**IEEE P802.24**

**Vertical Applications Technical Advisory Group**

|  |  |
| --- | --- |
| Project | IEEE P802.24 Vertical Applications Technical Advisory Group |
| Title | **Low Latency Communication White Paper** |
| Date Submitted | 2023-09-12 |
| Source | Allan JonesTim GodfreyBen RolfeDillon SeoAnn Krieger |  |
| Re: | N/A |
| Abstract | This contribution provides a first version of the Table of Contents of the Low Latency Communication White Paper. It will be updated (along with this Abstract) as the content materializes and is included. |
| Purpose | Assist in the development of the Low Latency Communication White Paper |
| Notice | This document has been prepared to assist the IEEE P802.24. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein. |
| Release | The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.24. |

# Background and Introduction

This white paper 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](https://ieeexplore.ieee.org/document/8870295).

# 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 below, but new applications with low latency requirements continue to emerge.

## Electric Utilities—Grid Protection

The utility is considered an entity (or entities) that manage 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.

Ethernet (carried over fiber and copper) is widely used for this application. The real-time behavior of Ethernet-based communication networks is defined in IEC 61784-2. 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.[[1]](#footnote-1) 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 a prior 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 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.

DTT is a protection scheme often used to connect medium to large-scale DER systems (such as wind farms and solar arrays) into the distribution grid (between 4 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.

**Low Latency Security Requirements**

Modern networks and applications have higher levels of cyber-security requirements, which can add overhead and delays that impede the goal of low latency.

Securus Communications [6] points out five reasons why low latency is important for today’s networks.

1. Nextgen Voice and Video Services have created an unprecedented low latency demand on current networks. High-definition 4K/8K streaming accommodating remote work requires high bandwidth and low latency to make these experiences as seamless as possible. Providing secure communications on top of the base requirements puts an even greater strain on low latency requirements.
2. Real-Time Retail Customer Analytics is another reason low latency networks are required. Companies try to identify customer trends in real time. This requires low latency networks. A combination of AI algorithms and real-time analysis often happening before the customer leaves the store after checking out with their purchase is pushing low latency and security requirements beyond previous levels.
3. IIOT where secure communications between massive scale devices providing analytics and control on a level never seen is pushing low latency in critical control systems.
4. Autonomous vehicles have also been pushing MEC which is only enabled by low latency networks. Secure communications are critical for this function as human safety is involved and real-time analysis of vehicular traffic is critical in this role.
5. 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 unincumbered experience for the potentially massive users interacting with each other across large geographic distances.

In addition to the above highlighted use cases involving secure low latency communications, there is another often overlooked area involving medical IoT devices. A paper published by the IEEE [7] points out these issues. The paper points out that within the scope of healthcare applications, delay would form a dangerous risk in case the system does not meet the compatibility requirements of health monitoring, in addition to the several security and privacy threats that are encountered. To 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 present study proposes a three-layered IoT-Fog computing model that deploys an authentication stage and an encryption stage with cloud computing.

Given the above use cases, it’s clear that the authors cannot just look a low latency through a single lens and that current use cases require us to look at secure low latency solutions.

## 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. Since the high latency spike is highly likely to cause packet loss and packet disorder, hence impacts the quality of experience [4].

## Wireless Console Gaming [4]

Console gaming involves various genres of games, but a challenging type is the online 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 in the first-person point of view with which 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 Wi-Fi. Most of the gaming consoles today support Wi-Fi 5. But Wi-Fi has an especially bad reputation among the gaming community. The main reasons are high latency, lag spikes, and jitter. According to a top-selling online console game in the United States, up to 79% of FPS players are using Wi-Fi-connected consoles [4].

## 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, the cloud server would update the game context depending on the received commands, and the cloud server would render the picture/video to be displayed at user devices and stream the picture/video content to the user devices. This cycle needs to be short enough so users do not feel lagging responses.

With cloud gaming experience, users can play a large amount of game titles as they will be provided and hosted by the cloud server. 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, which could motivate gamers to play the games more [4].

## 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:

* **IEEE 802.1 NENDICA Report Wired/Wireless Use Cases and Communication Requirements for Flexible Factories IoT Bridged Network (**[802.1-18-0025-06-ICne](https://mentor.ieee.org/802.1/dcn/18/1-18-0025-06-ICne.pdf)**).**
* **IEC/IEEE 60802** [**Use Cases for Industrial Automation**](http://grouper.ieee.org/groups/802/1/files/public/docs2018/60802-industrial-use-cases-0818-v11.pdf) **(TSN-IA Profile for Industrial Automation).**
* **3GPP** [**TR 22.804**](http://www.tech-invite.com/3m22/tinv-3gpp-22-804.html) **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 above 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 (e.g., 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 [4].

## Real-Time Video

Today, many devices handle video streaming via 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 [3].

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, i.e., 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 [4].



FIGURE Difference between buffered video and live video.

## Drone Control

A drone is an aircraft without a human pilot aboard. Drones are rapidly popularized and utilized for a wide array of uses. Gartner mentions that worldwide production of drones neared 3 million units in 2017 [8]. 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 [4].

## AR/VR

Use Cases: There are a number of AR/VR use cases that are expanded upon in the 802.21 document “Network Enablers for seamless HMD based VR Content Service” [5]. The authors would not replicate these here in this white paper, but they can refer to the appropriate document found in the reference section.

### Network Requirements

The network requirements for AR/VR can be summarized in Table 1. For more detail, the report on AR/VR Use Cases and Enablers can be found in [5].



Table VR requirements.

# Performance Metrics for Low Latency Communication

Derived from the discussion on applications in Section 2 and also using 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).[[2]](#footnote-2)
* Retry and retransmission strategy for failed packets.

# Key Technologies/Solutions Supporting Low Latency Communication

Summarizing 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 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.
* 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.

# 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](https://1.ieee802.org/tsn/).

 IEEE Std 802.1Q-2022: Bridges and Bridged Networks.

 IEEE Std 802.1AS-2020: Timing and Synchronization for Time-Sensitive Applications.

 IEEE Std 802.1AX-2020: Link Aggregation.

 IEEE Std 802.1BA-2021: Audio Video Bridging (AVB) Systems.

 IEEE Std 802.1CB-2017: Frame Replication and Elimination for Reliability.

 IEEE Std 802.1CM-2018: Time-Sensitive Networking for Fronthaul.

 IEEE Std 802.1CS-2020: Link-local Registration Protocol (approved draft standard).

 IEEE Std 802.1CBcv-2021: Amendment 1: Information Model, YANG Data Model, and Management Information Base Module.

 IEEE Std 802.1CBdb-2021: Amendment 2: Extended Stream Identification Functions.

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 [6].

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 [6].

IEEE P802.11be, Extremely High Throughput.

IEEE P 802.11be is 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 802.11bd-2022, Enhancements for Next Generation V2X.

Low latency is a requirement for V2V use cases. IEEE Std 802.11bd improves on 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 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 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 802.16-2017 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.

# 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 [4].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Use Cases** | **Intra BSS Latency/ms** | **Jitter Variance/ms[4]** | **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) |
| Real-time video [4] | <3–10 | <1–2.5 | Near-lossless | 100–28,000 |
| Robotics andindustrial automation [2][[3]](#footnote-3) | 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 |

Table 2 Requirements metrics of RTA use cases.

## New Capabilities to Support 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 802.11:** As described earlier, 802.1 TSN standards are addressing real-time applications over Ethernet and extensions of TSN over 802.11 can help better support such applications over wireless medium. TSN features have already been enabled in 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 802.11 in other to be adapted to wireless medium as discussed in [7]. Other TSN features may also be considered, such as alignment with the TSN management model defined by the 802.1Qcc standard.

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. So, requests for high concurrency, reducing the impact of interference, and traffic differentiation are becoming universal demands. Multiband operation is defined in 802.11be.

Multiband operations simultaneously can benefit not only real-time applications but also those applications that request high throughput and traffic separation [4].

**New MAC/PHY Capabilities That Reduce Latency and Improve Reliability**: There is also a need for improvements in the 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-cast 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 802.11 links are also needed to support emerging real-time applications. Although the operation is unlicensed spectrum makes it difficult to provide hard performance guarantees, many Wi-Fi deployments can be managed. Therefore, it is important to enabling 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 [4].

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

# Conclusion

IEEE 802 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.

# Appendix AGlossary

Standards Organizations Referenced in This Document:

* IEEE Institute of Electrical and Electronic 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.

# References

[1] *Utility Applications of Time Sensitive Networking White Paper*, document 802.24 and 802.1, Oct. 2019. [Online]. Available: <https://ieeexplore.ieee.org/document/8870295>

[2] *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>

[3] *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

[4] *RTA TIG Report*. [Online]. Available: <https://mentor.ieee.org/802.11/dcn/18/11-18-2009-06-0rta-rta-report-draft.docx>

[5] *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>

[6] A. Radford. (Dec. 16, 2021). *Why Is Low Latency Important? 5 Key Areas*. Securus Communications. [Online]. Available: <https://securuscomms.co.uk/why-is-low-latency-important/>

[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.

1. 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. [↑](#footnote-ref-1)
2. 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. [↑](#footnote-ref-2)
3. 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. [↑](#footnote-ref-3)