SPaRC

Secure Pathways for Resilient Communications



Introduction to Transmission Mediums for Secure Communication

U.S. DEPARTMENT of ENERGY | Office of Electricity

1. Introduction

Modern electric grid operation depends on the reliable exchange of information across geographically distributed assets. At its foundation, this exchange is enabled by physical communication mediums that provide a controlled pathway for transporting signals between endpoints.

From early telegraph systems utilizing bare conductive wires to today's high-speed digital communication networks, the fundamental requirement has remained unchanged: a signal must be transmitted across distance and received in a form that can be accurately interpreted.

This white paper reframes the discussion of communication mediums from a technology-centric view (e.g., copper vs. fiber) to a physics-based perspective, examining how different mediums support the propagation of information, how they interact with their environment, and how they influence communication performance, reliability, and security.

Ensuring secure communication within the electric utility infrastructure is essential for maintaining reliable and resilient energy distribution. A secure communications system protects the end-to-end physical pathway that transports data from origin to destination[1]. This Secure Pathways for Resilient Communications (SPaRC) white paper examines the various physical mediums utilized for communications that can support this critical pathway. Communication is the enabler of grid coordination, and the physical pathway is the foundation of Quality of Service and security.

2. The Role of a Communication Medium

A communication medium provides a bounded and controlled pathway through which energy is used to transport information between two endpoints. Regardless of the specific technology employed, all communication systems rely on the ability to transmit a signal across distance and recover that signal at the receiving end with sufficient fidelity to enable correct interpretation.

The presence of a defined physical pathway introduces some degree of determinism into the communication process. A guided transmission medium constrains how the signal propagates, allowing for predictable behavior in terms of latency, attenuation, and environmental interaction. This predictability is essential for applications that depend on consistent communication performance, particularly within electric grid operations where timing and reliability are critical.

Equally important is the role the medium plays in preserving signal integrity. As a signal propagates, it must maintain its amplitude, timing characteristics, and overall structure in the presence of environmental influences and inherent physical limitations. Degradation of these characteristics can result in errors, delays, or loss of information, directly impacting the performance of the communication system. In this way, the physical medium is not simply a passive conduit, but an active determinant of communication quality.

[1] https://securecomms.ornl.gov/publications/Grid-Communication-Technologies.pdf

3. Evolution of Communication Mediums

The development of communication systems has been marked by significant technological advancement, yet the fundamental requirement of transmitting interpretable signals over distance has remained constant. Early systems such as the electric telegraph relied on simple conductive pathways, where information was encoded through the presence or absence of voltage on a wire. This approach evolved into analog telephony, where continuous electrical waveforms represented voice signals, and later into time-division multiplexed systems that introduced structured and deterministic sharing of communication channels.

Modern communication networks, dominated by Ethernet and Internet Protocol (IP), have abstracted much of the underlying physical behavior through packetization and digital encoding. Despite this abstraction, these systems remain fundamentally dependent on the physical medium for signal transport. Whether the signal is carried as an electrical waveform, an optical pulse, or a radiated electromagnetic wave (cellular, microwave, or any radio frequency (RF) transmission), communications are still bound by the laws of physics that can constrain their medium. Signal degradation, propagation delay, and environmental interactions continue to define the limits of communication performance.

This continuity across generations highlights a critical insight: while protocols and architectures evolve, the physical medium remains the foundational layer that ultimately governs what levels of performance can be achieved.

4. Canonical Classification of Communication Mediums

Communication mediums can be most effectively understood by examining the mechanism through which they propagate signals. From this perspective, communication mediums fall into three primary categories: conductive electrical mediums, dielectric (optical) mediums, and unguided or radiated mediums.

Conductive electrical mediums transmit information through controlled variations in voltage or current within a physical, conductive material, typically copper or aluminum. This category encompasses a wide range of commonly used cable types, including twisted pair cables, coaxial cables, and control wiring, as well as systems such as Power Line Carrier (PLC), where communication signals are superimposed onto existing power conductors. These mediums are widely deployed due to their compatibility with existing infrastructure and cost-effective installation. However, because they rely on electrical conduction, their performance is inherently influenced by electromagnetic interference, grounding practices, and impedance characteristics.

Dielectric or optical mediums transmit information as light through physical, non-conductive materials such as glass fiber. Optical systems provide substantial advantages in bandwidth and transmission distance and their immunity to electromagnetic interference (EMI) makes them particularly well-suited for electrically noisy environments such as substations. It should be noted that while the fiber lines themselves are fairly EMI resilient, their connectors and switches are not. These benefits come at the cost of requiring specialized equipment to convert between electrical and optical domains, as well as greater installation complexity in some applications.

Unguided or radiated mediums transmit information through electromagnetic waves propagating in free space. This includes RF, cellular (LTE and 5G), microwave, and satellite-based communication systems. Because these mediums do not rely on a physical conductor between endpoints, they can enable rapid deployment and can provide connectivity across large geographic areas. At the same time, their performance is strongly influenced by environmental conditions, spectrum availability, and potential interference or obstruction. Viewing communication mediums through this physics-based classification provides a consistent framework for evaluating their applicability across diverse grid communication scenarios.

5. Signal Degradation Mechanisms

As signals propagate through any physical medium, they are subject to a range of degradation mechanisms that can impair their integrity and limit communication performance. These effects are inherent to the physics of the medium and must be considered in both system design and deployment.

Attenuation is one of the most fundamental mechanisms, representing the gradual loss of signal strength as energy is dissipated within the medium. As attenuation increases with distance, the signal becomes more difficult to distinguish from background noise, ultimately limiting the effective communication range unless amplification or regeneration is employed. This attenuation can be seen across all mediums such as RF, cellular, microwave, and satellite-based signals being scattered and absorbed through the atmosphere, electrical signals decreasing over distance due to the resistance of the wire or light being scattered or lost due to degradation of the glass through which they are transmitted.

Reflection occurs when there are discontinuities in the transmission path, typically due to impedance mismatches. In such cases, a portion of the signal is reflected back toward the source, interfering with the forward-propagating signal and distorting the waveform observed at the receiver. This effect becomes increasingly significant in high-speed communication systems, where even small impedance variations can introduce measurable distortion.

Interference is the result of external, non-communication signals introduced into the transmission medium. The most obvious example is in the RF medium where multiple RF sources are sharing the spectrum. This interference is often referred to as noise and it can be introduced to almost any medium. Interference in a communication channel can be represented by two people attempting to have a conversation in a crowded, noisy room. They can still have a conversation, but some words may be lost or need to be repeated.

In conductive mediums, EMI represents a major source of degradation. External electric and magnetic fields generated by nearby equipment—such as transformers, switchgear, and power lines—can induce unwanted currents in the communication conductor. These induced signals manifest as noise, reducing the signal-to-noise ratio and increasing the likelihood of errors. Crosstalk between adjacent conductors can produce similar effects, particularly in densely bundled cables where coupling between pairs is more likely.

These EMI effects further contribute to the distortion of the signal and can make accurate interpretation at the receiver more difficult. Collectively, these degradation mechanisms influence key communication performance metrics such as bit error rate, packet loss, latency variation, and overall system reliability.

As such, understanding and mitigating these effects is central to achieving the levels of Quality-of-Service required for modern grid operations.

6. Communication over Existing Infrastructure and Emerging Alternatives

In many utility environments, communication systems are purpose-built communication pathways that leverage existing utility infrastructure where it reduces the cost to deploy and operate the communications system and maintains resiliency. This approach leverages conductive mediums originally designed for power delivery, such as transmission and distribution lines, to carry communication signals. Technologies such as PLC, distribution line carrier systems, and protocols operating over control wiring exemplify this model.

When communication is implemented over these existing conductors, the medium is not optimized for data transmission and therefore inherits the electrical and environmental characteristics of the power system. High levels of electrical noise, variable impedance, and transient disturbances associated with switching events and faults can significantly impact signal integrity. These conditions often limit achievable data rates and introduce variability in communication performance.

Despite these limitations, the use of existing infrastructure has historically provided a practical and cost-effective means of establishing communication pathways across wide geographic areas without requiring extensive new construction. However, advances in communication technology are increasingly providing alternatives that can offer improved performance while maintaining broad coverage. Optical fiber and microwave links are two commonly utilized communication channels.

One notable development is the rapid expansion of low Earth orbit (LEO) satellite communication systems. These systems provide high-bandwidth connectivity across large geographic regions, including remote areas where traditional infrastructure is limited or unavailable. LEO-based systems can offer significantly improved communication performance and consistency over other applications, particularly for data-intensive, latency-insensitive applications. It should be noted that, for timing critical information such as protection systems, LEO-based comms links cannot yet be relied upon to have deterministic timing[2].

As a result, utilities now have access to a broader set of options for extending communication networks beyond traditional wired infrastructure. While PLC and similar technologies remain valuable in specific use cases, particularly where leveraging existing assets is advantageous, emerging alternatives such as LEO satellite communications are reshaping how wide-area connectivity can be achieved in modern grid architectures.

[2] Edmund Widl, Adolfo Anta, Anna Volkova, Hermann de Meer, Christof Brandauer, and Jonas Wohnig. 2026. Power Grid Black-Start through LEO Satellite Communication. In Proceedings of the 17th ACM International Conference on Future and Sustainable Energy Systems (E-Energy '26). Association for Computing Machinery, New York, NY, USA, 742–755. https://doi.org/10.1145/3744255.3811737

7. Relationship To Quality-of-Service (QoS)

The physical communication medium forms the foundation upon which all higher-level communication performance characteristics are built. Metrics such as latency, bandwidth, jitter, packet loss, and availability are often discussed in the context of network protocols and architectures, but they are fundamentally constrained by the behavior of the underlying medium.

Propagation delay, for example, is directly determined by the physical properties of the medium and the distance between endpoints. Similarly, the capacity of the medium defines the upper limits of achievable bandwidth, while susceptibility to noise and interference influences error rates and reliability. Variability in signal propagation and degradation contributes to jitter and packet loss, both of which can have significant impacts on applications requiring real-time or near-real-time performance.

As the electric grid becomes increasingly reliant on real-time coordination of distributed resources, these performance characteristics become critical. Communication systems must deliver data with sufficient speed, accuracy, and consistency to support protection, control, and operational decision-making. In this context, the selection and deployment of an appropriate physical medium is not simply an infrastructure decision, but a foundational element of overall system performance and resilience.

8. Implications for Grid Communication Design

The selection of a physical communication medium requires careful consideration of both the operational requirements of the grid and the environmental conditions in which the system will be deployed. Factors such as electromagnetic interference, terrain, distance, and infrastructure availability all influence the suitability of a given medium. At the same time, performance requirements related to latency, bandwidth, reliability, and availability must be met to ensure proper operation of grid functions.

No single communication medium is universally optimal. Instead, most utility communication networks are constructed using a combination of medium types, each selected to meet specific performance and deployment needs. Conductive mediums may be used for short-distance or cost-sensitive applications, optical fiber for high-capacity backbone communications, and wireless or satellite systems for high capacity, limited distance, remote or rapidly deployable connectivity.

By adopting a physics-based understanding of communication mediums and their relationship to system performance, utilities can make more informed decisions about how to mitigate some problems that can arise in their communication systems. This approach supports the development of resilient, adaptable communication systems capable of meeting the demands of the modern electric grid.

Upcoming white papers will provide more information about specific wired and wireless options for physical communication mediums

For more information, please visit https://securecomms.ornl.gov or email *SpaRC@ornl.gov*.









The US Department of Energy's SPaRC (Secure Pathways for Resilient Communications) program is leading grid communications research and development through a testbed spread across multiple DOE National Labs, established to design, test, evaluate, and benchmark next-generation secure communications architectures and technologies. A secure communications system protects the end-to-end physical pathway that transports data from origin to destination. Key SPaRC activities include the Grid Communications Test Bed, Next-Generation Communication Experiments, and Education & Technical assistance. For more information see: https://securecomms.ornl.gov/