Industrial Fieldbus Technologies: Understanding the basics and simplifying your decision

Abstract
Making a decision on which fieldbus technology to implement on industrial automation applications is getting more complicated. During early stages of the design, engineers must choose “Which fieldbus is the right choice for this application”. Properly answering this question ensures the application accommodates both short and long-term needs for the user.

This paper explores the basics of digital communications of fieldbus technology. An overview of the traditional and emerging digital communication protocols as well as topology concepts are presented, along with a definition of key terms.

Introduction
Machine builders (OEMs), systems integrators and users now have a plethora of fieldbus solutions to consider for use on their automation projects. These fieldbus solutions allow the common support of field measurement, control, status, and diagnostic information. For motion control and real-time tasks this information needs to be exchanged in a deterministic manner between field devices and automation controllers.

In addition, fieldbus communications are often used to network an entire plant, campus or corporation. For example, fieldbus networks are beneficial for collecting production data from the plant floor machines which is made readily available at all levels of an organization. This is why Ethernet-based fieldbus solutions have gained acceptance within most manufacturing marketplaces. Choosing a fieldbus technology that uses completely open standards, from hardware to software, ensures the fieldbus application and equipment, are maintainable and expandable for long-term support.
Fieldbus organizations and groups have been managing protocols and standards in the industrial automation marketplace for decades. These standards have allowed industrial automation systems from different vendors to be easily interfaced.

ISO OSI Model – The Basic Reference Model for Protocols

The International Standards Organization (ISO) developed the Open Systems Interconnection (OSI) Basic Reference Model in the late 1970s. Most fieldbus protocol descriptions and user documentation begin with a primer on the OSI model in the opening paragraphs. Some fieldbus protocols, incorporate all layers, or at minimum the Physical, Data Link and Application layers.

<table>
<thead>
<tr>
<th>OSI Model</th>
<th>Function</th>
<th>Layer</th>
<th>Data Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Network process to application</td>
<td>Application</td>
<td>Data</td>
</tr>
<tr>
<td>Presentation</td>
<td>Data representation and encryption</td>
<td>Presentation</td>
<td></td>
</tr>
<tr>
<td>Session</td>
<td>Interhost communication</td>
<td>Session</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>End-to-end connections and reliability</td>
<td>Transport</td>
<td>Segment/Datagram</td>
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<td></td>
<td>Path determination and logical addressing</td>
<td>Network</td>
<td>Packet</td>
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<tr>
<td></td>
<td>Physical addressing</td>
<td>Data Link</td>
<td>Frame</td>
</tr>
<tr>
<td></td>
<td>Media, signal and binary transmission</td>
<td>Physical</td>
<td>Bit</td>
</tr>
</tbody>
</table>

Physical Medium

The Physical Layer specifies how devices are electrically interconnected. The physical medium can be wire with copper cable, fiber or even wireless, although in automation applications the most prevalent method is to use wire. Ethernet-based fieldbus technologies use standards based on IEEE802.3 hardware so there are many sources of Physical Layer components. Some mediums are very rigid in their specifications for the wire resistance and capacitance, while others offer a range of
possibilities or have flexibility in the topology. As the need for higher speed and higher bandwidth communications grows, many vendors utilize Ethernet’s Physical and Data Link layers.

The physical medium plays an important role in the success or failure of fieldbus communications. A particular protocol may have excellent performance, great flexibility and multi-vendor support, but if the Physical Layer is not installed properly the fieldbus may fail to operate. When evaluating a fieldbus, look for cost of the network, immunity to noise, distance considerations and diagnostic capabilities.

### Topology

Topology describes how devices are physically wired together. Studies showed that the structured topology described in EN 50173 and ISO/IEC 11801 can almost completely be projected to industrial plants, only minor modifications have to be considered.

There are several wiring strategies for installing media for an industrial automation fieldbus network. The most beneficial fieldbus systems are ones that can comfortably support bus, star and/or tree type wiring topologies, without effecting capabilities.

<table>
<thead>
<tr>
<th>Physical Topology</th>
<th>Common Medium</th>
<th>Protocol Type</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>Twisted Pair</td>
<td>Serial</td>
<td>Easy to install and requires less cable.</td>
<td>Terminating resistors typically required and network shuts down if break in cable.</td>
</tr>
<tr>
<td></td>
<td>Coaxial Fiber</td>
<td>Ethernet</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiber</td>
<td>Token Passing</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star</td>
<td>Twisted Pair</td>
<td>Ethernet</td>
<td>Easy to install and no disruptions to network when connecting and removing nodes.</td>
<td>Requires more cable than linear topology and more expensive because of the cost of the concentrators.</td>
</tr>
<tr>
<td></td>
<td>Fiber</td>
<td>Token Passing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Token Ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree</td>
<td>Twisted Pair</td>
<td>Ethernet</td>
<td>Flexible installation and point to point wiring of individual segments.</td>
<td>Limited segment lengths and if backbone breaks segments nodes attached are disabled.</td>
</tr>
<tr>
<td></td>
<td>Coaxial Fiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td>Twisted Pair</td>
<td>Ethernet</td>
<td>Each node has access to transmit and receive and larger networks easily supported.</td>
<td>One bad node or module can create problems for entire network and modifications can also have bad effects.</td>
</tr>
<tr>
<td></td>
<td>Fiber</td>
<td>Token Ring</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Overview of various fieldbus topologies.
Bus Topology

A bus configuration has a main run of cable (called a trunk line), with drops off the trunk line. In medium and high speed networks there may need to be impedance matching terminating resistors at each end of the main line. The bus topology is by far the most common approach for implementing networks in automation applications.

Figure 4: Typical configuration of a Bus Topology.
Star Topology

A star configuration has a central point and devices are connected in a point-to-point manner to the center. Typically the central point is the master and slaves are connected directly to the master. This type of network tends to be most flexible for installation.

Figure 5: Typical configuration of a Star topology.
Tree Topology

A tree configuration combines features of a linear bus and star topology. It consists of a group of star-configured stations connected to a linear bus backbone cable. Tree topologies allow for expansion of an existing network, and enable machines or plants to meet their needs.

Figure 6: Typical configuration of a Tree topology.
Ring Topology

A ring configuration is a closed loop. Each device can access any other device using one of two possible paths. This topology has the advantage of being redundant, however at the hardware level such networks are more difficult to implement. With fieldbus systems that must use a ring topology, problems can occur when users think of new ideas for an extension after they are done laying cables for the network.

![Ring topology diagram]

Figure 7: Typical configuration of a Ring topology.

Only some of the real-time fieldbus systems on the market give users the same degree of freedom as Ethernet POWERLINK which supports all of these network topologies.

Baud Rate

Baud Rate has a profound impact on the throughput rate of a protocol. While it is not the determining factor, it is often the limiting factor. The original protocols released in the 1980s were based on serial RS-232 or EIA-485 communications. These protocols had baud rates on the order of 10k-20k baud.

The 1990s brought bit-oriented protocols such as DeviceNet and CANOpen, where baud rates were an order of magnitude higher (approximately 100k-500k). The 21st century has seen a 1-2 order of magnitude increase in baud rates, where speeds of 10M Baud, 100M Baud or 1G Baud routinely occur. This is due to acceptance of Ethernet as a Physical Layer.

Protocols that operate at 10k-20k baud are unacceptable for use in today’s industrial automation industry. The 1990s era protocols such as DeviceNet and CANopen were developed to address the needed update rate. These protocols have been used successfully for years and are field-proven. However, better technology exists and any new application should first consider Ethernet-based protocols such as EthernetPOWERLINK or Ethernet/IP.
Isolation

Isolation refers to the ability to couple one circuit to another without the use of direct wire connections. When it comes to fieldbuses, the most common technique to reduce common mode noise is to use optical isolation. Isolation solves many problems related to grounding, and offers protection to other devices within the system, such as the CPU and any sensors or actuators it may be controlling.

It is important to have an isolated network. While non-isolated systems will work, isolated systems tend to have fewer problems and are more robust during normal and extreme operating conditions.

Bit-oriented vs. Byte-oriented

This is a Data Link layer consideration. Byte-oriented protocols organize data into 8-bit bytes. Many of the protocols that use RS-232 or EIA-485 tend to be byte-oriented, as they likely use Quarts (Universal Asynchronous Receiver/Transceiver) to facilitate communications.

Bit-oriented protocols organize data packets into a series of bits. The packets are sent without any gaps in the message. The impact of bit-oriented versus byte-oriented can be seen in the hardware used to facilitate communications. Bit-oriented protocols will have dedicated chips for communications.

Bit-oriented protocols and byte-oriented protocol function equally well in automation applications. Where the Data Link considerations come into play is where there is a need for diagnostic equipment. With Ethernet, a byte-oriented protocol, networks can be analyzed using network traffic analysis equipment. There are many software diagnostic tools that enable the user to use a standard laptop PC to analyze data messages.

Bit-oriented protocols typically require special equipment. This type of equipment is usually readily available from a variety of sources, but it is special use and cannot be used for other purposes as is the case with Ethernet.

Asynchronous vs. Synchronous

At the Data Link level, data is transmitted either synchronously or asynchronously. In a synchronous communications scheme, there are no gaps in the transmission of the data. Once the message starts, all bits and bytes are sent. While it is not universally true, the general rule of thumb is bit-oriented protocols transmit data synchronously.

Byte-oriented protocols can be either asynchronous or synchronous. Modbus RTU (a serial protocol based on RS-232 or EIA-485) is an example of an asynchronous byte-oriented protocol.

As was the case with the consideration of bit-oriented vs. byte-oriented protocols, the impact is in the area of diagnostics. Synchronous protocols usually require special equipment, whereas asynchronous protocols can often be analyzed using lower cost equipment.
**Master/Slave vs. Peer-Peer**

Typically Master/Slave networks are simpler to implement and tend to be more deterministic when it comes to timing. In Master/Slave architecture, there is one Master that polls one or more Slave devices using a Request/Response mechanism. These types of networks also tend to be easier to diagnose and troubleshoot. Similar strategies are Client/Server and Publisher/Subscriber networks.

In most cases there is a single Master, although in some protocols it is possible to have multiple masters. Profibus can be designed with a Primary Master and a Secondary Master. The idea of a Secondary Master is to allow configuration/diagnostic tools on the fieldbus while the system is in operation. There will be an arbitration mechanism that allows multiple masters to share the bus.

A different strategy is to use peer-to-peer networking. Peer-to-peer fieldbus solutions are beneficial in that it reduces the overhead on the Master, compared to centralized or single master solutions, which some fieldbus technologies are based on. With peer-to-peer solutions, each slave has time to use the bus and can exchange data with other slaves, without involving the master. A bus arbitration scheme is used to determine when a device can access the bus.

In some cases, for example with Ethernet POWERLINK, there can be crosstalk between nodes. Data can be exchanged without the interaction of the Master. When a reply is sent from a Slave node, additional nodes can listen for that information and act accordingly.

**Protocols commonly used in Automation**

Below is a short list of the most commonly accepted fieldbus protocols used for industrial automation applications:

- DeviceNet
- PROFIBUS
- PROFINET
- CANopen
- Modbus TCP
- EtherCAT
- Ethernet/IP
- EthernetPOWERLINK

The original fieldbus solutions from the 1980s deliver some of the above mentioned features and are based on serial RS-232 or EIA-485 communication protocols. Experience has shown that these traditional serial fieldbus systems perform very well until a modification is made to the system such as adding additional nodes or demanding faster cyclic data updates in controllers, e.g. running machines faster. At this point the fieldbus application may then expose its limitations because of the inherent protocol design.

This list is by no means a complete list of the protocols available today. A brief description of each of these 7 protocols follows:

**DeviceNet**

DeviceNet is a communication protocol used to interconnect devices and exchange data in an automation environment between devices such as drives, I/O, PCs and HMI visualization stations. It uses the Application layer protocol that rides on top of CAN (Controller Area Network), which provides
the Physical and Data Link layers. DeviceNet was initially developed by Allen-Bradley and has since been turned over to ODVA (Open DeviceNet Vendor’s Association).

DeviceNet is a synchronous bit-oriented protocol that uses differential voltage mode signaling. The ISO 11898 standard (CAN) specifies the operating characteristics of the Physical and Data Link layers.

Communications rates up to 1M Baud are possible at network lengths below 40 m. With lower speeds, it is possible to increase the distance. At 125k baud, it is possible to have networks up to 500 m in length.

**PROFIBUS**

Profibus is a fieldbus used in Automation applications to facilitate communications of HMIs, I/O, PLCs, controllers, drives, PCs and other devices. Profibus DP (Decentralized Peripherals) implements the Physical, Data Link and Application layers of the OSI model and is considered a complete protocol. The other layers (Network, Transport, and Session and Presentation layers) are not utilized.

Profibus development originated in Germany in 1987 when a 21 member group of companies and institutes set out to develop a fieldbus to facilitate communications for the Automation and Process Control markets. When work was complete, Profibus had 2 versions, Profibus DP and Profibus PA (Process Automation). It then became a DIN (Deutsches Institute fur Normung) standard, DIN 19245. It was later accepted as an EN (European Norm) standard, EN 50170, and later as an international standard, IEC 61158/IEC 61784. As of 2007, there were about 20 million Profibus devices in use worldwide, making it one of the most prevalent automation fieldbuses in use.

There are several committees/groups that are involved in promoting and maintaining Profibus. PI (Profibus and PROFINet International) promotes the use of Profibus by providing information and Training. In North America, the PTO (Profibus Trade Organization) provides regional support under the umbrella of PI.

Profibus has several possibilities for the Physical Layer. The most common is EIA-485. EIA-485 uses twisted pair cabling and operates using differential voltage mode signaling. Baud rates range from 9600 up to 12M Baud. The performance is a function of the distances involved and the quality of the cable. Terminating resistors are required, so the network must be implemented as a Bus configuration.

**CANOpen**

CANOpen implements the OSI model layers above including the Network Layer, i.e. the Network, Transport, Session, Presentation and Application layers. In addition, it specifies requirements for device profiling. The Data Link and Physical layers are provided by the CAN (Controller Area Network) protocol. The CAN protocol was developed by Robert Bosch GmbH in the mid 1980s for use in automotive applications, where it gained wide acceptance. It is now an international standard ISO 11898. More than 2 billion CAN nodes have been sold world-wide.

CANOpen was developed for use in Automation applications. CiA (CAN in Automation) is a non-profit organization that supports CANOpen. More than 500 companies are members of CiA.

CAN is a synchronous bit-oriented protocol that uses differential voltage mode signaling over a twisted pair of wires. CANOpen provides the upper layers of the protocol stack. CANOpen specifies
message formats as well as services devices which have to be implemented in order to adhere to the protocol and provide interoperability with other devices and systems.

Communications rates up to 1M Baud are possible at network lengths below 40 m. With lower speeds, it is possible to increase the distance. At 125k baud, it is possible to have networks up to 500 m in length.

Modbus TCP

Modbus TCP is a variant of the Modbus protocol first introduced by Modicon in 1979. Modbus TCP uses the application layer of Modbus. Modbus RTU is a serial protocol that is implemented by thousands of vendors for use in Process Control and SCADA applications. Modbus RTU relies on RS-232 or EIA-485 for its physical layer, because of this its maximum Baud rate is severely limited in comparison to other protocols. The slow speed makes it unacceptable for almost all automation applications.

Modbus and Modbus TCP are often referred to as 'de-facto' standard protocols. They are open in the sense that anyone can use them, but there is no standards committee or user group maintaining the standard. The Modbus-IDA association is a group of independent users and suppliers of automation equipment that share user information about their protocols and applications. There are 3 standards that apply to Modbus TCP

- Modbus Protocol
- Ethernet
- TCP/IP

Modbus TCP is designed to operate using Ethernet, which can have speeds up to 1G Baud. Modbus TCP is essentially Modbus over Ethernet, using TCP/IP. It is basically Modbus wrapped in TCP/IP messages. This allows it to be used over the Internet.

By using Ethernet for the Physical and Data Link layers, it is possible to use Modbus TCP on the same physical network being used by other protocols and purposes. Because of recent developments between ODVA and IDA-Modbus, in the future it will be possible to have Modbus TCP co-exist with Ethernet/IP equipment.

EtherCAT

EtherCAT (Ethernet for control automation technology) is an industrial Ethernet fieldbus from Beckhoff Automation and primarily based on ring topology. It adheres to IEEE802.3 standards for physical wiring of connections, although recommends not to integrate hubs or switches to ensure maximum performance of the real-time communications. The benefits of this network performance become apparent in smaller controllers with comparatively moderate computing capacity. With EtherCAT technology the protocol process is handled in the hardware components, e.g. controllers, I/O and Servo drives, which house a specially designed and configurable ASIC (Application Specific Integrated Circuit).

Ethernet/IP

Ethernet/IP (Industrial Protocol) is an application layer protocol that uses Ethernet for all of the other layers. The specification for Ethernet/IP is maintained by ODVA, the same group that manages DeviceNet.
By using Ethernet for the Physical and Data Link layers, it is possible to use Ethernet/IP on the same physical network being used for other purposes. For protocol handling it uses Common Industrial Protocol (CIP) which is an object-based approach to design control devices. These communications objects have common elements and a standard set of services for accessing data and controlling device operations. The services are referred to as Implicit and Explicit messaging. Implicit messaging is used for I/O data transfers and Explicit messaging for client/server type transactions. It is also possible to have Ethernet/IP co-exist with Modbus TCP or any other Ethernet compatible protocol. It typically uses two types of messaging, either implicit or explicit depending on the task needing to be performed.

**Ethernet POWERLINK**

Ethernet POWERLINK is a real-time protocol for industrial automation systems. Originally developed by B&R Industrial Automation and introduced to the market in 2001, this [open source](https://www.ethernet-powerlink.org) protocol is managed by the Ethernet POWERLINK Standardization Group (EPSG).

Ethernet POWERLINK is a high performance fieldbus network that takes advantage of decentralized and modular automation architecture. It is considered the best fieldbus system for support of deterministic data at the device level, as well as offers the ability to communicate larger amounts of data between nodes. From simple I/O controls and secure diagnostics data, plus parameter sets with hundreds or even thousands of bytes for motion control servos, robots, etc… is seamless and POWERLINK guarantees the integrity of information being exchanged. Control data being shared between masters and slaves is exchanged in a collision avoidance manner.

POWERLINK allows for maximum protection of the automation investment. It uses unmodified standards, which makes moving from 100M and 1Gigabit communication speeds transparent to the user and owner of the automation equipment, because no controls equipment changes are needed. This philosophy also ensures migration to future applications possible regardless of bandwidth demands and data transmission rates required.

**Ethernet POWERLINK facts:**

- Totally free choice of star, tree, ring, or daisy chain
- Hot plugging for any node on the bus
- Configuration-free topology
- Flat network for unambiguous diagnostics
- All data is readily available at any point on the network
- Topology-independent configuration function
- Node switch setting or software addressing

For more details about Ethernet POWERLINK please visit [www.ethernet-powerlink.org](http://www.ethernet-powerlink.org).
Summary

This paper has covered a general overview of key concepts involved in various Automation fieldbuses and protocols. Some fundamental terms were introduced and the major protocols used in Automation applications were explored. The latest trend to use protocols based on Ethernet as their Physical and Data Link layers is expected to continue growing. However, basing your fieldbus decision on completely open Ethernet standards, from hardware to software, ensures the fieldbus application and equipment is maintainable without any limitations.

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