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Faster is not Always Better: Cost of High Bit-Rates in Wi-Fi Networks

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Abstract: Wi-Fi networks implementing the IEEE 802.11 standard are deployed in diverse use-cases for personal and industrial applications. The latest IEEE 802.11ax amendment supports physical layer bit-rates up to 9.6 Gbps. In this article, we evaluate the end-to-end performance of different Wi-Fi generations and configurations with maximum bit-rates between 144 Mbps and 1200 Mbps in an electromagnetically shielded room. We characterize their throughput in uplink, downlink, and bi-directional streaming. We measure end-to-end throughput, re-transmissions, and used physical layer bit-rates. We observe that using faster bit-rates comes at a cost of increased re-transmission, which pushes the link further away from its theoretical throughput. Therefore, the throughput improvement using fast bit-rates does not correspond to the increased channel bandwidth, because of lower end-to-end reliability. We address this in the context of the increased use of Wi-Fi in industrial robotics where high reliability is preferred for control traffic and high throughput is preferred for streaming traffic. Therefore, future work, can address how the physical layer can change on a frame-by-frame basis based on the type of traffic.

Key-words: Wi-Fi, IoRT, IEEE 802.11, performance evaluation, industrial networks

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Le coût des débits élevés dans les réseaux wi-fi

Résumé : Les réseaux wi-fi implémentant la norme IEEE802.11 sont déployés dans divers cas d'utilisation pour des applications personnelles et industrielles. Le dernier amendement IEEE802.11ax prend en charge les débits de la couche physique jusqu'à 9,6 Gbps. Dans cet article, nous évaluons les performances de bout en bout de différentes générations et configurations wi-fi avec des débits maximaux compris entre 144 Mbps et 1200 Mbps dans une salle blindée électromagnétiquement. Nous caractérisons leur débit en liaison montante, liaison descendante, et diffusion bidirectionnelle. Nous mesurons le débit de bout en bout, les retransmissions et les débits des couches physiques. Nous observons que l'utilisation de débits binaires plus rapides entraîne un coût de retransmission accru, ce qui éloigne la liaison de son débit théorique. Par conséquent, l'amélioration du débit en utilisant des débits binaires rapides ne correspond pas à l'augmentation de la bande passante du canal, en raison de la fiabilité de bout en bout inférieure. Nous abordons cette question dans le contexte de l'utilisation accrue du wi-fi dans la robotique industrielle où une fiabilité élevée est préférée pour le trafic de contrôle et un débit élevé est préféré pour le trafic en continu. Par conséquent, les travaux futurs peuvent aborder la façon dont la couche physique peut changer sur une base image par image en fonction du type de trafic.

Mots-clés : Wi-Fi, IEEE 802.11, évaluation des performances, réseaux industriels

1 Introduction

The demand for wireless connectivity has been constantly increasing as users are becoming further dependent on wireless networks for video streaming, voice calls, live conferences, and storage backups. These applications have created further need for higher network throughput that has to adapt to increased user demand and density.

At the same time, industrial automation has increased due to the use of robotic systems in manufacturing, monitoring, and inspection, also known as the Internet of Robotic Things (IoRT). Wired at first, industrial and robotic applications can have more degrees of freedom and cheaper deployment cost if connected to wireless networks. For example, IoRT implementations such as Turtlebot Mobile Robots [1,2] commonly use Wi-Fi for communication. Recent surveys describe the components and KPIs of IoRT architectures [1–3], where the network is part of a control loop that serves multiple purposes: human robot interaction, live data gathering and streaming, path planning and navigation, and swarm robot communications [3]. For such systems, reliability and throughput are a significant Key Performance Indicator (KPI), since they are used to deliver both control traffic and live streaming. For example, when a magnetic crawler robot is used for inspection of ship hulls, precise and timely control is required to maneuver the robot [4].

In 1999, the IEEE standardization body adopted the IEEE 802.11 standard [5] for wireless connectivity, which became commercialized under the Wi-Fi name. At the physical (PHY) layer, IEEE 802.11 proposed bit-rates of 1 Mbps. As faster and more complex modulations became possible to implement on circuit boards, amendments to IEEE 802.11 included faster PHY bit-rates to meet the increasing user demand. The latest amendment proposed in 2020, IEEE 802.11ax (officially marketed as Wi-Fi 6), supports bit-rates up to 9.6 Gbps [6].

But how does using high bit-rates in Wi-Fi networks impact their reliability and throughput? This is the question that we try to answer in this paper by making an end-to-end performance evaluation of different Wi-Fi generations. Specifically, the contributions of this article are three-fold:

- We evaluate the performance of different Wi-Fi generations in 7 configurations with maximum PHY bit-rates between 144 Mbps and 1200 Mbps in an electromagnetically (EM) shielded environment to avoid all external interference.
- We show that increasing the PHY bit-rate can lead to negative effects on throughput and reliability.
- We confirm these results by using different hardware with uplink (UL), downlink (DL), and bi-directional communication streams.

The rest of this article is organized as follows. Sec. 2 presents an overview of the IEEE 802.11 standard and its amendments, and the existing performance evaluation studies, highlighting the novelty of our contribution. Sec. 3 presents the experimental setup and methodology used in the experiments. We discuss the obtained results in Sec. 4 shows the results, and we conclude with the key lessons we learned in Sec. 5.

2 Related Work

This section introduces the related literature. In Sec. 2.1, we give an overview of the IEEE 802.11 standard. In Sec. 2.2, we present related work on performance evaluation of IEEE 802.11 networks, highlighting the novelty of our contribution.

2.1 An Overview of the IEEE 802.11 Standard

At the PHY layer, early amendments of the IEEE 802.11 standard defined bit-rates between 1 Mbps and 4.5 Mbps in the 2.4 GHz RF band. The IEEE 802.11b amendment introduced bit-rates up to 11 Mbps in the 2.4 GHz band. Simultaneously, The IEEE 802.11a amendment included bit-rates up to 54 Mbps using the orthogonal frequency division multiplexing (OFDM) modulation in the 5 GHz band. Later key amendments: IEEE 802.11g, IEEE 802.11n (commercially known as Wi-Fi 4), IEEE 802.11ac (commercially known as Wi-Fi 5), and IEEE 802.11ax (commercially known as Wi-Fi 6) included faster bit-rates. The latest IEEE 802.11ax amendment (2020) includes bit-rates up to 9.6 Gbps using 1024-Quadrature Amplitude Modulation (QAM) based OFDM [6]. These bit-rates are achieved using (mainly) three factors: 1) increased symbol rate by using denser QAM constellations in OFDM, 2) adopting multiple-input-multiple-output (MIMO) antennas to enable parallel transmit/received paths (introduced in the IEEE 802.11n amendment), and 3) multiplying channel bandwidth (BW) from 20 MHz up to 40, 80, and 160 MHz BW.

At the medium access control (MAC) layer, IEEE 802.11 uses carrier sense multiple access with collision avoidance (CSMA/CA) [5]. CSMA/CA is a non-deterministic MAC layer using a random back-off counter to mitigate collisions using the Hybrid Coordination Function [5]. The IEEE 802.11ax amendment introduced an essential improvement to the MAC layer, as highlighted by Khorov et. al., [7]. As IEEE 802.11 deployments have increased in density (e.g. in malls, airports etc.) a purely non-deterministic MAC based on CSMA/CA is challenged when hundreds of APs coexist [7]. At the MAC layer, IEEE 802.11ax introduces orthogonal frequency division multiple access (OFDMA) on top of CSMA/CA. Time and frequency resources are divided into resource units (RUs) and stations (STAs) request to allocate dedicated contention-free RUs for their transmissions. This way, they are guaranteed to not interfere with neighboring STAs running the same mechanism. It also allows parallel time-synchronized multi-stream and multi-user transmissions using the the full capacity of the MIMO antennas [7].

At the MAC layer, rate adaptation algorithm (RAA) selects a PHY bit-rate based on link quality. The RAA is outside of the scope of the IEEE 802.11 standard and it is left to vendor implementation (Sec. 10.7 in [5]). The large number of the available PHYs poses a challenge for the RAA for efficient and stable PHY adaptation [7]. Sammour et. al., [8] evaluate different RAAs and the different link quality metrics. They demonstrate the need for combining multiple hybrid metrics for effective RAA performance.

2.2 Performance Evaluation

Recent articles evaluate performance of IEEE 802.11 networks as summarized in Table 2.2. Muhammad et. al., [9] evaluate the performance of IEEE 802.11ax network using different channel BW and IEEE 802.11ac network with 20 MHz BW. The authors run UL and DL streams between a STA and an AP with and they report the performance results as a function of the link signal-to-noise ratio (SNR). They observe that the throughput of the IEEE 802.11ax network is saturated at the same rate using 80 and 160 MHz BW and that the network does not benefit from doubling the BW. Authors attribute this to hardware implementation.

Frommel et. al., [10] evaluate the performance of the IEEE 802.11ax network in the presence of IEEE 802.11n networks in the 5 GHz band. Authors use simulations and experimental setup in a lab environment. They observe that the IEEE 802.11ax reaches a maximum of 225 Mbps while the IEEE 802.11n network reaches a maximum of 140 Mbps in the same setup (60% throughput increase). The IEEE 802.11n network reaches throughput superior or similar to the IEEE 802.11ax network in several runs, both in simulation and experimentally.

Article	Generation			Band		Link Type			Reliability Measurement	PHY Rate Measurement
	n	ac	ax	2.4 GHz	5 GHz	UL	DL	UL/DL		
Muhammad et. al., [9]		✓	✓		✓	✓	✓			
Frommel et. al., [10]	✓	✓	✓		✓		✓	✓		
Tamarin et. al., [11]	✓					✓			✓	✓
Hayat et. al., [12]	✓	✓			✓	✓			✓	✓

Table 1: Overview of recent articles on IEEE 802.11 performance evaluation

Tamarin et. al., [11] study the reliability of IEEE 802.11 networks for industrial applications and they test how different RAAs react to decreased link quality. They test RAAs in IEEE 802.11n and they demonstrate that, depending on the type of the RAA, used bit-rate can drop instantaneously, or slowly, or fluctuate, before it stabilizes. In case of instantaneous bit-rate drops or fluctuations, frame loss and delay are severely impacted.

Finally, Hayat et. al., [12] compare the performance of the IEEE 802.11n and IEEE 802.11ac networks in mobility and they demonstrate the evolution of bit-rate and throughput as a the distance between the STA and the AP increases using drones as STAs. Authors find that at distances < 50 m the IEEE 802.11ac link is 50% higher in throughput despite using 200% faster bit-rate. In distances > 50 m, both networks maintained the same throughput.

As shown in Table 2.2, each article focuses on a subset of Wi-Fi configurations and stream types. Only two articles [11, 12] report reliability and evolution of PHY bit-rate used by the RAA.

Recent articles evaluated IEEE 802.11 performance specifically for industrial applications. Candell et. al., [13] study the performance of a wireless controlled robotic arm in the presence of interference, to see how link degradation impacts the robot's movement. They observe that the arm movements witness additional delay up to 100 ms when the signal-to-interference ratio increases by 3 dBm. Sudhakaran et. al., [14] experiment with a time sensitive networking (TSN) component in IEEE 802.11 to improve reliability. Branz et. al., [15] implement a control loop on a robot on top of a IEEE 802.11 link. The loop adjusts PHY bit-rate and maximum retries based on link SNR to optimize for packet latency.

Articles presented in this section give important insights on different performance aspects of IEEE 802.11 networks using experimental setups. They also show the importance of IEEE 802.11 as a standard protocol for IoRT connectivity. However, they have a common limitation: they do not show how increasing PHY bit-rate can impact the end-to-end throughput and reliability performance for IEEE 802.11 networks, two important KPIs for IoRT applications. This article goes one step further by addressing this question in an experimental evaluation different IEEE 802.11 generations in 7 different configurations.

3 Methodology

This section describes the experimental setup and how the KPIs are evaluated. We ran 7 different IEEE 802.11 configurations representing a range of fast and slow bit-rates in 3 different generations, as shown in Table 2. The fastest configuration supported by our equipment is the IEEE 802.11ax using 5 GHz band and 80 MHz channel BW with maximum 1200 Mbps bit-rate. The slowest is the IEEE 802.11n using the 2.4 GHz band and 20 MHz channel BW with maximum 144 Mbps bit-rate.

We conducted the experiments in the EM-shielded room of Cortex Lab [16] that acts as a Faraday cage to keep away external interference (Fig. 1). Tests ran autonomously without human presence in the room to avoid thermal interference with the RF signals. We disconnected all equipment from the Internet to avoid influence from external traffic.

802.11 version	RF band	channel BW	bit-rate
ax (Wi-Fi 6)	5 GHz	80 MHz	1201 Mbps
ac (Wi-Fi 5)	5 GHz	80 MHz	866 Mbps
ax (Wi-Fi 6)	5 GHz	20 MHz	286 Mbps
ax (Wi-Fi 6)	2.4 GHz	20 MHz	286 Mbps
ac (Wi-Fi 5)	5 GHz	20 MHz	192 Mbps
n (Wi-Fi 4)	5 GHz	20 MHz	144 Mbps
n (Wi-Fi 4)	2.4 GHz	20 MHz	144 Mbps

Table 2: The Wi-Fi configurations ordered by bit-rate



Figure 1: The EM-shielded lab used for the experimental setup.

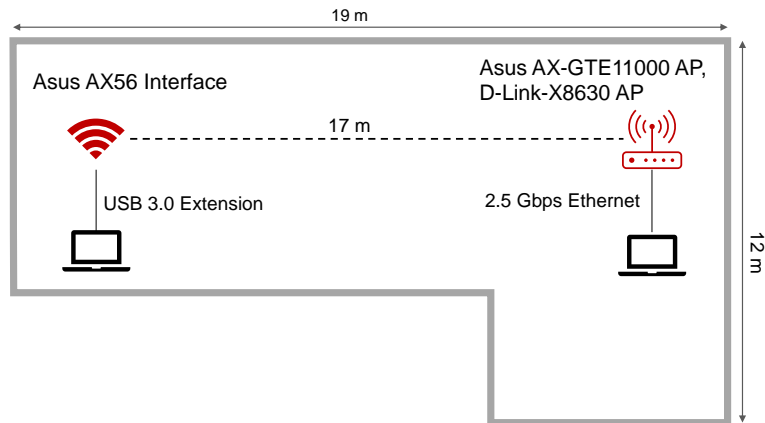


Figure 2: Layout of the experimental setup in the EM shielded CortexLab. IEEE 802.11 transceiver connects to the access point at 17 m distance

The setup consists of the following components. An HP Elitebook laptop was used as STA and was connected to an Asus AX56 Wi-Fi USB dongle with 2×2 MIMO antenna. A Dell Latitude laptop was configured as server and it was connected to an AP via 2.5 Gbps Ethernet interface. To ensure that our observations are not influenced by the AP implementations, tests were conducted on two different APs: D-Link-X8630 dual band AP [17] and Asus AX-GTE11000 tri-band AP [18]. Both APs are supplied with 4×4 MIMO antennas. Two different Asus AX56 dongles were used to connect to each AP.

We placed the equipment on tables in line-of-sight as shown in Fig. 2. The distance between the STA and the AP was fixed at 17 m. The STA was programmed to switch automatically between the different Wi-Fi configurations.

We used iPerf3 tool [19] to generate Transfer Control Protocol (TCP) streams between the client and the server as it is commonly used for IoRT applications for its reliability using re-transmissions and congestion control. For each Wi-Fi configuration, we generated: UL stream, DL stream, and bi-directional stream. Each stream ran for 5 minutes. This gives TCP time to adapt its congestion window to the link throughput until it converges on a stable setting [20]. TCP was configured with the recent standard CUBIC congestion control algorithm [21]. Both client and the server logged the stream statistics.

We evaluate two KPIs relevant to IoRT applications: end-to-end throughput, and end-to-end reliability. Several measurements are logged to evaluate these KPIs and to understand the network performance:

- Size of transferred data (b),
- Duration of the transfer (s),
- Number of TCP retries,
- TCP congestion window size (B),
- PHY bit-rate used by the STA for the Wi-Fi link (Mbps), captured from AP, and
- link RSSI (dBm), captured from AP.

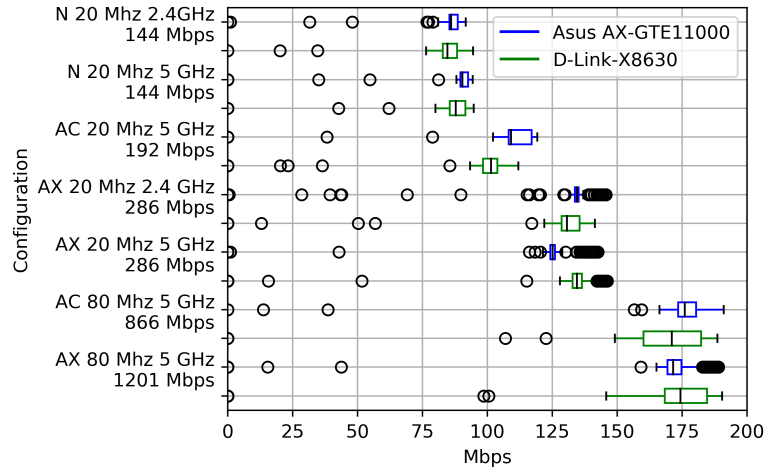


Figure 3: UL throughput of the different IEEE 802.11 networks in a unidirectional stream

Size of transferred bits and duration of transfer are used to calculate the throughput in 1 s intervals. Number of TCP retries is an indicator for end-to-end reliability. We target a bandwidth of 1800 Mbps to push the link to its limits for all the configurations. This allows us to test the reliability of each network under “worst case” conditions.

4 Results

We present in this section the experiment results. Sec. 4.1 shows the UL performance of the different Wi-Fi networks. Sec. 4.2 shows DL performance. Finally Sec. 4.3 discusses the aggregate performance of each Wi-Fi based on all the streams.

4.1 Uplink

We compare the UL throughput of each Wi-Fi configuration for both APs in the box-plot in Fig. 3. The plot shows the 25th and the 75th percentiles of the throughput achieved during a 5 min run.

The main observation is that **recent Wi-Fi generations increase their end-to-end throughput but not in a manner proportional to the increase in the PHY bit-rates** (listed in Table 2); the same pattern is seen on both APs. The lowest throughput is of the IEEE 802.11n network at 85 Mbps using 144 Mbps PHY (in both bands). The IEEE 802.11ax network with 20 MHz BW has ≈ 135 Mbps throughput (also in both bands); it is 23% higher than the similar IEEE 802.11ac configuration, although its PHY bit-rate is 50% faster. The IEEE 802.11ac network with 80 MHz BW in the 5 GHz band reaches 175 Mbps; it is only 60% higher than the IEEE 802.11ac with 20 MHz BW although its PHY bit-rate is 300% higher. Finally, IEEE 802.11ax network using 80 MHz BW in the 5 GHz band reaches 175 Mbps (same as the IEEE 802.11ac network); it is only 30% higher than the IEEE 802.11ax using 20 MHz BW, although its PHY is 300% higher in bit-rate.

Similar pattern is observed in the UL throughput in the bidirectional link plotted in Fig. 4. The throughput ranges between 70 Mbps for the IEEE 802.11n network up to 150 Mbps for the IEEE 802.11ax and IEEE 802.11ac networks. There is a throughput decrease for all configurations

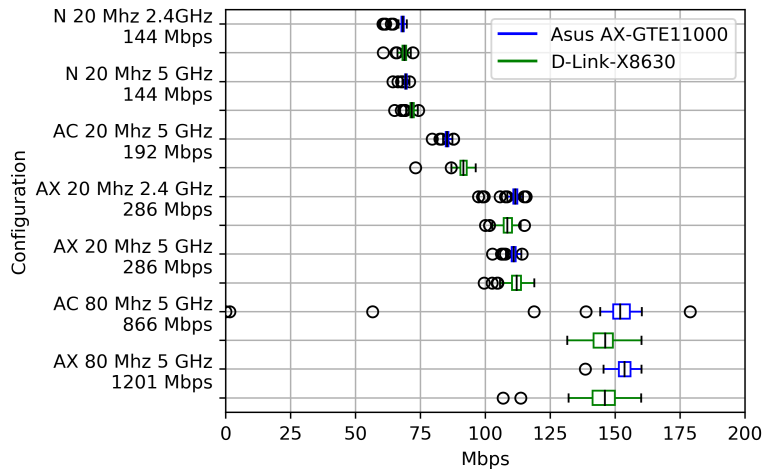


Figure 4: UL throughput of the different IEEE 802.11 networks in a bidirectional stream

by $\approx 15\%$ compared to the unidirectional link. This is expected as client, server, and network resources are shared by the parallel DL stream.

4.2 Downlink

We show the DL throughputs of the different networks in Fig. 5. While D-Link-X8630 AP shows lower DL throughput than the Asus AX-GTE11000 AP, which can be attributed to implementation specifics, the main observation holds. Similar to UL, we observe throughput improvement for faster bit-rate Wi-Fis but not proportional the PHY bit-rates used. We even observe a slight unexpected decrease of throughput of the IEEE 802.11ax 5 GHz network compared to the IEEE 802.11ac network.

The DL throughput is lower than the UL throughput seen in Fig. 3. This asymmetry is expected of TCP because of the cumulative ACK mechanism that makes UL more efficient, as previously studied in articles such as Park et. al., [22].

The DL throughput in the bidirectional link is plotted in Fig. 6. DL throughput is nearly 60% of UL (Fig. 4) for all networks because of TCP asymmetry [22]. Similar to previous streams, we observe that across all networks: the throughput increase is not proportional to the increase in PHY bit-rate.

4.3 Aggregate Results

We take a global look in Fig. 7 at the highest throughput achieved for each Wi-Fi network in *all* the streams, considering the maximum throughput achieved only 90% of the time to exclude momentary bursts. Performance of both APs is, in overall, similar with all streams considered.

But how is it that more recent Wi-Fi generations were not improving in throughput in a way proportional to their bit-rates?. This can be explained by a combination of two factors: packet loss along the path between the client and the server, leading to re-transmissions, and occasional use of slower bit-rates by the RAA [8].

First, we look at the number of TCP retries for each Wi-Fi network as an indicator of packet loss between the STA and the server. We noticed that the retries vary over time, so we plot the

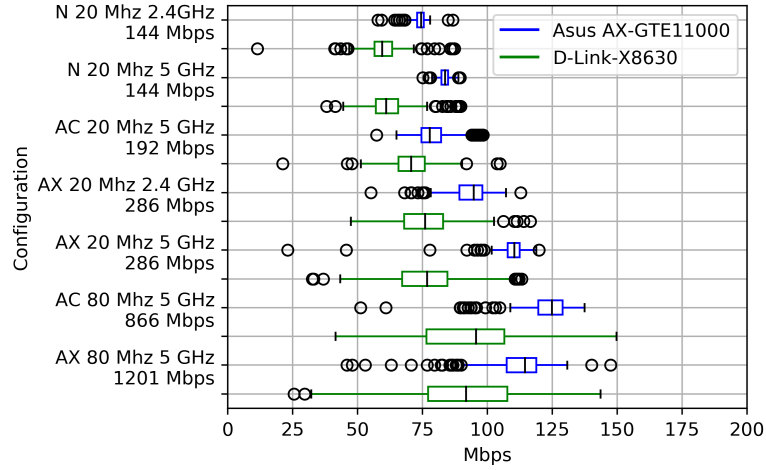


Figure 5: DL throughput of the different IEEE 802.11 networks

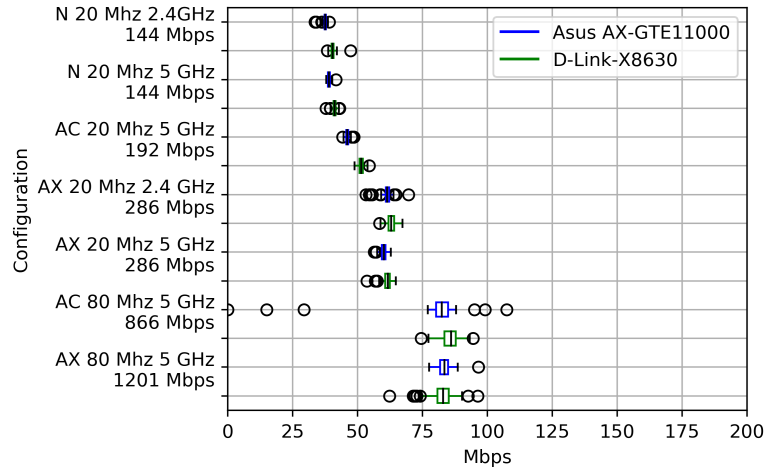


Figure 6: DL throughput of the different IEEE 802.11 networks in a bidirectional stream

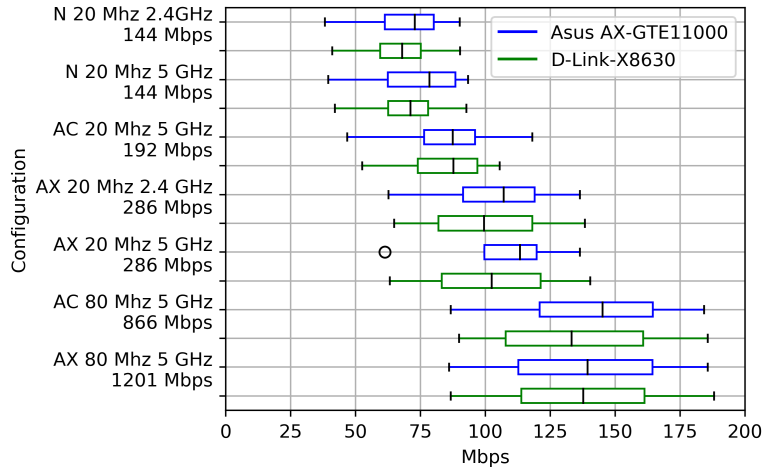


Figure 7: Maximum throughput of the different Wi-Fis across all streams.

Cumulative Distribution Function (CDF) of the retries for each network in Fig. 8. **Networks with faster PHYs have higher retries** (i.e., more packet loss and less reliability). For example, IEEE 802.11n network with 144 Mbps bit-rate (green) has median of 0 retries and a maximum of 1. But the IEEE 802.11ax 5 GHz with 80 MHz BW network with 1200 Mbps bit-rate (red) has a median of 4 retries and a maximum of 15. Packet loss can be caused by two factors: 1) higher bit-rate PHYs can be less robust so they may incur more frame loss than lower bit-rate PHYs as they can be less robust against reflections, multi-path fading, or path-loss attenuation and 2) higher bit-rate PHYs may lead to overflowing packet buffers across that path (STA, server, or AP), leading to higher rate of buffer overflow and, therefore, sub-optimal end-to-end throughput.

The IEEE 802.11n network notably maintained its maximum reliability despite the target BW of 1800 Mbps. This confirms that the TCP was successfully controlling the congestion and that packet loss is not related to the application layer or TCP congestion control.

Second, **end-to-end throughput is influenced by the dynamics of the RAA**. We look at the evolution of the PHY bit-rates for each network and we noticed that bit-rate varies at run time. We show in Fig. 9 a CDF of the bit-rates used for each network. Both IEEE 802.11ac and IEEE 802.11ax networks use sub-optimal bit-rates 20 % of the time – as low as 100 Mbps. The equipment documentation does not specify the used RAA. We are aware that some RAAs adapt the rate based on link RSSI/SNR, others depend on Packet Loss Ratio or Throughput [8]. Therefore, depending on the RAA dynamics, end-to-end throughput can be sub-optimal, despite using higher bit-rates.

RSSI remained stable at -55 dBm (± 1 dBm) and the TCP congestion windows for each stream remained unchanged after a maximum of 10 secs into the experiment.

5 Conclusion

Wi-Fi networks have become pervasive in personal and industrial applications. Some applications favor throughput while others favor reliability. In this article, we compared the performance of 7 Wi-Fi configurations with maximum PHY bit-rates between 144 Mbps and 1200 Mbps. We characterized their throughput in UL, DL, and parallel UL/DL streaming in an EM-shielded

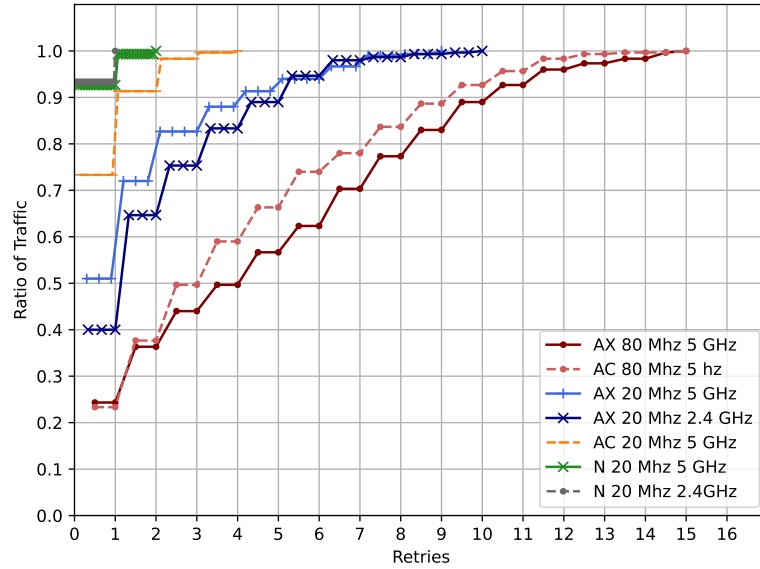


Figure 8: CDF of re-transmissions for each Wi-Fi Configuration, faster bitrates result in higher packet loss

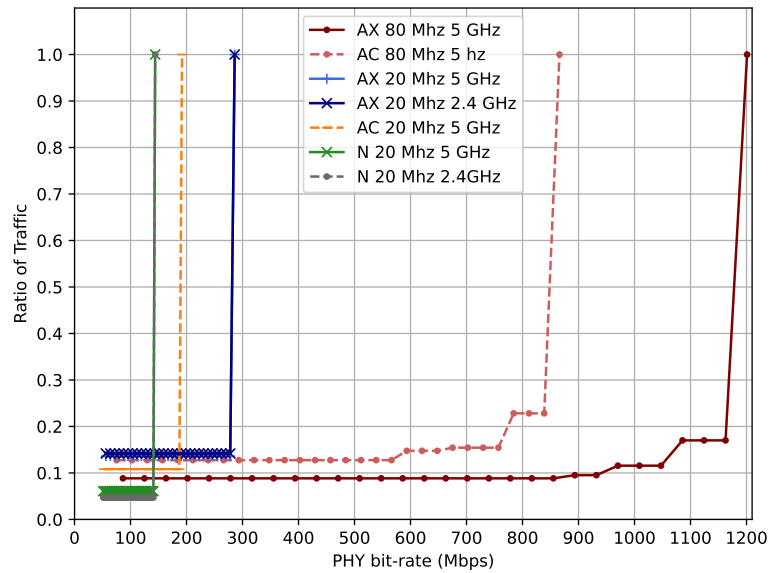


Figure 9: CDF of the PHY bit-rates used. Recent Wi-Fi generations still used slow bit-rate PHYs because of the RAA leading to sub-optimal throughput

environment. We are aware that different hardware setups can lead to different throughput setups based on available MIMO antennas, or chipset implementation efficiency. However, the main observation remains the same: *using higher PHY bit-rates comes at a cost of increased re-transmissions which pushes the link further away from its optimal throughput.* Therefore, increased PHY bit-rate can have a negative feedback on end-to-end throughput and reliability. This raises a question on how can the different configurations impact the Quality of Service IEEE 802.11 networks, specially when used for IoRT.

Currently the IEEE 802.11 standard supports four Quality of Service (QoS) access categories: voice, video, background, and best effort [5]. However, IoRT comes with QoS requirements that are not considered in the IEEE 802.11 specification. For example, control traffic can be interested in only the newest packet, or the latest N packets. So far, these requirements are addressed only at application layer. This leads to a question: “how can different PHYs be used for different types of traffic, depending on their QoS requirements?” For example, slower bit-rate PHYs can be used for critical control traffic and faster bit-rate PHYs can be used for media streaming. In future work, we address the question of building an agile wireless network for industrial robotics. This requires using diverse metrics that allow selection of the PHY bit-rate based on the QoS objective of each application.

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