Network Engineering: An Introduction to Signal Transmission

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I. Introduction

Network Engineering is a field responsible for the interconnection of multiple different network services in communication ranging from telephone networks to computer networks. It involves creating network architecture and configuring the network hardware and software through both wired (guided media) and wireless (unguided media) technologies to maintain and operate the communication systems.

II. Guided Media

Guided media, a physical medium where signals are transmitted, forms the physical foundation of network infrastructure, largely in wired networks. There are many types of guided media, most popularly: open wire, twisted-pairs, coaxial cables, and fiber-optic cables. All of the types of guided media mentioned, except fiber-optic cables, share a common characteristic. Open-wire, twisted-pairs, and coaxial cables all use copper in order to provide a physical path for the signals to transmit.

A. Open-wire

Open-wire, an older technology no longer relevant in the modern age, is a system of bare or insulated conductors (copper) attached to insulators (glass or porcelain) by tie wire. The conductors, or lines, are connected through poles between consumers and an intermediate switching point. Though open wire lines may be interpreted as endless lines and poles between different points, the engineering behind the technology allowed for weather protection through protection of its electronics and terminals.

B. Coaxial Cables

Coaxial Cable, also known as coax, is another type of guided media used in the modern age by telephone companies and internet providers to transmit data, whether visual or auditory. Coaxial cables transmit data in electrical form through a certain structure that ensures protection of the data transmitted. At its core, a central conductor, usually made of copper, used for the transmission of data. Surrounding the central conductor, a dielectric medium, usually plastic, used to maintain the spacing between the central conductor and the shielding. An outer conductor surrounds the dielectric medium with the purpose of preventing electromagnetic interference (EMI) that moves into and out of the coaxial cable. Finally, all aforementioned layers are then surrounded by a protective plastic layer, an insulating jacket, that is used to protect the internals from any damage.

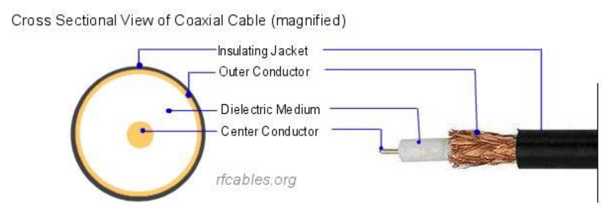

Fig. 1. Construction of Coaxial Cable

1) Types of Coaxial Cable: There are different types of coaxial cable, which vary by gauge and impedance. Gauge refers to the cable's thickness and is measured by the radio guide measurement or RG number. The higher the RG number, the thinner the central conductor core is.

Coaxial cables are differ according to the cable's thickness and its impedance. The cable's thickness, or gauge, is measured by the radio guide measurement (RG). As the RG measurement increases, the central conductor core is made to be thinner. From the impedance point of view, there are two main types of coaxial cables. First, there is the 50 Ohm cable; it is used mainly for data and wireless transmissions. Second, there is the 75 Ohm cable; it is used mostly for video transmission. The most common sizes of coaxial cables are RG-6, RG-11, and RG-59.

a) RG-6: RG-6 cables have larger conductors, which enhances signal quality. Their thicker dielectric insulation and shielding allows them to handle GHz level signals more effectively. Additionally, their thin design makes them easy to install in walls or ceilings.

b) RG-59: RG-59 cables are similar to RG-6 but have a thinner center conductor. This makes them ideal for short distances and low-frequency transmissions. They're common in domestic settings.

c) RG-11: RG-11 cable is characterized by its thickness, which can make it harder to handle. However, it has a lower attenuation level compared to RG-6 or RG-59, allowing it to transmit data over longer distances.

2) Connectors of Coaxial Cables and Their Types:

a) BNC Connector: BNC Connector, or Bayonet Neil-Concelman, are coaxial connectors used for quick setup in RF

Fig. 2. Types of Coaxial Cable

equipment, test instruments, radio, television, and video signal. They are capable of operating at frequencies up to 4GHz.

b) TNC Connector: TNC Connector, or Threaded Neill-Concelman, are the twisted/threaded variant of the BNC connector. They are small, weatherproof products found in telephones and RF/antenna connections. They are capable of operating at frequencies up to 12GHz.

c) SMA/SMB Connectors: Sub-Miniature Version A and Sub-Miniature Version B connectors are both coaxial RF connectors used for connecting cables and equipment, but they differ in size and coupling mechanisms; SMB connectors are smaller with a snap-on mechanism, while SMA connectors are slightly larger with a threaded mechanism. SMB connectors typically operate up to 4 GHz, whereas SMA connectors can handle frequencies up to 18 GHz or higher, offering lower insertion loss. Both types come in male and female variants and are used in various RF applications.

Fig. 3. Connectors of Coaxial Cable

C. Twisted-Pairs Cables

Twisted pair cables consist of two copper conductors, each with its own insulation, twisted together. One conductor carries the signal, while the other serves as a ground reference. The receiver detects the signal by comparing the difference between the two conductors. While parallel conductors are prone to high noise or cross-talk, this is significantly reduced in twisted pair cables due to the twisting. In one twist, one conductor is close to the noise source and the other is farther away; in the next twist, the positions reverse, balancing the noise and maintaining signal quality. This results in minimal noise reaching the receiver. The signal quality in twisted pair cables largely depends on the number of twists per unit length.

1) Types of Twisted-Pair Cables:

a) Unshielded Twisted-Pair Cables: Unshielded Twisted-Pair Cables are two insulated copper wires twisted without further insulation or shielding. The interference resulting from the EM waves is canceled only through the twisting. UTP Cables are arranged in pairs with a specific color code.

b) Shielded Twisted-Pair Cables: These cables have additional insulation or protective covering over the conductors, usually in the form of a copper braid. This covering strengthens the cable's structure and reduces noise and signal interference. The shielding allows the induced signal to be returned to the source via the ground and circulate around the shield without affecting the main signal. Shielded Twisted Pair (STP) cables, like Unshielded Twisted Pair (UTP) cables, are color-coded for different analog and digital transmission needs. However, STP cables are more expensive and harder to install. The extra insulation around the copper pairs enhances protection from electromagnetic interference (EMI), reducing noise and signal interference.

2) Difference between UTP and STP Cables: UTP cables are cost-friendly and offer easier installation over STP cables. They are used for short-distance transmission of data. However, connections built using UTP cables are not secure and are only efficient for a distance of up to 100m. In comparison, STP cables are more expensive due to the extra shielding. They are usually used for longer-distance transmission though in segments similar in length to UTP segments (up to 100m) and must only be installed underground. They also feature more bandwidth over UTP cables and require a larger amount of maintenance.

3) Categories of Twisted-Pair Cables:

a) CAT 1: UTP cables used in telephone lines

b) CAT 2: UTP cables used in transmission lines

c) CAT 3: UTP cables used in LANs or 10baseT Ethernet

d) CAT 4: UTP cables used in token ring networks

e) CAT 5: UTP cables used in LANs or 100baseT Ethernet

f) CAT 5e: UTP cables used in 1000baseT Ethernet

g) CAT 6: UTP cables used in high-speed LANs

h) CAT 7: STP used in super high-speed Gigabit Ethernet.

4) Pairs of Twisted-Pair Cables: Generally, Twisted-Pair cables consist of 4 pairs. In fast Ethernet, the first pair (PIN 1 and 2) is responsible for data transmission, the second pair (PIN 3 and 4) is responsible for receiving data, the third and fourth pair are either unused or used as Power over Ethernet (PoE). In Gigabit Ethernet, all pairs are used for bidirectional data transfer.

5) Connectors of Twisted-Pair Cables:

UTP Categories - Copper Cable				
UTP Category	**Data Rate**	**Max. Length**	**Cable Type**	**Application**
CAT1	Up to 1Mbps	-	Twisted Pair	Old Telephone Cable
CAT2	Up to 4Mbps	-	Twisted Pair	Token Ring Networks
CAT3	Up to 10Mbps	100m	Twisted Pair	Token Rink & 10BASE-T Ethernet
CAT4	Up to 16Mbps	100m	Twisted Pair	Token Ring Networks
CAT5	Up to 100Mbps	100m	Twisted Pair	Ethernet, FastEthernet, Token Ring
CAT5e	Up to 1 Gbps	100m	Twisted Pair	Ethernet, FastEthernet, Gigabit Ethernet
CAT6	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (55 meters)
CAT6a	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (55 meters)
CAT7	Up to 10Gbps	100m	Twisted Pair	GigabitEthernet, 10G Ethernet (100 meters)

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Fig. 4. Categories of UTP Cables

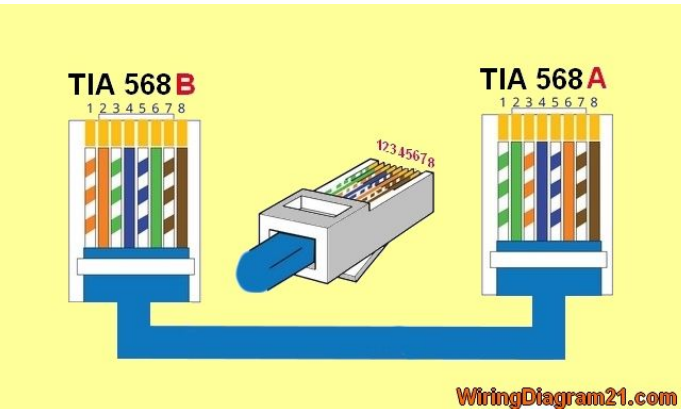

Fig. 5. Color coding of UTP Cables

a) RJ45: The standard choice for Twisted-Pair connectors is the RJ45 connector, where RJ stands for Registered Jack. The connectors consist of eight pins considering the four standard pairs of twisted-pair cables. They are commonly used for Ethernet networks in residential, commercial, and industrial networking applications

b) RJ11: Another choice for Twisted-Pair connectors is the RJ11 connector. It is similar to the RJ45 connector but with fewer pins for fewer pairs, typically 4 or 6 pins. They are used for telephone communications and for older network communication systems.

D. Optical Fiber Cables

A fibre optic cable is a type of network cable that is made up of strands of glass fibres that are enclosed in an insulated casing. They support multi-distance, high-performance data networking and telecommunications applications. As opposed to other types of guided media, fiber optic cables transmit data through light pulses instead of electricity. A fiber optic cable is made up of thin strands of glass or plastic enclosed in an insulated casing. They are characterized by their immunity to electromagnetic interference (EMI) allowing them to be utilized in high-voltage environments. In addition, due to their utilization of light pulses instead of electricity, they are also characterized by their ability of handling much larger bandwidths in comparison to electrical pulses. The use of light pulses also allows for farther distance when transporting the signal without being regenerated and without any power for at most 100km.

1) Types of Optical Fiber Cables: The different types of optical fiber cables are determined according to the size of the cable's core. In general, the smaller the core the farther the optical signal (light pulse) will go before it needs regenerated.

a) Single Mode Fiber: Single Mode Fiber Core is characterized by a standard size of 8-9 microns (um). The smaller core of the SMF allows for a more direct path making the signal travel farther without the need for frequent regeneration. SMF Cable is powered through a laser and is used for applications that need higher bandwidth and longer distances.

SMF cables are identified by their OS (Optical Fiber Cable Specification for Single-Mode) designation. OS1 is designed for long-distance transmission, and following the nature of SMF cables, only supports a single mode of light propagation. OS1 cables are utilized in telecommunications networks and data centers. It can support speeds up to 10G and distances up to 10km. OS2 is designed for long-haul telecommunication networks and backbone networks. They can support speeds up to 100G and distances of up to 200km.

b) Multi Mode Fiber: Multi Mode Fiber Core is characterized by a standard size of (50 and 62.5)um. MMF is powered through an LED and is used for applications that require shorter distances and a smaller bandwidth.

Multimode fibers are identified by the optical mode (OM) designation. The OM designation allows for distinguishing the different types of MMF cables. OM1 cables, with a standard orange jacket color, are characterized by a lower bandwidth to the other types of cables; it is used for shorter distances such as within a building. OM2 cables have twice the distance range of OM1 cables with the same speeds. OM3 and OM4 cables, with a standard aqua jacket color, are designed for high-speed data transmission over even longer distances. OM3 cables are capable of transmitting data at speeds of up to 40G, while OM4 cables are capable of transmitting data at speeds of up to 100G. Both OM3 and OM4 are used for high-speed networks, larger private networks, data centers, and more. In short, the numbers associated with these cables are an indication of their respective bandwidth capabilities.

2) Connectors of Optical Fiber Cables:

a) Adapter Panel Connectors:

- Lucent Connector (LC Connector): Most commonly-used connector in recent times.
- Square Connector (SC Connector): Suited for datacoms and telecom applications. Second most commonly-used connector.
- MTP/MPO Connector: Multi-fiber connector, used in 40G and 100G high-bandwidth optical parallel connections with complicated setup.

- Single Tip Connector (SC Connector): Used in both long and short distance networks for building multimode fiber applications.
- Ferrule Connector (FC Connector): Additional complexity in both manufacturing and installation. Not as commonly used.

Fig. 6. Adapter Panel Connectors

III. Unguided Media

A. Radio Waves

Radio waves are a form of electromagnetic radiation ranging from 3kHz to 300GHz, or a wavelength of either 1mm or 100km, on the electromagnetic spectrum. Though radio waves and microwaves are discussed separately, there is some overlap, and some even consider microwaves to be a part of radio waves as the boundaries between electromagnetic radiation is rather arbitrary.

1) Principles of Operation: The basic principle of telecommunications is comprised of a transmitter, a signal, a channel for the signal to propagate on, and a receiver. The transmitter is responsible for encoding the message and sending it at a specific wavelength. The channel is the specific wavelength or frequency where the signal travels. The receiver is responsible for obtaining the signal after tuning to the same wavelength and decoding the message, thus translating it into the desired form of data. Radio waves allow for all modern forms of telecommunication, radio, television, and more. The assigned boundaries of radio waves allow for efficient service in communications, where a band is assigned for a specific use. For example, police or fire brigade communication have their own separate band to ensure there is no interference from other sources such as radios or other personal property.

2) Modulation of Radio Waves: Some data cannot be directly sent over longer distances, this is solved by either modulation of the waves. Amplitude modulation, or AM, is the process of encoding the information of the wave according to different values of amplitude, all the while maintaining the same frequency. Frequency modulation works similarly to amplitude modulation, however, instead of altering the amplitude of the function, it encodes the data in the frequency. Decoders from the receiver are responsible for reading the changes in either the amplitude or frequency and translating them into electrical signals to be displayed as data.

B. Microwaves

Microwaves are defined as electromagnetic radiations with a frequency ranging between 300 MHz to 300 GHz. In contrast, the wavelength ranges from 1 mm to around 30 cm. Microwave radiation is commonly referred to as microwaves. They fall between infrared radiation and radio waves in the electromagnetic spectrum. A few of the properties of microwaves are as follows:

Microwaves, a subsection of Radio Waves, with frequencies ranging from 30MHz to 300GHz, or with wavelengths ranging from 1mm to around 30cm. The properties of microwaves allow them many uses. In communications, microwaves with certain wavelengths are able to pass through the Earth's atmosphere to the satellites with information encoded in the waves. This allows the metal satellite dishes to receive and transmit waves due to the microwave's reflectivity with metal.

However, not all frequencies of microwaves can be utilized in long range communication. At 60GHz, the interaction of oxygen molecules with RF waves causes significant attenuation to the waves. This occurs due to the molecular resonance of oxygen molecules being around the 60GHz frequency. Molecular resonance occurs with the matching of the frequency of the electromagnetic radiation with the natural frequency of molecules; this leads to more efficient energy absorption by the molecules, which leads to the attenuation of the electromagnetic radiation as they are absorbed into the molecules. In the case of oxygen molecules, their natural frequency is around 60GHz, this leads to the significant attenuation of microwave signals around this frequency. Similarly, water vapor causes similar attenuation at 24GHz and 184GHz.

C. Infrared

Infrared waves are electromagnetic radiation ranging in frequencies between 300GHz to 430THz, with wavelengths from 760nm to 100,000 nm (0.1 mm). Infrared waves can also be used for communications; there are two types of Infrared short-distance communication due to their relatively short wavelengths. The first type, Point to Point communication, requires a line of sight between between the transmitter and the receiver with no obstacles between them. The second type is the Diffuse Point; it differs from the Point to Point communication as it does not require a direct line of sight, but it instead relies on the reflections of the transmitted signal by the present surfaces such as ceilings, roofs, and more.

Infrared band of the electromagnet corresponds to 430THz to 300GHz and a wavelength of 980nm. The propagation of light waves in this band can be used for a communication system (for transmission and reception) of data. This communication can be between two portable devices or between a portable device and a fixed device.

IV. Networking Protocols

A protocol is a set of rules responsible for how data is sent and received over a network. Protocols help make sure that data moves smoothly and securely between devices on a network. There are certain key elements of network protocols such as syntax, semantics, timing, error control, and others. Syntax refers to the format of the data sent or received. For example, the first 8 bits are the address of the sender, and the 8 bits after that are the address of the receiver, then the remaining bits are the data. Semantics as in the rules and norms for determining the data element values and actions. Timing refers to the coordination between the devices in order to ensure the preservation of data and other timing-related issues. Error control is responsible for fixing data transmission faults through detecting and correcting noise, interference and other problems for the sake of maintaining data integrity.

A. *Types of Protocol*

a) Network Layer Protocols: Network layer protocols are responsible for packet routing, forwarding, and addressing of data packets throughout the network. IP and ICMP are the network layer protocols.

b) Transport Layer Protocols: Protocols at the transport layer facilitate end-to-end communication, ensuring the reliable transfer of data between applications on different devices. The most widely used transport layer protocols are TCP and UDP.

c) Application Layer Protocol: Operating at the application layer, these protocols enable communication between software applications on various devices. They handle the formatting, exchange, and interpretation of application data, ensuring effective cross-device communication. HTTP, FTP, and SMTP are some examples of application layer protocols.

d) Wireless Protocols: These protocols are essential for wireless communication, allowing data to be transmitted over wireless networks. Bluetooth, Wi-Fi, and LTE are notable examples of wireless protocols.

e) Routing Protocols: Routing protocols determine the most efficient paths for data transmission across a network. Routers utilize these protocols to share information and maintain routing tables, ensuring optimal data flow. Examples include RIP, OSPF, and BGP.

f) Internet Protocols: The Internet Protocol (IP) uniquely identifies devices and facilitates data communication by routing and forwarding packets between devices using a unique addressing scheme.

B. *TCP/IP Model*

This model outlines the method for data transmission across networks, ensuring reliable communication between devices. It comprises four layers: the Link Layer, the Internet Layer, the Transport Layer, and the Application Layer. Each layer has distinct roles that manage various aspects of network communication, making it crucial for understanding and working with modern networks. The primary function of TCP/IP is to facilitate the transfer of data from one computer to another. The key requirement for this process is to ensure that the data remains reliable and accurate so that the receiver gets exactly what the sender intended. To achieve this, the TCP/IP model splits data into packets for transmission and then reassembles them at the receiving end, which helps maintain data integrity throughout the transfer.

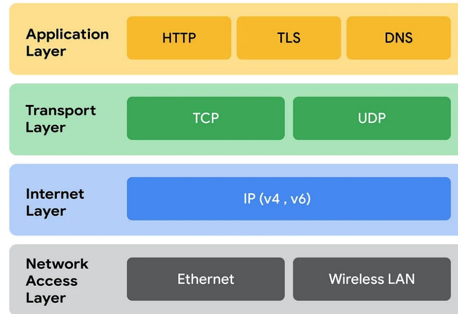

Fig. 7. TCP/IP Model

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