SPaRC

Secure Pathways for Resilient Communications



Transmission Mediums for Secure Communication – Metal Conductors

U.S. DEPARTMENT of ENERGY | Office of Electricity

1. Introduction

This white paper outlines the physical characteristics, benefits, and limitations of using metal conductors as a communication medium, emphasizing how conductive materials, like copper, enable data transmission but can also make cables vulnerable to electromagnetic interference. This covers common cable types such as serial, coaxial, and Ethernet, and explains how their construction, shielding, and impedance properties influence signal integrity and suitability for various environments. The paper highlights how electromagnetic fields can induce noise, degrade data quality, and reduce transmission range, and explains mitigation techniques such as proper shielding, grounding, connector selection, and thoughtful cable routing. It also illustrates the importance of choosing and installing wired communication mediums based on environmental conditions to ensure reliable network performance.

2. Background

In 1837 Samuel Morse transformed modern communication by introducing the electric telegraph. Data was transmitted on a copper wire over long distances by connecting and disconnecting an electrical source to the wire. Today's modern communication networks are the result of the evolution of this seemingly simple technology. Copper, and sometimes aluminum, wires are now commonly used for local communication. Although a network utilizing optical fiber may also be described as a "wired" network, this Secure Pathways for Resilient Communications (SPaRC) white paper examines only the advantages and disadvantages of using a metal wire for communication. Optical fiber as a communication medium will be discussed in a later paper.

3. Context

When discussing the performance of a wired communication network, it is difficult to separate the communication protocol from the physical medium itself. The metrics frequently associated with a network such as latency, bit error rate and bandwidth, are dependent on the protocol being used and the architecture of the network in combination with the physical medium. This white paper will attempt to discuss only the physical attributes of a metal wire being used as the communication medium. Information and recommendations for the more network architecture-based factors can be found in other publications on the SPaRC website https://securecomms.ornl.gov.

Physically, a wire used for communication generally contains a minimum of at least two parts: an internal core made of a conductive metal and an outer sheathing material made of some non-conductive material. Data is transmitted via this medium by changing either the voltage potential or the current in the conductor in some manner. These methods can be used to transfer either analog or digital information. For analog information, a direct mapping of current or voltage measurement is often (but not always) used to transmit measured values such as temperature or pressure. The most basic form of digital encoding is to represent individual bits of digital information as a measurable voltage. When the measured voltage is above or below a specified threshold, it is assumed to represent a "bit" of either a '1' or a '0'. This basic structure can be expanded to use both positive and negative amplitude to differentiate between bits. Other systems, such as Highway Addressable Remote Transducer (HART), can use the frequency of the

voltage modulation to represent the bits. One frequency is used to represent a '1' and a different frequency is used to represent a '0' bit.

The conductive nature of the wire is both a necessary feature and a disadvantage. Without proper precautions, many environmental factors can interfere with data transmission. Electromagnetic fields, such as those produced by high power transmission lines and rotating machinery, can induce current in the conductive medium which could cause a data signal to be distorted. This effect can also be seen if multiple wires transmitting different information are bundled together. Through inductive coupling, one wire may induce a signal on another wire causing data degradation.

Although there are many ways to mitigate these effects through both the construction of the cables themselves and proper installation practices, when designing a communication network for power infrastructure, it is critical to consider all the advantages and disadvantages of a particular data transport medium.

4. Options

There are many types of cables used in modern communication networks. The three common types of cables found in many power control system applications are serial, Ethernet, and coax. A wired communication cable always contains at least one conductor and a protective sheath. The conductors can be either solid core or stranded. A stranded core is one that consists of multiple smaller conductors bundled together into a single sheath. Another common feature of many cables is the shielding. This shielding can consist of a foil and/or braid made of a conductive metal such as copper or aluminum. Some cables may use both types of shielding.

Serial cables are generally composed of multiple stranded conductors bundled into a single sheath. The individual conductors are rarely individually shielded. The bundle itself can be either shielded or unshielded. Cable shielding and its importance will be addressed later in this paper. See *Figure 1* for representative serial cable examples.

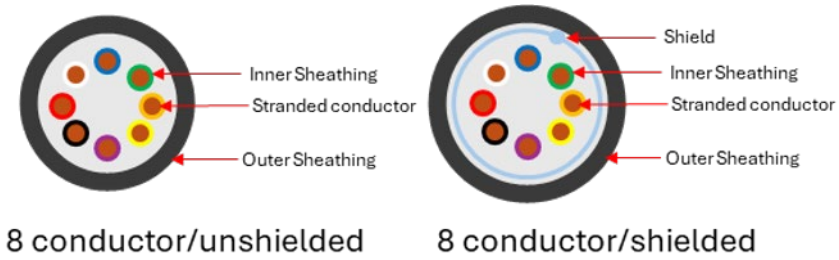


Figure 1: Serial Cable Cross Section

It is not uncommon for substation equipment such as relays to provide serial connections for some functions. In general, these are D-subminiature connectors with 9 pins or DB9 connections.

Another common cable is the coaxial cable. This cable consists of a solid core conductor surrounded by a dielectric. This type of cable always includes some amount of shielding. The shielding can be a single braided metal shield or multiple braided shields combined with a metal foil shield(s). The cable is then surrounded by an outer sheathing of some non-conductive

material. There are multiple varieties of coax ranging from lightly shielded cables like RG-58/59, to the more commonly used RG-6 and the larger core RG-11. The amount and types of shielding can vary even among the same RG version of cable. It is critical to evaluate the cable's construction before purchasing. For example, some coax cables are rated at 50 ohms impedance while another common option has an impedance of 75 ohms. Correctly matching the impedance as well as checking the frequency range and loss/attenuation for a given network is essential for reliable communication. *Figure 2* provides representative examples of some different coax cable configurations.

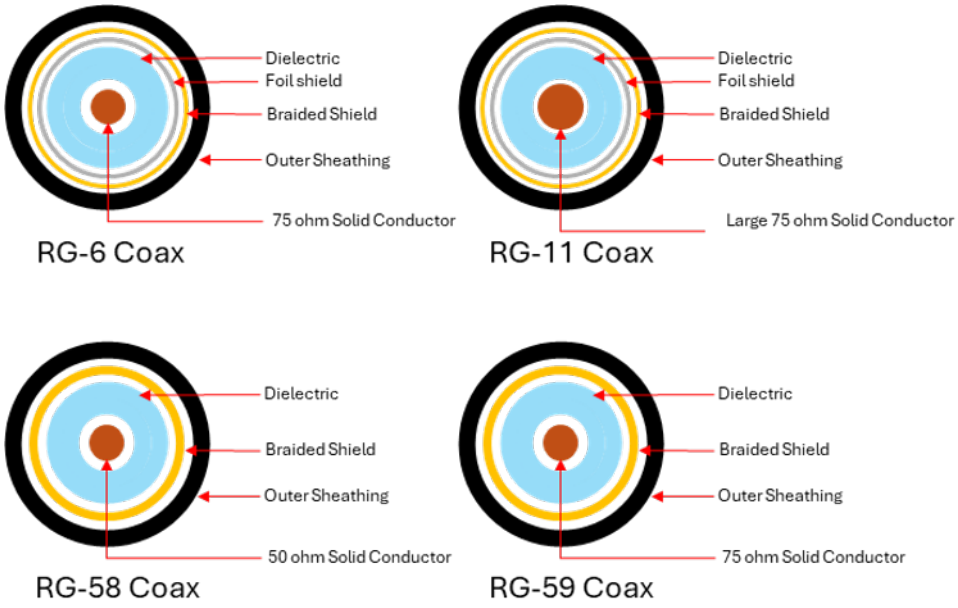


Figure 2: Coax Cable Cross Section

The use case of the cable and the installation environment should be determining factors in which type of coax cable to use. Coax, when used in and around power infrastructure, will often be used to connect RF transceivers to antennas or in some cases for networking between devices. It is important to assess the level and type of shielding required for the environment in which the cable will be used.

The most common form of metal conductor communication cable in use today is the Ethernet cable. It is designed for use in a communication network employing the Ethernet protocol specified in IEEE 802.3. Modern Ethernet cables consist of pairs of wires twisted around each other; often referred to as a "twisted pair". Each pair of wires transmits data in one direction. One wire is the '+' conductor and the other is the '-' conductor. This method of data transmission is called a differential pair. A receiver will compare the two signals to determine what bit is being represented. By twisting the pair around each other the effects of any external interference will affect each conductor equally. The receiver will invert one of the signals and sum them. Any interference will also be inverted and when summed with its inverted self will be mostly eliminated. The twist rate (the number of twists per length of wire) will also provide a specific capacitance per pair that can help minimize any coupling that might occur on an adjacent pair in the same cable. Most currently used Ethernet cables (cat5, cat5e, cat6, etc.) contain 4 of these twisted pairs even though some networks only use two of them. The connector is typically an RJ-45.

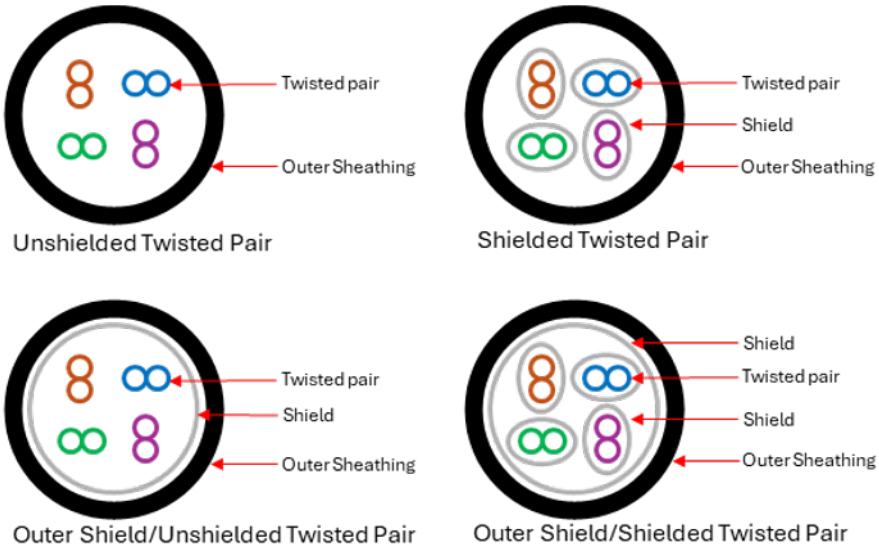


Figure 3: Ethernet Cable Cross Section

Ethernet cables can be purchased with a variety of shielding materials and configurations. *Figure 3* provides examples of 4 basic types of cable construction. As with every other cable discussed, it is important to understand and assess the environment in which the cables will be installed and used before selecting the appropriate type of cable.

5. Concerns to be Considered When Using Metal Conductor Communication

The same attributes that make some metals like copper and aluminum excellent options for transmitting information using electricity also make them susceptible to electromagnetic interference.

Electromagnetic interference is a broad term for any unwanted effect resulting from an electrical or magnetic source. A voltage difference on a conductor can produce an electric field. Electrical current flowing through a conductor will produce a magnetic field. Both types of fields can be disruptive by producing spurious unintended electrical fluctuations on the communication medium. When a communication line is too close to either an electric or magnetic field, these fluctuations can cause "noise" in the data carrier. This noise can make it difficult for a device to accurately interpret the received data[1].

This result can be corrupted or missing data as well as reduction in the effective distance over which data can be transmitted. Many types of devices can produce electromagnetic fields during operation. Some fields are relatively stable and constant while others can be short impulse bursts.

Examples of devices which could produce these fields around a typical substation are:

- Switchgear

[1] "Case Studies of Telecommunication Failure Caused by Electromagnetic Noise from Inverters," NTT Technical Review, Vol.18, No. 6, (June 2020): pp. 58–64, https://doi.org/10.53829/ntr202006pf1.

- Capacitors
- Battery chargers
- Transformers
- Distribution/transmission lines

6. Mitigations

The most basic mitigation for the disruptive effects of electromagnetic noise is to install cables away from potential sources of electromagnetic interference. Unfortunately, this is not always possible.

The next and most frequently employed mitigation is to use cables with internal shielding. This shielding is usually in the form of either a wire braid or a metal foil surrounding the sheathed wire(s) or dielectric. Most types of cables have multiple options for number and types of shields as discussed earlier in this paper. Generally, the better the shielding the more expensive the cable. Understanding the amount of electromagnetic interference to which a cable might be exposed can help determine the minimum amount of shielding required. This can help control the cost of installation. Additionally, shielded connectors should also be used. Unshielded connectors can allow even shielded cables to be affected by existing fields.

An additional precaution is occasionally overlooked. It is important to properly ground a cable and/or connector's shielding. When grounding a connector or cable, it is important to prevent a ground loop. A ground loop can occur when the two ends of the cable are grounded to different ground potentials. This ground loop can result in a hum if it is used for audio transmission or noise effects if it is a data connection. If the communication equipment on either end of the cable is not connected to the same ground, it is important to choose only one end of the cable for the shield ground.

7. Recommendations

To ensure metal conductor communications are operating within their capabilities users should review potential electromagnetic interference sources in the area to make sure signals on the line are not from unwanted sources. One of the most basic steps is to ensure matching impedance across connections, checking the attenuation of signals across the line, and ensuring the frequency ranges on the cables and connections are within operating range. Appropriately shielded cables and connectors should be used whenever possible since they can be weak points in the metal conductor communication chain[2]. Additionally, cables should be routed away from potential interference sources and wire shielding should be properly grounded.

If the potential for electromagnetic interference is significant, consider using alternative communication transmission mediums such as fiber or wireless.

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[2] MARTIN, A.R. (1982), HOW TO CHOOSE CABLE SHIELDING FOR EMI REDUCTION. Naval Engineers Journal, 94: 46-51. https://doi.org/10.1111/j.1559-3584.1982.tb02502.x

These options will be discussed in future white papers.

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/