Grid Communications Technologies

July 23, 2024

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Part of a series of white papers on
Secure Pathways for Resilient Communications.

SPaRC
Secure Pathways
for Resilient Communications

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Executive Summary

In today's rapidly changing energy landscape, achieving a more carbon-free grid will rely upon the efficient coordination of numerous distributed energy resources (DERs) such as solar, wind, storage, and loads. This new paradigm is a significant operational shift from how coordination of traditional generation assets is handled. This shift not only changes the fundamental technology of electricity generation, moving from traditional thermal synchronous generators to modern inverter-based resources (IBRs), but also transforms ownership models beyond conventional utilities and alters the distribution of power plants across the grid. As more DERs are integrated, maintaining a resilient and reliable energy infrastructure will hinge on robust secure data communication systems designed to meet performance standards.

Electric utilities depend upon a wide variety of communication technologies today to support existing operations; in many cases they have taken on the responsibility of engineering, procuring, constructing, maintaining, and in some cases leasing their communication networks to meet the needs of the operational processes they are supporting. These can include metering, substation monitoring/automation, protection systems, and generation dispatch, each with unique communication system demands that vary significantly to support the operational aspects. New grid operations and services paradigms, such as generation coordination of large numbers of DER with different ownership, will challenge and alter existing operational processes and will drive new and different performance characteristics of the communication channels.

This whitepaper describes the various communications technologies while describing the inherent limitations and advantages. The goal of this document is to demonstrate the foundational dependencies of communication technology to support grid operations while highlighting the need for a systematic approach for communications technology across a wide variety of electric utility operational processes. Informing the reader of the differences between communication technologies and their alignment to grid operations is intended to assist the interaction between communications providers and utility personnel at this confluence of industries.

Finally, this document highlights that no single "silver bullet" exists to solve these challenges, but a systematic approach to application requirements and communication technology can help mitigate challenges while improving reliability and resiliency of the applications supporting the grid operations.

Introduction

Welcome to the third paper in a series of whitepapers by the Secure Pathways for Resilient Communications (SPaRC) project, covering topics related to grid communication architecture. Topics include latency, Quality of Service (QOS), and communications technologies and their impact on grid communications.

As the resource portfolios of electric utilities evolve, become more distributed, and include more Inverter-Based Resources (IBR), the electrical grid will respond differently to both routine and unexpected actions. These changes will alter the requirements for grid communications that support integration and control of new resources while ensuring the operation of the legacy control and operational functions for the rest of the grid.

This paper describes the various communication technologies available and their limitations and advantages for different grid operational processes, aiming to assist the discussion between communications providers and electric utilities. It intends to bridge the knowledge gap between communications providers and grid utilities to bring about better understanding between the two groups and enable more efficient and effective deployment of communications to support the nation's electric grid.

Understanding Factors That Shape The Selection Of Communications Technologies For Grid Operations Today

To better understand how communications are used within the grid today, it is important to understand the diversity of grid utilities and services. The U.S. electric utility landscape is characterized by significant diversity, with over 3,000 utilities striving to deliver reliable electrical energy across a range of service types, ownership structures, sizes, regulatory environments, geographic locations, and levels of technology adoption. This diversity creates a complex and varied landscape of grid operations and technology deployment, each tailored to the specific needs and contexts of individual utilities.

Key Factors Influencing Diversity in Grid Operations

Below is a set of key factors influencing electric utility diversity and ultimately the technology diversity on the grid.

1. Service types
2. Ownership Structure
3. Size and Scale
4. Geographic Location
5. Jurisdiction
6. Technology Adoption and Integration
7. Customer Demographics
8. Resource Availability
9. Historical Development
10. Economic Factors
11. Workforce and Skills
12. Reliability Considerations
13. Cybersecurity Challenges

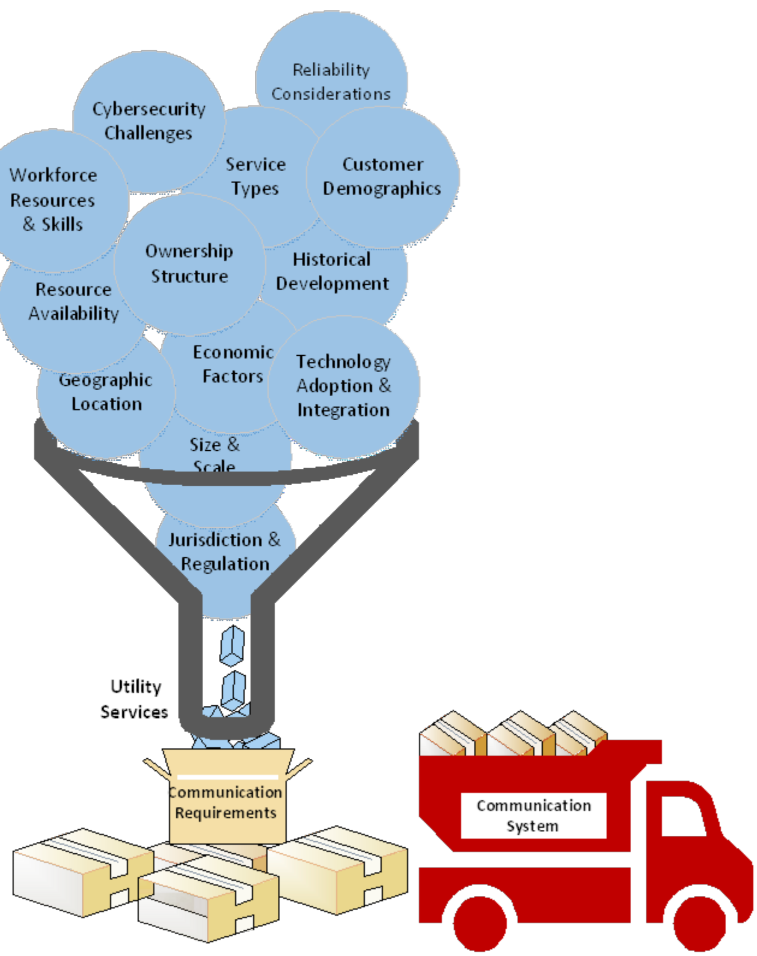

Figure 1. Key factors shape utility services. Communications requirements protect those services as they move to their destination.

Variations in each of the key factors above combine to form a complex set of requirements and challenges particular to that electric utility and the services it provides, which then informs the selection of appropriate communication technology. A grid utility must adopt a systematic approach tailored to its specific operational needs and context, leading to a wide range of technology solutions and implementation strategies supported by the correct communication technology. Additional information on these key factors is in Appendix A of this document. No single communication technology solves all diversified grid operations. Addressing these factors is crucial for effective grid management and the advancement of smart grid technologies, while ensuring safe, reliable, and efficient energy delivery across diverse regions and contexts. This comprehensive understanding of grid utility diversity highlights the importance of appropriate communication solutions to meet the unique challenges and requirements of different utilities, fostering a more resilient and adaptive grid infrastructure.

Matching Performance Criteria of Grid Applications to Communication Technology

A wide variety of communication technologies support grid operations today via multiple solutions driven by the key factors above. Figure 2, below, shows a basic representation focusing on grid communications, which can be thought of as higher layer applications, facilitated by protocols, carried by transport technologies that are riding on physical media. This model focuses on how high-level applications in power engineering and related fields are supported by underlying protocols, transport technologies, and physical media. In this discussion, we focus on the transport technology and media as the "communication pipe" supporting the protocols and upper layer applications. This model is less broad and generic than the OSI 7-layer model and provides focus for grid applications.

> **No single "silver bullet" exists for communications technology supporting grid operations. Solutions must have a systematic approach and be designed for that grid operational process.**

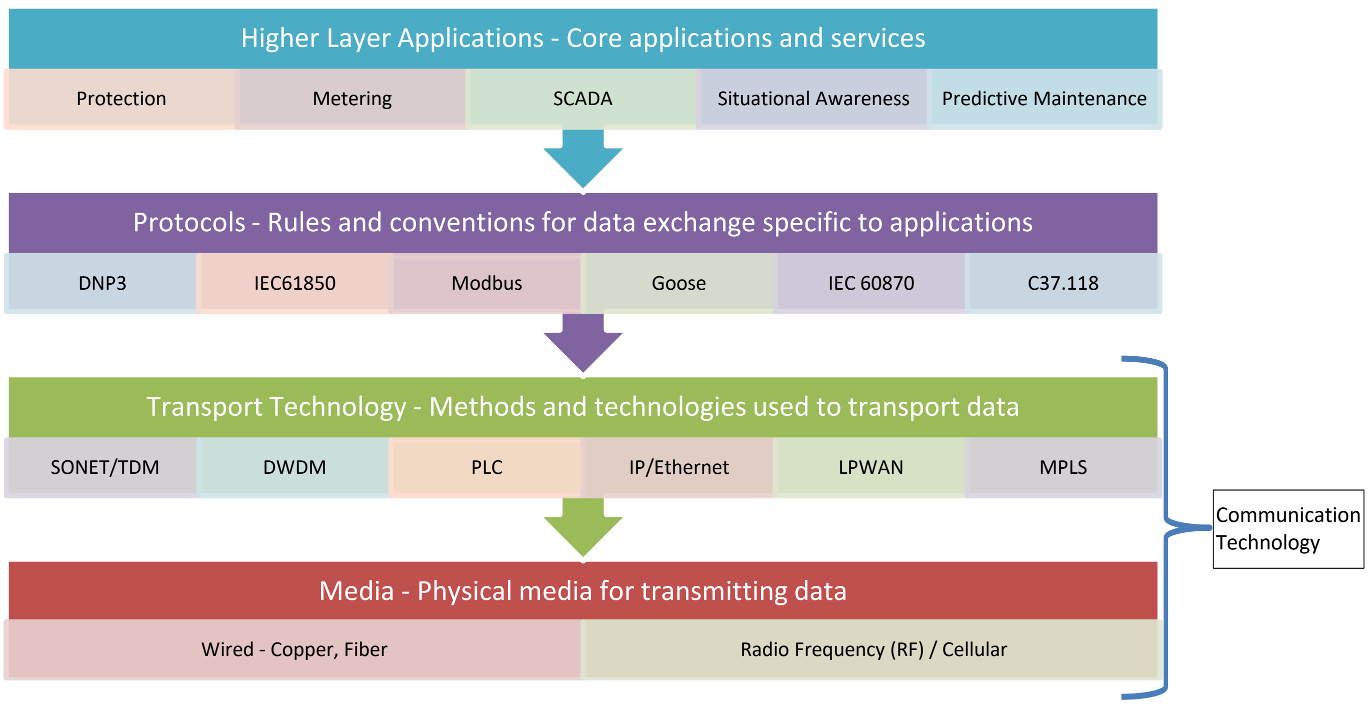

Figure 2. Application Diagram

Previous SPaRC whitepapers covering latency [1] and Quality of Service (QoS) [2] highlighted the need to match performance characteristics of the communication technology to the higher layer application requirements.

Methodology For Selecting Communications to Support Grid Requirements

Applying the appropriate communication technology to support grid requirements depends upon many factors beyond just the communication technology, how it is deployed (e.g., architecture) and operations. One method is to start with the grid services or processes needing support. Once these are identified, such as SCADA, protection schemes, or metering, associated requirements for the communications system can be ascertained. These will include Quality of Service (QoS) attributes, including latency, throughput, bandwidth, jitter, packet loss, availability, and security. With the above requirements known, another determining factor for selecting grid communications is the current state of communications technologies in place at the electric utility. Establishing the current state will form a basis for assessing the cost and effort required to implement the new communications required.

Common questions in this area include:

> **Establishing the current state of the utility's communications will form a basis for assessing the cost and effort required to implement the new communications required.**

1. Can existing communication capabilities support new grid application requirements?
2. Must the new communications technologies interoperate with the current technologies?
3. Will new protocols be used for the grid applications identified, or is there a solution currently in place to transport them?
4. Is the grid utility currently owning and operating a communications network in the area?
5. Are there internal resources to support expanding the network? Include Operations and Maintenance personnel or support contracts.
6. What capital or expense funding is available for new additions or acquisitions?
7. Is there a Network Operations Center (NOC) available or needed?
8. Are there existing agreements in place with third-party providers for similar grid systems?
9. Could a third-party communications provider provide the appropriate communications services to the area?
10. How will the communication technology identified for this application align with the current cybersecurity posture?

Some solutions will be relatively straightforward and can be achieved by leasing standard third-party products from a communications provider. However, if more control by the grid utility is desired, or the products being offered do not meet the requirements of the utility, the situation is more complicated. The factors, below, are examples of instances in which doing some research early in the planning process can help quickly narrow the options to the communications system ultimately selected.

- Physical media or media enablers: Check for microwave towers where communication providers lease space for RF antennas, fiber optic cable in the area, existing cellular backhaul, carrier offices, and related infrastructure. This can be an indicator of service availability and will often have identifying information for the owner. Being near existing facilities means that there may be excess capacity available or shorter builds for the grid utility needing the services. This can increase affordability and decrease deployment time.
- Utility fiber swaps: Many electric utilities have installed fiber optic cables with excess future capacity. These fibers may be available to lease from the utility and are likely maintained and restored to utility requirements. Also consider trading optical fibers with neighboring utilities to gain access to areas beyond the current utility communications footprint and increase route diversity.
- Cooperative utility agreements: Investigate opportunities with adjacent similar utilities to carry communications traffic for each other if the situation warrants. This is similar to the idea of fiber swaps, but can be via point-to-point radio, tower space, or bandwidth on transport technologies. This can be convenient if buildings are already shared in distribution or transmission substations or at repeater stations.

Addressing Interoperability, Compatibility, Scalability, and Security

Ensuring the grid application performance requirements are supported by the communications technology is one aspect of choosing a communication technology. Other key factors mentioned above also come into play along with considerations in the following areas.

- Compatibility with legacy systems: Some transport technologies (e.g., TDM) and protocols (e.g., Modbus) are essential for integrating older systems with newer technologies.
- Scalability and flexibility: Modern transport technologies like IP/Ethernet and MPLS, along with versatile protocols such as IEC 61850, support scalable and flexible grid architectures.
- Security: Grid utility cybersecurity posture often may drive technology choices. Examples include adjusting to additional compliance with NERC CIP when transitioning from non-routable technologies (e.g., TDM/Serial) to IP routed technologies.
- Interoperability: High-level applications like SCADA, protection, and metering often need to interface with different protocols and transport technologies. Ensuring interoperability between these components is crucial.
- Obsolescence: New and emerging technologies in IP/wireless and edge processing/storage supporting high-reliability, low-latency/deterministic communication should be investigated to avoid obsolescence in grid communication infrastructure.

Overall, many factors come into play when examining communication technology for grid applications. Understanding the strengths and weaknesses of each technology is critical for building and integrating grid operational processes and will be even more important as the grid evolves to support and rely upon distributed generation.

Common Grid Communication Media and Transport Technologies

Much of grid communication is performed over purpose-built communication networks owned and maintained by grid utilities. Broadly speaking, grid communication systems are comprised of multiple transport technologies and protocols carried by a variety of media. It is not a one-to-one mapping of media to technologies and/or protocols since some technologies and protocols can operate on multiple media and multiple media can carry a single transport technology or protocol.

These purpose-built networks may include leased facilities or services from communications providers, utility owned systems, or a combination of both. As the grid evolves, reliance on communication provider services may become more common. Communications providers offer specific physical connectivity such as leased fiber lines or services such as cellular, Ethernet, or others. This reliance on providers represents a potential risk that grid utilities need to understand and incorporate into their recovery planning.

In the sections that follow, the reader will be given a basic understanding of the variety of media, transport technologies, and protocols available for grid communications, whether owned by grid utilities or communication service providers.

Communications Media

Media – Physical media for transmitting data	
Wired – Copper, Fiber	Radio Frequency (RF) / Cellular

Figure 3. Communications Media Categories

Communications media can be grouped into two main categories: "wired" media using a cable and "wireless" media using radio frequencies. Each category contains multiple options that can be utilized by grid utilities depending upon the needs and challenges of a particular application and the media available in the area. Overall having some control over the media is critical for electric utilities hence wired technologies are better suited for core operational processes while wireless options for less critical or last resort.

Wired Options

Wired media carry information over physical cables containing copper, aluminum, or optical fiber. The most common forms are twisted pair copper, coaxial cable (also copper), and fiber optic cable. Unique to grid utilities is power line carrier communication that uses portions of the electric power conductors to transmit information. Additional uses of wired options for the utility include substation wiring for controls and sensors, which frequently involve current transformer (CT) and potential transformer (PT) wiring along with metering, and open/closed contacts.

The different technologies can be deployed in different portions of the network across different distances. Twisted pair copper is common within buildings, while coaxial cable is typically found in the access network. Fiber covers a range of applications. However, for long distances, transport fiber dominates due to its throughput, latency, and low loss characteristics. As costs for fiber continue to decrease, application of fiber continues to spread to the last mile. Power line carrier (PLC) is deployed infrequently in the US, although legacy systems can be found in transmission substation-to-substation communications and associated with distribution metering.

Twisted Pair:

Twisted pair cables are copper cables with roots in telephony and voice communications. Twisted pair cables were provided early in the deployment of voice communication across the U.S. and became the de facto standard in communication at the customer location. The CAT (Category) specifications for twisted pair cables define the performance standards and characteristics for various types of twisted pair cables used in telecommunications and networking. These specifications include parameters such as maximum data rate, bandwidth, and maximum cable length for optimal performance. The following is an overview of the most common CAT specifications for twisted pair cables.

CAT1: POTS lines, sensor control leads, varies in AWG wire size and twist per inch counts.
CAT3: Basic telephony and early Ethernet.
CAT5: Improved performance over CAT3, largely obsolete.
CAT5e: Enhanced CAT5, supports gigabit Ethernet.
CAT6: Higher performance supports gigabit and short-distance 10 gigabit Ethernet.
CAT6a: Enhanced CAT6, supports full-distance 10 gigabit Ethernet.
CAT7: High-speed, shielded cable for gigabit and future-proof applications.
CAT7a: Enhanced CAT7, higher frequency support.
CAT8: Ultra-high-speed, shielded cable for data centers and short-distance high-speed networking.

Coaxial Cable:

Coaxial cable is a copper-based technology typically implemented in the access network of a communications service provider. Its original use in the access network was to provide television signals to homes. Today the technology has been used to deliver television, telephone (voice), and data built upon the Data Over Cable Service Interface Specification (DOCSIS). The transmission is broadcast, designed for higher speeds toward the home or business (downlink) and lower speeds back to the provider (uplink). Coaxial cable is generally not used for transport within utility networks, but it is often used to distribute timing signals for protection equipment within the substation control house.

Fiber:

Fiber optic cable, both single-mode and multimode, is a high-speed transmission medium that uses light to carry data through strands of glass, offering significantly higher bandwidth and longer transmission distances with minimal signal loss compared to traditional copper cables. Due to their nonconductive qualities, fiber optic cables are often used in the transmission or distribution substations when electrical isolation is required for safety or to prevent damage to electronic devices during a substation fault.

Fiber makes up the core of the worldwide long distance communication network of today, from undersea cables to the backbone of the Internet. Fiber optic cables can be used in long-haul, regional and communication provider access networks and within buildings depending on the fiber itself and the technologies deployed on the end points. In long-haul transport networks, dense wave division multiplexing (DWDM) can be used to provide high bandwidth over long distances. This is accomplished by having multiple wavelengths on a single optical fiber. ITU-T G.694.1 is a recommendation standard that has been widely accepted and used in DWDM application and provides channel spacing for ITU wavelengths in the 15XX nm space including 12.5GHz, 25GHz, 50 GHz, 100 GHz, and above. Using DWDM, capacities of 32 Tbps have been achieved using 80 wavelengths at 200 Gbps with specific fiber. Fiber optic cables are often used for backbone communication networks in power systems, connecting substations and control centers. Common applications on transmission or distribution lines are Optical Ground Wire (OPGW) in the place of the shield wire above the conductors, or All Dielectric, Self-Supporting (ADSS) fiber cable installed below the conductors. On distribution lines, often a lighter-duty fiber optic cable is lashed to a messenger wire since spans are short. One disadvantage of fiber optic cables is that outages can be long while the damage is located and repaired, regardless of whether it is an aerial installation on powerlines or buried underground.

Wireless or Radio Frequency Options

As the name implies, wireless communication technologies communicate without the use of wires or cables as a primary communication medium. Wireless communication, depending upon the type deployed, can be flexible and cost-effective, making it a popular choice for remote and difficult-to-reach areas. Table 1 shows the IEEE frequency bands, which generally are separated by the propagation characteristics of the radio waves at those frequencies. Some wave lengths, for example, are better at covering a large area and bending around or going through obstacles, while others are more focused and required line-of-sight from one antenna to the next with no intermediate obstructions. This makes them more applicable to certain industries and applications.

- Private Radio Networks: Grid utilities may establish their own private radio networks to ensure reliable and secure communication. Private networks provide dedicated bandwidth and control over network infrastructure. Specifically in the 900 MHz range for metering as well as Smart City applications.
- Licensed and Unlicensed Bands: Licensed bands offer exclusive use of a specific frequency range, reducing interference risks, while unlicensed bands, such as the Industrial, Scientific, and Medical (ISM) bands, are available for use by any device but may experience interference.

Table 1. IEEE Frequency Bands with Industry and Application Information [3] [4]

IEEE Frequency Band	Frequency Range	Industry	Typical Applications
LF (Low Frequency)	30 kHz - 300 kHz	Maritime, Aviation	Navigation beacons, Non-Directional Beacons (NDB)
MF (Medium Frequency)	300 kHz - 3 MHz	Broadcasting, Maritime	AM radio, ship-to-shore communication
HF (High Frequency)	3 MHz - 30 MHz	Military, Aviation, Maritime, Amateur Radio	Long-range communication, global amateur radio

VHF (Very High Frequency)	30 MHz - 300 MHz	Broadcasting, Aviation, Maritime, Public Safety	FM radio, VHF TV, air traffic control, marine radio
UHF (Ultra High Frequency)	300 MHz - 3 GHz	Broadcasting, Telecommunications, Public Safety, Military	UHF TV, cellular networks (2G, 3G, 4G, 5G), Wi-Fi, Bluetooth, two-way radios
L-Band	1 GHz - 2 GHz	GPS, Satellite, Telecommunications	GPS navigation, satellite communication, mobile phones
S-Band	2 GHz - 4 GHz	Satellite, Telecommunications, Radar	Satellite communication, weather radar, Wi-Fi, 5G
C-Band	4 GHz - 8 GHz	Satellite, Telecommunications, Radar	Satellite communication, long-distance radio links, 5G
X-Band	8 GHz - 12 GHz	Military, Radar, Satellite	Radar systems, satellite communication
Ku-Band	12 GHz - 18 GHz	Satellite, Broadcasting	Satellite TV broadcasting, VSAT communication
K-Band	18 GHz - 27 GHz	Satellite, Radar	High-resolution radar, satellite communication
Ka-Band	27 GHz - 40 GHz	Satellite, Telecommunications	High-speed satellite communication, 5G, broadband
V-Band	40 GHz - 75 GHz	Research, Telecommunications	Millimeter wave communication, 5G, radio astronomy
W-Band	75 GHz - 110 GHz	Military, Research, Telecommunications	High-frequency radar, radio astronomy, experimental communication
EHF (Extremely High Frequency)	30 GHz - 300 GHz	Research, Military, Telecommunications	Radio astronomy, advanced radar systems, 5G millimeter wave communication

Cellular:

Within this discussion, cellular is placed as a media because it is part of the wireless technologies, however, in today's environment, cellular is inherently coupled with IP and could also be discussed as a transport technology. Cellular technology refers to the wireless communication systems that use a network of cell sites, or base stations, to provide radio coverage over a wide geographic area. These cell sites are interconnected and provide seamless communication as users move from one cell to another, ensuring continuous connectivity. Cellular technology provides robust and scalable communication for a wide range of applications, from mobile broadband to critical infrastructure like smart grids. The QoS characteristics of cellular networks, such as low latency, high bandwidth, reliability, coverage, scalability, and advanced QoS mechanisms, make them well suited for diverse and demanding applications. With the advent of 5G, these QoS characteristics are further enhanced, offering even greater performance and flexibility for future applications, including the evolving needs of grid infrastructure and smart cities.

Cellular communication is an increasingly popular choice for power systems due to its wide coverage, reliability, and scalability. Cellular networks offer varying levels of bandwidth depending on the generation of the network (e.g., 4G, 5G, & 6G from the Long-Term Evolution (LTE) paradigm), allowing for a range of applications from low-bandwidth monitoring to high-bandwidth video surveillance. Cellular networks provide a large coverage area with improved bandwidth and lower latency making them useful for applications such as advanced metering infrastructure (AMI), distribution automation, real-time grid optimization, and distributed energy resources management to connect devices like smart meters, and sensors in power systems for monitoring and control. As cellular networks continue to evolve, they will offer even greater capabilities and support for advanced power system applications. One disadvantage is that during mass calling events, such as large sporting events, parades, or emergencies, the public cellular system can be overwhelmed by calls and may impact utility traffic. That said, this technology is often a good solution where multiple lower cost connections are required, bandwidth requirements are limited, and impact to grid operations is lower when communications are disrupted.

Utilities often use cellular technology for:

- Real-Time Monitoring: Provides high-speed, low-latency communication for real-time monitoring and control of grid operations.
- Distributed Energy Resources (DER): Supports the integration and management of distributed energy resources, such as solar panels and battery storage systems.
- Advanced Metering Infrastructure (AMI): Enhances the capabilities of AMI with faster data collection and processing from smart meters and sensors.

Table 2 contains a sample of notable QoS parameters for common cellular technologies.

QoS Characteristic	***Description***	***4G LTE Characteristics***	***5G Characteristics***
Latency	Time for data to travel from source to destination	Typically, 20-50 ms	As low as 1 ms
Bandwidth and Data Rates	Rate of data transmission	Up to 1 Gbps	Up to 10 Gbps and beyond
Reliability	Consistency in data delivery	High, with redundant infrastructure	Very high, with enhanced protocols
Coverage	Geographic service area	Widespread, including urban and rural areas	Enhanced, with focus on high-density areas
Scalability	Support for growing number of users/devices	Efficiently scalable	Highly scalable, supports massive IoT
QoS Mechanisms	Techniques to prioritize and manage traffic	Bearers with different QCIs	QoS Flow Identifier (QFI) for granular control

Satellite:

Satellite communication technologies make use of satellites in the Earth's orbit for data transfer. In the past, satellite communication was typically reserved for situations that were challenging or infeasible for other types of wired and wireless communication technologies such as remote substations and feeders. However, modern developments in satellite communication technologies as well as deployments of low-earth orbit satellite constellations have the potential to increase the role of satellite communication technologies in the grid. The communication delay is higher compared to other media technologies, making satellite communications usable for situational awareness but less preferred for low-latency applications such as protection. Another disadvantage is the cost of installation and recurring subscription fees.

Microwave:

Microwave communication is a point-to-point, terrestrial wireless communication technology that utilizes frequencies in the microwave frequency spectrum (1 GHz to 90 GHZ). Microwave communication requires line-of-sight using a narrow beam, which reduces interference and allows for multiple point-to-point links in a given area. The line-of-sight nature of microwave communication technologies limits link distances to the visual horizon (30-50 miles) at the middle to lower end of the band, with limited impact from atmospheric factors such as rain cells. At higher frequencies, the link distance is much shorter but can often be used in an urban environment to propagate traffic from one building to another. One disadvantage of this frequency range is its susceptibility to attenuation during heavy rain due to the microwave signal scattering or being absorbed by the rain droplets.

Point-to-point microwave installation costs can range from very high ($1M+ for greenfield mountaintop repeaters in rural and remote areas) to relatively low (sites with existing towers, buildings, and power). For backhaul of grid utility traffic requiring high bandwidth, low latency, and high reliability, microwave can, however, be cost effective compared to fiber optic cable installation, especially when right-of-way must be purchased, and fiber installed. If using licensed microwave frequencies, interfering parties can be tracked down and required to remediate the interference or shut down their transmitters. If using unlicensed frequencies, these remedies are not available, potentially leading to unreliable operation.

Land Mobile Radio (LMR):

Land mobile radio is a radio system operating in VHF and UHF radio bands, below the microwave radio frequencies. Its primary grid utility use is to connect two or more individuals, via hand-held radios or radios mounted in vehicles, for operations and maintenance functions and for the safety of crews deployed in the field. Often stationary repeaters are deployed to traverse longer distances and for back-hauling voice or data from field crews to grid operators in control centers.

Transport Technologies

Transport Technology – Methods and technologies used to transport data					
SONET	DWDM	PLC	IP/Ethernet	LPWAN	MPLS

Figure 4. Sample Transport Technologies

In this whitepaper, we have identified a variety of physical media used for communications. Transport technology carries the communications (i.e., grid protocols) over these physical media. (As mentioned previously this model is more specific to grid applications and less broad and generic than the OSI 7-layer model.) Grid utilities have deployed and currently utilize numerous types of transport technologies to arrive at the correct combination to transfer grid information to and from where it needs to be.

Power Line Carrier:

Power Line Carrier (PLC) uses existing electrical power conductors as the physical communication medium. It is an attractive option because it doesn't require new infrastructure and allows the grid utilities to have full control over that portion of their communications. In this communication technology, higher frequency communication signals, from a few kHz to tens of MHz, are transferred on top of the electrical power signal. However, it is subject to lightning, switching surges, and attenuation and noise. Bandwidth for PLC is low, under 2 Gbps. In practice, a combination of both narrow band and broadband power line communication is generally utilized. A redundant backup network is essential in case a line trip event occurs since the communications is utilizing the line that is being protected as a medium. In addition to basic line protection, PLC can be used for other substation-to-substation communication, including smart metering, and other applications.

SONET and Time Division Multiplexing (TDM):

SONET (Synchronous Optical Network) is a standardized digital communication transport system used to transmit a large volume of data over relatively long distances using optical fiber. It was developed to meet the growing need for high-speed networking in telecommunications and provides a framework for efficiently multiplexing digital data streams over optical fiber. SONET is highly reliable and is widely used in telecommunications and grid applications due to its robust protection mechanisms. These mechanisms, including Unidirectional Path Switched Ring (UPSR), Bidirectional Line Switched Ring (BLSR), and Automatic Protection Switching (APS), ensure continuous service by quickly switching to backup paths in the event of failures. SONET operates with very low and deterministic latency with minimal jitter, maintaining high data integrity and timing accuracy. It offers dedicated bandwidth and scalable infrastructure, making it suitable for extensive network deployments. Time Division Multiplexing (TDM) is the basic building block to SONET timeslots. TDM is a communication method that divides the available bandwidth into time slots, each allocated to a different signal or data stream. This allows multiple signals to share the same communication channel by transmitting in rapid succession, as seen in Figure 3. TDM technology was primarily designed for voice handling, exemplified by the T-carrier system, where a single digital signal (DS0) supported a 64kbps channel for voice. Below is a table of the digital hierarchy built upon the DSO.

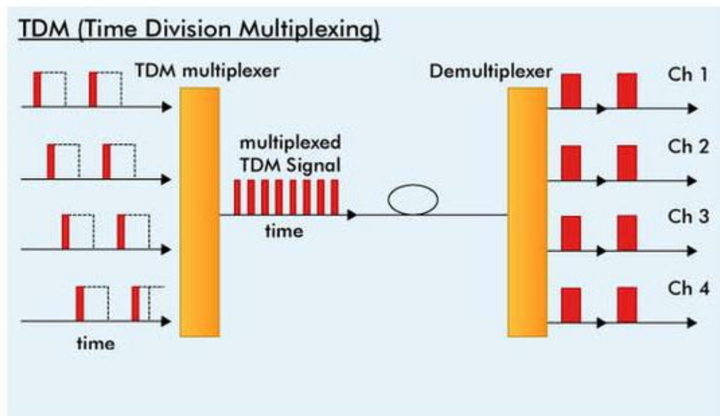

Figure 4.Time Division Multiplexing

Table 3. Digital Hierarchy in SONET and TDM

Level	Signal Type	Data Rate (Mbps)	Number of DS0 Channels	Typical Applications
DS0	Digital Signal 0	0.064	1	Single voice channel
DS1	T1	1.544	24	Voice/data multiplexing, T1 lines
DS3	T3	44.736	672	Large-scale data transmission, T3 lines

OC-1	Optical Carrier 1	51.84	672	Entry-level SONET signal
OC-3	Optical Carrier 3	155.52	2016	Higher-capacity SONET transmission
OC-12	Optical Carrier 12	622.08	8064	Backbone networks
OC-24	Optical Carrier 24	1244.16	16128	High-capacity backbone networks
OC-48	Optical Carrier 48	2488.32	32256	Very high-capacity backbone networks
OC-192	Optical Carrier 192	9953.28	129024	Major backbone networks

Grid utilities adopted TDM to leverage several advantages including: time synchronization, deterministic latency, high availability with restoration using SONET, availability from local communication providers at the time, and support for serial communication in sub-DSO channels like 9.6kbps, 19.2kpbs, and 56kpbs which aligned to many of the substation technologies. TDM and SONET support substation automation as well as serial, DNP3, and other SCADA connections from an Energy Management Systems (EMS) to the substation. Additionally, with support for a serial connection TDM provides for relay-to-relay communication in system protection. SONET/TDM was widely adopted by grid utilities and is still a component of communication, sometimes primary, transport technology used within utilities. TDM can be supported by both wired and wireless media. As the telecommunication industry shifted away from SONET/TDM to asynchronous packet switch communications many utilities have also shifted, but so have techniques of supporting other protocols (Ethernet/IP/MPLS) over TDM. TDM itself is a fundamental technology primarily used for synchronous data transmission, it can support various other-layer protocols, including IP, Ethernet, and MPLS, through appropriate encapsulation and interface technologies. Conversely, an upgrade path to MPLS is available due to MPLS systems' ability to encapsulate TDM traffic without losing the TDM characteristics.

SONET / TDM provides several key QoS characteristics that make it suitable for applications requiring low latency, minimal jitter, high reliability, and deterministic performance. Its predictable time slot allocation ensures consistent service quality, which is crucial for real-time communications, however SONET / TDM 's bandwidth efficiency and scalability are limited compared to modern packet-switched technologies. SONET / TDM remains a reliable and widely used technology in utilities and other mission-critical applications. Table 4 is a sample of notable QoS parameters for SONET / TDM.

Table 4. QoS Characteristics for SONET/TDM

QoS Characteristic	***Description***	***SONET / TDM Characteristics***
Latency	Delay from transmission to reception	Low and predictable due to fixed time slots
Jitter	Variation in latency	Very low, with consistent timing intervals
Bandwidth Efficiency	Effective utilization of available bandwidth	Less efficient, fixed time slots may lead to unused bandwidth
Reliability	Accurate and consistent data delivery	High reliability, no bandwidth contention

Deterministic Performance	Predictable and consistent performance	Guaranteed access to bandwidth, fixed intervals
Scalability	Increasing network capacity	Limited by number of time slots, scaling can be complex and costly
QoS Support	Prioritization and management of traffic	Inherent QoS with fixed time slots, lacks flexibility of modern QoS

IP/Ethernet (Internet Protocol/Ethernet):

Ethernet and Internet Protocol (IP) represent a transport technology in our model and a data link and network layer protocol, respectively, under the OSI 7-layer model. Ethernet and IP are independent technologies that can be deployed separately; however, IP and Ethernet have often been deployed together in industry. Combined, they make up a significant portion of IT systems, since IP is the native protocol of the internet. Therefore, we have considered this combination a transport technology.

Table 5. Standards for IP/Ethernet Transport

Protocol	Standard	Overview
Ethernet	IEEE 802.3	Defines Ethernet at the physical and data link layers.
IPv4	RFC 791	Defines the Internet Protocol version 4.
IPv6	RFC 8200	Defines the Internet Protocol version 6.

The low cost and capability of Ethernet and IP have allowed us to rapidly deploy networks to support common applications we use daily including near-real-time applications and provided the bandwidth, flexibility, and scalability for grid operations. IP/Ethernet continues to grow and is quickly being adopted in OT and grid utility environments. Ethernet standards have provided the basis to adapt to high data rates up to 200 and 400 Gbps (IEEE802.3bs). Table 6, below, provides an overview of the different Ethernet standards and associated data rates.

Table 6. Maximum Data Rate per Ethernet Standard

Standard	Maximum Data Rate
802.3u	100 Mbps Fast Ethernet
802.3z	1 Gbps Gigabit Ethernet over fiber (1000BASE-X)
802.3ab	1 Gbps Gigabit Ethernet over twisted pair (1000BASE-T)
802.3ae	10 Gbps Ethernet (10 Gigabit Ethernet)
802.3ba	40 Gbps and 100 Gbps Ethernet
802.3bs	200 Gbps and 400 Gbps Ethernet

IP/Ethernet has continued to expand in utility operations supporting high layer application including SCADA, situational awareness, predictive maintenance, and protection. Most grid protocols operate on Ethernet or IP/Ethernet such as:

- IEC61850 specifies the use of Ethernet for communications between devices in a substation network.
- DNP3 can use IP, usually over Ethernet.
- Modbus can use IP, usually over Ethernet.
- GOOSE is designed to operate with Ethernet.

Ethernet and IP each provide critical QoS characteristics that support a wide range of applications. Ethernet offers low latency, high reliability, and robust QoS mechanisms, making it suitable for local area networks and environments where predictable performance is crucial. IP provides the flexibility and scalability needed for wide area networks and internet communications, with various QoS mechanisms to prioritize and manage traffic effectively. Together, Ethernet and IP form the backbone of modern networking, enabling the seamless transmission of data across diverse and complex network environments. Table 7 shows a sample of Ethernet/IP technologies and notable QoS parameters.

Table 7. QoS Characteristics for Ethernet / IP Transport Technology

QoS Characteristic	***Ethernet***	***IP***
Latency	Low, but variable based on network congestion and distance	Variable, can range from low (milliseconds) to high (seconds)
Jitter	Low, but can be affected by congestion	Higher, variable depending on network conditions
Bandwidth	Supports speeds from 10 Mbps to 400 Gbps and higher	Varies widely, from low-bandwidth IoT to high-bandwidth video streaming
Reliability	High, with redundancy protocols like STP and link aggregation	High with TCP (reliable), lower with UDP (faster, less reliable)
Deterministic Performance	Standard Ethernet is non-deterministic, TSN provides deterministic	Generally non-deterministic, uses QoS mechanisms for prioritization
QoS Mechanisms	IEEE 802.1p, 802.1Q VLAN tagging, 802.3ad link aggregation	DiffServ, IntServ, MPLS, various IP-based QoS mechanisms

LPWAN (Low Power Wide Area Network):

LPWAN is a type of wireless telecommunication network designed to allow long-range communication at a low bit rate among connected devices, often used in Internet of Things (IoT) applications. LPWAN technologies operate across a range of frequencies, primarily in sub-GHz bands, with some technologies also using higher frequencies like 2.4 GHz. These frequencies are chosen to balance range, power consumption, and regulatory constraints. While LPWAN technologies generally trade off higher data rates and lower latency for lower power requirements and wide coverage, each LPWAN technology has specific QoS characteristics that make it suitable for particular applications. Understanding these characteristics helps in selecting the right LPWAN technology for a given use case, balancing the needs for data rate, latency, reliability, battery life, coverage, and scalability. LPWAN technology, in the 900 MHz range, has been adopted in the revenue metering space where each meter can communicate to its neighbors to pass along data that eventually makes it way to the headend facilities. This technology creates a geographic mesh network allowing other devices to participate, such as other distribution devices (reclosers, switching gear, voltage regulators) where the performance of the LPWAN technology can meet the higher layer applications. Table 8 is a sample of LPWAN technologies and notable QoS parameters.

Table 8: QoS Characteristics for LPWAN Technologies

QoS Characteristic	LoRaWAN	Sigfox	NB-IoT	LTE-M
Latency	Variable, typically seconds	Higher, due to duty cycle limitations	Milliseconds to seconds	Milliseconds to seconds
Data Rate	0.3 kbps to 50 kbps	100 bps to 600 bps	Up to 250 kbps	Up to 1 Mbps
Reliability	ADR and redundancy	Redundancy in message transmission	High, with LTE QoS mechanisms	High, with LTE QoS features
Battery Life	10+ years	10+ years	10+ years	Optimized, typically slightly less than NB-IoT
Coverage	Up to 10 km rural, 1-2 km urban	Up to 10 km rural, 3-5 km urban	Excellent indoor, several km urban	Extensive, similar to LTE
Scalability	Thousands to millions of devices	Millions of devices globally	Highly scalable	Highly scalable

MPLS (Multiprotocol Label Switching):

MPLS is a transport technology that employs a data-carrying technique designed to speed up and shape traffic flows across enterprise-wide area and service provider networks. It operates between the Data Link Layer (Layer 2) and the Network Layer (Layer 3) of the OSI model, often referred to as "Layer 2.5". MPLS directs data from one network node to the next based on short path labels rather than long network addresses, which avoids complex lookups in routing tables and enables high-performance data forwarding. MPLS enhances the performance, reliability, and scalability of networks and provides sophisticated QoS mechanisms that allow for precise traffic management and prioritization. This ensures that high-priority traffic (e.g., VoIP, video conferencing, real-time grid monitoring) receives the necessary bandwidth and low latency.

MPLS also provides Traffic Engineering (TE). MPLS-TE allows network operators to optimize the flow of network traffic based on current conditions, improving overall efficiency and performance. Its advanced QoS capabilities make it ideal for grid applications, where reliable and efficient communication is essential for managing and controlling electrical grids. By using MPLS, grid utilities can ensure high-quality service for critical applications, support the integration of renewable energy sources, and enhance the overall stability and reliability of the grid. Aspects useful to Grid Utilities include:

- Traffic Management: Ensures efficient and prioritized data routing for critical utility applications, such as real-time monitoring and control.
- Quality of Service (QoS): Provides guaranteed bandwidth and low latency for essential services like SCADA, protection relays, and voice communication.
- Network Scalability: Enhances the scalability of utility networks, accommodating the growth in connected devices and data traffic.

Table 9 shows a sample of notable MPLS QoS parameters.

Table 9. QoS Characteristics for MPLS Transport Technology

QoS Characteristic	Description	Benefit
Low Latency	Optimized paths reduce latency	Critical for real-time applications
Jitter Reduction	Ensures consistent packet delivery times	Enhances real-time communications quality
Bandwidth Guarantee	Allocates fixed bandwidth for critical traffic	Guarantees performance for essential services
Traffic Prioritization	Assigns different priority levels to different traffic	Ensures high-priority traffic is delivered first
Reliability and Resilience	Quickly reroutes traffic in case of failure	Minimizes downtime, ensures continuous service availability
Scalability	Handles large number of paths and nodes	Suitable for large-scale, complex networks

DWDM

Dense Wavelength Division Multiplexing (DWDM) is a key technology in modern optical communication networks, providing the capability to transmit multiple high-speed data channels over a single optical fiber by utilizing different wavelengths. It is characterized by its high bandwidth capacity, scalability, low latency, robustness, and efficient use of fiber optic infrastructure. DWDM is widely used across various industries, including critical infrastructure (telecommunications and electric utilities), data centers, enterprise networks, CATV, and research and education networks, to meet the increasing demand for high-speed and high-capacity data transmission. DWDM systems enable the transmission of multiple protocols and services over different wavelengths within a single optical fiber. Common protocols and services carried over DWDM include Ethernet, SDH/SONET, OTN, Fiber Channel, and IPoDWDM. Point-to-point protocols such as PPP, HDLC, OTU, Ethernet MAC, Fiber Channel Protocol, and ATM are used to encapsulate and transport these services over DWDM, providing flexible and high-capacity optical communication solutions.

Dense Wavelength Division Multiplexing (DWDM) is a crucial technology in grid applications, especially in the context of modern grids. DWDM enables the transmission of multiple data channels simultaneously over a single optical fiber by using different wavelengths (or colors) of light and is agnostic to protocols and transport technologies that traverse it. This allows for high-capacity, high-speed communication, which is essential for the efficient and reliable operation of grid applications. DWDM enables real-time data exchange between various components of the grid, such as substations, control centers, and distributed energy resources (DERs).

1. Data Aggregation and Distribution - DWDM facilitates the aggregation of data from smart meters and sensors and its distribution to control centers for analysis and decision-making.
2. Substation Automation - IEC 61850 Communication: DWDM supports the IEC 61850 protocol, which is widely used for communication in substation automation systems. It ensures that protection, control, and monitoring systems communicate efficiently.

3. Monitoring and Control - Phasor Measurement Units (PMUs): DWDM provides the necessary bandwidth and low latency required for the transmission of synchrophasor data from PMUs to control centers for real-time grid monitoring and control.
4. Utility Data Centers - High-Speed Data Transfer: DWDM enables high-speed data transfer between utility data centers, supporting large-scale data analytics, storage, and processing required for grid operations.

Table 10 contains notable QoS parameters for DWDM.

Table 10. QoS Characteristics for DWDM Transport Technology

QoS Characteristics	Description	Grid Application Examples
Latency	Extremely low latency due to the high speed of light transmission in optical fibers.	Real-time monitoring, protection relay coordination, phasor measurement unit (PMU) data transmission.
Jitter	Minimal jitter, ensuring stable and predictable data transmission timing.	Synchronization of PMUs, real-time control signals.
Bandwidth	Very high bandwidth capacity by multiplexing multiple wavelengths on a single fiber.	High-speed data transfer between utility data centers, aggregation of smart meter data.
Reliability	High reliability due to robust optical fiber infrastructure and low susceptibility to interference.	Substation automation, wide area monitoring and control (WAMC).
Scalability	High scalability by adding additional wavelengths to increase capacity without laying new fiber.	Expansion of communication infrastructure as demand grows, adding more devices and sensors.
Coverage	Extensive coverage as optical fibers can span long distances without signal degradation.	Connecting remote substations, DERs, and control centers across large geographic areas.
QoS Mechanisms	Ability to implement various QoS mechanisms such as traffic prioritization, bandwidth allocation, and error correction.	Ensuring critical grid communications are prioritized, managing bandwidth for different applications.
Latency Sensitivity	Highly sensitive to latency, suitable for applications requiring real-time data transmission.	Protection relay coordination, real-time grid control, and fault detection.

Transport Summary

These transport technologies play crucial roles in ensuring efficient, reliable, and scalable communication within electric utility networks, supporting a wide range of applications from real-time monitoring to advanced grid management. Table 11 is a view of the major transport technologies and their QoS characteristics and can assist the reader with finding appropriate options for transport given the characteristics desired.

Table 1. Summary QoS Characteristics for Transport Technologies

QoS Characteristic	SONET / TDM	Ethernet/IP	LPWAN	MPLS	Cellular	DWDM
Latency	Very low and predictable, typically microseconds to milliseconds	Variable, typically low in LANs (microseconds to milliseconds), higher in WANs (milliseconds)	High and variable, seconds to minutes	Low and predictable, optimized paths (milliseconds to low seconds)	Variable, typically low in 4G (20-50 ms), very low in 5G (1-10 ms)	Extremely low latency due to the high speed of light transmission in optical fibers
Jitter	Very low due to fixed time slots	Low in controlled environments, higher in congested networks	High and variable	Very low due to label-switched paths	Low in 4G, very low in 5G	Minimal jitter, ensuring stable and predictable data transmission timing
Bandwidth	Fixed, dedicated bandwidth	High, scalable from Mbps to Gbps	Low, typically in the kbps range	High, scalable, can be reserved for specific traffic	High, scalable from Mbps to Gbps	Very high bandwidth capacity by multiplexing multiple wavelengths on a single fiber
Reliability	High, due to dedicated channels	High with redundancy protocols (e.g., STP, link aggregation)	Moderate, dependent on environmental factors	High, with fast reroute capabilities	High, with robust infrastructure and redundancy	High reliability due to robust optical fiber infrastructure and low susceptibility to interference
Scalability	Limited by number of time slots	High, supports a large number of devices and high data rates	Very high, supports millions of devices	Very high, supports large networks with numerous paths	Very high, especially with 5G supporting massive IoT	High scalability by adding additional wavelengths to increase capacity without laying new fiber
Coverage	Typically limited to local or metro areas	Local to global, depending on network infrastructure	Very wide, up to tens of kilometers per base station	Wide, suitable for extensive enterprise and service provider networks	Wide, from urban to rural, enhanced in 5G	Extensive coverage as optical fibers can span long distances without signal degradation
QoS Mechanisms	Inherent due to dedicated time slots	IEEE 802.1p, DiffServ, IntServ, VLAN tagging, link aggregation	Limited, basic priority mechanisms in some technologies	Advanced QoS with traffic engineering, DiffServ, MPLS-TE	Advanced QoS in LTE and 5G	Ability to implement various QoS mechanisms such as traffic prioritization, bandwidth allocation, and error correction

Latency Sensitivity	High, suitable for real-time applications	Sensitive to configuration and traffic load	Not suitable for latency-sensitive applications	Highly suitable for latency-sensitive applications	Highly suitable for latency-sensitive applications in 4G/5G	Highly sensitive to latency, suitable for applications requiring real-time data transmission
Application Examples	Voice communication, legacy telephony networks	Data centers, enterprise networks, home networks	IoT, smart metering, environmental monitoring	Enterprise WANs, service provider networks, VPNs	Mobile broadband, IoT, smart grid, remote monitoring	High-speed data transfer between utility data centers, real-time monitoring, and control
Grid Applications	Substation automation, SCADA, protective relaying	Data collection, control systems, real-time monitoring	Smart metering, asset tracking, environmental monitoring	High-priority traffic management, VPNs for secure communications	Smart grid, AMI, remote monitoring and control, disaster recovery	Real-time monitoring, protection relay coordination, high-speed data transfer between utility data centers

Bringing It All Together

The goal of this section is to provide an example set of grid operations and how different media and transport technologies can provide potential solutions. Thus far, we have identified key factors that differentiate types of utilities and if or how grid operations are deployed which then drives the set of performance requirements for communication systems supporting these operations. We have developed a model of grid operations and protocols that are supported by transport technologies and are carried on different media types. We have discussed and identified media types and transport technology that are used and applicable for grid operations. The key is to ensure that the performance requirements of the grid operation are met by the appropriate communication technology.

Offerings from third-party providers have only been mentioned in this paper, however for some utility applications, these service offerings can be an appropriate solution. With this in mind, a sample gathering of communications service offerings has been included in Appendix B.

Below we represent different grid operations and make note that some grid operations have different time-bases for operations driving various requirements. Some applications require near real-time decisions and immediate action (less than 1 second), others may be decisions and actions in the minutes, and finally others are more historical or asset data that is not time sensitive. An example of this is data coming from protection relay indicating a trip for the EMS is needed is classified as near real-time, however the data on the event is used as a diagnostic tool for examining particulars after the event has been resolved would be less time sensitive. Another example is synchrophasor data (C37.118), which can be used for near real-time decisions and as historical data. In this example, near real-time data could be power system data (Real Power, Reactive Power, Voltage, Current, Phase Angle, Frequency, time: P, Q, V, I,θ,F, and time) sampled at 60 times a second or it could be historical data used sampled every 5 minutes. Understanding the grid application and what is needed for communications is critical. Below, Table 12 represents grid applications where both near real-time and historical examples are given.

Table 2. Grid Application Examples

** Not an exhaustive list*

Grid Application	Supporting Protocols	Time Sensitivity	Key QoS Attributes	Transport Technology	Media
AGC	DNP3, IEC 61850, ICCP-TASE.2	Minutes	Low Latency, High Availability, Minimal jitter, low packet loss, lower bandwidth and throughput	SONET/TDM, IP/Ethernet, MPLS	Wired / RF(Microwave)
Synchrophasor Data	C37.118	Near Real Time	Low Latency, High Availability, Minimal Jitter, low pack loss, high bandwidth and throughput	SONET/TDM, IP/Ethernet, MPLS	Wired / RF(Microwave)
		Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets),	SONET/TDM, IP/Ethernet, MPLS	Wired / RF(Microwave) / Cellular
EMS / Substation Monitoring and Control	DNP3, IEC 61850,	Near Real Time	Low Latency, Minimal Jitter, low pack loss, Varying bandwidth and throughput	SONET/TDM, IP/Ethernet, MPLS,	Wired / RF(Microwave)
		Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets),	SONET/TDM, IP/Ethernet, MPLS,	Wired / RF(Microwave)
Distribution Voltage Control	IP, HTTP, DNP3, IEC 61850,	Minutes	Moderate latency, bandwidth and throughput	IP/Ethernet / LPWAN	RF / Cellular / Wired
		Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets),	IP/Ethernet / LPWAN	RF / Cellular / Wired
Fault Location, Isolation and Service Restoration	IP, DNP3, IEC 61850,	Seconds to Minutes	Moderate Latency, high availability, low packet loss, lower bandwidth	IP/Ethernet / LPWAN	RF / Cellular / Wired
		Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets),	IP/Ethernet / LPWAN	RF / Cellular / Wired
Regulation Services and Reserve	ICCP, DNP3, C37.118, IEC 60870-5	Near Real Time to Minutes	Low Latency, Minimal jitter, low packet loss, lower bandwidth, high security	IP/Ethernet /	Wired / Cellular
		Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets),	IP / Ethernet	Wired / Cellular
RAS	IP, DNP3, IEC 61850, GOOSE, ICCP	Near Real Time	Low Latency, Minimal jitter, low packet loss, lower bandwidth, high security	SONET/DWDM/ MPLS	Wired / RF (Microwave)
Protection	GOOSE, mirror bits, IEC 60870-5-101	Near Real Time	Low Latency, Minimal jitter, low packet loss, lower bandwidth, high availability and security, ability to prioritize traffic to prevent packet loss is recommended	SONET/TDM / DWDM / MPLS IP / Ethernet / PLC	Wired / RF (Microwave)
Interconnection Metering	IEEE 2030.5, OPC UA, IEC 60870-, DLMS	Near Real Time to Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets), high availability for revenue metering, high security	SONET/TDM, IP/Ethernet, MPLS,	Wired / RF
Revenue Metering	Zigbee, Wi-SUN, SML	Historical	Latency is moderate to high, moderate bandwidth and throughput (tolerates re-transmitting dropped packets), moderate availability for revenue metering, high security	LPWAN / PLC	RF / Cellular

Conclusion

Ensuring the reliable and resilient delivery of electrical energy is critical for the U.S. economy, which increasingly relies on secure communications systems to support grid operations.

Adapting to the grid of the future requires a comprehensive understanding of the differences between communication technologies that support grid operations. Implementing the right communication technology effectively supports these requirements. Developing and deploying a robust, secure communications system necessitates a systematic approach that addresses multiple key factors to ensure that the performance requirements of grid operations are met.

The preceding discussion does not cover complications related to topics such as regulatory compliance and supply chain considerations, which will potentially affect the choices made in building a communications system.

This whitepaper describes the various technologies available to meet the new challenges facing electric grid operations and discusses their limitations and advantages. The framework outlined here will be further developed in the next white paper, which will describe the communications architecture that these technologies can be used to implement.

By leveraging a systematic approach and understanding the diverse communication needs of different grid operations, utilities can enhance the reliability and efficiency of the grid as it evolves to accommodate distributed energy resources, advanced metering, and real-time monitoring, all of which demand robust and flexible communication infrastructures.

References

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APPENDIX A
Key Factors Influencing Diversity in Grid Operations

1. Service Types

Electric utilities vary significantly in the types of services they provide, which include generation, transmission, and distribution of electricity. Utilities that primarily handle generation invest heavily in technologies for power production and grid stability, while those focused on distribution prioritize smart metering and local grid management. This differentiation in service type leads to varied operational needs and resulting technology requirements.

2. Ownership Structure

The ownership structure of grid utilities further diversifies the landscape. Investor-owned utilities (IOUs), driven by shareholder value, may emphasize efficiency and innovation. Publicly owned utilities (POUs) focus on community needs and affordability, rural electric cooperatives prioritize member benefits, federal power agencies manage large-scale infrastructure with regional impacts, and local government owned (Municipality) utilities focus on solving local community objectives. These differences in ownership influence decision-making, funding, and priorities, leading to diverse operational practices and technology adoption.

3. Size and Scale

Grid utilities range from small entities serving a few hundred customers to large corporations serving millions. Larger utilities typically have more resources to invest in advanced technologies and handle extensive transmission networks. In contrast, smaller utilities may focus on localized distribution and community-based solutions. This variation in size and scale affects their capabilities in managing complex grid systems and adopting new technologies.

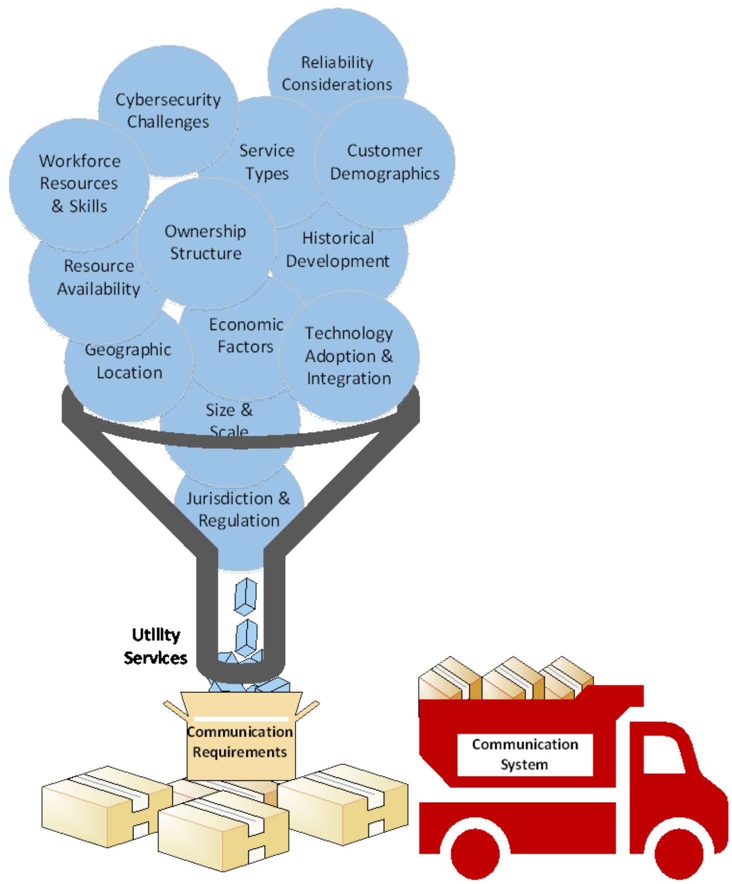

Figure A-1. Key factors shape utility services. Communications requirements protect those services as they move to their destination.

4. Geographic Location

The geographic location of a grid utility significantly influences infrastructure needs and operational challenges. Urban utilities may focus on managing dense network traffic and integrating distributed energy resources, while rural utilities might prioritize long-distance transmission and resilience against natural disasters. Geographic diversity necessitates customized technology solutions suited to local conditions and resource availability.

5. Jurisdiction and Regulation

Regulatory frameworks vary from local to federal levels and play a crucial role in shaping grid utility operations and technology adoption. Regulations can either facilitate or hinder the deployment of new technologies by allowing or disallowing the recovery of related expenses, mandating specific reporting requirements, or requiring compliance with new standards. This regulatory diversity leads to varied approaches in technology deployment across utilities, reflecting their need to navigate different compliance landscapes and reliability mandates.

6. Technology Adoption and Integration

The level of technology adoption across electric utilities is influenced by economic conditions, access to resources, and historical development. Utilities with better access to financing and modern infrastructure can adopt newer technologies and enhance grid operations more rapidly. In contrast, those with older infrastructure may face challenges in modernization. This results in a varied range of technological capabilities and grid modernization levels, highlighting the need for tailored solutions to meet the unique needs of each utility.

7. Customer Demographics

Different customer bases, including residential, commercial, and industrial users, influence grid utility operations. Industrial-heavy regions may focus on high reliability and power quality, while residential areas emphasize energy efficiency and demand management. This customer diversity necessitates different grid management strategies and technology deployments.

8. Resource Availability

The availability of natural resources, such as water, wind, and solar energy, influences the energy mix and generation technologies used by grid utilities. Regions rich in renewable resources may invest heavily in green technologies, while those with abundant fossil fuels rely more on traditional power plants. This resource availability drives diverse approaches to energy production and grid management.

9. Historical Development

The historical evolution of a grid utility, including legacy infrastructure and past investments, shapes current operations and technological capabilities. Utilities with older infrastructure may face challenges in upgrading their grid, while newer utilities have more flexibility in adopting state-of-the-art technologies. This historical context affects the pace and extent of technology transitions.

10. Economic Factors

Economic conditions and financial considerations, such as budget constraints and equipment depreciation, are critical factors in determining the feasibility of technology transitions. Grid utilities must balance the cost of new technology investments with the need for financial prudence and the recovery of existing investments. High transition costs and extensive financial planning requirements can act as barriers to adopting new technologies, leading to diverse levels of technological maturity across utilities.

11. Workforce Resources and Skills

The availability of skilled personnel and the capability to train or retain staff for new technologies influence the pace of technology deployment. Grid utilities must consider the long-term implications of training and maintaining staff for new technologies versus retaining expertise for legacy systems. Workforce diversity affects how utilities approach technology upgrades, with some focusing on incremental changes and others investing in significant upgrades.

12. Reliability Considerations

Ensuring grid reliability is a critical concern for grid utilities. The deployment of new technologies must be carefully planned to avoid service disruptions. The need to schedule outages for technology upgrades and the potential impact on grid stability require utilities to carefully plan these transitions and be flexible with outages to allow for delays if the grid is temporarily stressed. In high-availability environments, planning for a “make before break” cutover, where the new technology is run in parallel with the legacy technology is often used.

This operational diversity leads to different strategies for integrating new technologies to minimize disruptions to the grid.

13. Cybersecurity Challenges

The integration of new technologies introduces new cybersecurity risks, while legacy systems may have vulnerabilities that lack vendor support. Grid utilities must navigate these challenges by developing a cyber posture of implementing security measures that protect against evolving threats while maintaining compliance with regulatory standards and preserving the function of the system being protected. The varying levels of cybersecurity readiness reflect diverse approaches to safeguarding infrastructure.

APPENDIX B
Example of Third-Party Service Offerings

Service Type	Description	Typical Use Cases
Internet Access	High-speed internet access, typically ranging from 1 Gbps to multiple terabits per second.	General internet access for homes and businesses.
Dedicated Internet Access (DIA)	Dedicated fiber connections for businesses with guaranteed bandwidth and service level agreements (SLAs).	Business internet requiring high reliability and speed.
Multiprotocol Label Switching (MPLS)	Private networks supporting multiple types of traffic (voice, video, data) with enhanced performance and manageability.	Enterprise networking, traffic management.
Virtual Private LAN Service (VPLS)	Allows geographically dispersed sites to connect as if they were on the same local area network (LAN).	Corporate LANs across multiple locations.
Ethernet Private Line (EPL)	Point-to-point connections providing dedicated bandwidth and low latency.	Critical business applications requiring dedicated links.
Ethernet Virtual Private Line (EVPL)	Supports multiple virtual connections over the same physical line.	Flexible point-to-point or point-to-multipoint links.
Ethernet LAN (E-LAN)	Multipoint-to-multipoint service allowing several locations to connect over a single, scalable network.	Wide area networks for enterprises.
Dark Fiber	Leasing of unused fiber optic cables where customers manage their own network equipment.	Custom network deployments needing full control.
Optical Wavelength Services (OWS)	Uses Wavelength Division Multiplexing (WDM) to transmit multiple data streams simultaneously over a single optical fiber.	High bandwidth applications, long-haul networks.
Direct Cloud Connect	Private, high-speed connections to cloud service providers, enhancing security and performance.	Cloud-based applications, data storage.
Voice over IP (VoIP)	High-quality voice communication services delivered over fiber networks.	Control Center to Control Center
Data Center Interconnect (DCI)	Connects multiple data centers, enabling efficient high-speed data transfer, disaster recovery, and business continuity.	Data center connectivity.