Time-Sensitive Networking in IEEE 802.11be:
On the Way to Low-latency WiFi 7

Toni Adame, Marc Carrascosa, and Boris Bellalta
Department of Information and Communication Technologies, Universitat Pompeu Fabra
Email: {toni.adame, marc.carrascosa, boris.bellalta}@upf.edu

Abstract—Even being on the brink of WiFi 6, IEEE 802.11 working groups are already working on its successor in the wireless local area network (WLAN) ecosystem: WiFi 7. With IEEE 802.11be amendment as one of its main constituent parts, future WiFi 7 aims to support time-sensitive networking (TSN) capabilities to offer low latency and ultra-reliability in license-exempt spectrum bands.

This article introduces the key expected enhancements of IEEE 802.11be and reviews the IEEE TSN framework and its main components: time synchronization, traffic shaping and scheduling, ultra reliability, and resource management. Then, it focuses on those IEEE 802.11be features that may contribute to the integration of the TSN functionalities, such as the multi-link operation and the multi-access point (AP) coordination. In addition, several use cases with required TSN capabilities are presented: industry 4.0, cloud gaming, and interactive museums. Finally, as an illustrative example, the suitability of applying TSN packet prioritization techniques at the APs to keep latency low for time-sensitive packets in the interactive museum case.

I. INTRODUCTION

Time-sensitive communications have lately become increasingly important as industry has incorporated more and more automated systems into its manufacturing processes. Traditionally, wired Ethernet-like networks have been used for meeting the mission-critical control and safety requirements of time-sensitive applications. To introduce and homogenize deterministic networking into Ethernet, it stands out the time-sensitive networking (TSN) initiative driven by the IEEE. As a result, a set of newly developed and already existing sub-standards ensure zero packet loss due to buffer congestion, extremely low packet loss due to equipment failure, and guaranteed upper bounds on end-to-end latency [1]. However, while the use of cables and point-to-point communications notably simplify the technical solution, their usually cumbersome installation prevents to achieve the flexibility and interoperability requirements of modern manufacturing plants.

Since its emergence in the early 2000s, WiFi worldwide success has been mainly substantiated on high flexibility, mobility of devices, better cost efficiency, and reduced complexity. Although WiFi has been constantly evolving through successive amendments to improve peak throughput, capacity, and efficiency, it has not yet been able to produce a similar solution to manage time-sensitive traffic with bounded low latency. And actually, this represents a crucial requirement for current and upcoming real-time applications in industrial, entertainment or professional scenarios, such as high-resolution video streaming, augmented and virtual reality, and remote tactile-like interaction.

At this point, however, it is worth noting that WiFi will never be able to guarantee fully deterministic communications because of its operation in license-exempt bands, as they may also be used by other wireless networks. Nonetheless, there is still room to reduce the impact of all manageable causes, both external and internal, that result in a higher latency. On the one hand, contention with external networks may be minimized by considering dynamic spectrum access such as non-contiguous channel bonding and multi-link operation, as well as cooperative AP strategies. On the other hand, prioritization and scheduling mechanisms inside the same WLAN may provide an efficient solution to reduce the latency of time-sensitive traffic in the presence of large packets from best-effort flows.

In May 2019, IEEE P802.11be Task Group (TGbe) [2] was created to address the design of a new physical (PHY) and medium access control (MAC) amendment. It will be the core piece of next WiFi 7 along with other IEEE 802.11 amendments under development to improve security, resource management, and coexistence. Considered as the successor of IEEE 802.11ax [3], IEEE 802.11be aspires to increase throughput of existing applications up to 30 Gbps, integrate multi-link aggregation and operation, and improve coordination among access points (APs), thus supporting emerging multiple-input multiple-output (MIMO) technologies such as distributed MIMO (D-MIMO) [4].

As for deterministic real-time communications, IEEE 802.11be sets out to include at least one TSN-based operation mode capable of improving worst-case latency and jitter. To tackle this issue, some of the original TSN mechanisms need to be adapted to the inherent constraints of the wireless medium (namely; unreliability of links, asymmetric path delay, channel interference, signal distortion, lack of accurate clock synchronization methods, and incompatibility of network interface cards) [5], while ensuring backward compatibility with previous WiFi versions. Overall, all of this opens a new research direction for the upcoming years, with new contributions in the fields of performance models, channel access mechanisms, transport layer protocols, and resource management solutions.

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If not explicitly stated otherwise, all information contained in the current article regarding the technical features of IEEE 802.11be has been directly obtained from TGbe group published documents.
A careful design of WiFi 7 technologies oriented towards TSN could certainly reduce latency up to a few milliseconds and ensure extremely high throughput at the same time. Consequently, WiFi could be expanded into new sectors (for instance, telesurgery and exoskeletons in health care; factory automation, haptic technology and human machine interface in the industrial sector; or automated guided vehicles in the transport sector), and broaden its potential applications in well-known ones, such as virtual and augmented reality, cloud gaming, and 4K/8K video streaming in the audiovisual sector.

This paper offers a comprehensive overview of the main IEEE 802.11be features, describes the main TSN components, and discusses some ideas for their integration on top of IEEE 802.11be. For the sake of illustration, the use case of an interactive museum, where visitors enjoy an immersive experience with multiple heterogeneous real-time audiovisual exhibits, is used to show the benefits of adding a new traffic category for time-sensitive traffic with preemption capabilities. In this particular case, the incorporation of this new access category guarantees bounded low latency in presence of best-effort traffic.

The remainder of this paper is organized as follows: Section II describes the main features of IEEE 802.11be in terms of PHY and MAC layers. Whereas Section III elaborates on TSN features for Ethernet networks, Section IV compiles a set of enhancements that allow IEEE 802.11be to properly support the TSN technology. Section V provides a review of the potential use cases that could leverage more low-latency and reliable communications, such as the interactive museum, whose performance is analyzed in Section VI. Lastly, Section VII presents the obtained conclusions and discusses open challenges.

II. IEEE 802.11BE

This section introduces the main ongoing technical discussions in the TGbe group for both PHY and MAC layers. Following the traditional IEEE 802.11 evolution, IEEE 802.11be will adopt IEEE 802.11ax contributions, further refining and extending them, and adding some new features. Indeed, while IEEE 802.11ax was a major upgrade in the IEEE 802.11 universe with the incorporation of OFDMA, spatial reuse, and AP-controlled operation using trigger frames (among other key features), IEEE 802.11be is expected to be less disruptive.

A. PHY layer

The announcement of the Federal Communications Commission (FCC) of the US in October 2018 of releasing a maximum of 1.2 GHz of spectrum in the 6 GHz band (from 5.925 GHz to 7.125 GHz) and a similar study of the European Commission published in May 2019, with respect to the 500 MHz comprised between 5.925 GHz and 6.425 GHz, open new opportunities and challenges for WiFi.

In line with these regulatory decisions, the use of the 6 GHz band in addition to the traditional WiFi industrial, scientific and medical (ISM) bands (i.e., sub-1GHz, 2.4, and 5 GHz) is already adopted for IEEE 802.11ax and will be one of the key characteristics of IEEE 802.11be.

IEEE 802.11be intends to use more efficiently the spectrum by supporting 320 MHz channels, thus doubling their maximum width with respect to its predecessor. Also, to maximize the use of a potentially fragmented spectrum, IEEE 802.11be aims to enhance the preamble puncturing feature already included as optional in IEEE 802.11ax for non-contiguous channel bonding. On this matter, the TGbe group is studying new puncturing patterns in 160 MHz and even 320 MHz channels.

As for the maximum number of spatial streams, it is expected to double its number from 8 in IEEE 802.11ac/ax to 16 in IEEE 802.11be, thus further benefiting from fundamental advantages of predominantly indoor WiFi operation: rich scattering, higher angular spreads, lower correlation, and diversity of channels with good propagation conditions. Similarly, the maximum supported modulation size in IEEE 802.11be is expected to be boosted with the adoption of the 4096 QAM modulation in certain network configurations.

B. MAC layer

Many significant features of IEEE 802.11ax such as multi-user (MU)-MIMO, OFDMA, and spatial reuse will be extended in IEEE 802.11be. The support of more spatial streams will enable greater throughput benefits and more flexible multi-user MU-MIMO arrangements. However, current explicit channel state information acquisition procedure may not cope well with such higher number of antennas and, for that reason, the TGbe group is already working on an implicit channel sounding procedure.

As for OFDMA, novel and enhanced resource unit (RU) allocation schemes will allow to allocate multiple contiguous and non-contiguous RUs to a single station (STA). Consequently, these schemes could significantly increase spectral efficiency and overall network throughput far beyond current OFDMA with just one RU per user.

Two new features of IEEE 802.11be are the multi-link operation and the support for multi-AP coordination. Multi-link aggregation will likely become the most representative feature, aiming to efficiently use the available spectrum, achieve higher data rates, and implement band-based load balancing techniques. Proposed multi-link techniques [6] are represented in Figure I and described in the following lines:

- **Multi-band aggregation** combines two or more channels at different bands to achieve higher transmission rates. In this regard, a single frame is split and transmitted through the different channels, reducing its total transmission time, or allowing the transmission of larger aggregated frames in time-constrained transmission opportunities.
- **Multi-band and multi-channel full duplex** enables full duplex communication by dedicating different channels (whether from the same or different bands) to transmit and receive at the same time.
- In case **full duplex with interference cancellation** is supported, multi-link support would also open the pos-
sibility of using the same channel to simultaneously transmit and receive information.

- **Data and control plane separation** sets out to decouple data and control information, by dedicating different channels (whether from the same or different bands) to each purpose.

A second remarkable novel feature proposed for IEEE 802.11be consists in the coordinated use of neighboring APs in enterprise WLANs to enhance WiFi performance by means of:

- **Coordinated OFDMA** optimizes the efficiency of the wireless communication channel both in time and frequency, as APs are able to allocate the available RUs to their corresponding STAs in a coordinated way.

- **Distributed MIMO (D-MIMO)** allows several APs to perform joint data transmissions to multiple STAs reusing the same time/frequency resources.

Lastly, hybrid automatic repeat request (HARQ) is also proposed for IEEE 802.11be. While the use of HARQ alone offers notable performance gains in varying channels compared to the traditional stop & wait approach, it is not yet clear if such gains will also be observed when combined with the CSMA/CA operation.

III. **Time-sensitive Networking (TSN)**

TSN consists of a set of sub-standards defined by the IEEE 802.1 TSN Task Group [7] to support deterministic messaging on standard Ethernet. Essentially, TSN technology relies on a central management that uses time scheduling to guarantee reliable packet delivery with bounded latency and low packet delay variation (jitter) in deterministic real-time applications.

TSN also ensures backwards compatibility with non-deterministic communications. In consequence, a bridged Ethernet network manages to transport, through a single infrastructure, data frames with heterogeneous quality of service (QoS) requirements, ranging from background traffic to time-critical traffic.

To achieve the aforementioned capabilities, TSN classifies all its sub-standards into four key components:

- **Time synchronization** is accomplished by means of IEEE 802.1AS, which includes an IEEE 802-specific precision time protocol (PTP) version. It enables the distribution of a single reference clock across network devices in a master/slave basis with an accuracy from 100 ns to 1 µs.

- **Traffic shaping and scheduling** allows for different traffic classes to coexist with competing priorities in the same network thanks to two IEEE sub-standards:
  - **IEEE 802.1Qbu** implements frame preemption to interrupt the ongoing operation of a low-priority (preemptable) queue if a time-sensitive (preempting) queue is selected for transmission. In addition, low-priority frames are split into smaller fragments to further reduce overall latency.
  - **IEEE 802.1Qbv** creates a time division multiple access (TDMA) scheme that splits communication time on an Ethernet network into repetitive cycles of fixed length. A time-aware shaper defines the time period in which time-sensitive frames can be transmitted with the certainty that they will not be interfered by other traffic.

- **Ultra reliability** is responsibility of IEEE 802.1CB, which requires the existence of multiple paths between sender and receiver. It simply sends duplicate copies
of each frame over disjoint paths to provide proactive seamless redundancy.

- **Resource management** refers to those policies adopted by the network to manage the available resources (e.g., communication paths, bandwidth, scheduling patterns, and so forth). According to the stated application and user requirements, IEEE 802.1Qcc implements either a centralized or a distributed approach.

IV. **Enhancements to support TSN in WiFi 7**

Once reviewed the main key components of TSN, this section introduces some technical features considered by the TGbe group along with other IEEE 802.11 amendments that could contribute to efficiently support time-sensitive communications in WiFi 7. Table 1 provides a summarized view of all the enhancements described in the following lines.

A. **Enhancements to support time synchronization**

IEEE 802.1AS can already be operated over IEEE 802.11 by means of the timing measurement (TM) procedure defined in IEEE 802.11v, which takes wireless link asymmetric delay into consideration. Time is propagated in private action frames between a master and a slave, being the latter able to compute the clock offset and adjust its own time accordingly.

Furthermore, the next revision of the IEEE 802.1AS standard (IEEE 802.1AS-Rev, still in draft version) will contain a novel synchronization method by using the IEEE 802.11mc fine timing measurement (FTM) procedure. FTM provides 0.1 ns of timestamp resolution, far more accurate than TM, whose timestamp resolution is 10 ns [8].

B. **Enhancements to support traffic shaping and scheduling**

1) **Traffic identification**: When classifying different traffic flows, the conventional enhanced distributed channel access (EDCA) mode included in IEEE 802.11e defines 4 access categories: background, best effort, video, and voice. However, EDCA access categories are insufficient for fine control of real-time applications.

One of the mechanisms considered by the TGbe group is the adoption of a modified priority tagging system based on the differentiated services field codepoints (DSCP), which uses 6 bits of the IP header for packet classification. The main disadvantage of this mechanism is, though, that priority can only be preserved in the local network if configured in a controller or edge router, which requires the implementation of a traffic identification and classification system.

2) **Traffic isolation**: IEEE 802.1Qbu frame preemption is contemplated as a feasible option to isolate time-sensitive from background traffic. Nonetheless, it is still necessary to define the MAC enhancements that will support this technique, such as the format of preemptable frames, the arbitration between time-sensitive and preemptable frames, and the methods to fragment frames and preserve integrity of preemptable traffic (see Figure 2b).

3) **Admission Control**: Admission control systems, where only a certain number of STAs are admitted in the basic service set (BSS), can also be applied in IEEE 802.11be in different ways:

- IEEE 802.11e incorporates new MAC-layer QoS schemes and parameters that allow both EDCA and hybrid coordination function controlled channel access (HCCA) to execute admission control mechanisms based on network condition measurements (measurement-based) or performance metrics (model-based) for EDCA, and on deterministic schemes for HCCA [10].

- Multi-link operation and the incorporation of the 6 GHz band in IEEE 802.11be foresee the emergence of simple multi-band admission control systems. For instance, access could be restricted at 6 GHz band for time-sensitive traffic but unrestricted at 2.4 and 5 GHz bands.

4) **Scheduled operation**: Transmission of time-sensitive and non-time-sensitive traffic is performed on a periodic basis, according to the rules of a schedule created from any of the following options:

- The adaptation of the IEEE 802.1Qbv time-aware shaper on top of one of the IEEE 802.11 MAC modes would result in giving each device a transmission schedule indicating the specific time period to release packets from its buffers according to their priority (see Figure 2a).

- The **Trigger-based** scheduled channel access mode for MU transmissions from IEEE 802.11ax [11] is also in the spotlight of the TGbe group. Particularly, two potential directions have been identified to enhance it: 1) to replace the basic trigger frame (TF) with an extended one including schedule information of subsequent time periods, and 2) to reduce the control overhead (especially in small packets).

- WiFi 7 also expects to take advantage of the target wake time (TWT) mechanism from IEEE 802.11ax to establish a *wake time schedule* for STAs. With TWT, STAs are only allowed to wake up when required, thus significantly reducing overall network contention, hence facilitating collision-free operation.

- Lastly, though rarely used in the IEEE 802.11 ecosystem, already existing mechanisms such as power-save multi-poll (PSMP) and HCCA could also conduct deterministic time scheduling.

C. **Enhancements to support ultra reliability**

There exists an important reliability gap to overcome in IEEE 802.11, especially given the potential for interference in license-exempt bands. On this matter, solutions range from traditional rate adaptation mechanisms (e.g., selection of lower modulation and codification schemes (MCSs) for time-sensitive frames in trigger-based access) to more complex systems aimed at multiplexing transmissions of STAs in the same time/frequency resources (e.g., spatial reuse techniques and D-MIMO mechanisms).
IEEE 802.1CB can already be applied in the wireless domain by means of the IEEE 802.11ak amendment, which is able to create link-disjoint or node-disjoint paths. However, to actually improve wireless path reliability is necessary to consider other complementary enhancements:

- Use of spectrum diversity both in separated bands (multi-band) or channels (multi-channel) to simultaneously transmit multiple copies of the same frame.
- Use of joint transmissions from multiple APs (multi-AP transmission) to increase frame reception probability by improving signal levels at the destination.
- Use of HARQ over different channels to outperform spectrum diversity enhancements, as it does not only ensure reliability, but also provides higher throughput.

Lastly, temporal diversity can be always exploited by transmitting the same frames multiple times over time, although at the cost of higher latency.

### D. Enhancements to support resource management

Enhancements aimed at supporting TSN in IEEE 802.11be should consider normal and managed operation. Normal operation is characterized by the lack of coordination among APs, where unmanaged interference and contention is expected in the targeted scenario (e.g., public hot spots, apartment buildings or homes). On the other hand, managed operation assumes that all wireless devices belonging to the same administrative domain are coordinated, thus operating under controlled interference and contention levels. In this case, typical scenarios are indoors (e.g., factories or enterprise networks).

The TGbe group aims to develop the necessary coordination protocols and security procedures to enable a managed overlapping basic service set (OBSS) like the one from Figure 2c, where TSN strategies are spread from the coordinator AP to the coordinated APs, and then in turn to the STAs deployed in the coverage area. This approach, known as multi-AP resource coordination, assumes that all APs are under control of a single entity (i.e., the network controller) and interference from unmanaged STAs/BSSs can be minimized by means of admission control and other management tools. Hence two different types of traffic patterns could be simultaneously handled: predictable/time-sensitive and unpredictable/best-effort.

### V. Use cases

Providing bounded latency is highly critical both in traditional industrial and in new promising cutting-edge use cases. As shown in Table II these can be classified into five big sectors: audiovisual, health care, industrial, transport, and financial. By way of illustration, this section describes in depth three potential use cases of time-sensitive networking in WiFi 7.

#### A. Industry 4.0

Industry 4.0 is based on the cyber-physical transformation of processes, systems and methods of manufacturing in the industrial sector, thus enabling autonomous and decentralized operation while ensuring proper coordination with commercial and logistics systems.

One of the multiple existing Industry 4.0 applications is known as connected factory, involving monitoring, management, and direct control of machines, robots, and other industrial assets. Time-sensitive networking is here crucial due to the critical nature of some specific manufacturing processes, with typical latency requirements from 1 to 200 ms. The most critical problem is then to guarantee reliability with determinism; that is, each message must reach its destination within its scheduled period [12].

In particular, a connected factory use case may consist of a combination of best effort uplink (UL) traffic coming from periodic reports of monitored machines, time-sensitive downlink (DL) specific commands, time-sensitive UL events and/or alarms generated by unattended machines, and time-sensitive UL/DL frames corresponding to the remote control of robots.

| Component                  | Subcomponent                  | Proposed enhancement              | Latency | Targeted feature | Reliability | Management |
|----------------------------|-------------------------------|-----------------------------------|---------|------------------|-------------|------------|
| Time synchronization        |                               |                                   |         |                  |             |            |
| Traffic shaping and scheduling | Traffic identification         | IEEE 802.1AS over IEEE 802.11     | x       |                  | x           |            |
|                             | Traffic isolation             | IEEE 802.11mc FTM                 | x       |                  | x           |            |
|                             | Admission control             | Priority tagging with DSCP        | x       |                  |             |            |
|                             |                               | Frame preemption                  | x       |                  |             |            |
|                             | Scheduled operation           | Admission control in EDCA and HCCA| x       |                  |             |            |
|                             |                               | Multi-band admission control      | x       |                  |             |            |
|                             |                               | Time-aware shaper                 | x       |                  | x           |            |
|                             |                               | Trigger-based access              | x       |                  | x           |            |
|                             |                               | TWI mechanism                     | x       |                  | x           |            |
|                             |                               | TPSMP and HCCA                    | x       |                  | x           |            |
| Ultra reliability           | Rate adaptation in trigger-based access | x | x | x | | |
| Resource management         | Spatial reuse techniques      | x | x | x | | |
|                             | D-MIMO mechanisms              | x | x | x | | |
|                             | IEEE 802.11ak + frequency diversity | x | x | | | |
|                             | IEEE 802.11ak + multi-AP transmission | x | x | x | | |
|                             | Frame retransmission          | x | | x | | |
|                             | Multi-AP resource coordination | x | | x | | |
Fig. 2: TGbe group proposed enhancements to support TSN in WiFi 7.

B. Cloud gaming

For the last decade, video games have been enriched with online components, from competitive and cooperative multiplayer modes to downloadable content such as maps and player customization. Cloud gaming is the next step, with games being streamed completely from a server, without needing any physical hardware to play. Google Stadia is at the forefront of this technology, promising 4K quality remote gaming at 60 fps.

Most current online games have a noticeable lag around 50 ms. However, scientific studies show that the brain can identify images with as little as 13 ms [13], which is less than the time duration of a single frame at 60 fps (i.e., 16.7 ms). Therefore, in order to offer the best user experience, for video game companies it will be increasingly important to keep delay controlled while maximizing reliability.

Most of cloud gaming traffic consists of time-sensitive frames relaying player movement and actions to the server in the UL and the subsequent environment response in the DL. At the same time, other users in the same network may be connected to audio and/or video streaming services.
C. Interactive museum

Worldwide museums have long relied on technology to display information, give context, and involve visitors in their exhibitions. Well-known examples are informational videos, audio guides, interactive games, hands-on experiments, and smartphone apps. In this regard, the latest advancements on augmented reality (AR) allow its adoption by interactive museums, thus giving curators a chance to layer more information on top of existing exhibits [14].

To cope with the volume, distribution, and dynamic behavior of visitors across the different halls (usually moving far and wide and even creating densely populated clusters of people), museum’s wireless network requires not only the deployment of a high number of APs, but also a coordinated operation under a multi-AP scheme.

VI. INTERACTIVE MUSEUM: RESULTS

In the following lines, the use case of an interactive museum is used to illustrate the benefits of integrating a TSN feature such as frame preemption into IEEE 802.11be. MATLAB is used to simulate the considered scenario. The parameters used in the simulation are detailed in Table III.

Let us consider a circular hall of radius $R = 15$ m containing an interactive exhibit with a single AP placed in the center, as shown in Figure 3a. Users are placed uniformly at random on the museum’s hall. The AP provides visitors in that hall with a set of customized interactive services by means of DL unicast transmissions that can be categorized according to their priority level:

- **Best effort (BE) traffic** is tagged as low-priority and consists of video streaming of additional contents, an interactive audio guide, and real-time information feeding the museum mobile app. BE traffic amounts to $B_{BE} = 2$ Mbps per user.

- **Time-sensitive (TS) traffic** is tagged as high-priority and transports a stream of information corresponding to an immersive AR installation. TS traffic amounts to $B_{TS} = 5$ Mbps per user and has a maximum tolerable latency of $t_{TS} = 5$ ms.

The AP implements two access categories (BE and TS), and supports three different prioritization policies:

- **No prioritization**: Packets are sent in strict order of arrival regardless their type (BE or TS).

- **Non-preemptive prioritization**: As long as the TS queue contains packets, they are sent prior to BE ones. In case there is an ongoing transmission of a BE packet, and a new TS packet arrives to the TS queue, the transmission of the latter is delayed until the end of the former one.

- **Preemptive prioritization**: As in the previous policy, TS packets are sent prior to BE ones. However, the transmission of a BE packet is interrupted if a new TS packet arrives. Only when the transmission of the TS packet finishes, the TS queue is empty, that the transmission from the BE packet is resumed. Pre-emption, however, entails an extra delay caused by overheads of the $N_f$ fragments in which the BE packet is divided ($N_f \cdot T_{ov}$).

Visitors may request low- or high-priority services, or even both at the same time. Four different network configurations were considered, being $N_{BE} = \{15, 20, 25, 30\}$ users requesting BE services and $N_{TS} = 5$ users requesting TS services. For each configuration, $k = 1000$ simulations changing user locations were executed. Then, according to the TMB path loss model for 5 GHz indoor scenarios [15] and the MCS table from IEEE 802.11ax data rate of each user was automatically computed.

Average latency of BE and TS packets (shown in Figure 3b and Figure 3c respectively) was computed for the three aforementioned priority policies and the four different network configurations (based on the number of $N_{BE}$ and $N_{TS}$ users). As expected, those policies giving priority to TS

| Sector | Use case | Requirements |
|--------|----------|--------------|
|        |           | Latency (ms) | Reliability (%) | Throughput (Mbps) |
| Audiovisual | High-quality video | 3 - 10 | \(>99.9\) | 5 - 25 |
|     | Virtual reality (VR) | 10 - 20 | \(>99.9\) | 25 - 500 |
|     | Augmented reality (AR) | 1 - 50 | \(>99.99\) | 1 - 200 |
|     | Real-time pro gaming | 5 - 50 | \(>99.9\) | \(\sim 5\) |
|     | Cloud gaming | 5 - 50 | \(>99.99\) | 10 - 35 |
| Health care | Telesurgery | 1 - 10 | \(>99.9999\) | \(\sim 10\) |
|     | Telechagnosis, Telemonitoring, and Telerehabilitation | 50 - 200 | \(>99.9\) | 0.5 - 5 |
|     | Exoskeletons and Prosthetic hands | 5 - 20 | \(>99.999\) | 0.2 - 1 |
| Industrial | Process automation | 1 - 50 | \(>99.99\) | 0.1 - 5 |
|     | Human machine interface (HMI) | 50 - 200 | \(>99.99\) | \(\sim 5\) |
|     | Tactile / Haptic technology | 1 - 5 | \(>99.99\) | \(\sim 1\) |
|     | Drone control | <100 | \(>99.99\) | 1 - 10 |
| Transport | Automated guided vehicle (AGV) | 10 - 50 | \(>99.9999\) | \(\sim 1\) |
|     | Remote-controlled vehicle with video | 10 - 100 | \(>99.99\) | \(\sim 10\) |
|     | Real-time traffic information | 40 - 500 | \(\geq 99\) | 0.1 - 1 |
| Financial | High-frequency trading | 0.1 - 1 | \(>99.9999\) | 0.1 - 1 |
If we observe the latency of BE packets, it grows in all three policies when increasing $N_{BE}$, attaining the \textit{preemptive prioritization} policy the highest values but with a median contained below 20 ms. Moreover, although outliers achieve up to 125 ms in some concrete cases, they are always below 150 ms. As for latency of TS packets, its value grows in line with $N_{BE}$ when using the \textit{no prioritization} policy, unable to meet the stated requirement (i.e., $t_{TS} < 5$ ms) on average for more than $N_{BE} = 20$ users.

On the contrary, \textit{non-preemptive} and, especially, \textit{preemptive prioritization} policies are able to keep latency values regardless $N_{BE}$ below 3.83 ms and 2.58 ms, respectively. In addition, these values attain very low dispersion, thus ensuring predictable bounded latency and, therefore, supporting time-sensitive communications.

VII. CONCLUSIONS

The limitations, at least those caused by BSSs under the same administrative domain, that currently hinder effectiveness of time-critical applications over wireless networks in license-exempt bands could be overcome in WiFi 7. Indeed, the adaptation of well-known Ethernet-based TSN schemes and protocols to the next-generation WiFi standard will improve its current performance and make it appealing for use in time-sensitive networking.

The new PHY and MAC technical features announced for IEEE 802.11be, actual precursor of WiFi 7, should be accompanied with a well-defined and backward compatible time-sensitive operation mode to support low-latency communications. In this regard, this article provides a comprehensive overview of the time-sensitive networking enhancements that could fulfill that mission according to four key components: time synchronization, traffic shaping and scheduling, ultra reliability, and resource management.

As a matter of example, the straightforward implemen-
tation of one of these enhancements (in our case, frame preemption) over a mixed BE/TS traffic environment in a future interactive museum proves the potential latency reduction in TS traffic, the practical removal of dispersion in computed values, and, in consequence, the confinement of latency under predictable bounded limits.

All in all, although time-sensitive networking can open a range of possibilities for future WiFi, its successful implantation to support deterministic real-time applications will depend on its ability to deal with the uncertainty of license-exempt radio bands, and the resulting impact on the achievable latency bounds as well as on network’s capacity and efficiency.

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REFERENCES

[1] N. Finn, “Introduction to time-sensitive networking,” IEEE Communications Standards Magazine, vol. 2, no. 2, pp. 22–28, 2018.

[2] “IEEE P802.11be Task Group (TGbe),” http://www.ieee802.org/11/Reports/tgbe_update.htm, Accessed: 2019-12-11.

[3] B. Bellalta, “IEEE 802.11 ax: High-efficiency WLANs,” IEEE Wireless Communications, vol. 23, no. 1, pp. 38–46, 2016.

[4] E. Au, “IEEE 802.11 be: Extremely High Throughput [Standards],” IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 138–140, 2019.

[5] A. Mildner, “Time Sensitive Networking for Wireless Networks-A State of the Art Analysis,” Network, vol. 33, 2019.

[6] D. López-Pérez, A. Garcia-Rodríguez, L. Galati-Giordano, M. Kaslin, and K. Doppler, “IEEE 802.11 be Extremely High Throughput: The Next Generation of Wi-Fi Technology Beyond 802.11 ax,” IEEE Communications Magazine, vol. 57, no. 9, pp. 113–119, 2019.

[7] “IEEE Time-Sensitive Networking Task Group,” http://www.ieee802.org/1/pages/tsn.html, Accessed: 2019-12-11.

[8] K. Stanton and C. Aldana, “Addition of p802.11-MC Fine Timing Measurement (FTM) to p802.1AS-Rev: Tradeoffs and Proposals,” March 2015.

[9] D. Thiele and R. Ernst, “Formal worst-case performance analysis of time-sensitive Ethernet with frame preemption,” in 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1–9, IEEE, 2016.

[10] D. Gao, J. Cai, and K. N. Ngan, “Admission control in IEEE 802.11e wireless LANs,” IEEE network, vol. 19, no. 4, pp. 6–13, 2005.

[11] B. Bellalta and K. Kosek-Szott, “AP-initiated multi-user transmissions in IEEE 802.11 ax WLANs,” Ad Hoc Networks, vol. 85, pp. 145–159, 2019.

[12] S. Bush and G. Mantelet, “Industrial Wireless Time-Sensitive Networking: RFC on the Path Forward.” Avnu Alliance White Paper, January 2018.

[13] M. C. Potter, B. Wyble, C. E. Hagmann, and E. S. McCourt, “Detecting meaning in RSVP at 13 ms per picture,” Attention, Perception, & Psychophysics, vol. 76, no. 2, pp. 270–279, 2014.

[14] A. Pardes, “For Museums, Augmented Reality Is the Next Frontier.” Wired Magazine, September 2018. https://www.wired.com/story/museums-augmented-reality-next-frontier/, Accessed: 2019-12-11.

[15] T. Adame, M. Carrascosa, and B. Bellalta, “The TMB path loss model for 5 GHz indoor WiFi scenarios: On the empirical relationship between RSSI, MCS, and spatial streams,” in 2019 Wireless Days (WD), pp. 1–8, IEEE, 2019.