path loss increases.

As depicted in Figure 9 (c), for the same value of average SNR the 5 GHz band provides better results than the 2.4 GHz. However, the range needed to achieve such SNR its shorter as aforementioned. For both bands the average SNR needed is reduced by 3 dB when adding a second redundant channel. When combining two links at different bands the results are almost identical to MLO with both channels at the 5 GHz band. A plausible explanation is the wider bandwidth of the 5 GHz band, which allows more uncorrelation between the channels.

B. *Latency*

1) Legacy Setup: Results for the legacy devices scenario described in Table I are compiled in this subsection.

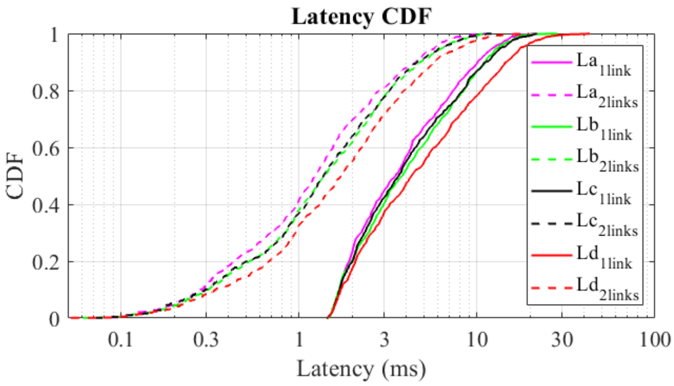


Fig. 10: Legacy Scenario - Cumulative Distribution Function for latency results.

A fixed channel has been used for the simulations over these setups, meaning the only difference between each of them is the level of interference. As set in Table I this interference is measured by the number of legacy STA present in the network and their probability of transmission.

Results gathered in Figure 10 depict the contribution of MLO towards improving the latency in this type of scenario. Each of the setups has been simulated using first one single link and then two parallel links .

When using a single link, no packet can be transmitted with less than 1 ms of latency. By adding a second parallel link, around 40% of the transmissions are able to reach its destination in the sub-millisecond range.

2) Industrial Setup: This subsection compiles the results for the control network scenario described in section IV, Table II, where there is only interference coming from disconnected devices attempting to reestablish the connection.

Figure 11 depicts the latency results obtained for the Industrial Scenario. Setup Ia consists of a very friendly scenario with low interference probability and acceptable average SNR. In single link setup $\text{Ia}_1 link$, no packet transmission has failed more than twice, average latency is around 5 ms and the worst achieved latency is of 16 ms for 1000 simulated packets. By introducing a second parallel link in setup $\text{Ia}_2 links$ the

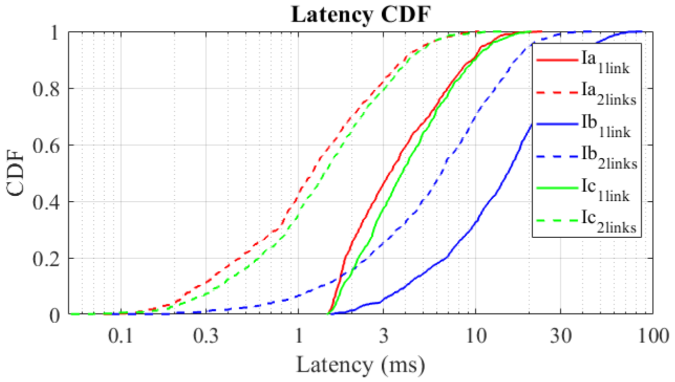


Fig. 11: Industrial Scenario - Cumulative Distribution Function for latency results.

results improve significantly, the average latency and worse case latency are reduced to 2ms and 9 ms, respectively.

Oppositely, setup Ib represents a very harsh scenario, where over 40 re-transmissions are needed for some packets when a single link is used. This amount of errors and collisions implies that the average latency in Ib$_2links$ is about 20ms with peaks of 100 ms. Note that in the 802.11 standard the number of retransmissions is capped to a certain number (e.g. 7) and these results are exclusively meant for latency comparison.

Finally, setup Ic emulates setup Ib, but including a second BSS. The STA under measurement deploys 2.4 GHz band links (as the previous setups) towards the first BSS but also 5 GHz band links to the second BSS. The 5 GHz band in this scenario is less crowded which translates into less interference, which can be seen by comparing the latency CDF for Ib$_2links$ and Ic$_1link$. Four parallel links have been used for setup Ic$_2links$, two on the 2.4 GHz band for the first BSS and two on the 5 GHz for the second BSS. By using this number of parallel channels the latency is reduced and results are similar to those obtained for Ia$_2links$.

VI. Conclusion

This paper presents an evaluation of the MLO technique proposed for the next 802.11 standard, 802.11be, with a specific focus on industrial and latency-bound Wireless TSN operation. The presented simulations highlight that important performance gains, in terms of latency and reliability, can be obtained under realistic industrial scenarios with constrained interference. In particular, gains of more than 3 dB for a latency target of 1 ms and 99.9% success rate are feasible over 802.11ax when combined with MLO. The latency gain mainly comes from the reduced number of re-transmissions required to successfully transmit a frame.

We think that MLO, combined with novel techniques being proposed in 802.11be, such as the Scheduled Trigger Frame and AP Coordination, will be the key feature to achieve WLAN-based TSN operation. Therefore, an interesting future line will be to further analyze MLO in combination with other 802.11be techniques. Finally, real implementations of MLO in a hardware testbed are necessary to assess Multi-Link capabilities in real industrial scenarios.

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