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| IEEE 802 Standards for Smart Grid |
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|  | **IEEE P802.24****Smart Grid Technical Advisory Group**  |
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IEEE 802 Standards for Smart Grid

## Introduction to the 2025 revision

This white paper was first published in 2014. Over the past decade, the utility industry has seen many changes, and IEEE 802 has continued to release new standards and revisions. The term “Smart Grid” is less frequently used now, because it became associated with specific use cases, such as metering. Terms such as “Grid Modernization” and “Integration of Renewables” better express the system-level changes that are driving an increasing requirement and dependence on telecommunications to enable the operation of the future grid. The title will remain unchanged for historical continuity.

The use of communication in the grid is a type IoT, in the sense that the communication is primarily machine to machine over a collection of multiple IP-based networks. It diverges from typical IoT because the networks that are used for utility grids are typically not carried over the public Internet, but are private and secured.

## History and values of IEEE 802

IEEE 802® is the leading standards development organization for networking. IEEE 802 is actively developing standards for both wired and wireless networks.

Smart Grid is defined as an evolution of the energy supply and consumption infrastructure that will enable providers and consumers with unprecedented levels of reliability and control while reducing the adverse environmental impact of energy generation and consumption. One of the key aspects of the Smart Grid is the underlying communication between the various network elements. The integration of renewable energy sources like solar and wind presents unique challenges for Smart Grids. IEEE 802 standards play a role in enabling real-time communication and monitoring between distributed energy resources (DERs) and the grid. For example, IEEE 802.15.4 might be used for monitoring DERs while IEEE 802.11 is used for higher volumes of data flow from renewable assets.

 The first IEEE 802 network standard, IEEE Std 802.3™ (Ethernet), was approved more than 40 years ago. The first IEEE 802 wireless standard, IEEE Std 802.11™, was approved in 1997, and has evolved through seven generations of increasing performance. IEEE Std 802.15™ and IEEE Std 802.16™ were both initiated in 1999 and have achieved substantial success as well. The IEEE 802.15 SUN PHY has launched the Wi-SUN Alliance specifically targeting utility use cases. While IEEE 802.16 was unsuccessful in the commercial cellular market, the standard’s narrow channel amendments 802.16s and 802.16t provide options for operation in licensed spectrum with channels too small to support LTE. Other groups in IEEE 802 that are relevant to Smart Grid applications are as follows:

* IEEE Std 802.1™ provides foundational bridging, time-sensitive networks, and security capabilities. 802.1 standards are often referred to by other standards.
* IEEE Std 802.21d developed a multicast group management amendment that was seen as promising for use in electrical metering networks. 802.21 has entered into hibernation, 802.21d did not achieve market adoption.
* IEEE Std 802.22™ for wireless regional area networks (WRAN) in the TV white space (TVWS) bands was a promising technology for Smart Grid when introduced. The use of unused channels for long-range outdoor communication was well suited to many smart grid use cases. The FCC auctioned 600 MHz spectrum in 2017 for cellular use, resulting in the elimination of unused TV channels, except in the most remote locations. 802.22 has entered into hibernation. [[1]](#footnote-1)

Placeholder for section on the introduction of spectrum sharing approaches in the 2014-2024 decade. Dynamic Spectrum Access (DSA) technologies have evolved significantly. Although it is typically used with 3GPP standards and not IEEE 802, the CBRS (Citizens Broadband Radio Service) band is used to help utilities access spectrum without interference. Other bands have been identified as shared spectrum or are being considered for re-allocation as shared spectrum. Spectrum management frameworks could enhance the understanding of how Smart Grids can operate efficiently within the available spectrum.

IEEE 802 follows the IEEE SA development process, which embodies a set of principles. These are aligned with the ANSI Standards Development Principles[[2]](#footnote-2)

Many utility applications are examples of the broader application area of Machine-to-machine (M2M) technology, which enables devices to communicate with each other. There are three general layers in M2M, as shown in Figure 1.

 

Figure 1: Layering of M2M technology

The application layer, which is the highest layer, provides the relevant application data. Standard from IEC and IEEE (Such as IEEE 1547 and IEEE 2030) are involved in the definition of this layer.

A middle layer called the common service layer may be used to enable the exchange of information between the application layer and the access independent underlying network. Organizations such as oneM2M led efforts to standardize this layer. However, over the past 10 years, the general direction of the middle layer has trended towards pure IP, using both IPv4 and IPv6.

Below the common service layer is the underlying network layer. IEEE 802 standards provide underlying networks with enhanced coverage and accessibility, quality of service, security (such as authentication and encryption), and reliability (high availability of network infrastructure). IEEE 802 standards can also provide additional capabilities for an ad-hoc self-organizing network, such as low cost, low power, low duty cycle, and low data rate.

Some IEEE 802 networking technologies offer the ability to bound communication latency of a link. IEEE 802 technologies that are not based on multi-hop networks will generally offer better ability to bound communication latency.

A list of IEEE 802 standards (which define PHY and MAC layers) addressing Smart Grid use cases have been documented and approved by IEEE 802 [1].

## Characteristics of IEEE 802 networks that support Smart Grid applications

IEEE 802 networking technologies bring the following advantages to Smart Grid communications:

* Enterprise grade security compatibility
* Huge ecosystem (billions of products, hundreds of manufacturers)
* Long-term (20 year), battery-powered operation
* Continued operation during line fault events when using wireless media
* Wide choice of products across the spectrum of power versus performance
* Ability to be implemented in resource-constrained devices
* Ongoing development of standards to address changing environment and technology
* Wireless standards that operate in a licensed and license-exempt spectrum
* Offers a rich set of data rate/range/latency tradeoffs
* Common upper layer interface to seamlessly integrate into existing IT systems

Utilities have historically owned licensed spectrum, but the allocations are typically a group of narrow-band channels intended for Land Mobile Radio voice operation. As Smart Grid use cases demand additional bandwidth, additional spectrum was needed. Operation in license-exempt spectrum offers an alternative for utilities, but also introduces new constraints from limited power and greater interference. Shared spectrum has also been explored by utilities. TV White Space (TVWS) is an example a first step towards spectrum sharing between licensed and license exempt services, but was limited by the auctioning of most of the TV spectrum. Citizens Broadband Radio Service (CBRS) defines shared operation in the 3.65 GHz band and has been adopted by many utilities.

Multi-hop mesh networks are built on the MAC/PHY of IEEE 802 standards. IEEE 802 standards, are widely used in the utility network. The Wi-SUN standard, built on IEEE 802.15.4 SUN technology, is a successful and widely deployed example used for metering networks. There are a number of characteristics that make the mesh topology favorable in some deployment situations.

Mesh topology extends the range of the network well beyond the range of a single radio link. Multi-hop delivery can assist in reaching endpoints in poor RF environments, as adjacent neighbors will forward messages to the hard-to-reach node. This in turn allows greater network range with low power radios that can operate in license-exempt frequency bands.

In dense deployment scenarios, mesh topology can allow reducing the transmit power and/or increasing the symbol rate, which are both measures that can reduce interface from and with other nodes by reducing the interference footprint. An inherent tradeoff in multi-hop network topologies is that forwarding will, in some cases, increase latency. In interference limited environments, use of mesh topology can improve delivery reliability, which will reduce retransmission delays. Similarly, the resistance to interference improves delivery reliability, which can improve the effective throughput as well, as retransmission caused by collisions increases the spectrum bandwidth required to deliver the message.

In a wireless system, rate (throughput) and range are inversely related if all other factors are equal. A lower rate can operate over a longer range. In multi-hop (relay or mesh networks), there is also an inverse relationship between latency and range. If range is extended by forwarding packets through a mesh or multi-hop network, the latency increases proportionally to the number of hops. This topic is presented in greater depth in NISTIR 7761 V2 (2013), Section 6.1 [2].

# Applications for Smart Grid

The electric power system is logically separated into three main domains; these domains include Generation, Transmission, and Distribution. Among the categories of Smart Grid applications are Advanced Metering Infrastructure (AMI) and Distribution Automation (DA).

## AMI

AMI improves utility metering by providing two-way communication, which enables the following features: Utility service outage and restoration management, meter reading, demand response, load management, remote service disconnection/re-connection, and service pricing capabilities (including Real Time Pricing, Time of Use pricing, and Critical Peak pricing). For more information, refer to NISTIR 7761 V2 (2013) [2].



Figure 2: High level example of an AMI system

## DA

DA extends intelligent control to the distribution system that includes the following capabilities: Voltage Optimization, Load Reduction/Optimization, system fault detection and remediation, and SCADA. For more information, refer to NISTIR 7761 V2 (2013) [2].

## Application requirements for network communications

### Security

The security of power grid communications is vital from a national security point of view. Security protocols and encryption need to be certified by international bodies. Security protocols need to be interoperable, widely deployed, and have years of testing and deployment in the field. IEEE 802.1X link layer security is based on FIPS approved technologies and defines the encapsulation of Extensible Authentication Protocol (EAP) over an IEEE 802 network. In addition to providing port-based authentication to a server, the 802.1X protocol provides a secure mechanism for transferring keys used for link-layer encryption. IEEE 802 link layer security has been widely deployed in enterprise environments where security of corporate data is of utmost importance. These protocols have been vetted by a large number of security professionals.

The IEEE 802.15.9 Key Management Protocol standard has been developed to allow support of security protocols and keying over constrained wireless networks such as a mesh of 802.15.4 nodes. IEEE 802.15.4 also includes link layer security that has been widely used. The IEEE 802.15.9 Key Management Protocol standard also provides a method of using external key management protocols (like IEEE 802.1X) to generate like keys.

### Non-mains powered operations (for some devices)

There are many Smart Grid applications that require non-mains powered operation, for example, certain types of sensors may not have access to the mains power in a cost-effective manner or need to operate during power outages.

Many IEEE 802 standards have been developed with energy constrained devices in mind. This focus enables the implementation of networked devices that operate for years from small capacity primary cell batteries. Some IEEE 802 standards have been developed with the goal to work from energy harvesting as well.

IEEE 802.15.4 has always been focused on low power and low complexity (compared to other wireless standards). In the last 10 years, 802.15.4 has further enhanced low power operation with amendments such as 802.15.4k (Low Energy Critical Infrastructure Monitoring – LECIM) and 802.15.4w (Low Power Wide Area – LPWA).

### Coverage requirements

In general, Smart Grid systems need to provide network services throughout the utility’s service area. To do this, Smart Grid systems need to support a hierarchy of networks that have different link distance requirements. In addition, the network needs to be robust enough to allow end point devices to reach the gateways. There are a variety of IEEE 802 standards for the networks that implement these requirements.

To achieve the required coverage, IEEE 802 standards provide a variety of solutions

* Multi-hop, non-deterministic networks (e.g., wireless mesh networks and bridged wired networks). Wireless mesh networks may be designed with self-healing properties that increase resilience. Specifically, these networks can automatically reroute communication in the case of node failures, reducing the need for manual intervention. IEEE 802.15.4 and Wi-SUN can enable network restoration and self-healing capabilities for metering, fault detection, DER control, and a variety of other uses.
* Star networks with a base station and relatively long-distance wireless links using licensed spectrum, such as IEEE 802.16s and IEEE 802.16t.
* A variety of physical layers with different data rates (e.g., modulation, coding, etc.)
* Fiber links when right of way is available

While 80% of the people lie within 20% of the service territory, AMI networks need to service 100% of the meters. Multi-hop networks can be used for hard-to-reach meters to get 100% coverage.

For resource constrained devices, multi-hop networks provide connectivity with low power usage. In some cases, constraints on the allowed transmit power levels for wireless networks restrict the practical link distance. In these cases, multi-hop networks may offer a solution. Multi-hop networks, both wired and wireless, also allow resiliency during the failure of nodes in the system.

Communications over fiber or wireless gives resilience to induced voltage differences when operating in proximity to high voltages.

For connectivity within a single facility, e.g., intra-substation networking and the head end, IEEE 802.3 (Ethernet) provides a cost-effective solution. Recent developments in Single Pair Ethernet (SPE) enable new use cases in plants and facilities to re-use legacy copper wiring.

### Advantages of IEEE 802 networks

Utilities expect that deployments of telecommunications networks will have a minimum lifetime of ten (10) to twenty (20) years. In general, IEEE 802 standards support backward-compatibility, as continuous improvements are adopted. This framework assists in preventing the need for "fork-lift upgrades" in the field. IEEE 802 has more than forty years of history in creating successful, backward-compatible standards.

Network and devices upgrades are achieved via incremental implementations that support multiple generations of IEEE 802 standards in the same network. In addition, the process in IEEE 802 includes the evaluation of coexistence with existing networking technologies to ensure good performance.

### Other Standards and Non-802 Networks

In April 2024, the 802.24 TAG published a white paper titled “[IEEE 802® Networks for Vertical Applications](https://ieeexplore.ieee.org/document/10494858)”. It highlights some of the architectural characteristics of IEEE 802 that make it particularly well suited for network supporting vertical applications. This is contrasted with commercial networks, where the network access itself is the product.

In other cases, network technologies that are intended for broad use by service providers, such as 3GPP LTE and 5G, are appropriate for vertical markets. The value of the broad ecosystem of suppliers outweighs the overhead because the architecture is not aligned with the use case. An example is the broad adoption of Private LTE and 5G by utilities, which are seeking higher reliability, availability, coverage, and cyber security than is available from commercial carriers.

Use of proprietary point-to-multipoint wireless

Need for Peer to Peer communications for dynamic reconfiguration of microgrids and outage recovery. No existing standards provide long range (> 1 km ) connectivity on a peer to peer topology. Possible adaptation of 802.16t?

# Conclusions

The IEEE 802 standards family provides a foundation of connectivity that network and application layer protocols can build upon to form a flexible, interoperable ecosystem serving a variety of applications.

The IEEE 802 family is well established in many utility communications applications. IEEE Std. 802.3 (Ethernet) finds broad application in enterprise LANs and intra-substation networks. IEEE Std. 802.16 and 802.15.4 (SUN PHY) are deployed for utility field area networks. IEEE Std. 802.15.4 (DSSS PHY) and IEEE Std. 802.11 (Wi-Fi) are used for Home Area Networks and other customer premises networks for energy management, load control, and automation.

The variety of IEEE 802 standards address the different requirements for different tiers of an integrated utility network (performance, range, latency, etc.) The unified architecture enables integration across the network. The architecture and design principles of IEEE 802 have been extended into other standards that have utility application, such as the IEEE1901 PLC standards, enabling broader integration.

IEEE 802 standards backward compatibility between generations, protecting investments and allowing incremental upgrades, while evolving to address new requirements.

In summary, IEEE 802 standards provide a platform to support the communication requirements of diverse applications across the range of utility operations, and other devices in support of the SmartGrid, eHealth industry, intelligent transportation systems, smart city applications, and general Internet of Things (IoT).

# Citations

1. “IEEE 802 recommendations on IEEE 802 related Smart Grid standards”, [2](https://mentor.ieee.org/802.24/dcn/12/24-12-0033-04-0000-package-of-802-smart-grid-standards.docx)
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