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Real-time Control on Ethernet

This article first gives you an introduction about the use of Ethernet networks in general. And it discusses the problems of Ethernet usage in real-time applications. To solve these poblems, different protocols have been developed. ControlNet's Control and Information Protocol (CIP) is one of these protocols and this is what the rest of this article tells you more about.

INTRODUCTION

It would be rash to say that Ethernet for industrial automation is sure to be a short-lived fad. Not only rash, but unwise as well. Today, Ethernet is the undisputed networking champion for information-layer (i.e. office environment) communications. Now, with the recent introduction of Fast and Gigabit Ethernet, as well as more reliable Ethernet switches, it is creating a buzz in the automation industry where proponents are eager to take Ethernet to the plant floor for control and even device-layer applications.

In fact, Ethernet is being touted as the solution to virtually every network-related automation problem. Ethernet for device-level communication. Ethernet for control. Ethernet for high-level data transfer. Ethernet for everything under the sun. However, those that predict Ethernet world domination seem to be missing vital information. To its credit, Ethernet has many benefits, like availability, familiarity and cost. But when compared against its cons - non- deterministic and no interoperability - using Ethernet for industrial control application has shortcomings.

IN THE BEGINNING

Xerox Palo Alto Research Center developed Ethernet in the 1970s, primarily for use as a Local Area Network (LAN) technology for office environments. In 1979, Digital Equipment Corporation and Intel joined Xerox in partnership to promote the new network, and in 1980 they published the first Ethernet specification. Ownership of the Ethernet specification was eventually passed to the Institute for Electrical and Electronic Engineers (IEEE), who approved and released it as IEEE Std 802.3 in 1983. In 1985 the International Standards Organization (ISO) released the first international draft of the standard.

ALL THOSE IN FAVOR, SAY "FAMILIARITY"

Defying the familiarity-breeds-contempt axiom, Ethernet has gained popularity due to the fact that it is readily available and subsequently low in cost. And although the "low cost" factor deals directly with the physical media and hardware, it also translates to manpower and training. For years, IS and IT departments worldwide have been using Ethernet. Such long-term exposure to the Ethernet technology has produced an expansive knowledge base and unparalleled resources.

In addition, Ethernet is fast. Based on data rate alone (which is only one factor of a network's overall performance), 100Mbps Ethernet has a considerably higher data transfer rate than both ControlNet and Profibus.

THE OPPOSED SAY: "DETERMINISM AND INTEROPERABILITY"

Being able to predict when information will be delivered is referred to as determinism. All networks provide a degree of determinism. If a network only has two nodes - and the transfer of data between the nodes is restricted to avoid collisions - the network has absolute

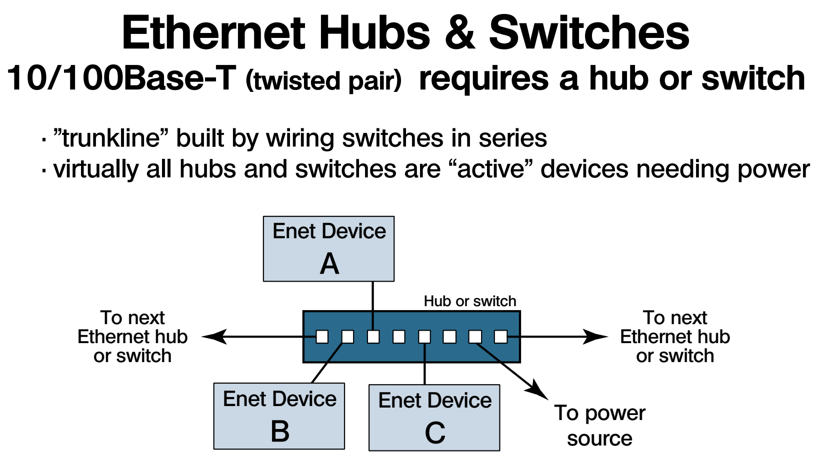

Figure 1. Ethernet Hubs & Switches

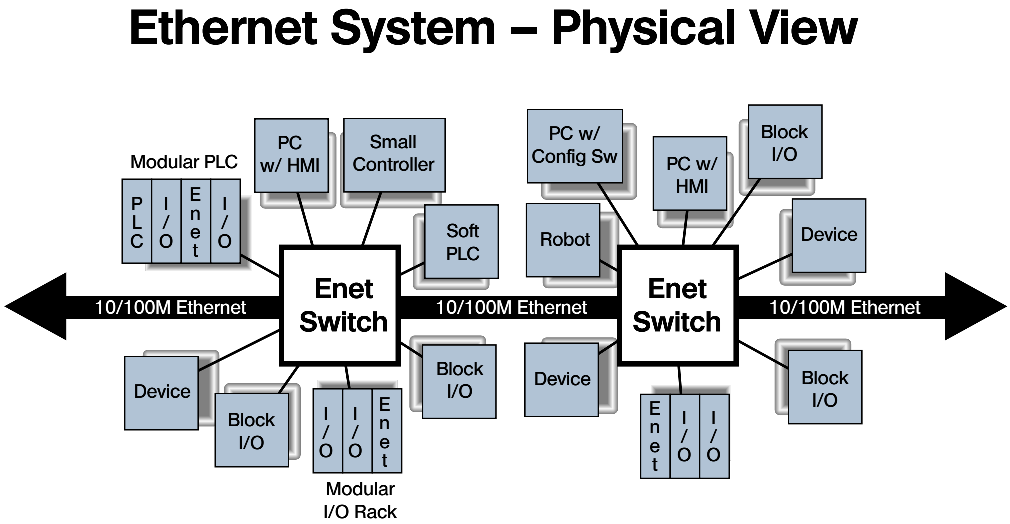

Figure 2. Ethernet is used as a trunk line to network individual switches

determinism. However, this scenario is hardly realistic. More often than not, the number of nodes on a network continually changes. In order to guarantee determinism, a network must provide scheduled bandwidth (or time slots) that are reserved for time-critical data transfer. Ethernet does not. To illustrate the possible effects of using a non-deterministic network like Ethernet in real-world terms, consider the following:

A cut-to-length application is networked using Ethernet. Every 50 milliseconds, a saw is scheduled to drop on a piece of metal tubing. Transported at a rate of 1 in./25 milliseconds (10 mm/millisecond), the tube is supposed to be cut in 2-in. (5 cm) lengths. However, the network is often flooded with traffic, the 50-millisecond period passes and the message waits in a long queue. Consequently, the saw is often lowered well beyond 50 milliseconds and the tubing is sliced too long Not only does productivity suffer, but product is ruined as well. No matter the urgency or importance of a given message (i.e. 50 milliseconds have expired, drop saw), each node on Ethernet has to wait if the network is busy.

Recent advancements in switching technology have enabled Ethernet networks to be configured in a "star" topology (where the switch acts as a network concentrator for connecting multiple devices or Ethernet network segments - see Figures 1 and 2). The switches have reduced data collisions and increased the network's efficiency, albeit at the added cost of switches and dependency on powered, active components. In addition, IEEE 802.3 provides standardized full-duplex operation, which gives a single node - in a peer to peer connection - full wire concentration. Full-duplex products, as a result, are theoretically able to avoid collisions. Nonetheless, Ethernet has yet to completely shrug off the non-deterministic label.

Also to its detriment, Ethernet (in an automation environment) doesn't deliver interoperability and/or inter-

7-Layer OSI Network Model

Application	Protocols/services for applications Selection of type of dialog Identification and Authorization	7	**FTP, SNMP SMTP, HTTP Telnet, CIP**
Presentation	Representation of data Definition of coding type Definition of used characters	6	
Session	Dialog control Synchronization of session connection	5	
Transport	Sequencing of application data Control of start/end of transmission Error detection and clearing	4	**UDP/TCP**
Network	Routing, prioritization Setup/release of connections Flow control	3	**IP**
Data Link	Framing Sequence Control Flow Control	2	**Ethernet**
Physical	Bit transmission Coding Synchronization	1	

Figure 3. The 7-Layer OSI Network Model. For interoperability among different networked devices, a common application layer (Layer 7) is required.

AD PHARLAP

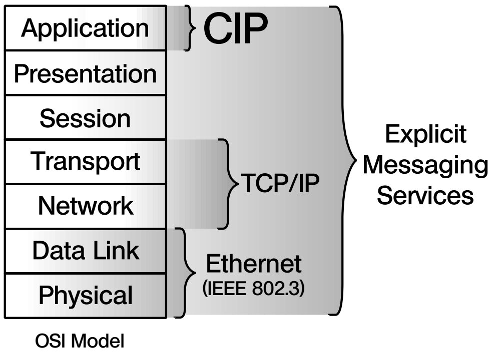

Figure 5. Explicit messaging uses TCP/IP running on Ethernet Data Link Layer Chips

changeability between competing vendors' devices. That's because Ethernet technology by itself only provides a set of physical media definitions, a scheme for sharing that physical media and a simple frame format and addressing scheme for moving packets of data between devices on a LAN. Using the OSI seven-layer model, Ethernet provides only physical and data-link layer protocols. For that reason, all Ethernet networks support one or more upper layer protocols that run on top it, providing sophisticated data transfer and network management functionality. It is the upper layer protocol that determines level of functionality the network supports, which devices may connect to the network, and how devices interoperate on the network.

NOT ETHERNET, ETHERNET TCP/IP

Transmission Control Protocol/Internet Protocol (TCP/IP), which most people are familiar with, is the network and transport-layer protocols of the Internet and is commonly linked with Ethernet in the business world. The TCP/IP protocol suite provides a set of services that two devices may use to communicate with each other over an Ethernet LAN or over a wide-area network that spans the globe. However, using TCP/IP alone does not guarantee that two devices can communicate effectively, if at all. It only guarantees that application-level messages will be successfully transferred between the two devices. For interoperability, a common application-layer protocol is needed (see Figure 3).

Although common protocols for file transfer (FTP), terminal emulation (Telnet), e-mail (SMTP), World Wide Web (HTTP) and others have been established for Internet applications, the situation is not so simple in the area of industrial automation. Each vendor of automation equipment that runs over Ethernet-TCP/IP has implemented its own application-layer protocol. As a result, a standard application layer, common object model and universal device profiles don't exist. Ethernet users are currently tied to proprietary application-layer solutions and aren't able to benefit from the best-in-class and best-in-value options offered by an open market. In many ways, switching to a proprietary Ethernet solution has caused end users to step back in the evolution of networking technologies even as they attempt to move forward.

EVERYBODY OVER ETHERNET

The upper-layer enigma that plagues Ethernet has also created a race among network-savvy companies and open standards organizations alike. The contestants are scurrying to become the Ethernet-solutions provider. For the most part, engineers are taking existing protocols and bundling them with TCP/IP. Such a union has created widely varying results, from the Modbus/TCP specification, Profibus over Ethernet, and Control and Information Protocol over Ethernet (also referred to as ControlNet services over Ethernet). These various options have also created confusion.

However, the easiest method of separating the field is to take a look at the networks porting their services over Ethernet. In short, an organization's Ethernet efforts can only be as efficient as the network whose upper-level protocols are being used.

	ControlNet Services over Ethernet	ControlNet	DeviceNet	Profibus-DP	Interbus	Modbus	AS-i
Application							
I/O	·	·	·	·	·		·
Program Up/Down	·	·	·	DP V1 Only	·	·	
Messaging	·	·	·	DP V1 Only	·		
Hierarchies							
Master/Slave	·	·	·	·	·	·	·
Multimaster	·	·	·				
Peer-to-Peer	·	·	·	(limited)			
I/O Exchange							
Polled	·	·	·	·	·		·
Cyclic	·	·	·				
COS	·	·	·				
Connection Relationship							
One:One (client/server)	·	·	·	·	·		·
One:Many(multicast)	·	·	·	(limited)			
One:All (broadcast)	·	·	·				
Routable Protocol	·	·	·				

Figure 4. The Control and Information Protocol (CIP) used in ControlNet and DeviceNet offers a complete set of services required for Control. Other application-layer protocols have only a limited set of services

CONTROLNET SERVICES OVER ETHERNET

Beginning in the spring of 1998, a ControlNet Special Interest Group (SIG) developed a way to apply ControlNet's open, published and widely accepted application layer - Control and Information Protocol (CIP) - over Ethernet. CIP provides Ethernet users with both explicit (information) and implicit (control) messaging services.

As a result, the ControlNet SIG brought three key attributes to the Ethernet field:

1. **A Robust (and Growing) Object Library**

   One of the greatest strengths of ControlNet is its object library. The objects and device profiles make it possible for plug-and-play interoperability among complex devices from multiple vendors. The object definitions are rigorous and support real-time I/O messaging, configuration and diagnostics over the same network. This means users can connect to complex devices like drives, robot controllers, bar code readers and weigh scales without custom software. This results in faster start-ups and superior diagnostics.

2. **A Robust (and Growing) Vendor Community**

   A little known fact is that ControlNet shares the same object library as DeviceNet. To translate, over 350 vendors worldwide have developed interoperable products for any one of these three CIP-based networks: DeviceNet, ControlNet or Ethernet.

3. **Complete Services for Control**

   The primary benefit of ControlNet services over Ethernet is that ControlNet offers end users every service that is essential in a control network. The following chart shows where the competition stands in comparison (see Figure 4).

There are numerous control services - essential in many applications - that are noticeably absent in other networks. For example, routing among any of the CIP-based networks - Ethernet-to-DeviceNet, Ethernet-to-ControlNet, ControlNet-to-DeviceNet, etc. - is simplified because the protocols are the same. Complex gateways (single board computers which must convert protocols between the networks) are required for Profibus-to-Ethernet.

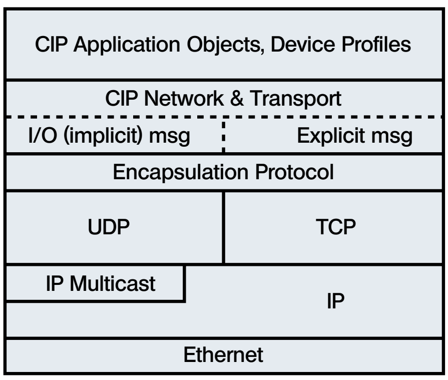

Figure 7. The use of UDP/IP and TCP/IP for ControlNet services over Ethernet allows both explicit (information) and implicit (control) messaging

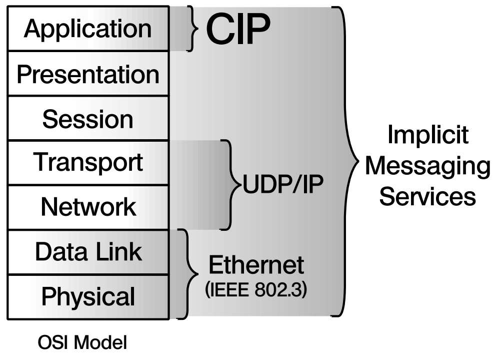

Figure 6. Implicit Messaging uses UDP/IP running on Ethernet data-link layer chips

THE NUTS AND BOLTS VERSION

It should be stated up front that the word "Ethernet" in "ControlNet services over Ethernet" refers to standard (802.3), garden-variety Ethernet. Not a modified, proprietary version. Nonetheless, an approach called TCP/IP encapsulation is used to apply ControlNet messaging services over Ethernet (see Figure 5). TCP/IP encapsulation allows a ControlNet node to encapsulate a ControlNet message as the data portion in an Ethernet message. The node is then able to send the message - TCP/IP protocol with the ControlNet message inside - to an Ethernet communication chip on the data-link layer instead of a ControlNet communication ASIC. CIP is used as the application layer, making interoperability and interchangeability of industrial automation and control devices on Ethernet a reality for automation applications.

The fact that TCP/IP is inherently point-to-point, however, initially limited ControlNet services over Ethernet to explicit messages only - those in which the data field carries both protocol information and instructions for service performance (the information part of CIP). With explicit messaging, nodes must interpret each message, execute the requested task and generate responses. These types of messages are used for device configuration and diagnostics, and are highly variable in both size and frequency.

By using UDP/IP, which can multicast, implicit messaging is now a reality (see Figure 6). With implicit messaging, the data field contains no protocol information, only real-time I/O data (the control part of CIP). The meaning of the data is predefined at the time the connection is established and processing time in the node is therefore minimized during runtime. Such messages are low overhead, short and provide the required, time-critical performance needed for control. Implicit messaging services - via the UDP/IP protocol - will be added to the ControlNet International specification by the end of 1999.

By employing both TCP/IP and UDP/IP protocols to encapsulate ControlNet messages, both real-time I/O and explicit messaging can occur (Figure 7). And by providing Ethernet users with real-time I/O, device-configuration and diagnostic capabilities, along with inter-

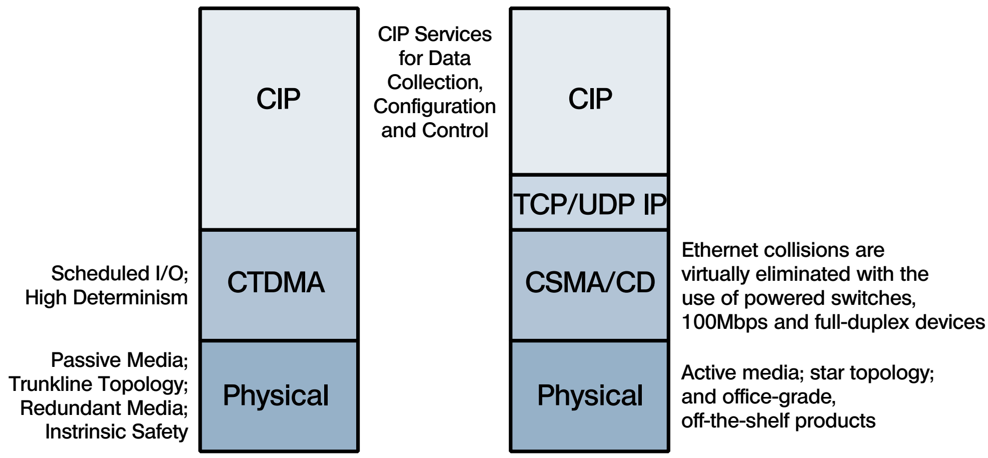

Figure 8. Using ControlNetÕs Control and Information Protocol (CIP) on Ethernet does not provide the absolute scheduled determinism of ControlNetÕs native data-link layer

operability and interchangeability, ControlNet International has positioned itself as the Ethernet solutions provider for automation.

CIP IN THE 21ST CENTURY

While mapping of I/O services over UDP/IP completes the offering of CIP on Ethernet, it doesn't bring the absolute scheduled determinism of ControlNet to Ethernet. ControlNet's native data-link layer uses Concurrent Time Domain Multiple Access (CTDMA) which provides guaranteed access for scheduled I/O. Ethernet uses Carrier Sense Multiple Access/Collision Detection (CSMA/CD) and is not modified by using CIP (see Figure 8).

Control over Ethernet poses several other concerns:

- The lack of a standard way to IP Multicast. The IGMP standard provides a way to propagate multicast addresses to switches and routers, but the method to select the address is not standardized. For this reason, it is recommended that the control domain be limited to a single subnet.
- The realization that UDP/IP broadcast is an unconnected message. Consequently, message delivery isn't guaranteed. CIP transports, however, provide end-to-end connections that notify both applications if a connection has become unreliable.
- The end user must rely on performance benchmarks due to the fact that there are no enforced

	DeviceNet	ControlNet	CIP Services on Ethernet	Fast Ethernet, ATM Firewire, USB
1. Messaging Types				
I/O Control (implicit)	4	4	4	
Messaging (explicit)	4	4	4	
Both at the same time	4	4	4	
2. Node Relationships				
Master/Slave	4	4	4	
Multimaster	4	4	4	What's
Peer-to-Peer	4	4	4	
3. I/O Exchange				
Polled	4	4	4	Next
Cyclic	4	4	4	
COS (Change of State)	4	4	4	
4. Delivery Mechanisms				
One-One (point-to-point)	4	4	4	
One-Many (multicast)	4	4	4	
One-All (broadcast)	4	4	4	
Routable Protocol	4	4	4	

Figure 9. The robust Control and Information Protocol (CIP) is the most flexible and complete protocol for any wire and any communication chip, now and in the future.

protocol or software tools to determine if the solution is good or on the edge.

- A plant's systems administrator has to program switches to block office traffic from plant floor control subnets. As a result, a human is required to enforce security and prevent data storms at all times. The use of firewalls or virtual LANs can help.
- The control network is dependent on powered media components such as switches. The reliability of these components is improving as market demand for industrialized versions and back-up power supplies grows.

Such present day limitations are the focus of ongoing SIG efforts. And there are many activities in the commercial Ethernet market that will improve the usability of Ethernet for control. For example, the push to run video simultaneously with other messaging is driving Quality of Service (QoS) standards on the use of IEEE 802.1P Ethernet Frame Prioritization to guarantee bandwidth. This will be a good fit for the scheduled I/O services of ControlNet. In addition, developments in Ethernet switches have greatly improved the level of determinism on Ethernet networks. As a result, Ethernet will begin to approach the guaranteed delivery provided by ControlNet's native data-link layer.

THE FUTURE OF CONTROLNET

By examining the advantages of ControlNet services over Ethernet and "classic" ControlNet (see sidebar), it is evident that CIP-based networks offer the full range of necessary services for control applications. That is why ControlNet International will take its robust protocol and deploy it over standard, commercially available communication technology. Today it's Ethernet. Tomorrow it may be up-and-coming networks like FireWire, Asynchronous Transfer Mode (ATM) and Universal Serial Bus (USB). In brief, ControlNet International will link to and leverage other standards as they become available. Regardless of the name, the concept is simple. Any wire, same complete control services for automation (see Figure 9) ■

William H. Moss serves as the executive director for ControlNet International. Moss was formerly managing director of WorldFIP, a multinational vendor consortium that promotes and manages digital networking standards and communications products for the factory automation information superhighway. He has more than 10 years experience with manufacturing companies in the process automation industries - Bailey Controls Company and Computer Products, Inc. - where he was an executive in charge of new products, sales, application engineering and business development. Prior to that, Moss spent 10 years with a 400-person engineering firm where he was chief environmental engineer. He is a registered engineer and holds an MBA and an MS in chemical engineering from Case Western Reserve University and a BS in chemical engineering from Case Institute of Technology.

See next page for more on Classic ControlNet 101

CLASSIC CONTROLNET 101, A CONTROLNET PRIMER

The immediate question that ControlNet's branching out raises is, "Does ControlNet services over Ethernet (or any other network) obsolete ControlNet?" The answer is a definite, "No." Ethernet can't match the services and benefits inherent in ControlNet.

Passive Media Components

One of the most critical aspects of "control" is that system failures result in very serious repercussions. While technical difficulties within the business environment can definitely cause a nuisance, failures within a control application can result in equipment damage, environmental hazards and even personal injury. Powered components are key contributors to system failures because loss of power means a loss of communication. (Would you want to operate a plant making explosives with the HMI devices going dark because communication was lost?). ControlNet, however, uses passive taps, which means the network is unpowered, and loss of any one node will not result in a network failure. In contrast, switched Ethernet has powered switches and routers. Loss of a switch results in the loss of all network communications for the nodes attached to the switch and causes a rift in the nodes on either side of the switch

Media Redundancy

While redundancy is an integral part of some network systems, other networks require massive re-engineering to provide redundancy. Features such as automatic re-routing and immediate failure detection are also part of a network management system with inherent redundancy. ControlNet offers physical media redundancy as a standard option. This is critical in process industries that require constant monitoring, even if network cables get cut or damaged. For example, it is imperative that the HMI devices do not go dark in a process plant if the network wire is cut.

Determinism

As stated previously, all networks have the ability to provide determinism to some degree. But by having bandwidth that can be scheduled, data on ControlNet is guaranteed to arrive at specified intervals regardless of the number of nodes on the network. This scheduled bandwidth is typically reserved for time-critical I/O data. In addition, the determinism of ControlNet (and bandwidth utilization) is aided by the fact that it employs a producer/consumer communication model.

Producer/Consumer Communication Model

When it comes to a network's speed, baud rate is only one of the factors to consider. The network communication model used to exchange data and information between devices actually has the most impact on network functionality. All networks fall into one of two categories: source/destination or producer/consumer. The difference between the two can be compared to telling a room full of people the time of day. With source/destination, one person reads a clock and then proceeds to tell each person in the room, one at a time. In producer/consumer mode, the same person announces the time to everyone at once. In a manufacturing environment, "identifiers" embedded into each message are used by the devices to determine which messages they should "consume." Although the network model does not impact the rate at which data is transmitted, it does affect bandwidth. Because a producer/consumer network transmits a piece of information only once, it uses less bandwidth. And less bandwidth equates to greater efficiency and overall speed.

ControlNet, DeviceNet and Foundation Fieldbus are examples of networks based on the producer/consumer technology. While Remote I/O, Data Highway Plus, Profibus and Modbus are based on source/destination technology.

Intrinsic Safety

To earn the intrinsically safe designation, a network's energy and frequency spectrum must be able to be controlled without performance degradation. Likewise, network products must be designed to limit electrical and thermal energy capable of igniting atmospheric mixtures. Intrinsic safety requirements are strict because mistakes are potentially deadly. ControlNet and specially designed ControlNet products meet the demanding and rigid requirements for use in a wide range of hazardous areas: Zone 0, 1 and 2; Class I, II and III Division 1 and 2; and Class I Zones 0, 1 and 2. ControlNet also provides the ability for intrinsically safe ControlNet products to interface with non-intrinsically safe ControlNet products.

Open Technology

ControlNet International, an independent organization for users and vendors of ControlNet products, was formed in July 1997. The organization manages the ControlNet specification and supports worldwide growth of ControlNet. Any and all automation vendors are invited to join ControlNet, shape the future direction of the network and/or develop ControlNet-related products.