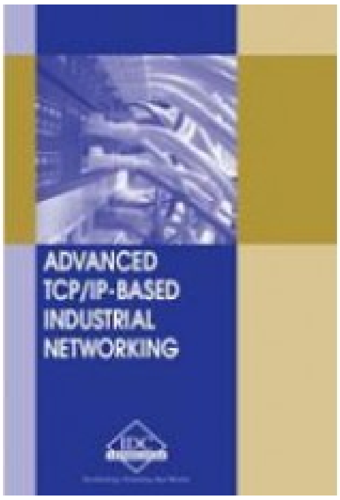
AV-E - Advanced TCPIP-based Industrial Networking for Engineers and Technicians



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Short Description

This manual is for engineers and technicians who need a practical and extensive knowledge of the design and troubleshooting of Industrial Ethernet networks, as well as the selection, installation, and configuration of components such as routers and switches.

It deals in-depth with the underlying TCP/IP protocols, and specifically addresses both design and configuration issues related to IPv4 and the more recent IPv6.

It also covers the more advanced aspects and applications of Ethernet such as advanced switching and routing, CCTV over IP, OPC and Modbus/TCP over Ethernet, industrial security, intrinsically safe applications, switched rings (included the latest IEC 62439-3 redundant ring standard), and highly-deterministic Ethernet-based field buses (e.g. for servo control) capable of 1 millisecond repetition rates and jitter of less than 1 microsecond.

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Network Interface Layer: Ethernet

Upon completion of this module, you will be able to:

- Elaborate on Ethernet, its features, and evolution
- Explain the Frame structure and MAC addresses
- Compare Bluebook (V2) with IEEE 802.3
- Explain the different Variants - 10 Mbps Ethernet, Fast Ethernet, GbE, 10GbE, 40 and 100GbE
- Elaborate on Industrial Ethernet
- Explain Intrinsically Safe (Ex) Ethernet
- Discuss Power over Ethernet (PoE)
- Explain Point-to-Point Protocol over Ethernet (PPPoE)

1.1 Introduction to Ethernet and its Origin

Ethernet is the LAN technology most commonly used today. It is an (OSI) Physical and Data Link layer technology for LANs. The Ethernet network concept was developed under the leadership of Dr. Robert Metcalfe in 1976 at Xerox's Palo Alto Research Center (PARC). It was based on the work done by the researchers at the University of Hawaii where campus sites on the various islands were interconnected with the ALOHA network, using radio as the medium. The network was colloquially known as ‘Ethernet’ since it used the ‘Ether’ (also referred to as ‘Aether’) as the transmission medium. Ethernet was originally called the Alto Aloha Network protocol or ‘ALOHAnet’ and was later renamed *Ethernet* to indicate multiplatform compatibility. This primitive system did not rely on any detection of collisions when two radio stations happened to transmit at the same time. Instead, they expected acknowledgment within a predefined time. A lack of acknowledgement indicated that the transmitted data was possibly corrupted by simultaneous transmission, and the sender would simply re-transmit.

When first widely deployed in the 1980s, Ethernet supported a bit rate (‘raw data rate’) of 10 megabits per second (Mbps). Later, the ‘faster’ Ethernet standards increased this maximum data rate first to 100 Mbps, and then to 1 gigabit per second (1 Gbps) . Today, the fastest Ethernet products support 100 Gbps, and it is envisaged that speeds will eventually increase into the terabit (1000 Gbps) region.

1.2 Progress and Evolution of Ethernet

In 1980, the Ethernet Consortium (also known as the DIX consortium) consisting of Xerox, Digital Equipment Corporation (DEC), and Intel issued a joint specification based on the Ethernet concept, known as Ethernet Version 1. This was later superseded by the Ethernet Version 2 (‘V2’), also known as the Blue Book specification.

Version 2 was offered to the IEEE for ratification as a formal standard and in 1983 they issued the IEEE 802.3 CSMA/CD (Ethernet) standard. IEEE 802.3 was based largely on the DIX specification, but with small changes in frame format. Like Ethernet, IEEE802.3 uses a medium access method called *Carrier Sense Multiple Access with Collision Detection* or CSMA/CD. Using CSMA/CD, all computers monitor the transmission medium and wait till the line is available before transmitting. When two computers accidentally transmit simultaneously, a collision occurs and the frame (packet) is corrupted. Both computers will stop and attempt to transmit again after a certain (random) time interval.

1.3 Comparison between Bluebook (V2) and IEEE 802.3

The following table shows the differences between IEEE 802.3 and Ethernet Blue Book 2:

IEEE 802.3	**Ethernet Blue Book 2**
IEEE 802.3 supports bus and star topology	Supports only bus topology
Supports both baseband and broadband signalling	Supports only baseband signalling
Data Link Layer (DLL) divided into LLC and MAC	No division of DLL
Consists of 7 octets of preamble plus SFD	Consists of 8 bytes with no separate SFD
The Type field of Ethernet V2 is represented here as Length field in data frame	Has a Type field in data frame

The voltage swings were from –0.225 to –1.825 volts in the original Bluebook Ethernet specification. In IEEE 802.3 voltages on coax cables are specified to swing between 0 and –2.05 volts with a rise and fall time of 25 ns at 10 Mbps. IEEE 802.3 voltages on UTP swing between -0.7V and +0.7V.

1.4 Basic Features of Ethernet

Here are some of the basic features of Ethernet:

- Legacy Ethernet transmits data at a clock speed of 10 Mbps. Fast Ethernet supports 100 Mbps, Gigabit Ethernet supports 1 Gbps or 1,000 Mbps, and 10 Gigabit Ethernet supports 10 gigabits per second (10,000 Mbps). 40 Gbps and 100 Gbps are also currently available.
- Legacy Ethernet supports networks built with Cat3 twisted-pair (10BaseT), thin and thick coaxial (10Base2 and 10Base5, respectively), and fiber-optic (10BaseF) cabling. Faster Ethernet networks can be built with Cat5e twisted-pair (100/1000BaseT) and fiber-optic (100BaseFX/1000BaseSX/1000BaseLX) cabling. All Ethernet versions up to 1 Gbps support twisted-pair, and all versions up to 100 Gbps support

fiber-optic cables. Currently, 100BaseTX and 1000BaseT Ethernet is the most common for use within buildings.

- Data is transmitted over the network in discrete packets or frames which are between 64 and 1,518 bytes in length (not including the preamble). Jumbo frames can carry payload up to 9000 bytes. To use Jumbo frames, the network must support Jumbo frame packets. The IEEE Ethernet standard supports only 1500-byte frames, but manufacturers are incorporating 9000 bytes as the conventional jumbo frame size.
- Each device on an Ethernet network operates independently and equally, and does not need a central controlling device.
- Ethernet supports a wide array of protocols, such as, DECnet, Novell IPX, MAP, TOP, the OSI stack, AppleTalk, and TCP/IP. Of these, TCP/IP is more popular with the advent of the global Internet.

1.5 Function and Anatomy of Ethernet and its Frame

A data packet transmitted by Ethernet is called a ‘frame’ and consists of binary data, arranged in various fields.

An IEEE 802.3 Ethernet frame includes the following:

- Preamble: A sequence of bits used to mark the beginning of the frame. This consists of 7 bytes containing 10101010, resulting in a square wave being transmitted. The preamble is used by the receiver to synchronize its clock to the transmitter.
- Start Frame Delimiter (SFD): This single byte field consists of 10101011. It enables the receiver to recognize the commencement of the address fields. Technically speaking this is just another byte of the preamble and, in fact, in the Ethernet version 2 specification it was simply viewed as part of an 8-byte preamble.
- Destination address: The 6-byte (48 bit) physical address of the network adapter that is receiving the frame.
- Source address: The 6-byte (48 bit) physical address of the network adapter that is sending the frame.
- Length or Type: A 2-byte (16 bit) field. The type field is used to indicate which protocol is encapsulated in the payload of an Ethernet Frame.
- Data: The information that has been handed down to the Data Link layer for transmission. This varies from 0 to 1500 bytes. The padding is conceptually part of the data field. The CRC is calculated over the data in the pad field. Once the CRC checks OK, the receiving node discards the pad data. Pad data therefore varies between 0 and 46 bytes.
- Frame Check Sequence (FCS): This is a 4-octet or 32 bit Cyclic

Redundancy Check (CRC) which verifies data and helps to detect corrupt data within the entire frame.

The three fields of the Destination address, Source address, and Type/Length makes up the Header.

Header
Figure 1.1

Ethernet Frame Format

1.6 Ethernet MAC

A MAC address is known by other names such as *physical address* (in Windows), *Ethernet address*, and *hardware address*. This address is a 12-character hexadecimal string (0-9, plus A-F, capitalized). This uniquely identifies every Ethernet device in the world. Each vendor that creates network devices pre-programs these addresses into their devices.

The Ethernet network uses two MAC addresses that identify the source and destination of each frame sent on the network. A computer sends all packets that it creates with its own hardware source (MAC) address, and receives all packets that match its MAC address. All computers on the network read packets sent to a 'broadcast address'.

By convention, MAC addresses are usually written in one of the following two formats:

- MM:MM:MM:SS:SS:SS
- MM-MM-MM-SS-SS-SS

The first half of a MAC address contains the ID or OUI (Organizationally Unique Identifier) number of the adapter manufacturer. This uniquely identifies the vendor or manufacturer. The second half of represents the serial number assigned to the adapter by the manufacturer. In the example,

00:A0:C9:14:C8:29, the prefix 00A0C9 indicates Intel Corporation as the manufacturer.

1.7 Types of Message Addressing

There are several types of message addressing or ways by which packets can be received:

- **Unicast Addressing**: Unicast delivery requires that a message should be addressed to a specific recipient. This is the most commonly used messaging system and is present in almost all protocols. First bit of the address is 0. A typical unicast MAC address is 00-06-5B-12-45-FC.
- **Broadcast Addressing**: Broadcasts are normally implemented through a special address that is reserved for that function. Through this system messages are broadcasted to all connected devices on a network. The destination address is set to all ‘1’s or FF-FF-FF-FF-FF-FF.
- **Multicast Addressing**: Multicasts are the most complex type of message because they require a means of identifying a set of specific devices that will receive a message. A multicast transmission is addressed and sent to a select group of devices. In this case there may be one or more senders and the information is distributed to a set of receivers. The first bit of the destination address in multicast is always set to 1. Unlike broadcast transmission, multicast clients receive a stream of packets only if they previously decided to do so, by joining the specific multicast group address. Membership of a group is dynamic and controlled by the receivers. The multicast mode is useful if a group of clients require a common set of data at the same time, or when the clients need to receive and store common data. If a common data is required by a group of clients, then multicast transmission may provide significant bandwidth savings.

1.8 Variants of Ethernet

Different variants of Ethernet technologies are distinguished according to the type and diameter of the cables used. The range of cable types includes coaxial, twisted pair and fiber optic cable.

1.8.1 10 Mbps Ethernet

Though 10 Mbps Ethernet is a legacy technology, it is still used in older installations. The IEEE 802.3 standard has several variants. Here are some of the versions still in use:

- **10Base5:** Thick wire coaxial cable (RG-8), single cable bus
- **10Base2:** Thin wire coaxial cable (RG-58), single cable bus
- **10BaseT:** Unscreened Twisted Pair cable (TIA/IEA 568B Cat3) star topology

- **10BaseFL:** Optical fiber, 10 Mbps, twin fiber point to point

10BaseT is an Ethernet standard that transmits data at 10 Mbps over twisted wire pairs. It uses Cat3 or AWG24 UTP cable for connection to the node. The physical topology is a star, with nodes connected to hub. Logically it forms a (chained) bus, since when one station transmits all others can 'hear' it. The four-pair cable from hub to node has a maximum length of 100 meters. One pair is used for receive and another is used for transmit. The connectors specified are RJ-45. The figure below shows schematically how the 10BaseT nodes are interconnected by the hub.

Figure 1.2

Schematic 10BaseT system

This is also known as a 'chained bus' configuration, as opposed to 10Base5 and 10Base2 that are 'branched bus' configurations.

Collisions are detected by the NIC and so a signal received by the hub must be retransmitted on all ports. The electronics in the hub must also ensure that the stronger retransmitted signal does not interfere with the weaker input signal. The effect is known as far end crosstalk (FEXT), and is handled by special adaptive crosstalk echo cancellation circuits.

The 10BaseT star topology became very popular but has been largely superseded by faster versions such as Fast and Gigabit Ethernet. The shared hubs have also been replaced with switching hubs, and the preferred mode of operation is full-duplex instead of CSMA/CD.

10Base5 (Thicknet) is a legacy technology but some systems still use it in industrial applications. It uses a coaxial cable as a bus (also referred to as a 'trunk'). The RG-8 cable has a 50-ohm characteristic impedance and is yellow or orange in color. The naming convention '10Base5' indicates a 10 Mbps data rate, baseband signaling, and 500-meter segment lengths. The cable is difficult to work with, and so cannot normally be taken to the node directly. Instead, it is laid in a cabling tray and the transceiver electronics (the Medium Attachment Unit or

MAU) is installed directly on the cable. From there an intermediate cable, known as an Attachment Unit Interface (AUI) cable is used to connect to the NIC.

10Base2 is the other type of coaxial cable in an Ethernet network and is sometimes referred to as ‘Thinnet’ or ‘Thinwire Ethernet’. It uses the thinner (5 mm diameter) RG-58 A/U or C/U coax cable with 50-ohm characteristic impedance. The cable is connected to the 10Base2 NICs or 10Base5 MAUs by means of BNC T-piece connectors.

Connectivity requirements stipulate that:

- It must be terminated at each end with a 50-ohm terminator
- The maximum length of a cable segment is 185 meters
- No more than 30 transceivers may be connected to any one segment
- There must be a minimum spacing of 0.5 meters between nodes
- It may not be used as a link segment between two ‘Thicknet’ segments
- The minimum bend radius is 5 cm

The physical layout of a 10Base2 Ethernet segment is shown in the figure below:

Figure 1.3

10Base2 Ethernet segment

10BaseF has a star topology and uses wiring hubs. It comprised of three variants namely 10BaseFL, 10BaseFP and 10BaseFB, of which only 10BaseFL is still being used. 10BaseFL is a point-to-point technology using two fibers, with a range of 2000m.

1.8.2 Fast Ethernet

100 Base-T or Fast Ethernet is an Ethernet standard that has a data transfer rate of 100 Mbps. It is 10 times faster than the original Ethernet speed of 10 Mbps and remained the fastest version of Ethernet till it was superseded by Gigabit Ethernet. Fast Ethernet was first deployed in 1995 and is officially the IEEE 802.3u standard. There are several different cabling schemes that can be used with 100BASE-T, such as, 100BASE-TX, 100BASE-T4, and 100BASE-FX.

100Base-BX and 100Base-LX10 are the newer versions of Fast Ethernet.

100BASE-TX and 100BASE-FX

100BASE-TX uses two pairs of high-quality twisted-pair copper wires, whereas **100BASE-FX** uses fiber optic cables. Sometimes both 100Base-TX and 100Base-FX are simultaneously present on one switch.

100Base-TX uses RJ-45 connector with a physical star topology and a logical bus. 100BASE-TX runs over two wire-pairs inside a category 5 or above cable. Like 10BASE-T, the active pairs in a standard connection are terminated on pins 1, 2, 3 and 6. Since a typical category 5 cable contains 4 pairs, it can support two 100BASE-TX links with a wiring adaptor.

Each network segment can have a maximum cabling distance of 100 meters (328 ft). In its typical configuration, 100BASE-TX uses one pair of twisted wires in each direction, providing 100 Mbps of throughput in each direction, as in full-duplex configuration.

The configuration of 100BASE-TX networks is very similar to 10BASE-T. When used to build a local area network, the devices on the network (computers, printers etc.) are typically connected to a hub or switch, creating a star network. Alternatively it is possible to connect two devices directly using a crossover cable.

100BASE-T4 was an early implementation of Fast Ethernet. It requires four twisted copper pairs, but those pairs were only required to be category 3 rather than the category 5 required by TX. One pair is reserved for transmit, one for receive, and the remaining two will switch direction as negotiated. 100Base-T4 never gained widespread acceptance. Yet another version, 100BaseT2, was to operate over 2 pairs of Cat3 cable, but was never implemented by any vendor.

1.8.3 Gigabit Ethernet (GbE)

Gigabit Ethernet (**GbE** or **1 GigE**) is the technology for transmitting Ethernet frames at the rate of one gigabit per second (1,000,000,000 bits per second), as defined in the IEEE 802.3z and IEEE 802.3ab standards. It operates at ten times the clock speed of Fast Ethernet, i.e. at 1Gbps. 100 Gigabit Ethernet (or 100GbE) and 40 Gigabit Ethernet (or 40GbE) refers to transmitting of Ethernet frames at the rate of 100 or 40 gigabits per second.

1000BaseX is the shorthand identifier for the Gigabit Ethernet system based on the 8B/10B block encoding scheme adapted from the fiber channel networking standard, developed by ANSI.

1000BaseX includes 1000BaseSX, 1000BaseLX and 1000BaseCX.

- 1000BaseSX is the short wavelength fiber version.
- 1000BaseLX is the long wavelength fiber version
- 1000BaseCX is a short (25 m) copper cable version, based on the fiber channel standard. It is also known as a short-haul copper bus, and was mainly used for interconnecting devices in the same wiring closet, or group of closets.

1000BaseT, on the other hand, is a 1000 Mbps version capable of operating over Cat5e UTP and has largely replaced 1000BaseCX.

When first developed, some thought achieving gigabit speeds with Ethernet would require using fiber optic or other special cables. However, today's Gigabit Ethernet works using twisted pair copper cable (specifically, the CAT5e and CAT6 cabling standards) similar to older 100 Mbps Fast Ethernet. Gigabit Ethernet uses the same IEEE 802.3 frame format as 10 Mbps and 100 Mbps

Ethernet systems. By retaining the same frame format as the earlier versions of Ethernet, backward compatibility is assured. 1000BaseT uses all four cable pairs for simultaneous transmission in both directions. Thus it cannot be used on networks where one of the pairs is used for a phone connection.

IEEE 802.3z defines the Gigabit Ethernet Media Access Control (MAC) layer functionality as well as three different physical layers like 1000Base-LX and 1000Base-SX using fiber, and 1000Base-CX using copper. These physical layers use 8B/10B encoding to reduce the bandwidth required to send high-speed signals. The IEEE merged the fiber channel with the Ethernet MAC using a Gigabit Media Independent Interface (GMII), which defines an electrical interface, allowing existing fiber channel PHY chips to be used and future physical layers to be easily added.

1000Base-SX

This Gigabit Ethernet version was developed for the short backbone connections of the horizontal network wiring. The SX systems operate full-duplex with multimode fiber only, and incorporate SC fiber connectors.

1000Base-LX

This version was developed for use in the longer backbone connections of the vertical network wiring. The LX systems can use single mode or multimode fiber with the more expensive 1300 nm laser diodes. The maximum distance recommended by the IEEE for these systems operating in full-duplex is 5 km for single mode cable and 550 meters for multimode fiber cable. The standard 1000Base-LX NICs available today are full-duplex and incorporate SC fiber connectors.

1000Base-CX

This version of Gigabit Ethernet was developed as ‘short haul copper jumpers’ for the interconnection of switches, hubs or routers within a wiring closet. It is designed for 150-ohm ‘twin-ax’ STP cable similar to that used for IBM Token Ring systems. The maximum cable length is 25 meters for both full- and half-duplex systems.

The newer versions of Gigabit Ethernet include 1000BASE-LX10, 1000BASE-BX10, 1000BASE-ZX, and 1000BASE-TX.

1000BASE-LX10

This version of gigabit Ethernet is similar to 1000BASE-LX which is specified to work up to 10 km, over a pair of single-mode fiber with higher quality optics.

1000BASE-BX10

This version is capable of up to 10 km over a single strand of single-mode fiber. It is designed to transmit with different wavelength in each direction. The fiber terminals on each side are not equal, as the one transmitting "downstream" uses 1,490 nm wavelength and the one transmitting "upstream" uses 1,310 nm wavelength.

1000BASE-ZX

1000BaseZX operates on ordinary single-mode fiber-optic link, spans up to 70 km using a wavelength of 1,550 nm. It is used as a Physical Medium Dependent (PMD) component for Gigabit Ethernet interfaces found on various switch and router. It operates at a signaling rate of 1250 Mbaud, transmitting and receiving 8B/10B encoded data.

1000BASE-TX

This version transmits over four pairs of cable, two pairs in each direction of transmission (as opposed to all the four, for 1000Base-T over Cat5). Its simplified design has reduced the cost of required electronics. Since it does not carry out two-way transmission, crosstalk between the cables is significantly reduced, and encoding is relatively simple. 1000Base-TX will only operate over Cat6.

The Gigabit Ethernet versions are summarized in the following figure:

Figure 1.4

Gigabit Ethernet versions

1.8.4 10 Gigabit Ethernet (10 GbE)

10 gigabit Ethernet (10GE or 10GbE or 10 GigE) refers to the technology of transmitting Ethernet frames at a rate of 10 gigabits per second (10×109 or 10 billion bits per second), which was first defined by the IEEE 802.3ae-2002 standard. The standard permits distances up to 40 kilometers over a single-mode fiber. Both single-mode and multi-mode fiber systems can be used with 10 GbE applications.

10-Gigabit Ethernet is an efficient way to move data on backbone connections between networks. 10GbE supports both copper and fiber cables. However, for its high bandwidth requirements, higher-grade copper cables, such as, category 6a or Class F/Category 7 cables are required for links up to 100m. 10 gigabit Ethernet defines only full duplex point-to-point links which are generally connected by network switches and it does not support half duplex operation and hubs. The 10 gigabit Ethernet standard includes different physical layer (PHY) standards. A 10 GbE networking device needs pluggable PHY modules to support the different PHY types.

1.8.5 100GbE and 40GbE

100 Gigabit Ethernet (or **100GbE**) and **40 Gigabit Ethernet** (or **40GbE**) refers to the transmission rates of 100 and 40 gigabits per second respectively. Both the speeds are defined by the IEEE 802.3ba-2010 standard, first announced in July 2007 and later ratified in June, 2010. Both speeds support end-point and link aggregation needs. 40 Gbps version mainly supports local server applications while 100 Gbps was mainly meant for internet backbones.

Initially, 40 Gigabit Ethernet applications were meant for short-reach data center core and aggregation layers or Top-of-Rack (ToR) server aggregation with copper cable or Multi-Mode Fiber (MMF) up to 125m. But, longer-reach interfaces for inter-data center, metro, and campus core networks with distances up to 10 km over Single-Mode Fiber (SMF) are also defined in the standard.

On the other hand, 100 Gigabit Ethernet, is mainly applicable for SP core and aggregation networks, metro core, and large campus core networks and support distances up to 40 km over SMF. These ultra-high-capacity Ethernet network applications require very high bandwidth and redundancy.

40GBASE-CR4, 40GBASE-SR4, 40GBASE-FR, and 40GBASE-LR4 are the various variants of 40 GbE, while those for 100 GbE are 100GBASE-CR10, 100GBASE-SR10, 100GBASE-LR4, and 100GBASE-ER4.

1.9 Industrial Ethernet

As industrial organizations recognize Ethernet as the leading networking solution, they are gradually porting their traditional field bus architectures to Industrial Ethernet. Industrial Ethernet not only gives manufacturing devices a much faster way to communicate, but also gives users better connectivity and transparency, enabling them to connect the devices without using separate gateways. But the industrial world presents a more harsh and hazardous environment. The equipment, such as, the switches, hubs, and cabling systems should be designed to cope with these kinds of environmental circumstances:

- Temperatures that can range from -40°C to +85°C
- Exposure to solvents, lubricants and other strong chemicals
- Exposure to UV radiation
- Humidity up to 99%
- Exposure to dust and oil
- Exposure to vibration, shock, and strong pulling forces for the cables

1.9.1 Coping with the Problems of Industrial Ethernet

Certain design modifications and innovations have been made to operate the active industrial devices under the stringent conditions.

Connectors and Cabling

Earlier industrial Ethernet systems such as the first-generation Siemens SimaticNet (Sinec-H1) were based on the 10Base5 configuration, and thus the connectors included screw-type N-connectors and D-type connectors, which were fairly rugged. The heavy-gauge twin-screen (braided) RG-8 coaxial cable is also quite impervious to electrostatic interference.

Most modern industrial Ethernet systems are, however, based on a 10BaseT/100BaseTX configuration and thus have to use the RJ-45 connectors and Cat5-type UTP cable. The RJ-45 connectors are not rugged and not suitable when subjected to great temperature extremes, contact with oils and other fluids, dirt, UV radiation, EMI, shock, vibration, and mechanical loading. So to solve this issue, RJ-45 connectors should be used within enclosures.

As an interim measure, in the early days, some manufacturers started using D-type (known also as DB or D-Subminiature) connectors. These are mechanically quite rugged, but are neither waterproof nor dustproof. They can therefore be used only in IP20 rated environments.

Industrial Ethernet, require IP67 class protection. So suitable connector technology, meeting IP67 standards has to be defined for transmission speeds up to 100 Mbps. As solutions to this problem, a modified RJ-45 connector (As shown in the figure below) and an M12 (micro-style) connector are being used.

Figure 1.5

Modified RJ-45 connector

The use of the M12 connector in Ethernet systems is covered in standard EN 61076-2-101. The transmission performance of 4-pin M12 connectors (As shown in the figure below) for Ethernet up to 100Mbps is comparable with, if not better than, standardized office-grade Ethernet products. Also, for industrial applications two-pair cables are less expensive and easier to handle.

Figure 1.6

M12 connectors

Typical M12 connectors for Ethernet can accept various types of Cat5e twisted pair wiring such as braided or shielded wire (solid or stranded), and offer excellent protection against moisture, dust, corrosion, EMI, RFI, mechanical vibration and shock, UV radiation, and extreme temperatures (-40ºC to 75ºC). Several manufacturers are producing Cat5e wiring systems using braided or shielded twisted pairs.

Cat5 cables and connectors are applicable mainly for lower transmission rates. But for Gigabit Ethernet, Cat6 hardware is a necessity. At GB Ethernet speeds, compatibility between connector and cable is important and to keep signal distortion within acceptable limits, it is important to use cable and connectors that have minimal line-to-line and line-to-ground capacitance.

All 8-wire cables are not suitable for GB Ethernet. The jacket material, core structure, agency ratings, shielding, environmental ratings, etc. need to be considered during cable selection for such high speeds. Many 8-wire Ethernet cables are only rated for Cat5 applications, and may or may not have the ratings and specifications required for Gigabit Ethernet applications.

There are various suppliers for Gigabit Ethernet connectors. These connectors require special shielding and ensure reliable data transmission even under strong electromagnetic fields. They are also extremely robust and can be used even under rugged environmental conditions.

Packaging

Commercial Ethernet equipments (hubs, switches, etc.) are only rated for usage up to IP20, temperatures below 40^{o}C, and are not suitable for vibration and other power supply issues.

Some manufacturers are now offering industrially-hardened switches with DIN-rail mounts, IP67 (waterproof and dustproof) rating, industrial temperature rating (60^{o}C), DIN-rail mounts, and redundant power supplies as shown in the figure below.

Figure 1.7

IP67 Industrial grade switch

Coating and Hardening

Conformal coating: Most industrial hardened Ethernet switches are deployed in critical and harsh environments, where it is important to apply conformal coating to protect them against moisture, dust, chemicals, and temperature extremes. Conformal coatings when applied to electronic components help to keep away moisture, fungus, dust, and other environmental contaminants. The coating provides significant environmental and mechanical protection, effectively reduces the effects of mechanical stress, vibrations or temperature changes, and extends the life of the components and circuitry.

Hardening: Hardened devices (As shown in the figure below) are available for outdoor use where large temperature swings can occur. A typical temperature range is -40^{o}C to +75^{o}C. The specially-designed casing dissipates the heat generated by the electronics. Because of the sealed enclosure they are also dust- and waterproof. Typical applications for **hardened Etherne**t and substation hardened products, include power substations, railroads, airports, manufacturing plants, oil & gas installations, water treatment plants, etc, where products are designed to exceed industry specifications. For example, communications equipment used in power substations are subject to extremes of temperature and humidity, as well as electrical transients from high voltage switching.

Figure 1.8

Hardened switch and power supply

Deterministic versus Stochastic Operation

One of the most common complaints regarding early Ethernet was that it used CSMA/CD (a probabilistic method) as opposed to other automation technologies that use deterministic access methods such as token passing or a master-slave mechanism. CSMA/CD also did not guarantee delivery of a possibly critical message within a certain time. Industrial processes often require data to be scanned within 5 to 20 millisecond range, and some demanding processes could even require less than 1 millisecond. On 10BaseT Ethernet, for example, the access time on a moderately loaded 100-station network could range from 10 to 100mS, which is unacceptable for industrial processes.

Industrial versions of Ethernet typically operate at 100 Mbps and above in full-duplex mode. The advent of Fast and Gigabit Ethernet, switching hubs, IEEE 802.3Q VLAN technology, IEEE 802.3p traffic prioritization and full-duplex operation has resulted in very deterministic Ethernet operation.

Size and Overhead of Ethernet Frame

Data link encoding efficiency is another problem, with the Ethernet frames taking up far more space than an equivalent DeviceNet, PROFIBUS or FOUNDATION Fieldbus frame. If the TCP/IP protocol is used in addition to Ethernet, the overhead increases significantly. The efficiency of the overall system is, however, more complex than simply the number of bytes transmitted on the cable and issues such as raw speed on the cable and the overall traffic need to be examined carefully. For example, if 2 bytes of data from an instrument had to be packaged in a 60-byte message (because of TCP/IP and Ethernet headers) this would result in an enormous overhead compared to a conventional field bus protocol. However, if the communications link is running at 100 Mbps or 1 Gbps with full-duplex communications, then that makes the overhead issue almost irrelevant.

Modern Ethernet field buses such as EtherCAT can address up to 12,000 digital I/O points in a single Ethernet frame, which takes care of the problem of Ethernet overheads.

Noise and Interference

Due to higher electrical noise near the industrial LANs some form of electrical shielding and protection is useful for copper cables to minimize errors in the communication. Twisted pair can be used but care should be taken to route the cables far away from any potential sources of noise and advisable to use screened twisted pair cable (ScTP) rather than the standard UTP. If the network supports fiber-optic cables, then their usage ensures there are minimal problems due to ground loops or electrical noise and interference.

In substations, a variety of Intelligent Electronic Devices (IEDs) are used, which employ Ethernet as the underlying network technology. A key requirement of most substations IEDs and LAN equipment is that they must operate properly and withstand the different tests designed to simulate EMI (Electro Magnetic Interference) phenomena such as inductive load switching, lightening strikes, electrostatic discharges from human contact, radio frequency interference due to personnel using portable radio handsets, ground potential rise resulting from high current fault conditions within the substation, and a variety of other EMI phenomena commonly encountered in the substation. Often the Ethernet switches are installed in the same compartment or even on the same rack as the protective relaying IEDs. Therefore, from an EMI immunity perspective, the Ethernet equipment should be “substation hardened” to the same extent as the protective relaying IEDs.

Partitioning of the Network

It is very important that the industrial network operates separately from that of the commercial network, as speed of response and real time operation are often critical attributes of an industrial network. Also, security is another concern where the industrial network is split off from the commercial networks so any problem in the commercial network will not affect the industrial side.

Industrial networks are also often partitioned with routers into individual subnets for reasons of security, and/or segmented with bridges and switches to increase speed.

Security of Industrial Ethernet Systems

With Ethernet being increasingly used in industrial automation, security of Industrial Ethernet has become an important issue. Since all Industrial Ethernet protocols use IP, using secured versions of TCP, UDP, and IP stack offers valuable security measures. This can be done on the network layer, or the transport layer, or the application layer. Security can also be installed by splitting the network into different VLANs and shielding them by firewalls.

Suitability for Real Time Operation

In the early days of Ethernet it was often said that Ethernet was not suitable for Real Time (RT) applications. The very demanding isochronous (clock synchronous) RT operations with sub-millisecond cycle times do pose a challenge for any networking technology.

Cycle time in RT refers to how often a master device can access a specific slave device. Jitter, on the other hand, refers to the repeatability of the said access. In motor drive control applications, the present norm is the ability to access 100 drives with a 1 mS cycle time and 1 µS jitter.

It is not possible to achieve this with the standard or COTS (Commercial Off-The-Shelf) Ethernet devices. So it is required to combine the COTS Ethernet devices with switches with full-duplex operation, VLANs, switch port prioritization, and 100 Mbps Ethernet. This approach for example, is used by Ethernet/IP and PROFInet v1.

For more demanding applications, PROFInet v2 uses a modified stack, where TCP and IP are bypassed and replaced by alternative protocols, optimized for real-time applications, where required. This approach is referred to as ‘Soft Real Time’ or SRT.

For the most demanding applications, the Ethernet hardware needs to be modified. One approach is to cyclically ‘disable’ the Ethernet communication and send hardware-controlled ‘isochronous’ messages across the network for the benefit of those devices that require sub-millisecond deterministic access.

This approach is taken by PROFInet v3 and Ethernet PowerLink (EPL). Another method is to introduce IEEE 1588 clocks into the hardware. This approach is followed by Ethernet/IP CIPSync and EtherCAT.

1.10 Intrinsically Safe (Ex) Ethernet

1.10.1 Overview

Ethernet systems are being widely used in numerous process automation applications. But explosion protection is one hindrance for wide application of Ethernet in process automation. Intrinsically Safe (Ex) Ethernet is a solution to this problem which now offers high speed in combination with explosion protection.

Intrinsic safety is based on the fact that a specific amount of energy is required to ignite an explosive atmosphere. The amount of energy in an intrinsically safe circuit is reduced to a safe level by limiting current and voltage so that sparks or other thermal effects no longer represent sources of ignition. This situation applies under normal operating conditions and also under certain fault conditions. The resulting advantage, which makes it possible to work on, install and maintain live equipment in the hazardous areas, has made this type of protection the most widely used in process automation today. Intrinsic safety is typically used for 4mA to 20mA signals, and also for field buses such as Profibus PA or Foundation Fieldbus H1.

Due to the high transmission rate for Industrial Ethernet of 100Mbps, special attention must be paid to the usual components such as Zener diodes, transistors, transmitters, and optocouplers. A system without appropriate high quality components and a clean high frequency design, can result in signal distortion and transmission errors.

1.10.2 Protections for Intrinsically Safe Ethernet

Isolators:

Similar to conventional installations with intrinsically safe circuits, an apparatus like an **isolator**is required. This apparatus isolates the intrinsically safe circuits in zone 1 from the non-intrinsically safe circuits in the safe area. Initially, safety barriers without electrical isolation were used for this purpose. In modern systems, however, electrical isolators are being increasingly used. The result is that simpler installation, higher transmission accuracy, and significantly more robust EMC properties for earthing and screening can be achieved.

These electrical isolators are more appropriate for an intrinsically safe Ethernet installation with copper cables. The electrical isolators must be of a special design that can cope with the high transmission rates and be very robust to external interference.

As no Ethernet installation can go without the corresponding switches, hubs or routers, it is appropriate to integrate the isolator functionality into these modules. In this way possible signal corruption or interference due to additional connectors and contact resistances is eliminated.

Intrinsically Safe Cables:

Electrical cables for intrinsically safe circuits have special PVC outer jacket material which is resistant to oil, petrol, and flame. They have to be specially marked with a blue outer jacket (RAL 5015) according to DIN VDE.

The installation of these cables outside of intrinsically safe circuits is not permitted and need to be installed with separate power circuit.

Flameproof Enclosures and Specially Designed Cable Glands:

Another type of protection that can be considered is flameproof enclosures in the form of connection boxes. This solution is based on the requirement that although an explosion can occur inside an enclosure, the energy from the explosion must not escape to the outside, or only an insufficient amount of energy can escape to the outside, and the explosion must not destroy the enclosure. Secondly, proper precaution should be taken for cable entry. For increased safety, specially designed Ethernet-flameproof cable glands are required. They not only transmit high frequency Ethernet without distortion, but also do not allow the energy from the explosion to escape outside.

Specially Designed Connectors:

Hazardous area plug and socket connectors can be used in Zone 1 and Zone 2 areas and they enable the operator to remove equipment from a power or signal line in a hazardous area, without having to isolate the supply. After isolating the electrical circuit, the connector is not yet separated mechanically. So any sparks produced should remain inside the flameproof space.

Using Special Optical Fibre Cables

Optical fibre cables can connect components in a plant over larger distances, and depending on the fibre, distances as far as 2000 m or more are possible. But if the fibre optic cables lead through areas with explosive atmospheres, it is important to ensure that ignition is prevented. This is covered by IEC/EN 60079-0:2007 and mainly IEC/EN 60079-28:2006.

Optical fibres focus light onto a very small spot. In case of cable damage or an open plug connector, the optical radiation can cause an explosion. Therefore, users must ensure that in case of cable breaks, a specific irradiance level (an energy value per surface) is not exceeded and that the released light energy is not too high in absolute terms. This requires, for instance, specially built and certified senders and receivers. Users can use components and systems that implement ignition protection always ensure safe failure detection with interruption and locking of the signal. Fibre breaks are immediately detected, and the optical radiation is switched off at once.

The second solution is to contain the radiation. Fibre optic cables must therefore be sufficiently robust, or be equipped with protection against destructive influences. Enclosures must be designed in a way that explosions within cannot cause an ignition of the outer atmosphere, and no dangerous amount of light energy can escape. Therefore, this ignition protection type largely corresponds to the "flameproof enclosure" class and also requires special cable glands, and suitable plug connectors.

1.11 Power over Ethernet (PoE)

1.11.1 Overview

Power over Ethernet or PoE technology describes a system to safely transfer electrical power from a central location, along with data, to remote devices over standard data cables in an Ethernet network (Cat3/Cat5/Cat5e/Cat6).

PoE provides both data and power connections in one cable, so equipment doesn't require a separate cable for each need. PoE can provide long cable runs, like 100 m (330 ft) and deliver 12 W of galvanically isolated power. PoE-plus provides even more power.

Transmission of power can take place over the signal pairs (1/2 and 3/6) or over the unused pairs (4/5 and 7/8). A range of devices are available to support PoE. If the switch or hub is not able to supply power, a separate DC power supply is used in conjunction with an ‘injector’ box to place the power on the line. On the receiving side, a ‘picker’ or ‘splitter’ (As shown in the figure) is used to pick the power off the bus to power a legacy (non-Ethernet) device. Injectors and pickers with ratings up to 40 watts are currently available

Figure 1.9

PoE Splitter

1.11.2 PoE Standard

The IEEE standards for PoE require category 5 cable or higher for high power levels, but can operate with category 3 cable if less power is required. Power is supplied in common mode over two or more of the differential pairs of wires found in the Ethernet cables and comes from a power supply within a PoE-enabled networking device such as an Ethernet switch or can be injected into a cable run with a midspan power supply.

The original **IEEE 802.3af-2003** PoE standard provides up to 15.4 W of DC power (minimum 44 V DC and 350 mA) to each device. Only 12.95 W is assured to be available at the powered device as some power is dissipated in the cable.

The updated **IEEE 802.3at-2009** PoE standard also known as **PoE+** or **PoE plus**, provides up to 25.5 W of power. The 2009 standard prohibits a powered device from using all four pairs for power. Some vendors have announced products that claim to be compatible with the 802.3at standard and offer up to 51 W of power over a single cable by utilizing all four pairs in the Category 5 cable.

IEEE 802.3af-2003 standard specifies Power over Ethernet (PoE) technology in two different methodologies:

- Power-Supplying Equipment (PSE) may use either End-Span or Mid-Span
- Powered devices (PD’s) accept power from either type of power source

1.11.3 Uses

Some types of devices with PoE include:

- IP Security Cameras
- Network routers
- A mini network switch installed in distant rooms, to support a small cluster of ports from one uplink cable
- Network webcams
- Network Intercom / Paging / Public address systems and hallway speaker amplifiers
- VoIP phones
- Wall clocks in rooms and hallways, with time set using Network Time Protocol
- Wireless access points
- Outdoor roof mounted radios with integrated antennas
- Industrial devices (sensors, controllers, meters etc.)
- Access control and Help-points (intercoms, entry cards, keyless entry, etc.)
- Lighting controllers
- Remote Point of Sale (POS) kiosks
- Physical Security devices and controllers

1.11.4 PoE Key Benefits

If a device already has power available but no data link, then PoE may not be attractive. Depending on the application, some of the advantages with PoE over other technologies may be:

- Inexpensive cabling
- Fast data rate
- No batteries required
- Peer-to-peer network access
- Installation Cost Savings
- Eliminates the need for electrical outlet installation.
- Dramatically reduces cost of deployment as a single Cat5/5e/6 cable is used for both data and power.
- Bulky AC power adaptors are not required.
- Centralized power backup and provides continuous operation during power interruptions.
- Provides centralized power management as devices can be remotely powered down during periods of low usage or for security purposes.
- Provides safe power and does not damage Non-PoE devices or legacy peripherals.

1.12 Point-to-Point Protocol over Ethernet (PPPoE)

1.12.1 What is Point-to-Point Protocol (PPP)?

Point-to-Point Protocol (**PPP**) is a Data Link layer protocol mostly used to establish a direct connection between two networking nodes. It can provide connection authentication, transmission encryption, and compression.

PPP provides a standard method for transporting multiprotocol datagrams over point-to-point links.

PPP comprises of the following three main components:

1. A method for encapsulating multiprotocol datagrams
2. A Link Control Protocol (LCP) for establishing, configuring, and testing the data-link connection
3. A family of Network Control Protocols (NCPs) for establishing and configuring different network-layer protocols

PPP is used over many types of physical networks including serial cable, phone line, trunk line, cellular telephone, specialized radio links, and fiber optic links. Internet Service Providers (ISPs) have used PPP for customer dial-up access to the Internet, since IP packets cannot be transmitted over a modem line on their own, without some data link protocol.

1.12.2 Overview of SLIP

PPP is commonly used as a data link layer protocol for connection over synchronous and asynchronous circuits, where it has largely superseded the older Serial Line Internet Protocol (SLIP).

The **Serial Line Internet Protocol** (**SLIP**) is an encapsulation of the Internet Protocol designed to work over serial ports and modem connections. It is documented in RFC 1055. On personal computers, SLIP has been largely replaced by the Point-to-Point Protocol (PPP), which is better engineered, has more features and does not require IP address configuration setting before it is established. On microcontrollers, however, SLIP is still the preferred way of encapsulating IP packets due to its very small overhead.

SLIP modifies a standard TCP/IP datagram by appending a special ’SLIP END’ character to it, which distinguishes datagram boundaries in the byte stream. SLIP requires a serial port configuration of 8 data bits, no parity, and either EIA hardware flow control, or CLOCAL mode (3-wire null-modem) UART operation settings.

SLIP does not provide error detection. Therefore SLIP on its own is not satisfactory over an error-prone dial-up connection. It is however still used for testing operating systems' response capabilities under load, by looking at flood-ping statistics.

SLIP is also currently used for communication between Bluetooth modules and host computers.

1.12.3 Overview of Point-to-Point Protocol over Ethernet or PPPoE

Point-to-Point Protocol over Ethernet (PPPoE) is a derivative of PPP frequently used by internet service providers to establish a Digital Subscriber Line (DSL) Internet service connection with their customers.

Point-to-Point Protocol over Ethernet or PPPoE is a network configuration used to establish a PPP connection over an Ethernet protocol. Since DSL modems typically connect to computers through an Ethernet connection, a standard dial-up PPP connection cannot be used. Therefore, PPP over Ethernet helps to connect computers with an ISP through a DSL modem.

In order to create a PPPoE connection, a service name provided by the ISP as well as a username and password is required. This provides a simple way for the ISP to uniquely identify a system and establish an Internet connection.

1.12.4 Pros and Cons of a PPPoE Configuration

- The biggest advantage of a PPPoE configuration is that it is easy to set up. It also supports multiple computers on a local area network (LAN).
- The downside of PPPoE is that it requires additional overhead, or extra data, to be sent over the Internet connection.

A standard PPPoE connection adds 8 bytes of data to each transmitted packet. This may add to a significant overhead in case of connections which use packets as small as 60 bytes. For this reason, nowadays, many DSL providers also offer DHCP configurations.

1.13 Summary

In this module you've learned about the features and evolution of Ethernet, its frame structure and MAC addresses, the differences between the Bluebook (V2) and IEEE 802.3, and about the different variants of Ethernet. Now, you can also elaborate on Industrial Ethernet, explain Intrinsically Safe (Ex) Ethernet, and discuss Power over Ethernet (PoE), as well as the Point-to-Point Protocol over Ethernet (PPPoE).