



IEEE P802.24

LOW LATENCY COMMUNICATION WHITE PAPER

Authored by

Oliver Holland

Allan Jones

Tim Godfrey

Ben Rolfe

Dillon Seo

Ann Krieger

TRADEMARKS AND DISCLAIMERS

IEEE believes the information in this publication is accurate as of its publication date; such information is subject to change without notice. IEEE is not responsible for any inadvertent errors.

The ideas and proposals in this specification are the respective author's views and do not represent the views of the affiliated organization.

The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2024 by The Institute of Electrical and Electronics Engineers, Inc.

All rights reserved. 31 July 2024. Printed in the United States of America.

PDF: STDVA26617 979-8-8557-0317-7

IEEE is a registered trademark in the U. S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated. All other trademarks are the property of the respective trademark owners.

IEEE prohibits discrimination, harassment, and bullying. For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system, or otherwise, without the prior written permission of the publisher.

Find IEEE standards and standards-related product listings at: <http://standards.ieee.org>.

NOTICE AND DISCLAIMER OF LIABILITY CONCERNING THE USE OF IEEE SA DOCUMENTS

This IEEE Standards Association (“IEEE SA”) publication (“Work”) is not a consensus standard document. Specifically, this document is NOT AN IEEE STANDARD. Information contained in this Work has been created by, or obtained from, sources believed to be reliable, and reviewed by members of the activity that produced this Work. IEEE and the members of the IEEE P802.24 working group expressly disclaim all warranties (express, implied, and statutory) related to this Work, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; quality, accuracy, effectiveness, currency, or completeness of the Work or content within the Work. In addition, IEEE and the IEEE P802.24 working group disclaim any and all conditions relating to: results; and workmanlike effort. This document is supplied “AS IS” and “WITH ALL FAULTS.”

Although the IEEE P802.24 members who have created this Work believe that the information and guidance given in this Work serve as an enhancement to users, all persons must rely upon their own skill and judgment when making use of it. IN NO EVENT SHALL IEEE SA OR IEEE P802.24 MEMBERS BE LIABLE FOR ANY ERRORS OR OMISSIONS OR DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS WORK, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Further, information contained in this Work may be protected by intellectual property rights held by third parties or organizations, and the use of this information may require the user to negotiate with any such rights holders in order to legally acquire the rights to do so, and such rights holders may refuse to grant such rights. Attention is also called to the possibility that implementation of any or all of this Work may require use of subject matter covered by patent rights. By publication of this Work, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. The IEEE is not responsible for identifying patent rights for which a license may be required, or for conducting inquiries into the legal validity or scope of patents claims. Users are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. No commitment to grant licenses under patent rights on a reasonable or non-discriminatory basis has been sought or received from any rights holder.

This Work is published with the understanding that IEEE and the IEEE P802.24 members are supplying information through this Work, not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought. IEEE is not responsible for the statements and opinions advanced in this Work.

TABLE OF CONTENTS

LOW LATENCY COMMUNICATION WHITE PAPER	5
1. BACKGROUND AND INTRODUCTION	5
2. LOW LATENCY COMMUNICATIONS APPLICATIONS.....	5
2.1. ELECTRIC UTILITIES—GRID PROTECTION.....	6
2.2. MEDICAL IOT.....	7
2.3. REAL-TIME MOBILE GAMING	7
2.4. WIRELESS CONSOLE GAMING [5]	8
2.5. CLOUD GAMING	8
2.6. INDUSTRIAL SYSTEMS.....	9
2.7. REAL-TIME VIDEO	10
2.8. DRONE CONTROL.....	11
2.9. AR/VR	11
3. PERFORMANCE METRICS FOR LOW LATENCY COMMUNICATION	12
4. KEY TECHNOLOGIES/SOLUTIONS SUPPORTING LOW LATENCY COMMUNICATION	13
5. ADAPTIONS AND RECOMMENDATIONS FOR IEEE 802 STANDARDS TO ENHANCE LOW LATENCY COMMUNICATIONS SUPPORT.....	14
6. NEW CAPABILITIES TO SUPPORT REAL-TIME APPLICATIONS	15
7. CONCLUSION	16
8. REFERENCES.....	17
APPENDIX A IEEE 802 STANDARDS SUPPORTING LOW LATENCY COMMUNICATIONS	19
APPENDIX B GLOSSARY	22

LOW LATENCY COMMUNICATION WHITE PAPER

1. BACKGROUND AND INTRODUCTION

This white paper's intent is to inform users and IEEE 802® working groups on the applications and requirements for low latency communications. Low latency is challenging to implement in wired or wireless networks. Some wireless applications are located in physical environments over which the operator/owner can exert control in unlicensed and licensed spectrum. However, in many environments, devices are subject to the effects of other wireless communication devices that can disturb their operation. Wired communications are less subject to these effects.

Latency refers to the concept of ensuring a delivery time is bounded. Different applications have a wide range of required latency or delivery time. Low latency is typically achieved by a combination of access control and scheduling along with increasing bandwidth (overprovisioning) in the network. Low latency alone does not cover all the problems addressed by time-sensitive networks (TSNs), which are discussed in a prior white paper, [Utility Applications of Time Sensitive Networking](#) [1].¹

2. LOW LATENCY COMMUNICATIONS APPLICATIONS

The need for low latency communication is being driven by a group of application requirements. A set of such applications is described next, but new applications with low latency requirements continue to emerge. Modern networks and applications have higher levels of cyber-security requirements, which can add overhead and delays that impede the goal of low latency.

¹ Numbers in brackets correspond to references listed in Section 8.

2.1. ELECTRIC UTILITIES—GRID PROTECTION

The utility is considered an entity (or entities) that manages the distribution of electricity on the transmission grid and the distribution grid. The power distribution network involves substations and various protective and control devices that communicate over communications networks.

Low latency communication is one-factor enabling real-time performance of the network as required for specific grid use cases and applications.

IEEE 802.3 (i.e., Ethernet) (carried over fiber and copper) is widely used for this application. The real-time behavior of Ethernet-based communication networks is defined in the IEC 61784-2 series [2]. There are eight (plus one technology-specific) consistent sets of parameters described to define the requested and achieved real-time Ethernet behavior of end-to-end stations.² TSN is an ongoing effort in IEC SC65C and IEEE 802.1 with the IEC/IEEE 60802 joint project. It is developing a TSN profile for industrial automation applications. The application of IEEE 802.1 TSN for utilities is the topic of another white paper [1].

A leading grid application for low latency is protection. Protective relays protect electrical transmission lines against fault conditions (line down, short circuits between conductors or to ground). Simple protection schemes measure voltage and current at one end of the transmission line. Differential protection schemes determine fault conditions by measuring real-time differences in voltage and current between the ends of the line. This requires an independent communication link with end-to-end latency of less than 10 ms to carry the measurements between the relays at the ends of the line. The communication link latency is required to be consistent and predictable. The latency requirement is less than one cycle of the ac waveform (16.6 ms or 20 ms). The time required for the mechanical operation of the relay in the case of a fault reduces the network latency that can be tolerated.

The communication link connection is typically fiber, although copper circuits are also used. Power line carriers and point-to-point microwaves are less commonly used.

While the highest voltage transmission lines are likely to rely on fiber due to its reliability and predictability, there are other less critical protection applications where low latency wireless can offer a solution.

Direct transfer trip (DTT) is a protection scheme often used to connect medium to large-scale distributed energy

² Delivery time, number of RTE end-stations, basic network topology, number of switches between RTE end-stations, throughput RTE, non-RTE bandwidth, time synchronization accuracy, and redundancy recovery time.

resources (DER) systems (such as wind farms and solar arrays) into the distribution grid (between 4 kV and 35 kV). Low latency is required because the fault detection system sends commands to remote breakers. A delay in the “disconnect” command can cause damage due to the fault current. DTT is also used for “anti-islanding” protection, to disconnect a DER system from the main distribution feeder if the main feeder has an outage. This prevents “backfeeding” electricity into a feeder that should not be energized from the DER system.

A third application for low latency is wildfire protection. In areas that are susceptible to wildfires, there is a risk of energized conductors falling to the ground and starting a fire because of wind or other events. Low latency communications from sensors to circuit breakers can be used to identify a break or fault and de-energize the circuit before the conductor hits the ground.

All of the preceding grid use cases have demanding cyber-security requirements that are included as part of the initial design. Additional overhead and processing will need to be accounted for in the overall latency budget.

2.2. MEDICAL IOT

Another use case for low latency communications is medical IoT devices. A paper published by the IEEE [3] points out that within the scope of healthcare applications, delay would form a dangerous risk in case the system does not meet the compatibility and performance requirements of health monitoring, in addition to the several security and privacy threats that are encountered. To help ensure the safe transmission of data between IoT devices and the cloud, while keeping the possible network latency and response time to a minimum, the referenced study proposes a three-layered IoT-Fog computing model that deploys an authentication stage and an encryption stage with cloud computing.

Given the previous use cases, it is clear that low latency cannot just be looked at through a single lens and that current use cases require a close look at secure low latency solutions.

2.3. REAL-TIME MOBILE GAMING

Real-time mobile gaming is a fast-developing application category. Different from traditional games, real-time mobile gaming is very sensitive to network latency and stability.

The mobile game can connect multiple players together in a single game session and exchange data messages between the game server and connected players. Real-time means the feedback should be present on screen as

users operate in the game. For a good game experience, the end-to-end latency plus game server processing time should not be noticed by users as they play the game.

The challenge that real-time mobile gaming encounters is the worst-case latency. The high latency spike is likely to cause packet loss and packet disorder; hence, it impacts the quality of experience [4].

2.4. WIRELESS CONSOLE GAMING [4]

Console gaming involves various genres of games, but a challenging type is the online first-person shooter (FPS) games where low latency is critical. This is an interactive gaming experience with real-time feedback and response. A synchronized game state is established among players in the same match to get the best performance. FPS gaming is centered around guns and other weapon combats from the first-person point of view where the player sees the action through the eyes of the player character.

In multiplayer FPS games, more than one person can play in the same game environment at the same time either locally or over the internet. Multiplayer games allow players to interact with other individuals in partnership, competition, or rivalry, providing them with social communication absent from single-player games. In multiplayer games, players may compete against two or more human contestants, work cooperatively with a human partner to achieve a common goal, supervise other players' activities, and co-op. Multiplayer games typically require players to share the resources of a single game system or use networking technology to play together over a greater distance.

Playing online on a console has two types of internet connectivity, which are either wired or wireless. Most of the gaming consoles today support Wi-Fi 5. According to a top-selling online console game in the United States, up to 79% of FPS players are using Wi-Fi-connected consoles [3]. However, wireless networks have an especially bad reputation among the gaming community. The main reasons are high latency, lag spikes, and jitter.

2.5. CLOUD GAMING

Cloud gaming is another type of video game potentially played on lightweight devices at the user's premise. Unlike other gaming hardware, user devices do not need to render pictures or video. Instead, they are rendered at the cloud server. The pictures/videos generated at the cloud server are streamed to the user devices, and the user devices just display the received picture/video on its display. The cloud game can accommodate and connect multiple players in a single game session just as mobile gaming scenario.

Cloud gaming requires low latency capability as the user commands in a game session need to be sent back to the cloud server, where the cloud server updates the game context depending on the received commands, and then renders the picture/video to be displayed before streaming the picture/video content to the user devices. This cycle needs to be short enough so that users do not feel lagging responses.

With cloud gaming experience, users can play a large number of game titles. Users can pick up game titles from the library on the cloud server. Another benefit of cloud gaming is that the user device could be lightweight in terms of hardware footprint. The user devices only need to decode and display received picture/video content. This way, users can enjoy a realistic and immersive game experience without requiring heavy computation at user devices. The lightweight user device leads to lower cost and longer battery life [3].

2.6. INDUSTRIAL SYSTEMS

Industrial systems include a wide range of applications: process monitoring, automation, control systems, HMIs, AGVs, robotics, and AR/VR. Recently, several standard developing organizations have published detailed descriptions of industrial application and their requirements, such as the following:

- IEEE 802.1 NENDICA Report Wired/Wireless Use Cases and Communication Requirements for Flexible Factories IoT Bridged Network (802.1-18-0025-06-ICne).
- IEC/IEEE 60802 TSN Profile for Industrial Automation.
- 3GPP TR 22.804 Technical Specification Group Services and System Aspects; Study on Communication for Automation in Vertical Domains.

The purpose of this document is not to repeat the detailed application descriptions, which can be found in the previous references. Instead, the focus is to summarize the challenges and requirements of real-time and time-sensitive applications that are most relevant to IEEE 802.

Many industrial applications can be considered delay-tolerant (process monitoring, industrial sensor networks, etc.) with latency requirements in the order of 100 ms or more. Such applications may be served by existing wireless standards and are not considered in this report. This report focuses only on time-sensitive and real-time applications [3].

2.7. REAL-TIME VIDEO

Today, many devices handle video streaming via IEEE 802.11 wireless LAN. Most of them are not latency-sensitive. However, some video applications require low latency capability when the application provides interactive play. Example of such applications includes AR/VR, and video cable replacement [6].

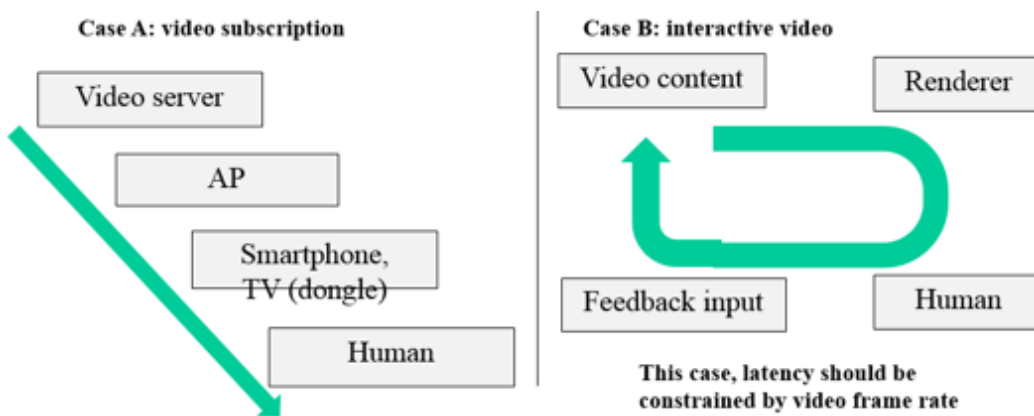
In many of these cases, the latency requirements are derived from the video frame rate. As of today, a 60-Hz framerate is commonly used, i.e., 16.7 ms/frame. However, it is possible that the video rendering system would migrate to a high frame rate solution (120 Hz, which results in 8.33 ms/frame, etc.) in the future.

To accommodate end-end signal processing in a video frame, the signal processing delay plus transmission latency needs to be less than 16.7 ms. For these applications, ideally, 10 [ms] one-way or roundtrip delay should be considered as a targeted specification for the radio link transmission, allowing 6.7 ms for other signal processing including, but not limited to, video signal encoding (compression), in-device frame forwarding, video signal decoding (decompression), etc.

When the video frame rate of 120 Hz (8.33 ms/frame) is used, ideally, a 3-ms delay should be considered as a target for the radio link transmission, allowing 5.33 ms for other signal processing.

Figure 1 shows the difference between a video application that does not require low latency capability and a video application that requires low latency capability. In general, low latency requirements arise when there is a control loop in the system [3].

FIGURE 1 Difference between buffered video and live video



2.8. DRONE CONTROL

A drone is an aircraft without a human pilot aboard. Drones are rapidly popularized and utilized for a wide array of uses. Wi-Fi has an important role in controlling drones by providing the following functions:

- **Tele Control**
Controlling motions and functions of the drone. A few Kb/s of data rate is required.
- **Data Transmission**
Monitoring information from sensors in a drone or information on the status of the drone itself. A few Kb/s–Mb/s of data rate is required.
- **Picture/Video Transfer**
Transferring recorded pictures or videos by the drone. More than tens of Mb/s of data rate is required [3].

2.9. AR/VR

Virtual reality and the metaverse are one of the latest emerging technologies that require real-time secure communications as people use AR/VR headsets to intercommunicate across virtual worlds. Low latency and security are essential in providing a smooth and unencumbered experience for the potentially high numbers of users interacting with each other across large geographic distances.

There are a number of AR/VR use cases that are expanded upon in the IEEE 802.21 document “Network Enablers for Seamless HMD based VR Content Service” [3]. These will not be replicated in this white paper, but they can be referred to in the appropriate document found in Section 8.

The network requirements for AR/VR can be summarized in Table 1. For more detail, the information of the report on AR/VR Use Cases and Enablers can be found in Section 8.

TABLE 1 VR requirements

		VR HMD Requirements
Data transmission rate		~ 20 Gbps
Latency		~ 5 ms (at wireless medium), 20 ms (motion-to-photon/audio)
Jitter		< 5 ms
Transmission range	Indoor	5 m
	Outdoor	Several hundred meters
Mobility	Indoor	Pedestrian speed < 4 km/h
	Outdoor	200 km/h
PER		10^{-6}

3. PERFORMANCE METRICS FOR LOW LATENCY COMMUNICATION

Derived from the discussion on applications in Section 2 and also consulting other sources such as the ITU definition of URLLC, performance metrics for low latency communication include the following:

- End-to-end data transfer latency (edge to edge).
- Session establishment latency.
- Radio access latency (noting that in some technologies, a specialized process is required to access the channel) could affect use cases with edge intelligence where the device-to-edge computing service is the critical path.

- Availability, noting that many applications also have this requirement.
- Channel capacity (there are trade-offs between achieving low latency and the most efficient use of bandwidth, which may be different than real-time throughput).
- Synchronization among data flows (e.g., with audio/video for haptic+AV applications).³
- Retry and retransmission strategy for failed packets.

4. KEY TECHNOLOGIES/SOLUTIONS SUPPORTING LOW LATENCY COMMUNICATION

It is important to summarize those technologies that have to be considered/utilized in order to achieve low latency, often in conjunction with high reliability. For example:

- Changes to framing to reduce wait time to receive a frame before processing the frame.
- The rendering of video can be optimized based on the importance of the image, and whether the user's eye is looking in that direction. This can allow lower latency overall.
- Video interpolation can potentially compensate for bandwidth limits that would otherwise limit frame rate.
- Prioritization of data within an application can help ensure that the most user-perceptible aspects are provided the lowest latency handling in the overall system.
- Optimize communication path by invoking elements in software at better locations.
- Network sharing to optimize communication path, e.g., neutral hosting.

³ Examples of traffic type characteristics: cyclic, data delivery requirements, and time-triggered transmission and the isochronous traffic type categories: time-aware stream, stream, traffic engineered nonstream, and nonstream.

- Multiconnectivity as a means to achieve reliability while reducing latency—noting that many low latency applications also require a vast *increase* in reliability compared with what is currently achieved (at least wirelessly).
- New coding approaches to achieve bounded latency and high reliability.
- Using adaptive links, multiple paths, and multiband links.

5. ADAPTIONS AND RECOMMENDATIONS FOR IEEE 802 STANDARDS TO ENHANCE LOW LATENCY COMMUNICATIONS SUPPORT

The IEEE 802.1 TSN TG will continue to provide the overall framework and architecture for low latency across multiple standards.

The RTA TIG in IEEE 802.11 discussed multiple real-time applications in several domains (gaming, industrial automation, drone control, etc.) and their requirements are summarized in Table 2. Real-time applications have been evolving, and so do their communication requirements. While voice and video accounted for most of the real-time traffic in the past, new, and emerging applications such as real-time gaming, AR/VR, robotics, and industrial automation are expected to become more prevalent in the future. Some of these applications also impose new worst-case latency and reliability requirements for Wi-Fi systems. Therefore, one of the recommendations of the RTA TIG to the IEEE 802.11 working group is to consider a broader range of real-time application requirements as summarized in Table 2 [3].

TABLE 2 Requirements metrics of RTA use cases

Use Cases	Intra BSS Latency/ms	Jitter Variance/ms [3]	Packet Loss	Data Rate/ Mb/s
Real-time gaming [4]	<5	<2	<0.1%	<1
Cloud gaming [4]	<10	<2	Near-lossless	<0.1 (Reverse link) >5 Mb/s (Forward link)

Use Cases		Intra BSS Latency/ms	Jitter Variance/ms [3]	Packet Loss	Data Rate/Mb/s
Real-time video [4]		<3–10	<1–2.5	Near-lossless	100–28,000
Robotics and industrial automation [3] ⁴	Equipment control	<1–10	<0.2–2	Near-lossless	<1
	Human safety	<1–10	<0.2–2	Near-lossless	<1
	Haptic technology	<1–5	<0.2–2	Lossless	<1
	Drone control	<100	<10	Lossless	<1 >100 with video

6. NEW CAPABILITIES TO SUPPORT REAL-TIME REAL-TIME APPLICATIONS

Potential enhancements and new capabilities to address the requirements of emerging real-time applications can be grouped into the following categories:

Extensions of TSN capabilities to IEEE 802.11: As described earlier, IEEE 802.1 TSN standards are addressing real-time applications over Ethernet and extensions of TSN over IEEE 802.11 can help better support such applications over wireless medium. TSN features have already been enabled in IEEE Std 802.11, including traffic/stream identification, time synchronization, and integration with Ethernet bridging. However, new extensions are required to address the worst-case latency problems in current Wi-Fi deployments. Time-aware shaping and redundancy through dual links (FRE capability) are examples discussed in this report, which exist in Ethernet TSN, but need support from IEEE 802.11 in order to be adapted to wireless medium as discussed in Jaber and Manaa [7]. Other TSN features may also be considered, such as alignment with the TSN management model defined by IEEE Std 802.1Qcc.

Multiband operation simultaneously: Due to the diverse demands for Wi-Fi networks, dual-band even tri-band AP and STA products have been brought up to market and more features are expected, since nowadays one end user tends to utilize multiple media thus multiple traffic streams. Therefore, requests for high concurrency, reducing the impact of interference, and traffic differentiation are becoming universal demands. Multiband

⁴ There may be other wireless applications in industrial automation that are not considered real-time, therefore they are out of the scope of this report.

operation is defined in IEEE Std 802.11be.

Multiband operations simultaneously can benefit not only real-time applications but also those applications that request high throughput and traffic separation [3].

New MAC/PHY Capabilities That Reduce Latency and Improve Reliability: There is also a need for improvements in the IEEE 802.11 MAC and PHY layers to enable more predictable latency, which is a fundamental requirement for most real-time applications, as discussed previously in the report. It should be noted that for many real-time applications, predictable worst-case latency does not necessarily mean extremely low latency, but the ability to provide more predictable performance is the main requirement. However, in some use cases, the worst-case latency requirement may also need to be low. Another related area for improvement identified is reliability. Enabling features that can be used to improve the overall reliability of IEEE 802.11 links are also needed to support emerging real-time applications. Although the operation in unlicensed spectrum makes it difficult to provide hard performance guarantees, many Wi-Fi deployments can be managed. Therefore, it is important to enable capabilities that can be leveraged in managed environments to provide more predictable performance.

Potential areas for further enhancements include reduced PHY overhead, predictable and efficient medium access, better support for time-sensitive small packet transmissions, improved management and time-sensitive data coexistence, coordination between APs, a more flexible OFDMA resource allocation scheme, and so on [3].

These enhancements will be considered in the IEEE 802.11 UHR TGbn Task Group.

7. CONCLUSION

The IEEE 802 family of standards address low latency requirements on a number of fronts.

Many vertical applications require low latency, both in absolute time, as well as predictability and bounded delivery time.

Wired and wireless media are inherently different. The dedicated nature of the wired medium allows for better control of latency.

The wireless standards operating in the unlicensed spectrum have progressed significantly from their early

versions in terms of minimizing and managing latency. Progress continues in this area.

Wireless standards are optimized for specific use cases and applications. Most of the IEEE 802 wireless standards are trying to reduce latency. To a more limited extent, they are adopting aspects of IEEE 802.1 TSN to further improve latency predictability. The predominant use of unlicensed spectrum by IEEE 802 wireless standards adds to the challenge of delivering predictable, low latency services.

The different IEEE 802 wireless standards address this challenge in different ways: predictive channel access, multiple spatial streams, coordinated multipoint transmission, and other new innovations continue to be discussed. Low latency represents a rich area for new innovations and technical approaches.

8. REFERENCES

The following sources either have either been referenced within this paper or may be useful for additional reading:

- [1] *Utility Applications of Time Sensitive Networking White Paper*, document IEEE 802.24 and IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802 Access Network 802.1, Oct. 2019. [Online]. Available: <https://ieeexplore.ieee.org/document/8870295>
- [2] IEC 61784-2 series (consisting of IEC 61784-2-0, IEC 61784-2-1, IEC 61784-2-2, etc.), Industrial communication networks—Profiles—Part 2: Additional fieldbus profiles for real-time networks based on ISO/IEC 8802-3.
- [3] *Goal of the ‘Network Enablers for Seamless HMD Based VR Content Service’ SG*. [Online]. Available: <https://mentor.ieee.org/802.21/dcn/18/21-18-0065-00-0000-21-18-0065-00-0000-goal-of-the-network-enablers-for-seamless-hmd-based-vr-content-service-sg.pptx>.
- [4] *IEEE 802.11 Real Time Applications TIG Report*. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-2009-06-0rta-rta-report-draft.docx> (Accessed 16 Oct. 2023).
- [5] *IEEE 802.11 TGay Use Cases*. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/15/11-15-0625-07-00ay-ieee-802-11-tgay-usage-scenarios.pptx> (Accessed 16 Oct. 2023).

- [6] *IMT-Vision—Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond*, Recommendation ITU-R document M.2083-0, Sep. 2015.
- [7] A. B. Jaber and M. E. Manaa, “A robust fog-computing security approach for IoT healthcare applications,” in *Proc. Int. Conf. Commun. Inf. Technol. (ICICT)*, Jun. 2021, pp. 174–179.

APPENDIX A

IEEE 802 STANDARDS SUPPORTING LOW LATENCY COMMUNICATIONS

The following IEEE 802 standards and amendments can assist or realize in achieving low latency (some in tandem with high reliability) communication.

IEEE 802.1 TSN Family of Standards.

- **IEEE Std 802.1Q-2022**—IEEE Standard for Local and Metropolitan Area Network—Bridges and Bridged Networks.
- **IEEE Std 802.1AS-2020**—IEEE Standard for Local and Metropolitan Area Networks—Timing and Synchronization for Time-Sensitive Applications.
- **IEEE Std 802.1AX-2020**—IEEE Standard for Local and Metropolitan Area Networks—Link Aggregation.
- **IEEE Std 802.1BA-2021**—IEEE Standard for Local and Metropolitan Area Networks—Audio Video Bridging (AVB) Systems.
- **IEEE Std 802.1CB-2017**—IEEE Standard for Local and Metropolitan Area Networks—Frame Replication and Elimination for Reliability.
- **IEEE Std 802.1CM-2018**—IEEE Standard for Local and Metropolitan Area Networks—Time-Sensitive Networking for Fronthaul.
- **IEEE Std 802.1CBcv-2021**—IEEE Standard for Local and Metropolitan Area Networks—Time-Sensitive Networking for Fronthaul—Amendment 1: Information Model, YANG Data Model, and Management Information Base Module.
- **IEEE Std 802.1CBdb-2021**—IEEE Standard for Local and Metropolitan Area Networks—Time-Sensitive Networking for Fronthaul—Amendment 2: Extended Stream Identification Functions.
- **IEEE Std 802.1CS-2020**—IEEE Standard for Local and Metropolitan Area Networks—Link-local Registration Protocol.

Interspersing Express Traffic (according to IEEE Std 802.3-2022, Clause 99) provides a fundamental latency reduction capability by allowing a large frame to be suspended, transmit a small latency-sensitive frame, and then resume the suspended frame.

IEEE Std 802.11-2020 includes Fast Initial Link Setup (FILS) and Fast Handover.

IEEE Std 802.11ax-2021, Enhancements for High Efficiency WLAN.

The amendment, IEEE Std 802.11ax, was approved on February 21, 2021. The amendment improves the performance of Wi-Fi networks in dense areas.

IEEE Std 802.11ax is designed to operate in 2.4 GHz, 5 GHz, and the newly opened 6-GHz bands. Through increased link efficiency in the frequency domain, time domain, and modulation schemes, IEEE 802.11ax can achieve as high as 12.01 Gb/s under ideal conditions [3].

Latency is reduced through the use of OFDMA for uplink and downlink, with the associated scheduling by the AP. The use of MU-MIMO is extended to the uplink, and the use of 1024 quadrature amplitude modulation (1024-QAM) is enabled to carry more bits per symbol.

IEEE Std 802.11ad and IEEE Std 802.11ay (60 GHz).

IEEE Std 802.11ad was the first 60-GHz standard, and it defined a scheduled MAC layer. The follow-on IEEE Std 802.11ay was approved in 2021 and achieves a maximum throughput of at least 20 Gb/s using the unlicensed mm-Wave (60 GHz) band while maintaining or improving the power efficiency per STA.

IEEE Std 802.11ay can provide a high throughput utilizing various methods, such as channel bonding/aggregation, MIMO, and multiple channel access [3].

IEEE Std 802.11bd-2022, Enhancements for Next Generation V2X.

Low latency is a requirement for V2V use cases. IEEE Std 802.11bd improves on IEEE Std 802.11p by increasing throughput and implementing PHY adaptations to better support high-speed movement (doppler and rapidly changing channel conditions). Latency reduction is primarily achieved by the higher rate and lower packet loss (and thus retries) from the PHY improvements.

IEEE P802.11be, Extremely High Throughput.

IEEE P802.11be is a draft standard primarily focused on increased data rates, but some of the enhancements also improve latency. MLO allows STAs to operate on multiple channels with a single logical connection. MLO can support a single-radio or multiradio implementation and can reduce latency by transmitting on the first available channel. The introduction of R-TWT also improves latency by requiring other STA's transmissions to end before the start of the TWT service period advertised by the AP.

IEEE Std 802.15.3-2016 supports low latency, isochronous streaming, and two-way streaming. IEEE Std 802.15.3 specifies fast link setup and teardown. Amendments have added THz support and higher rates.

IEEE Std 802.15.4-2020 has features for predictable latency such as TSCH, which provides more predictable, but not extremely low latency in the 100 ms range (depending on the PHY).

IEEE Std 802.15.4z-2020 UWB and IEEE P802.15.4ab for AR/VR and other applications to provide real-time positioning and low latency audio with channel access of 1–2 ms.

IEEE Std 802.15.6 defines a “Wireless Body Area Network,” which is used for medical applications. It uses existing industrial scientific medical (ISM) bands as well as frequency bands approved by national medical and/or regulatory authorities.

IEEE Std 802.16-2017 and IEEE Std 802.22-2019 provide scheduled MAC with predictable latency (10s of ms). Operation in the licensed spectrum provides more predictable packet delivery and thus latency, compared to unlicensed, due to the lower potential for interference.

APPENDIX B

GLOSSARY

Standards organizations referenced in this document:

IEEE	Institute of Electrical and Electronics Engineers
3GPP	3rd Generation Partnership Project (Mobile Telecommunications)
IETF	Internet Engineering Task Force (Internet Protocol Suite)
IEC	International Electrotechnical Commission
ITU	International Telecommunications Union

Acronyms:

AGV	automated guided vehicles
AP	access point
AR/VR	augmented reality/virtual reality
DER	distributed energy resources
DTT	direct transfer trip
FPS	first person shooter
HMI	human–machine interface
IIOT	Industrial Internet of Things
IoT	Internet of Things
MAC	medium access control
MEC	multiaccess edge computing
MIMO	multiple-input and multiple-output
MLO	multilink operation
MU-MIMO	multiuser multi-input/multi-output

OFDMA	orthogonal frequency-division multiple access
PHY	physical access layer
R-TWT	restricted target wake time
STA	station
TG	IEEE 802 Task Group
TIG	IEEE 802 Topic Interest Group
TSCH	time slotted channel hopping
TSN	time-sensitive networking
UHR	ultra-high reliability
URLLC	ultra-reliable low latency communication
UWB	ultra wide band
V2V	vehicle to vehicle
V2X	vehicle to everything
VLAN	virtual LAN
VR/AR/XR	virtual reality/augmented reality/extended reality
WLAN	wireless local area network
WRAN	wireless regional area networks

RAISING THE WORLD'S STANDARDS

3 Park Avenue, New York, NY 10016-5997 USA <http://standards.ieee.org>

Tel.+1732-981-0060 Fax+1732-562-1571