SPECIFYING INDUSTRIAL FIELD BUS NETWORKS FOR AUTOMATION

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ABSTRACT

An important trend in factory automation is the continual increase in networked interconnection between sensors, controls, actuators and other system components. Automation designers face many challenges and tradeoffs in the development of a successful network solution. This paper discusses the necessary choices in selecting a network technology appropriate for various specific applications. Technical constraints of several common field buses will be compared, and guidelines for selecting media and protocol will be discussed.

The intended audience is system designers who will develop networked automation, but who may not be familiar with the details of data transmission design. The audience should come away with a general overview of common field buses available, and some knowledge of the kinds of questions to consider when choosing an architecture, a protocol, and an implementation.

I. INTRODUCTION

There are at least two scenarios that can arise when selecting a bus network for an application. In one scenario, the engineer begins with a blank sheet of paper (*carte blanc*) , and can specify any network that best meets the needs of the application at hand. In another scenario, the engineer will be constrained to specify a network compatible with an existing installation. In an ideal world, all networks would be compatible, and it would be easy to translate from one to another. In actuality, interconnecting different networks can be very difficult, so we'll leave *that* can of worms alone. This leads us to assume the choice of network for the second scenario is pre-determined, and we can therefore focus on the first scenario.

We look for ways to compare different network choices, and find a long list of possibilities. Specific parameters of comparison and design concerns include:

- data rate and data latency
- physical interconnect medium
- noise immunity
- bit error rate and bus faults
- allowable interconnection length
- allowable number of network nodes
- ease of adding additional nodes
- power consumption, cost, reliability and isolation requirements

In the following paragraphs, we'll look at several of these, discuss why each of the characteristics is of concern for automation networks, and what tradeoffs come into play for making appropriate field bus selection. We'll see how there is no universal answer, but that in optimizing one parameter, there are tradeoffs and compromises involving other parameters, as shown in **Figure 1** .

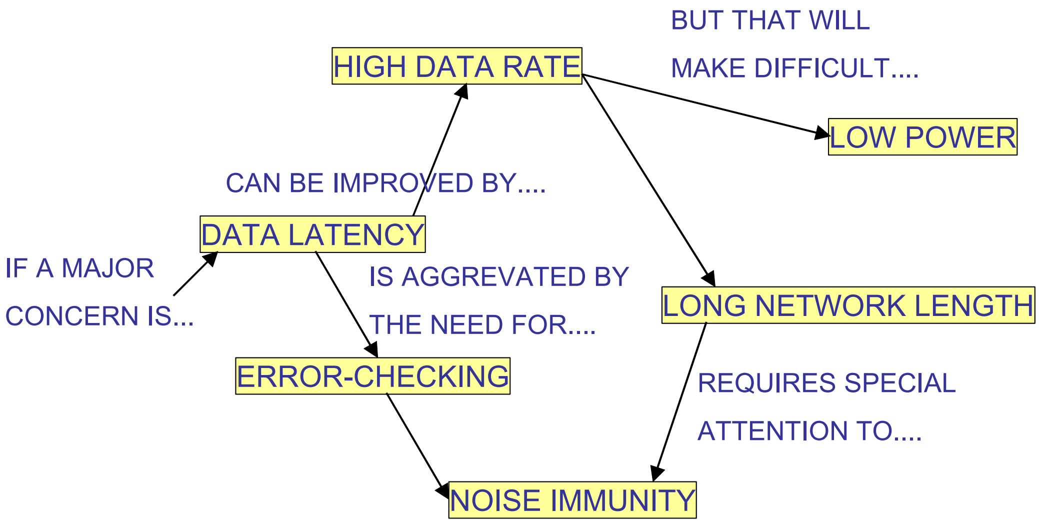

Figure 1 Network requirements are interrelated and require tradeoffs

II. INDUSTRIAL AUTOMATION BUS CHOICES

A few brief comments present a cross-section of the available field bus choices:

4-20 mA – This analog current loop network is slow but simple. It is limited to one transmitter per loop, but can have several receivers. The analog format limits the higher-level functionality, but this is still a wide-spread implementation for communicating simple sensor measurements to a central controller.

HART – The Highway Addressable Remote Transducer network augments the 4-20 mA loop with a modulated signal. This allows transmission of digital information, although the data rate is relatively slow.

RS-232 – This standard interface has been around for a long time, and is still used in many simple interfaces for initial setup of systems, diagnostics, and other non-time-critical functions. A single-ended network, RS-232 does not have the same noise immunity as the majority of the other standards, which take advantage of differential signaling.

RS-485 – An outgrowth of RS-232 and RS-422, the RS-485 electrical specification is the basis for several industrial network standards, including Profibus, Interbus, Modbus, and others. The strengths of RS-485 are it's immunity to noise and ground offsets, bidirectional and multiple driver capability, and party-line simplicity.

Interbus – A ring-based network, Interbus uses RS-485 signaling with point-to-point connections, and full-duplex operation to make an adaptable bi-directional structure. Other variations of Interbus use fiber or infrared media for signaling.

Modbus – Modbus has several variations, the most common is based on RS-485 signaling. Other implementations use Ethernet or RS-232. In addition to industrial automation, it is also used in building control applications.

Profibus DP – Based on RS-485 signaling technology, Profibus DP (Process Field Bus, Decentralized Peripheral) is a commonly used fieldbus network for factory automation, especially in

Europe. The Profibus standard specifies the protocol, electrical layer, termination, signaling rates, and grounding/isolation schemes. There are other variants of Profibus for fiber media, intrinsically safe applications, and motor control applications.

DeviceNet – Based on the CAN signaling specification, the DeviceNet standard specifies the electrical layer (voltages, current loading, termination, isolation/grounding) and protocol requirements for a device-level network.

ControlNet – With a high signal-to-noise ratio and using coaxial media, ControlNet is a robust, relatively high-speed industrial network. It's strengths are deterministic timing, robust electrical characteristics, and simplicity of expansion.

Industrial Ethernet – Several different variations of Industrial Ethernet are now available. These include ProfiNet, EtherCAT, Ethernet/IP (Industrial Protocol) and others. Each is based on the IEEE 802.3 Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Standard for Local Area Networks. Each variation has differences (and is not easily interconnected with the others), mainly due to how the requirement for known data latency (deterministic timing) is handled. Versions with 10 Mbps (mega bits per second) and 100 Mbps are commonly used for industrial automation applications.

III. ALLOWABLE NUMBER OF NODES

Automation applications may require connecting many sensors and actuators, as well as controllers and human-machine interface panels. The maximum allowable number of nodes may be limited by the system architecture, the electrical or optical characteristics of the physical layer, or by the addressing scheme inherent in the network protocol.

Network architecture may be bus, ring, star, or other arrangements. Bus networks such as DeviceNet or Modbus accept nodes anywhere along their length, but usually have restrictions on the spacing between the nodes. Ring networks such as Interbus form a closed-chain with point-to-point links between each two adjoining nodes. Star networks such as Ethernet allow a heirarchical structure, with many stars connected in various patterns. Loop connections such as 4-20mA may have several receivers on one loop, but are limited to one transmitter.

Table 1 Maximum nodes for standard networks

Standard	Constraint mechanism on the number of nodes	Maximum allowable nodes
RS-485	Total current loading on the active driver	32 Unit Loads[1] (up to 256 nodes possible)
Profibus DP	Total impedance per segment	32 devices per segment
Interbus	Point-to-point propagation delay	63 devices per loop
ControlNet (Coax)	Impedence and signal reflections	48 per segment
DeviceNet	Specified by the standard	64
Ethernet	Interconnection heirarchy	Star arrangement (typical) depends on protocol choice

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[1] The unit-load specified by the TIA/EIA-485-A standard (RS-485) specifies a hypothetical current-voltage loading unit as a basis of transceiver comparison. RS-485 transceivers are available with ratings of 1/8 unit load, allowing up to 8 x 32 or 256 transceivers on a single bus, without exceeding the standard.

IV. DATA RATE

The basic function of any communications network is to move data from place to place. Data rate is a measure of how much data can be moved in a certain amount of time. But data rates of different networks may be measured in different ways. For analog communication such as 4-20 mA, the bandwidth of the circuit elements limits the rate. For digital communication, the rate is determined by how many bits (binary digits) can be communicated per second, and what fraction of the communicated bits actually have meaning for the application.

Another parameter related to the speed of the network is data latency, the time interval between data being sent from one node and received at another. Data rate affects data latency, as does transceiver propagation delay, media propagation delay, and protocol overhead.

Transceiver propagation delay is typically on the order of a microsecond or less; the propagation delay through the media (fiber or copper) is limited to some fraction of the speed of light, and is therefore on the order of 3 to 5 nanoseconds per meter of cable. Therefore only in very long cables (or very fast networks) will the media delay be significant. The protocol delay accounts for the time added by the protocol overhead (parity, addressing, error check, handshaking bits) required in addition to the data payload on any message. This varies by network standard, but is significant for the higher-level protocols with complex formats.

An illustration of the difference between data rate and data latency:

Fast data rate / long data latency – listening to a pre-recorded tape of a Spanish-language sports show
Slow data rate / short data latency – listening to James Earl Jones (live) on the phone

Table 2 surveys the raw data rates and message protocol latency for several field buses.

Table 2 Data rates and latency for standard networks

Standard	Data Rate	Minimum message	Protocol latency
4-20 mA	Limited by analog components, less than 30 Hz (typical)	none	None
HART	1.2 kbps	11 bits	> 9000 usec
RS-485	0 to 50 Mbps	1 bit	Depends on specific protocol
DeviceNet	125 kbps, 250 kbps, 500 kbps	41 bits	> 81 usec
ControlNet	5 Mbps	56 bits	> 11 usec
Profibus	Up to 12 Mbps	140 bits	> 12 usec
Ethernet 100BaseTX	100 Mbps	300 bits	> 3 usec

V. NOISE IMMUNITY

The industrial environment involves challenges due to high-current components such as motors, pumps, switching power supplies, welding equipment and robotics. Immunity to these sources of noise is necessary to ensure reliable operation of the network. At the physical layer, this requires proper attention to grounding, shielding, and transceiver features. High signal levels on the network will increase the signal-to-noise ratio. Receiver threshold levels (often called “squelch”) as high as possible will descrimate proper signals from noise. Hysteresis in the receiver thresholds decreases the possibility of erroneous switching due to noise during signal transitions. See Figure 2 which shows how hysteresis improves noise rejection.

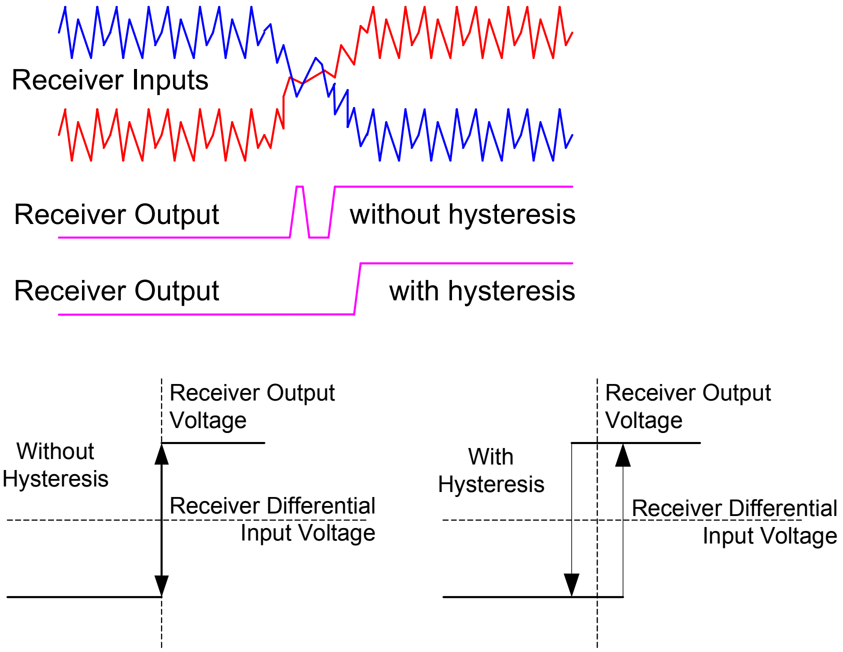

Figure 2 Effect of receiver threshold hysteresis

Each of these improvements in noise immunity comes with some cost, however. High signal levels require more power, and may generate noise to other components. High receiver thresholds mean the system is less tolerant of signal losses in the media, which can decrease allowable network length. Receiver hysteresis can introduce propagation delay and pulse width distortion if not properly balanced. Note in Figure 2 how the receiver output with hysteresis is slightly delayed in response compared to the output without hysteresis.

VI. LENGTH OF NETWORK

Another measure of a network is how far the data can be communicated. Industrial networks often require long interconnections, more so than in consumer, computer, or automotive applications. Factors which limit allowable network length are losses in the media and electrical noise pickup (both of which affect signal-to-noise ratio) and propagation delay through the media which affects latency.

Losses in the media occur whether the medium is copper, fiber, or wireless. Optical fiber losses are very low (0.3dB/1000m at λ=1310nm), allowing very long connections using optical networks. Typical twisted pair copper wire has higher losses, in the neighborhood of 1.5 dB to 5 dB per 100 meters at 1 MHz. See Figure 3 for a comparison of typical cable attenuation for various types of networks.

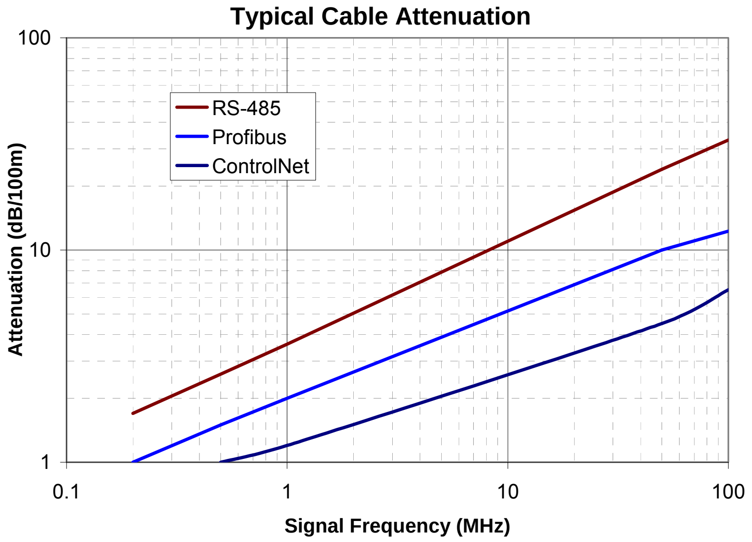

Figure 3 Twisted-pair cable attenuation per unit length vs. frequency

Network standards take the media losses into account by requiring much higher transmit signal amplitudes than receive levels. For example, RS-485 signaling requires at least 1.5V driver output, and receiver thresholds of 200 mV. This gives a factor of 7.5, or equivalently 17.5 dB of margin, which allows cable lengths up to about 1200 meters at low signaling rates. Table 3 presents example calculations for typical industrial networks. Note that the losses in the media may not be the only consideration in determining maximum allowable network length.

Table 3 Example Limits on Network Length

Standard	Driver Output	Receiver Sensitivity	Signal margin	Typical cable attenuation	Media-loss cable length limit (typical)	Protocol network length limit
RS-485	1.5 V	200 mV	17.5 dB	2.5 dB/100 m @ 0.5 MHz	700 m @ < 0.5 Mbps	None
				10 dB/100 m @ 10 MHz	175 m @ 10 Mbps	
Interbus	1.5 V	Same as RS-485				200 m per loop @ 500 kbps
Profibus DP	2.1 V	200 mV	20.4 dB	6 dB/100 m @ 12 MHz	340 m @ 12 Mbps	100m @ 12 Mbps 1200m @ <94 kbps
ControlNet (Coax)	8.2 Vpp	510 mVpp	24 dB	2 dB/100 m @ 10 MHz	1200 m @ 5 Mbps	< 1000 m
DeviceNet	1.5 V	400 mV	11.5 dB	1.2 dB/100 m @ 1 MHz	950 m @ < 0.5 Mbps[2]	500m @ 125 kbps 250m @ 250 kbps 100m @ 500 kbps
Ethernet 10Base-T	2.2 V	585 mV	11.5 dB	10 dB/100 m @ 10 MHz	115 m @ 10 Mbps	Typically 100 m
Ethernet 100Base-TX	1.0 V	1 Vpp	6 dB	15 dB/100 m @ 10 MHz	40 m @ 100 Mbps[3]	Typically 100 m See footnote below

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[2] The CAN (ISO11898) physical layer on which DeviceNet is based restricts network length to limit the time needed for cable propagation delay between nodes. Therefore, the allowable cable length is shorter than is predicted by media-loss calculations.

[3] 100Base-TX Ethernet receivers typically employ adaptive equalization techniques to compensate for losses in the cable. Therefore the allowable cable length is longer than is predicted by simple media-loss calculations.

VII. APPLICATION EXAMPLE

An example solution using an RS-485 PHYsical layer-based network will show how the network implementation is critical to support application performance. A contrast between the requirements of a precision motion-control application and a multi-sensor process control application illustrate how system requirements affect network design choices. See Figure 4.

In the motion control example, tool speed and encoder precision combine to dictate a high data rate. The number of nodes is limited, as is the distance of the network. Data latency would also be critical for the position and velocity information used to close the servo loops. In this application, some of the slower networks, such as DeviceNet or HART, would not be appropriate, due to the data rate requirements. Other networks, such as 100Base-TX Ethernet or Profibus, or ControlNet are also possible choices for this application.

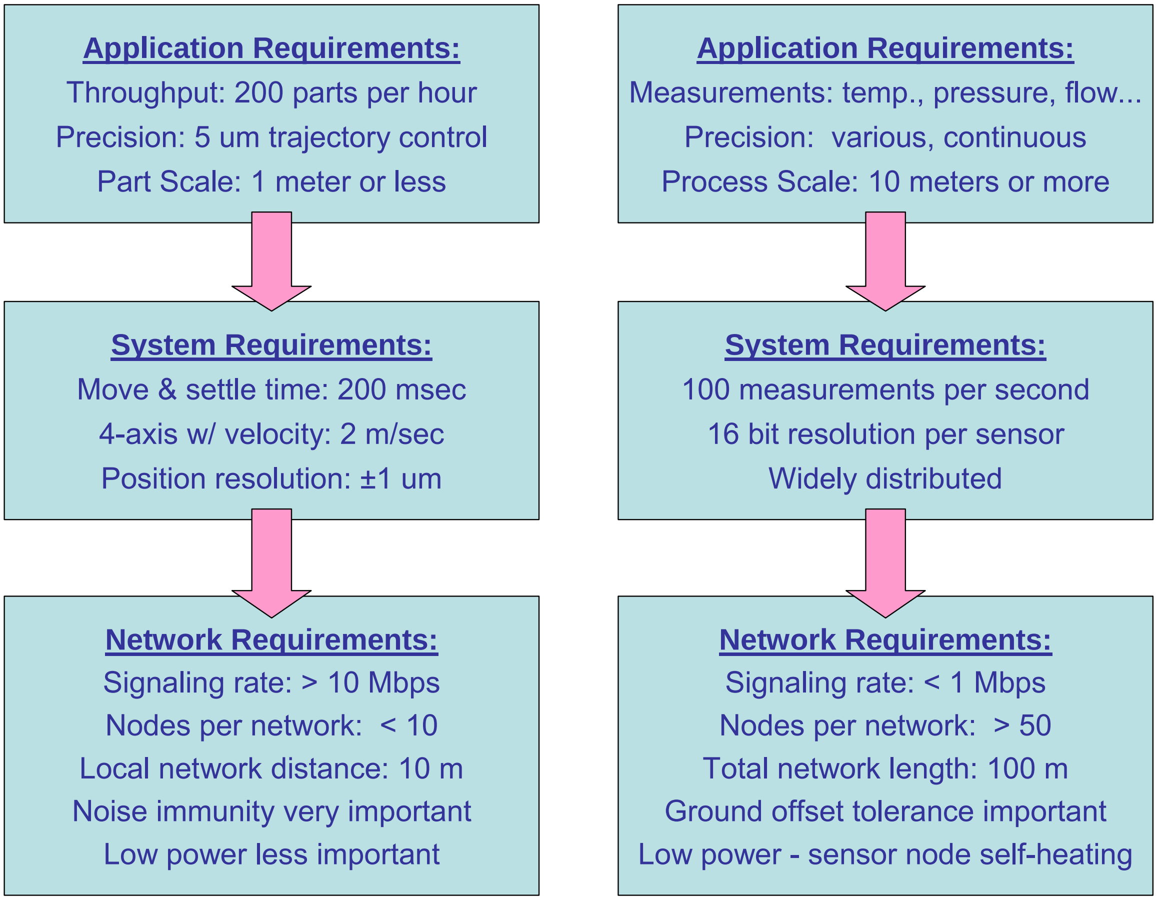

Figure 4 Application requirements flow to network implementation

In the process control example, overall signaling rate is less important, because the process time constants are much longer than the motion control application. This network may span a much longer distance, and have several dozen nodes interconnected. Ground offsets between the nodes may caused by localized high-current surges. The high node count makes Profibus a less attractive choice, while slower networks such as DeviceNet and Interbus are now contenders for this application.

For either application in these examples, there will almost certainly be constraints regarding total cost of the solution, interoperability with other systems and legacy hardware, and motivation to standardize with other applications already supported in the field.

VIII.SUMMARY

In this presentation, only a few of the comparisons and tradeoffs between various automation field buses have been touched on. An in-depth discussion between all choices would take volumes. It is important that the performance of the end application be the driving force in determining the best solution. At the same time, there are always engineering tradeoffs that need to be made between such parameters as speed, power, number of nodes, noise immunity and network length. The panorama of field buses available reflects the various solutions that engineers have found to optimize the performance for a particular application. Designers may explore the references below for additional discussions regarding these networks.

IX. REFERENCES

[1.] Application Note 104, “4-20 mA Transmitters“, Dataforth Corporation, www.dataforth.com
[2.] Application Note SLLA067, “Comparing Bus Solutions”, Texas Instruments, Inc., www.ti.com
[3.] “Fellowship of the Fieldbuses?”, Jim Montague, Control Engineering, June 11 2004,
[4.] “Fieldbus jump predicted”, David Greenfield, Control Engineering, October 1 2004,
[5.] “The Grid Connect Fieldbus Comparison Chart”, Gridconnect, www.gridconnect.com
[6.] “ControlNet Specifications, Release 3.0, Errata 3”, ControlNet International, 2003
[7.] “DeviceNet Specifications, Release 2.0, Errata 5”, Open DeviceNet Vendor Assoc., 2002