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IEEE 802® Networks for Vertical Applications White Paper

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IEEE 802 Networks for Vertical Applications White Paper

1. Background and Introduction

IEEE 802® technologies are used for a wide variety of applications and markets. Despite the widespread usage and overwhelming adoption of PHY and Link layer technologies for all kinds of information and communication solutions, a common perception of the value and differentiation of the IEEE 802 architecture in the context of vertical markets is not established. There are no clear views about why IEEE 802 would be better suited to deployments in the communication infrastructure of private enterprise, industry, and the individual user, and how IEEE 802 compares to network architectures oriented toward service providers.

In the first stance, it could be agreed that the IEEE 802 architecture enables networks that are like IEEE 802.3 Ethernet—well understood, mature, predictable, offering a “cleaner” integration of disparate technologies under the common architecture and addressing.

This white paper aims to collect and spell out commonalities of IEEE 802 technologies and set the scene in relation to other well-known communication standards of similar behavior.

1. Requirements of Vertical Applications

This section defines the characteristics of vertical applications that usually integrate various systems, including network connectivity, in order to perform specific tasks or enable use cases for their industry.

In the context of this white paper, “vertical applications” refers to networks that serve specific use cases in specific market segments. The network is used by the entity to enable its business processes. This is in contrast to an access network, where the network services are the product.

Vertical markets involve the following specific usage models:

* Industrial automation
* Building automation
* Smart cities
* Smart grid/utility
* Automotive/transportation
* Agriculture
* Connected supply chain
* Critical infrastructure protection and control
* Wide area gaming (including AR/VR)

There are other ways of looking at “vertical.” Vertical integration is really a competition/antitrust term rather than a technical term. In that context, it describes a technical situation in that some set of functionalities that may be provided by the same company could actually in practice also be provided by different companies. So, for instance, “5G” is “vertically integrated” because it actually assumes in its technical specifications that a single commercial provider will be responsible for a whole range of different features that are not really separable. In that sense, IEEE 802 technologies are not “vertically integrated” because they can be deployed by different operators of completely different networks (e.g., one leverages wired connections, while others are based on wireless connectivity). Nevertheless, IEEE 802 plays a role in vertical integration by providing the plain connectivity layer, e.g., IEEE 802.11 in IEEE 1609 vehicle-to-vehicle communications, or IEEE 802.15.4 in the SEP.

Vertical markets often require highly engineered networks to guarantee the quality of the required communication services. Quite often, vertical markets follow extended lifecycles; the vertical network is expected to remain in service for a longer time than a service-provider network. Vertical markets may have different cost models compared with usual public communication networks where some are opex averse and others are more capex averse.

1. Economic Aspects for Vertical Application Networks

IEEE 802-based networks are usually aimed to “enable creating/delivering a product” instead of “the network is the product” defined by an open standard:

* An IEEE 802 network is deployed in vertical markets, where the network is owned and operated by the user of the services.
* There are also other models than subscriptions that provide ancillary economic value.
* An economy of scale can be accomplished by creating a network that can be leveraged by multiple entities. This is similar to cloud thinking—the model of sharing the infrastructure (network) without needing them to be independently installed and managed. It is a similar concept to a data center, just providing computing resources but not dealing with installing and running software for all the services needed.
* The trend toward more virtualization is a strength of IEEE 802 because it allows the network to be better prepared for that virtualization. It provides a clean separation between the infrastructure and the service running on the infrastructure. In the IEEE 802 case, this is the layer 2 to layer 3 boundary.
* The IEEE 802.3 Ethernet transport is the most well-understood transport in existence. This is analogous to the X86 computer architecture that became the basis for the computing resources of data centers.
* IEEE 802 and unlicensed spectrum enable faster innovation.
* Many of the breakthrough innovations were not as planned.
* The story of why IEEE 802 complements everything else, and everything else (alone) is not sufficient.
* The IoT is built around many specialized niches. The challenge is meeting their diverse requirements. No single standard can address all of them well. IEEE 802 provides multiple standards to address multiple IoT applications (see Appendix A).
* The model for network management requires special attention when the owner/operator of the network may have less expertise in network management. Guidance is desired on how to manage and operate a private network. Usually, this is simpler because the IEEE 802 network is simpler (compared to 3GPP, for example), but the documentation is often not really mature or available. Yang modeling describes the interface, but more knowledge is needed to understand how to use the network management data available through the interface.

### Modularity and Interchangeability, Competition Economics

A user of a vertical application may want to be able to replace parts of their vertical application network with a better, newer product when one arrives (for instance, installing a new AP when a better one is available from a different vendor). IEEE 802 products lend themselves to this form of user-empowered modularity.

Building blocks with smaller functional content and broader variation offer this flexibility to the vertical application. 3GPP 5G (or cellular networks in general) does not have this modular feature. Although many UE vendors can be certified to the specifications, it is much harder for the network owner to mix multiple vendors in the RAN and core of the network.

### Possibility of Small Business Entities Deploying Small-Scale Networks

It would be possible for a small utility or municipality with only a few employees to set up a reasonably secure Wi-Fi network at their workplace, perhaps with temporary help from a consultant if they were making sure it was really secure. However, they would find it much more difficult to acquire a municipal spectrum license for LTE technologies and install, configure, and maintain a 3GPP private network infrastructure.

IEEE 802 also enables a greater degree of scalability. A network that starts small can easily be scaled to more complexity and users as the business grows. A 3GPP access network is designed from the start for a large scale and is more difficult to apply at a small scale.

1. Key Aspects of the IEEE 802 Technologies for Vertical Applications

## Layering

* IEEE 802 is a transport network.
* IEEE 802 is layer 2.
* IEEE 802 provides direct and simultaneous support of IPv4 and IPv6 or pure layer-2 protocols.
* IEEE 802 offers trade-offs and optimizations between flexibility (L2) and scalability (L3).

## Routing and Bridging

* IEEE 802 enables networks to scale with routing and bridging.
* IEEE 802 supports layer-3 protocols such as IP, which enables routing to enable IEEE 802 networks to expand to a higher scale.
* IEEE 802 networks can be built on a smaller scale to provide more flexibility.
* The smaller scale provides an opportunity for real-time.
* IEEE 802 standards can emulate a point-to-point network over a wireless point-to-multipoint network to enable bridging over the wireless link.
* IEEE 802 can support multiple different L3 and above protocol suites.
* IEEE 802 can also offer L2 routing when appropriate (e.g., IEEE 802.15.10).
* Note: This is not an alternative to L3 routing, but used to address a different problem.

## Management and Control

* IEEE 802 does not provide as many means of control for a specific end device and its traffic on a path.
* There are some management facilities with some standards.
* It is easier for IEEE 802 to support an “unmanaged” network, such as consumer Wi-Fi.
* IEEE 802 provides local networks that may be (but do not have to be) connected to the internet or other networks.
* Public operator networks are focused on services for single devices, while IEEE 802 networks support and include multiple devices (networks of networks)—devices can communicate with each other as well as with other networks.

1. Common Network Model for Vertical Application Networks

A common foundation of the network architecture for a variety of vertical applications is provided by IEEE Std 802.1CF™-2019, IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802 Access Network.

All communication networks providing the means to connect various communication endpoints (terminals) to the same or different information servers over a shared infrastructure follow the same architectural principles. IEEE 802 technologies support the realization of an access network, which establishes the shared infrastructure, allowing the management of the connections of a wide variety of terminals through wired or wireless interfaces to their communication peers, either through bridging in the local area, or through routing by an access router in more widespread networks.

## Network Reference Model

Figure 1 shows the mapping of the IEEE 802 NRM to usual communication network topologies. The core of the NRM is the access network that connects terminally either directly through bridging or forward traffic to the access router when the communication peer is behind the same Layer 2 domain. Various control entities support the access network to provide secured and managed connectivity.

1. Network reference model design



NMS denotes the network management system that provides the functions to configure and monitor the correct operation of the access network infrastructure. The subscription service is the control entity that deals with the communication demand of the individual terminals. It provides authentication to restrict the usage of the access network to only known terminals and provides to the access network the configuration parameters that each of the terminals expects for proper operation.

Subscription service is a general term that can mean any function from a traditional operator subscription service to a private network’s authentication and device policy control function.

Figure 2 further details the NRM by exposing the internal structure of the access network as well as the terminal and access router, and through the definition of reference points labeled R1–R12 to denote control and user data interfaces of the access network. Solid lines indicate the path of the user data, while dotted lines indicate the flow of control information. The figure also shows an additional control entity called Coordination and Information Service, which is only needed when multiple access networks dynamically share the same communication resources, like in the case of dynamic spectrum management or dynamic resource sharing of virtual and virtualized access networks.

1. IEEE 802 Network reference model



The IEEE 802 NRM is a conceptual model that allows many different implementations to leverage the same foundation and network functions, but it is not intended as an exact blueprint for the installation of a real network. Vertical applications have very specific networking requirements. To accommodate the variety of requirements, IEEE Std 802.1CF provides guidance and a common structure to build powerful networks out of the universal IEEE 802 technology building blocks.

The applicability and flexibility of the approach are demonstrated in IEEE Std 802.1CF through the mapping of the NRM to a number of deployment scenarios from a simple WLAN router, home networks, simple and more complex enterprise networks, industrial networks, public WLAN hotspots to virtualized WLAN access networks for in-building IoT services and networks for fog computing.

## Generic IEEE 802 Access Network Functional Behavior

In addition to a common NRM introduced above, the specification also provides a generic functional description of the operation of an access network built through IEEE 802 technologies. Figure 3 shows the functional phases of an access network during a session of an IEEE 802 terminal. The session begins with the terminal searching for potential access to a network and ends with either the terminal or network tearing down the connectivity.

1. Lifecycle of a user session



There are many network functions invoked between the beginning and the end of a session, and Figure 3 shows a typical example mainly aligned to the IEEE 802.11 air interface. The functional description provides a comprehensive reference of the management and control information conveyed over the reference points between the access network and external control and management entities. Such reference is not only helpful for educational purposes but also fosters commonalities in the design of the control gear of IEEE 802 access networks and provides a development base for the virtualization of IEEE 802 access networks.

## Network Virtualization, Instantiation, and Slicing

While well-known models like VLANs in IEEE 802 or the network slicing solution of 3GPP provide several isolated user data planes in a common infrastructure, which can be either assigned to different services or different tenants of the network, the network functional modeling provides the prerequisites for setting up multiple instances not only for the user data path but also for all the control associated with a user data path. Separating not only the data paths of multiple tenants but also all the controls associated with a data path allows to address one of the main prerequisites of the deployment of vertical application networks—the need for independent operational domains for each of the verticals. Virtualized IEEE 802 access networks behave exactly the same way as dedicated access networks but have the cost and scalability benefits of making use of a common infrastructure. It is the same approach that was taken through VMs, leading to the establishment of cloud computing.

Figure 4 displays the concept of virtualization of the IEEE 802 access network. Three instances are shown based on a common infrastructure, each with its own control entities and interfaces towards terminals and application servers reachable through the access router. As infrastructure resources can be dynamically shared among the virtualized networks, the CIS acts as a control entity managing the dynamic assignment of infrastructure resources.

The virtualized access network example shown above is directed into potential network evolution beyond the current understanding of network slicing. However, IEEE Std 802.1CF already provides the model and concepts of virtualized access networks, which can be fully built based on existing IEEE 802 protocol specifications. It is shown that the realization of such powerful networking concepts with IEEE 802 technologies is a matter of implementation without the need for lengthy standardization activities.

1. Multiple instances of virtualized IEEE 802 access network



1. Higher Layer Functions and Service Design in Vertical Application Networks

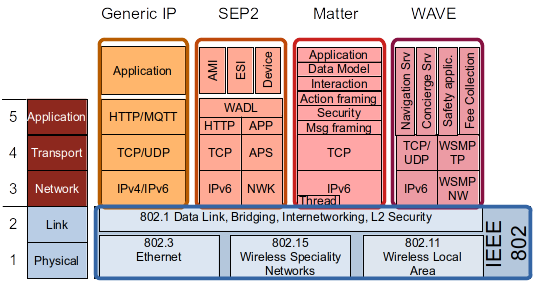
IEEE 802 provides a high variety of wired and wireless solutions for the Physical and Link layer functions of communication links to serve a very wide range of requirements of applications. Each of the applications can choose from the common IEEE 802 communication toolbox the features that best fit its particular needs without compromises or exaggerated complexities due to a common higher layer architecture.

Application-specific protocol stacks for network layer, transport layer, and application layer functions have been mostly replaced through IP protocols in the past decades to leverage the huge benefits of the common IP protocol regarding flexibility, performance, availability, and cost. IEEE 802 technologies played a huge role in the transformation to IP protocols as the protocols and technologies provided excellent support for the transport of IP packets, and they were able to cope with the growth of IP traffic through steady enhancements.

Therefore, usually, the Generic IP protocol stack is used for realizing vertical applications, leveraging IPv4/IPv6 in the Network layer, TCP or UDP in the Transport layer, and well-known IP protocols such as HTTP, CoAP, or MQTT in the Application layer.

However, the IEEE 802 technologies allow for more specific network solutions when special requirements or conditions arise. Legacy networking protocol stacks can be operated for transition and interoperability aside from IP protocol solutions on the same communication infrastructure. Figure 5 illustrates a few examples of the approaches to realize vertical application networks on top of IEEE 802 technologies.

1. Examples of vertical applications based on IEEE 802 networking



Vertical application networks often not only deploy the IP-based protocol suite but leverage more specialized transport solutions.

The Smart Energy Profile 2 (SEP 2) standard was initially specified by the ZigBee Alliance in conjunction with the HomePlug Alliance and later adopted by IEEE through IEEE Std 2030.5 [4]. It provides a RESTful messaging protocol for information and control for energy management in home area networks for both wired and wireless networks. It can be applied to transport based on IETF IP protocols or other specialized transport protocols for particular link technologies like IEEE 802.15.4.

Matter is a smart-home connectivity standard that originated from the former CHIP project. It aims to provide interoperability among smart home devices and IoT platforms of different vendors and providers. Matter provides a multilayer application protocol suite that is provided as open source for easy adoption. In addition to plain IP-based connectivity over any kind of link technology, it also supports thread-based connectivity over IEEE 802.15.4.

WAVE is specified through IEEE Std 1609, leveraging IEEE Std 802.11 as wireless link technology. Various optimizations in the upper part of the Data Link layer and above were applied to cope with the particularities of a rapidly changing wireless environment. The IEEE 1609 series of standards describes the architecture and services necessary for devices to communicate in a mobile vehicular environment. It follows the open system interconnect model and provides support for the IP and its transport protocols. In addition, securing WAVE management messages and application messages is addressed, as well as administrative functions necessary to support the core security functions.

1. Architectural Approaches

An IEEE 802 network could be considered as a set of building blocks or a heap of stones, representing an open architecture. The 3GPP architecture is already defined as a Castle. IEEE 802 is somewhat different as it does not have pre-conceived ideas about the resulting network, making it better able to support diverse vertical applications.

|  | IEEE 802 | Others, e.g., 3GPP |
| --- | --- | --- |
|  | Open architecture | Defined architecture |
|  |  |  |
| IEEE 802 is developing profiles for different domains to provide the ability to specify a more defined architecture from the building blocks. To extend the previous analogy, the profiles could define several building types out of the building blocks, not just a castle. General Paradigms | | |
| Aim | Simplicity first | Perfect solutions |
| Approach | Divide and conquer | Strictly hierarchical |
| Goal | Common solutions | Extreme optimization |
| Purpose | Unifying layer for network of networks | Specifically defined network structure |
| Scalability | Very small to large | Higher entry burden but expandable to extremely large |
| Spectrum | Unlicensed | Licensed |
| Ownership | Anybody | Often bound to some authorization |
| Provisioning (Planning and Installation) | | |
| Approach | Limited size local area network | Nationwide services network |
| Tools | Small set of functions | Comprehensive architecture |
| Objectives | Link layer connectivity | End2end service delivery |
| Applicability | Very small to large | Higher entry burden but expandable to extremely large |
| Standardization | Set of individual standards | Suite of related standards |
| Interoperability | Layered interoperability | Service interoperability |
| Execution | Easy entry | Comprehensive knowledge required |
| Administration | | |
| Approach | Self-configuration, often distributed | Centrally controlled |
| Tools | Use of simple security means | Complex security architecture |
| Objectives | Flat-fee services | SLAs and contracts |
| Applicability | More choices for customization and sophisticated use cases | Better suited to standard deployments |
| Standardization | Limited to L1 & L2; higher layers adopted from IETF | Complete suite of specifications partly leveraging IETF protocols |
| Interoperability | Basic tools provided, but finally relying on peer-to-peer agreements | Fully specified |
| Execution | Very scalable depends on operational needs | Only full scope according to specifications |
| Operation | | |
| Approach | Usually, over-provisioning used to avoid operational complexity and expenses | Dynamic readjustments of network resources to optimize operational cost |
| Tools | Simple means for verification of proper operation | Comprehensive monitoring |
| Objectives | Simplicity and automation | Full control and deep insights |
| Applicability | Keep bits flowing | Generate value |
| Standardization | Comprehensive standards for automation | Adjustable interfaces for operational excellence |
| Interoperability | Plug and play | Plug and configure |
| Execution | Switch it on and let it run | Operations center |
| Maintenance | | |
| Approach | Highly modular to allow for gradual replacements and enhancements | Introduce a next-generation end-to-end network for the next level |
| Tools | Incremental enhancements | Complete replacements |
| Objectives | Foster and grow | Revolutionize the network |
| Applicability | Incremental adjustment of network capabilities | Harmonized infrastructure renewal |
| Standardization | Individual standards enhancements | Generational suites of standards |
| Interoperability | Forward and backward compatibility | Generational interworking |
| Execution | One piece at a time | Regular swap of complete infrastructure |
| Troubleshooting | | |
| Approach | It depends | Count and measure everything |
| Tools | Simple tools for detection and localization | Comprehensive network management suite |
| Objectives | Base functions for proprietary solutions and common sense | Ensure detection of any malfunction and quick recovery |
| Applicability | Economic solutions adjusted to the needs of the use cases | Guaranteed availability of highly complex infrastructures |
| Standardization | Definition of managed attributes | Standardized attributes, architecture, and procedures |
| Interoperability | Enable basic commonality | Interoperable higher layer network management |
| Execution | Low barrier to entry for vertical asset owners | Unique skill sets and workforce |

1. Conclusion

The IEEE 802 family of standards provides a solid foundation of connectivity for many kinds of vertical applications. The various IEEE 802 technologies are able to address the wide variety of requirements that result from deploying networks optimized for very specific purposes.

Through modularity and interchangeability of functional building blocks, IEEE 802 networks are suited to easily scale from very small to very large infrastructures with modest to very demanding data transfer capacities fostering not only functional but also economic competition among different approaches. Nevertheless, the various solutions follow common architectures and a common NRM to facilitate gradual improvements and to keep necessary learning curves for design, implementation, and operation relatively flat.

Even when IEEE 802 standards are providing by far the primary transport technologies for IP-based communication solutions, other network protocols, as often used for optimization or interoperability in vertical applications, are supported as well and can even run in parallel with IP on the same network infrastructure.

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6. IEEE Std 1609.0™-2019, IEEE Guide for Wireless Access in Vehicular Environments (WAVE) Architecture*.*

# Appendix A

IEEE 802 STANDARDS AIMED FOR VERTICAL APPLICATIONS

## A.1 IEEE 802 Overview and Architecture

* IEEE Std 802®-2014—IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture.
* IEEE Std 802c-2017—IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture—Amendment 2: Local Medium Access Control (MAC) Address Usage.
* IEEE Std 802d-2017—IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture—Amendment 1: Allocation of Uniform Resource Name (URN) Values in IEEE 802® Standards.
* IEEE Std 802E-2020—IEEE Recommended Practice for Privacy Considerations for IEEE 802® Technologies.

## A.2 IEEE 802.1 Bridging and Management

* IEEE Std 802.1AB-2016—IEEE Standard for Local and Metropolitan Area Networks—Station and Media Access Control Connectivity Discovery.
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* IEEE Std 802.1CS-2020—IEEE Standard for Local and Metropolitan Area Networks—Link-local Registration Protocol.
* IEEE Std 802.1Q-2022—IEEE Standard for Local and Metropolitan Area Network—Bridges and Bridged Networks.
* IEEE Std 802.1Qcz-2023—IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks—Amendment: Congestion Isolation.
* IEEE Std 802.1X-2020—IEEE Standard for Local and Metropolitan Area Networks—Port-Based Network Access Control.

## A.3 IEEE 802.3: Ethernet

* IEEE Std 802.3-2022—IEEE Standard for Ethernet.
* IEEE Std 802.3cs-2022—IEEE Standard for Ethernet—Amendment 2: Physical Layers and Management Parameters for increased-reach point-to-multipoint Ethernet optical subscriber access (Super-PON).
* IEEE Std 802.3ck-2022—IEEE Standard for Ethernet—Amendment 4: Physical Layer Specifications and Management Parameters for 100 Gb/s, 200 Gb/s, and 400 Gb/s Electrical Interfaces Based on 100 Gb/s Signaling.
* IEEE Std 802.3db-2022—IEEE Standard for Ethernet—Amendment 3: Physical Layer Specifications and Management Parameters for 100 Gb/s, 200 Gb/s, and 400 Gb/s Operation over Optical Fiber using 100 Gb/s Signaling.
* IEEE Std 802.3dd-2022—IEEE Standard for Ethernet—Amendment 1: Power over Data Lines of Single Pair Ethernet.
* IEEE Std 802.3de-2022—IEEE Standard for Ethernet—Amendment 5: Enhancements to the MAC Merge and Time Synchronization Service Interface for Point-to-Point 10 Mb/s Single Pair Ethernet.
* IEEE Std 802.3cx-2023—IEEE Standard for Ethernet—Amendment: Media Access Control (MAC) Service Interface and Management Parameters to Support Improved Precision Time Protocol (PTP) Timestamping Accuracy.
* IEEE Std 802.3cy-2023—IEEE Standard for Ethernet—Amendment: Physical Layer Specifications and Management Parameters for greater than 10 Gb/s Electrical Automotive Ethernet.
* IEEE Std 802.3cz-2023—IEEE Standard for Ethernet—Amendment: Physical Layer Specifications and Management Parameters for Multi-Gigabit Optical Ethernet Using Graded-Index Glass Optical Fiber for Application in the Automotive Environment.
* IEEE Std 802.3.1-2013—IEEE Standard for Management Information Base (MIB) Definitions for Ethernet.
* IEEE Std 802.3.2-2019—IEEE Standard for Ethernet—YANG Data Model Definitions.

## A.4 IEEE 802.11: Wireless LAN

* IEEE Std 802.11-2020—IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.
* IEEE Std 802.11-2020/Cor 1-2022—IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Corrigendum 1—Correct IEEE 802.11ay Assignment of Protected Announce Support Bit.
* IEEE Std 802.11ax-2021—IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 1: Enhancements for High-Efficiency WLAN.
* IEEE Std 802.11ay-2021—IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above   
  45 GHz.
* IEEE Std 802.11ba-2021—IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 3: Wake-Up Radio Operation.
* IEEE Std 802.11az-2022—IEEE Standard for Information Technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 4: Enhancements for positioning.
* IEEE Std 802.11bd-2022—IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 5: Enhancements for Next Generation V2X.
* IEEE Std 802.11bb-2023—IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment: Light Communications.
* IEEE Std 802.11bc-2023—IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment: Enhanced Broadcast Service.

## A.5 IEEE 802.15: Wireless Specialty Networks

* IEEE Std 802.15.3-2016—IEEE Standard for High Data Rate Wireless Multi-Media Networks.
* IEEE Std 802.15.3f-2017—IEEE Standard for High Data Rate Wireless Multi-Media Networks—Amendment 3: Extending the Physical Layer (PHY) Specification for Millimeter Wave to Operate from 57.0 GHz to 71 GHz.
* IEEE Std 802.15.3d-2017—IEEE Standard for High Data Rate Wireless Multi-Media Networks—Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer.
* IEEE Std 802.15.3e-2017—IEEE Standard for High Data Rate Wireless Multi-Media Networks—Amendment 1: High-Rate Close Proximity Point-to-Point Communications.
* IEEE Std 802.15.4-2020—IEEE Standard for Low-Rate Wireless Networks.
* IEEE Std 802.15.4-2020/Cor 1—IEEE Standard for Low-Rate Wireless Networks Corrigendum 1: Correction of Errors Preventing Backward Compatibility.
* IEEE Std w802.15.4y-2021—IEEE Standard for Low-Rate Wireless Networks—Amendment 3: Advanced Encryption Standard (AES)-256 Encryption and Security Extensions.
* IEEE Std 802.15.4w-2020—IEEE Standard for Low-Rate Wireless Networks—Amendment 2: Low Power Wide Area Network (LPWAN) Extension to the Low-Energy Critical Infrastructure Monitoring (LECIM) Physical Layer (PHY).
* IEEE Std 802.15.4z-2020—IEEE Standard for Low-Rate Wireless Networks—Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques.
* IEEE Std 802.15.4aa-2022—IEEE Standard for Low-Rate Wireless Networks—Amendment 4: Higher Data Rate Extension to IEEE 802.15.4 Smart Utility Network (SUN) Frequency Shift Keying (FSK) Physical Layer (PHY).
* IEEE Std 802.15.7-2018—IEEE Standard for Local and metropolitan area networks—Part 15.7: Short-Range Optical Wireless Communications.
* IEEE Std 802.15.8-2017—IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC).
* IEEE Std 802.15.9-2021—IEEE Standard for Transport of Key Management Protocol (KMP) Datagrams.
* IEEE Std 802.15.10-2017—IEEE Recommended Practice for Routing Packets in IEEE 802.15.4 Dynamically Changing Wireless Networks.
* IEEE Std 802.15.10a-2019—IEEE Recommended Practice for Routing Packets in IEEE 802.15.4 Dynamically Changing Wireless Networks—Amendment 1: Fully Defined Use of Addressing and Route Information Currently in IEEE Std 802.15.10.
* IEEE Std 802.15.13-2023—IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with ranges up to 200 meters, for both stationary and mobile devices.

## A.6 IEEE 802.16: Broadband Wireless MANs

* IEEE Std 802.16-2017—IEEE Standard for Air Interface for Broadband Wireless Access Systems.

## A.7 IEEE 802.19: Wireless Coexistence

* IEEE Std 802.19.1-2018—IEEE Standard for Information Technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements—Part 19: Wireless Network Coexistence Methods.
* IEEE Std 802.19.3-2021—IEEE Recommended Practice for Local and Metropolitan Area Networks—Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the   
  Sub-1 GHz Frequency Bands.

## A.8 IEEE 802.21: Media Independent Handover Services

* IEEE Std 802.21-2017—IEEE Standard for Local and Metropolitan Area Networks—Part 21: Media Independent Services Framework.
* IEEE Std 802.21-2017/Cor 1-2017—IEEE Standard for Local and Metropolitan Area Networks—Part 21: Media Independent Services Framework—Corrigendum 1: Clarification of Parameter Definition in Group Session Key Derivation.
* IEEE Std 802.21.1-2017—IEEE Standard for Local and Metropolitan Area Networks—Part 21.1: Media Independent Services.

## A.9 IEEE 802.22: Wireless Regional Area Networks

* IEEE Std 802.22-2019—IEEE Standard—Information Technology-Telecommunications and information exchange between systems—Wireless Regional Area Networks—Specific requirements—Part 22: Cognitive Wireless RAN MAC and PHY specifications: Policies and Procedures for Operation in the Bands that Allow Spectrum Sharing where the Communications Devices May Opportunistically Operate in the Spectrum of Primary Service.
* IEEE Std 802.15.22.3-2020—IEEE Standard for Spectrum Characterization and Occupancy Sensing.

TV White Space has not been widely adopted in North America because most of the “white space” spectrum has been auctioned off for commercial cellular, leaving broadcast television packed into the remaining channels. The use of CBRS has been adopted for small regional networks, despite the downsides of a much shorter range due to the higher frequency band.

# Appendix B

Glossary

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)

Acronyms:

AR/VR augmented reality/virtual reality

CBRS Citizens Broadband Radio Service

CHIP Connected Home over IP

CoAP Constrained Application Protocol (IETF).

HTTP Hypertext Transport Protocol (IETF).

IP Internet Protocol (IETF)

L2 Layer 2 of OSI Model (Link)

L3 Layer 3 of OSI Model (Network)

LTE long-term evolution (mobile communications)

MAC medium access control

MQTT Message Queuing Telemetry Transport (IETF)

NMS network management system

NRM Network Reference Model

PHY physical access layer

RAN radio access network

SEP Smart Energy Profile

TCP Transport Control Protocol (IETF)

UE user equipment

UDP User Datagram Protocol (IETF)

VM virtual machines

WAVE wireless access in vehicular environments

WLAN wireless local area network

WRAN wireless regional area networks

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