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Examining Fieldbus Quality

A comparative study of fieldbus attributes

Bachelor of Science Thesis in the Software Engineering and Management

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***Abstract* — Fieldbuses are industrial networks which define the communication protocols and hardware interface. Fieldbuses have been seen in a broader range of complex systems. In this paper, we briefly interpret the current situation of fieldbuses to highlight two major problems: the comparison and selection of fieldbuses. For the first objective, the essential application target are identified in the areas of process, automotive, industrial and building automations, we compare multiple fieldbuses technical attributes. The second objective aimed on presenting a quality model to facilitate the adoption of fieldbuses. Based on these major problems, the company we cooperate with had assisted us to narrow down the research scope and the amount of fieldbuses. A literature review was employed. Furthermore, we examine and discuss two fieldbus implementation scenarios, and the options of fieldbuses available.**

***Index terms* — Fieldbus; profiles; fieldbus comparison; automation; attributes; quality model**

I. INTRODUCTION

A fieldbus is a communication network usually based on the OSI seven-layer model (Zimmermann, 1980), connecting field devices such as sensors, actuators, and field controllers such as PLC, drive controllers, etc. Thomesse (2005) presented that in the late seventies early eighties there was no standards and multiple IT providers developed FAN (Field Area Network) solutions for different end users. Realizing the importance of the fieldbus, these companies then strived to standardize their technology and even more were developed creating the excess of standards and fieldbuses existing today.

Fieldbuses have an increasingly influential role in automation systems, embedded systems and in building automation. The fieldbus domain presents a wide array of problems which are similar, but requires slightly different solution. Nowadays, the fieldbus technology has been providing a vast variety of solutions and techniques, which related but works and performs differently making them suitable for different application areas. Fieldbuses considered having reached a mature state, but evolving requirements provide new challenges and demands. This pushes the development further in the field.

Fieldbuses are inherently difficult to compare because of their high complexity. Many choices are possible in each of the OSI layers, for both the services and the protocols provide lots of differentiation in quality outcome, which makes the selection difficult. However, we will not explain all the technical details in depth instead focus on the qualities provided by the different features.

Based on this research question: How to evaluate and compare fieldbus quality in a given scenario?
This study aims to provide a clear understanding of existing fieldbuses, regarding their main features and differences. And also provide understanding about common scenarios where fieldbuses are used and what attributes are most critical for these scenarios.

The main goal of this paper is to provide a way to compare and select the most appropriate fieldbus for intended use. We approach this by these sub goals:

- Compile an up to date comparison with a wide spectrum of eminent fieldbuses.
- Create a quality model.
- Validate the model by examining scenarios requirements and prioritizing qualities attributes, giving suggestions on appropriate fieldbuses and applying the quality model.

All data gathered by literature reviews and presented in tabular form. This table divided to separate tables by category and abstraction. With the goal of extracting the most relevant concepts, the data selected and analysed using impressions coupled with the themes found in related literatures.

In the next section is a more detailed view of the data collection process and analysis. In the third chapter, we compare different fieldbuses and briefly explain the different attributes. Then introduce the quality model by looking at how these attributes interlace and correlates to quality attributes. This model based on the abstraction of technical attributes, features and combinations of those in to resulting quality attribute. Finally, the scenarios analyzed from the viewpoint of the requirements, qualities and solutions.

II. DATA COLLECTION AND ANALYSIS

A. Data Collection

We chose the fieldbuses used by collaborating with supervisors from a local company and Gothenburg University, committed to covering different application fields (e.g. Automotive, building automation). The gathering of data focus on two parts: detailed and accurate technical overviews of every single fieldbus; comprehensive and multidimensional articles of fieldbus technology. For each part, we defined the goals of the papers we looked at as following:

- Provide all-around analysis (e.g. Interoperability, Quality of service) for fieldbus technology
- Provide an all-inclusive attributes comparison analysis (e.g. Bandwidth, topologies, nodes) of representative fieldbuses

We searched and collected previous works of this field by querying keyword which involved fieldbus description/ concepts, the evolution of international fieldbus standards, fieldbus application in process automation/ automotive/ building, fieldbus interoperability and quality of service. We gathered 25 published literatures of 19 types of fieldbuses and 10 papers for fieldbus industry which published in scattered journals, we inspected literatures individually to ensure that all of which directly related to fieldbus technology and its application. Here are the electronic databases we used for collection:

- IEEE/IET Electronic Library
- Science Direct
- ACM Digital Library
- Chalmers Library
- Gothenburg University Library

These literatures provided theoretical guiding on fieldbus requirements and metrics of quality of service which related to the scenarios and modelling.

In view of the limitation of previous studies, none of the papers can provide a comprehensive attributes comparison of fieldbuses, or merely focus on the fieldbuses in one area. Hence we not only integrated all the forms together, but also supply new attributes, which we think crucial to fieldbus system, to offer a full range of knowledge on fieldbuses. The attributes we converged from literatures presented in the form of an exhaustive table, which will help us to choose suitable fieldbuses for scenarios.

Since the parameters of each attribute primarily shown in introductory articles or installation guides, therefore, we collected them by querying keywords, for example, fieldbus (name) + introduction, fieldbus (name) + features or fieldbus (name) + attributes. This was an agile approach, on examples was that we modified keywords constantly to seek more exact results. In addition, we acquired new information (e.g. Major vendors of fieldbuses) after looked through the papers:

- Beckhoff (EtherCAT)
- PI (Profibus, Profinet)
- ODVA (DeviceNet)
- CiA (CANopen)
- BMBF (Profibus)
- SAE (J1939)
- Fieldbus Foundation (H1,HSE)
- Honeywell (Zigbee)
- EPSG (PowerLink)
- FlexRay Consortium (FlexRay)
- Factory Instrumentation Protocol (WorldFIP)
- KNX Association (KNX)
- Local Interconnect Network Consortium (Linbus)

Furthermore, we referred vendors' guidebooks and companies' solutions, for instance, Siemens (BACnet, Profinet, and Profibus) and Schneider (Modbus).

We aim to compare the most recent capabilities of the different fieldbuses since they are subject to continuous development.

B. Data Analysis

The technical data grouped thematically. It analyzed by observers' impression in the context of the reviewed literature. We are aiming to cover all relevant aspects of the fieldbuses possibly by mere literature reviews. Also including the other notable features observed like module size, documentation and interoperability, which cannot be compared through the literature. The results from this process are apparent in the next section where we compare and discuss fieldbuses. The analysis and reasoning for the quality model will be further explained in the quality model and analysis part.

III. FIELDBUS ATTRIBUTES COMPARISON

A. Introduction

There are four main parts in this section. In the first part, we discuss the background and main target areas of fieldbuses. In the following three parts, we compare the general attributes, physical characteristics and communication mechanism of nineteen fieldbuses. The three later parts presented in tabular form with brief explanations.

B. Background

In practice, the choice of fieldbus often made based on politics, legacy or already held experience. Regardless the choice of fieldbus is a very impactful decision, setting the limitations of the system. Changing or selecting a new fieldbus would usually only occur when developing a new product, or limitations of the current fieldbus coupled with increasing requirement pushes to explore alternatives.

The biggest target areas: automotive, building, process and industrial automation fieldbuses has come a long way in performance and meeting the functional requirement in these areas. However, today fieldbuses are used so widely in so many areas that flexibility, security, reliability and overall high performance have become more valuable to fieldbuses that want to be attractive in a wider target area.

Although derived from targeted development fieldbuses can be seen used outside that area, CANOpen, is for example used for hospital equipment and the CANOpen application layer supported and used over other fieldbuses like EtherCAT and Ethernet PowerLink.

In the following sub-sections, we discuss how the requirements of the target areas have shaped today's fieldbuses and what qualities are prioritized in the different areas. These differences are also apparent later in the tables where we compare different fieldbuses attributes.

1) Building Automation

In building automation, there are many sensors and devices reacting to these sensors. For example, in ventilation, temperature, fire control, lighting, security and so on. These devices do not care about the other sensors in the system making a publisher-subscriber based communication structure a natural fit. It is certainly possible to use any other communication structure to but less simply.

In static long-term systems like building automation, the power usage is an increasing concern and lead to the development of different low power modes and power saving features.

High security is required, while; install time, module size and maintainability have been of moderate importance depending on the scenario.

2) Automotive

In the automotive industry today, there are usually several fieldbus systems in one vehicle, For example, a bigger CANOpen system and FlexRay for some more safety critical parts etc. However, it is possible to have one system with the right performance and good task prioritisation. In addition to low delay and hard real time requirements, the automotive field requires high security and reliability. The bandwidth requirements have been relatively low but are increasing as more and more computerized features put into vehicles. Furthermore, lower range between nodes required because of the limited space the nodes will never be very far apart. This can be seen clearly in the next section (Figure2) where the fieldbuses targeting automotive industry; CANOpen, J1939, FlexRay and Linbus all have relatively short maximum distance between nodes. The limited space also pushes for smaller devices to make efficient use of the space.

Furthermore, from a cost perspective install time have a greater impact when making large series, which is common in the automotive industry; a few minutes shorter or longer install time will be multiplied by hundreds of thousands.

3) Industrial/ Process Automation

In Industrial automation, there is PLCs (Programmable Logic Controllers) and synchronized automation leading to high requirements on real time, low latency and jitter. High safety and reliability is often critical because of big cost of failures and downtime, and use over long periods of time.

The scale of these systems can vary a lot, from a small PLC system to systems for nuclear power plants. With the larger systems more bandwidth, longer distances and higher number of nodes are required to accommodate for the scale of the system, whiles still meting the performance requirements.

In factory automation, the factors interoperability and modifiability are a more relevant than in the other target areas, for example, users often want to modify or expand their production line. Larger systems can create an enormous legacy where to the extent that replacing the system becomes practically impossible. This makes interoperability important, to be able to combine several different systems to work together with the legacy systems already in place.

C. General Attributes

In figure 1, we compare basic information about the fieldbuses target areas, SIL level, real-time support and OSI layers affected/used. Blank segments in the table indicate that we were unable to find that information.

A complete table with references can be found in the appendix.

General				
Fieldbus/Attributes	Application Target	Safety	Real-time	OSI Layers
EtherCAT	Process Automation	SIL 3	Hard	1,2,7
Ethernet/IP	Process Automation	SIL 3	Soft	7
PROFInet	Process Automation	SIL 3	Hard	1,2,3,4,7
DeviceNet	Process Automation	SIL 3	Hard	1,2,7
Zigbee	Building Automation		None	1,3,7,MAC
BACNet	Building Automation	SIL 3	Hard / Soft	1,2,3,7
KNX	Building Automation	SIL 3	Hard / Soft	1,2,3,4,7
Modbus RTU/ASCII	Building Automation			1,2,7
Modbus PLUS	Building Automation			
CANOpen	Automotive	SIL 3	Hard	1,2,7
J1939	Automotive	SIL 2		1,2,3,4,7
FlexRay	Automotive	SIL 4	Hard	1,2
Linbus	Automotive		Soft	1,2,7
Profibus DP (high speed bus)	Industrial Automation	SIL 3	Hard	1,2,7
Profibus PA (low speed bus)	Process Automation	SIL 3		
Foundation Fieldbus (H1: low speed)	Process Automation	SIL 3	Soft	1.2.7
Foundation Fieldbus (HSE)	Process Automation	SIL 3	Hard	1.2.3.4.7
Ethernet PowerLink	Industrial Automation	SIL 3	Hard	2,7
WorldFIP	Process Automation	SIL 3	Soft	1,2,7

Figure1: General

A SIL stands for Safety Integrity Level and applies to the entire fieldbus system. There are four defined SILs based on IEC 61508. SIL 4 is most dependable, and provides the highest level of risk reduction, SIL 1 the lowest. M. Charlwood, S Turner and N. Worsell (2004), further explains SIL and the four levels.

The term real-time suggests a system that provides time constrained communication service and a protocol able to manage these constraints. Real time can be further divided into hard and soft real-time. A hard real-time system guarantees that critical tasks complete on time. A soft real-time system where a critical real-time task gets priority over other tasks and retains that priority until it completes. Audsley et al. (1991) pointed out that if the consequence of a failure is catastrophic, in that way the system often referred to as a hard real-time system. Soft real-time systems can finish the task on time or exceed the deadline time for a short amount of time.

OSI layers are short for Open System Interconnected, is a worldwide standard for communications. It defines a networking framework for implementing protocols in seven layers: Physical (Layer 1), Data Link (Layer 2), Network (Layer 3), Transport (Layer 4), Session (Layer 5), Presentation (Layer 6) and Application (Layer 7), the most commonly used layers are 1, 2, and 7. The OSI layers affect the interoperability of the fieldbus; Thomesse (1999) discusses layer-interoperability in depth.

D. Physical characteristics

In figure 2, we compare the physical characteristics of the nineteen fieldbuses.

Physical Characteristics			
Fieldbus\Attributes	Max no. of nodes	Max Distance	Topology
EtherCAT	65536	100m (CAT 5) 100 km (Fiber optic)	Linear, ring, tree, star, or daisy-chain
Ethernet/IP	Almost unlimited	2000m	Star, bus
PROFInet	255	100m (copper cable)	Star, linear, tree, ring
DeviceNet	64	500m (baud rate dependent) 6 km with repeaters	Linear (Trunkline/dropline)
Zigbee	65540 (pro)		Star, peer to peer, mesh
BACNet	255	1200m (at low speed)	Star, Bus, distributed star
KNX	256/segment, (57600 for complete system)	700 m	Tree, line, star
Modbus RTU/ASCII	250 nodes per segment	350m	Line, star, tree
Modbus PLUS	64 /segment with bridge capabilities	500m /segment	Linear
CANOpen	127	25-1000m (baud rate dependent)	Linear (Trunkline/dropline)
J1939	30 (J1939 / 11). 10 (J1939/15)	40m	Linear
FlexRay	22 nodes (bus), 22 / 64 nodes (star), 64 nodes (hybrid)	24 m	Bus, star, hybrid
Linbus	17 (1 master+ 16 slaves)	40 m	Daisy-chain or Bus with shunt
Profibus DP (high speed bus)	126(per network), 32 (per segment)	100m between segments	Star, bus, ring
Profibus PA (low speed bus)	32 (per segment)	24 km (fiber) baud rate and media dependent	Bus, tree, point to point
Foundation Fieldbus (H1: low speed)	240/segment, 65,000 segments	1900 m	Tree, daisy chain, star
Foundation Fieldbus (HSE)	Almost unlimited	100m at 100Mbit/s, 2000m at 100Mbit/s (fiber)	Bus, star, tree,ring, mesh
Ethernet PowerLink	240	1500 m	Star, tree, ring, or daisy chain
WorldFIP	256	40 km	Bus

Figure2: Physical Characteristics

Maximum number of nodes includes both per segment (a part of the larger network) and the complete fieldbus system. The Maximum number of nodes limits the scale of a system.

Maximum distance refers to the distance between nodes and depends on the bandwidth and media supported (fiber, coax, etc). Longer distances are often possible but at the lower speed.

Topology means the arrangement of the various elements (nodes, devices, etc.). Some widespread topologies like bus, ring and the star will present later in quality model part. In Grnarov et al. (1980), authors defined that in a daisy-chain topology, all links are active, and the links form one loop in one direction (basic loop) and one or two loops in the opposite direction (backward loops). Here, we label topology under physical characteristics. However, it affects other parts of system like the communication mechanism. For example, cabling redundancy can be achieved through the ring topology. Yoon et al., (2006) mentioned that a ring topology would be the logical choice of redundancy since a break at any point along the ring would still leave all stations connected. The trunk line and drop line, in short, means the topology based on trunk line (main trunk) with drop lines (derivations). For instance, DeviceNet requires that the trunk line must be made of a thick DeviceNet cable and the drop lines with a flat / thin cable.

There are two physical attributes that may have significant impact but excluded since we were unable to compare them in a proper way: one is the size of the modules (the actual devices), when deployed in limited spaces like a car or plane. The other one is the cabling durability, which used for reflecting the lifetime and resistance to mistreatment of the cabling.

E. Communication Mechanism

In Figure3 (on page 6), we compare the communication mechanism of the fieldbuses. The blank segments indicate that we did not find that information or that it depends on the transmission media.

The term electrical characteristics show the serial communication protocols compatible with the fieldbus, EIA/TIA-232, 422 and 485. These protocols composed by Electronic Industries Alliance (EIA), to ensure the equipment of different manufacturers were compatible and interchangeable. EIA/TIA-232, EIA/TIA-422 and EIA/TIA-485 are also commonly referred to RS-232, RS-422 and RS-485.

Communication method used by a client and server for exchanging information. One of the most widely used ones is master-slave, which the master device issues a command and the slave device responds to it. In Rajkumar et al. (1995), authors pointed out that publisher-subscriber associate logical handles to message types. Once the logical handle is created, publishers can send messages with that handle. Subscribers can subscribe to or receive all messages published with that handle. Whenever, the publishers need not know the subscribers and vice-versa. Token-passing related to the way that whichever device has the token can put data into the network, when its transmission is complete; the device passes the token along to the next device. Peer-to-peer means that any node can talk with each other on the net. However, if the user sets one of the devices act as a master and others as slaves, the communication method turns into Master-slave.

Transmission has two types: full and half-duplex. A full-duplex allows communication in both directions simultaneously; half-duplex provides communication in both directions, but only one direction at a time.

Bandwidth is the throughput rate of which data is transferred. Higher bandwidth fieldbuses enables large amounts of information to be transferred in a shorter time. Analog signal bandwidth is measured in hertz, aka the frequency of the signal.

Error checking is used to check for accidental changes in the data (corrupt data). The most common technique in the table is called cyclic redundancy checking (CRC), by calculating a number of check bits that gets added to the message and later checked. The amount of bits depends on the maximum length of the block protected and the desired protection. In addition to this, there is one more called echo check also used as error detection. This technique uses remote echo to determine that data received at the remote end of a communications line are the same as data sent. Forster (2000) provided Manchester encoding for error detection, which mainly used in Ethernet systems. It maintains synchronization between the transmitting and receiving devices by using signal changes. However, this technique might require double bandwidth. The Hamming code is a linear error-correcting code, which can detect up to two and correct up to one bit errors.

Communication Mechanism								
Fieldbus \ Attributes	Electrical Characteristics	Communication methods	Transmission	Bandwidth	Error Checking	Network Imposed Delay	Jitter	Cabling redundancy
EtherCAT	EIA/TIA-232 EIA/TIA-422 EIA/TIA-485	Master-Slave	Full-duplex	100Mbit/s	32 bit CRC	≤ 100 µs	≤ 1 µs	Yes
Ethernet/IP	EIA/TIA-422 EIA/TIA-485	Master-Slave	Full-duplex	10Mbit/s, 100Mbit/s	32 bit CRC	<10000 µs	0.1 µs (100 ns)	Optional
PROFInet	EIA/TIA-232 EIA/TIA-485	Master-Slave	Full-duplex	100Mbit/s	16 bit CRC	< 250 µs	< 1 µs	Optional
DeviceNet	EIA/TIA-232 EIA/TIA-485	Master-Slave	Full / Half-duplex	0.5Mbit/s (500Kbit/s)	CRC	<2000 µs	≤ 0.01 µs	No
Zigbee	EIA/TIA-232 EIA/TIA-485	Transmitter-Receiver	Half-duplex	0.24Mbit/s (250Kbit /s)	16 bit CRC			
BACNet	EIA/TIA-232 EIA/TIA-485	Master-Slave / Token passing	Full / Half-duplex	Ethernet(10 to100Mbit/s) ARCNET(0.156 to10Mbit/s) MS/TP(9.6 to78.4 Kbit/s) LonTalk2(4.8 to1250 Kbit/s)	8 bit CRC	<10000 µs		Yes (for Ethernet-based)
KNX	EIA/TIA-232 EIA/TIA-485	Peer-to-Peer	Half-duplex	Ethernet (10/100Mbit/s), Twisted Pair (9600bit/s)				Y (for Ethernet-based)
Modbus RTU/ASCII	EIA/TIA-232 EIA/TIA-422 EIA/TIA-485	Master-Slave	Half-duplex	300 bit/s - 38.4Kbit/s				No
Modbus PLUS		Token passing	Half-duplex	1Mbit/s	16 bit CRC			
CANOpen	EIA/TIA-232 EIA/TIA-485	Producer-Customer	Half-duplex	1Mbit/s	CRC	≤ 1000 µs		No
J1939	EIA/TIA-232	Transmitter-Receiver	Half-duplex	0.24Mbit/s (250Kbit /s)	16 bit CRC			
FlexRay	EIA/TIA-485	Autonomous, Master-Slave	Full / Half-duplex	2 Channels: 5MBit/s, 10MBit/s	11or 24 bit CRC			Yes
Linbus	EIA/TIA-232 EIA/TIA-485	Master-Slave	Half-duplex	20Kbit/s (20000bit/s)	2 bit checksum			No
Profibus DP (high speed bus)	EIA/TIA-232 EIA/TIA-485	Master-Slave, peer to peer	Half-duplex	12Mbit/s	HD4 CRC	< 2000 µs	≤ 8 µs	Optional
Profibus PA (low speed bus)				0.03Mbit/s (31.25Kbit/s)				No
Foundation Fieldbus (H1: low speed)	EIA/TIA-485	Master-Slave, Publisher-subscriber	Half-duplex	0.03Mbit/s (31.25Kbit/s)	16 bit CRC	<100,000 µs		No
Foundation Fieldbus (HSE)			Full-duplex	100Mbit/s, 1Gbit/s	CRC			Optional
Ethernet PowerLink	EIA/TIA-232	Master-Slave	Half-duplex	100Mbit/s	32 bit CRC	< 200 µs	< 1 µs	Yes
WorldFIP	EIA/TIA-485	Master-Slave	Full-duplex	2.5Mbit/s	16 bit CRC, data "freshness" indicator	<20000 µs	< 1 µs	

Figure 3: Communication Mechanism

The speed of a fieldbus usually referred to in terms of latency, cycling time or network imposed delay. Thomesse (2005) explained that the network imposed delay is the elapsed time for a packet to be passed from a sender to a receiver. These are hard to compare because they very dependent on various things like the network setup, I/Os, message type and message size and can scale differently with, for example, the size of the message or number of node in the case of cycling time. There is detailed information on single fieldbuses and detailed comparisons of two fieldbuses in specific settings. Prytz, G. (2008) provides a comprehensive comparison of EtherCAT and PROFINET IRT. The information in the table is approximate and in a lesser than (<) form.

Jitter means the undesired deviation from true periodicity of an ideal clock period or packet delay variation(PVD). Jitter can be caused by electromagnetic interference (EMI) and unpredictable electronic timing noise. High jitter increases the bit error rate, requiring more error checking. Also in order to achieve high-precision device synchronization, jitter need to minimize so that the shortest clock period approaches the ideal clock period.

The term cabling redundancy is one common form of redundancy that has extra strength of cabling to recover from a network failure. Meier and Weibel (2007) presented an applied redundancy standards which named Parallel Redundancy Protocol (PRP). It operates on two independent networks. A source node sends simultaneously two copies of a frame (one over each port). The receiving node accepts the first frame of a pair and discards the second. Moreover, Giorgetti et al., (2013) introduced another protocol called Media Redundancy Protocol (MRP), which only allowed ring topology. In this protocol, the ring manager used as a dedicated node blocks, one of its ring ports to establish a line as the active topology. Once the network failure, this line breaks into two isolated ones which are reconnected by de-blocking previously blocked ports.

IV. QUALITY MODEL AND ANALYSIS

A. Introduction

The quality model is based on the abstraction of technical attributes, features and combinations of those in to resulting quality attribute derived from the original attributes combined. For example, a feature like cabling redundancy will result in reliability quality, as well error checking and so on.

When evaluating quality we have to consider the requirements and expectations of the end user. The quality of a specific system will always be relative to the imposed requirements. What can be considered is a high quality fieldbus in one case may not be suitable in another. Qualities that are critical in one case may be trivial in another. This makes prioritizing qualities a crucial aspect when selecting a fieldbus. We hold the opinion that a high quality fieldbus is invisible to the end user and meets all expectations well, not merely able but also suitable and effective. And quality is defined as by the IEEE (IEEE_Std_610.12-1990):

- The degree to which a system, component, or process meets specified requirements.
- The degree to which a system, component, or process meets customer or user needs or expectations.

The goal of this quality model is to aid in the selection of fieldbus. The intention is not necessarily to assure/achieve perfect quality but, necessary and sufficient quality for the specified context.

Examples of uses of the quality model:
- Evaluate fieldbus quality VS specified requirements
- Identify fieldbus systems requirements
- Identify fieldbus system design objectives
- Identify fieldbus system testing objectives

The figure 4 illustrates the quality model of fieldbus. This model categorizes fieldbus quality into six properties: physical characteristics, reliability, usability, performance, transport mechanism, interoperability. All containing related sub-characteristic. The grouping of which is further explained in the following sections.

B. Categorization

There are many options when categorizing fieldbus attributes. We approached it by referencing the software quality model ISO/IEC 9126-1(2001) and requirements of different implementation scenarios. Our goal was to make the model as useful as possible, making every category a relevant/important subject of discussion when selecting a fieldbus.

We created the quality model in several steps by coupling fieldbus attributes/features that affect the same quality attributes together. There are many attribute interfering with multiple qualities for example; jitter relates to both performance and reliability by affecting the bit error rate and synchronization capabilities; topology relates to several qualities by affecting the physical set-up/wiring, the delay between two given nodes, modifiability, maintainability and fault tolerance. This leads to an extremely complex map of relations if draw up, we have placed the interfering attributes in the category we relate them with the most.

As can be seen in figure 4 the six categories contain both functional and non functional attributes. For example diagnostics and maintainability are closely related, diagnostics is a subject important enough to have a separate topic. At the same time maintainability is equally relevant but derived from multiple attributes all of which not necessarily fits into usability. Maintainability represents the combination of features

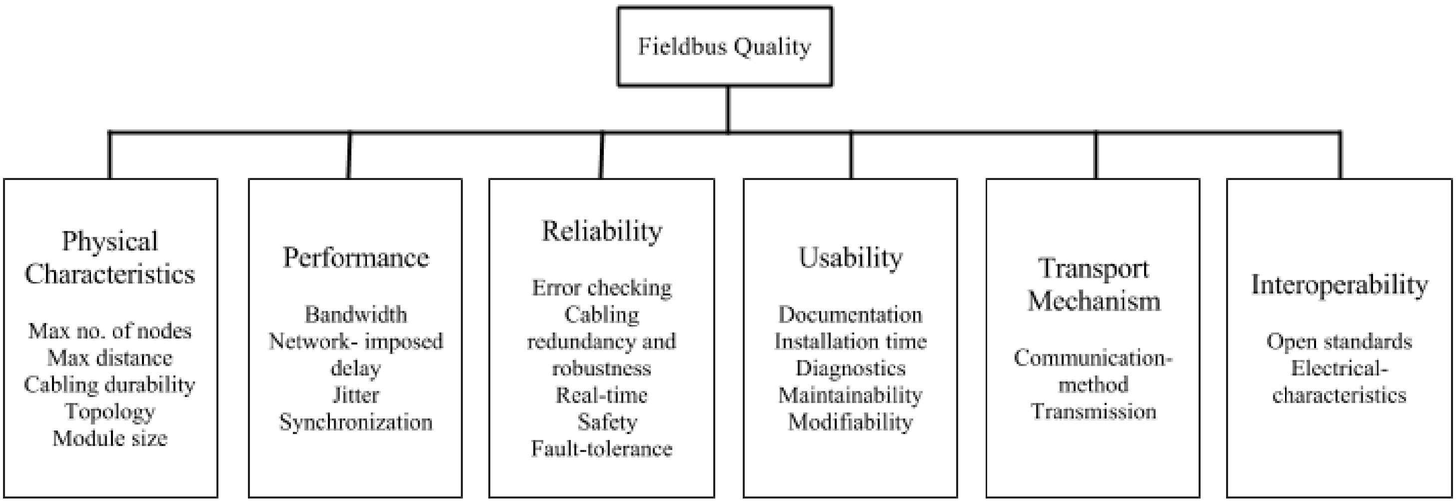

Figure 4 - Quality Models

and attributes affecting it.

The relevance of the different attributes is of course dependent on the implementation scenario, from the range of critical to irrelevant. Some are more frequent than others for example reliability is a quality that is essential in almost all scenarios whilst module size only is relevant in cases with very limited space.

The model excludes these important aspects:

- Security: protection against outside threats (hacking) which is a relevant enough subject to be its own category in the model.
- Efficiency: the ability to make effective use of rescores, for example utilizing the cables full potential.
- Flexibility: the ability to provide a higher degree of freedom in the different aspects, for example having multiple options for cabling, topology or communication methods.

The model also does not account for several aspects listed below that are not in direct correlation with the fieldbus itself, more related to the organization behind the fieldbus but are still relevant when selecting a fieldbus:

- Global distribution
- Devices available
- Vendor support
- Costs
- Licensing

C. Physical Characteristics

This property relates to the properties affecting the physical setup of the system including: number of nodes, distances, module size and topology.

The number of nodes and distance between them are often known requirements and in many situations provided by almost all the fieldbuses. Also consider if the system might need to be expanded in the future with more nodes or longer range.

Cabling durability relates to the physical treatment of the cable, many cables lose performance if bent more than 90° degrees or are continually moving or being bent back and forth. This can result in significant lower performance and lifetime of the system.

Topology affects many parts of the system in addition to the wiring. This favours fieldbuses with a lot of flexibility in terms of the setup, being able to provide many topology options and the ability to combine different topologies.

Figure 5 below compare some of the advantage and disadvantages of three common network topologies.

Topology	Advantages	Disadvantages
Bus with spur	1.Easy to install 2. Less cable 3. Cheap 4. No specialized network equipment required	1. If the main cable breaks, the entire network will go down.
Ring	1.Easy to install 2. Easy to add /remove device 3. Caballing redundancy	1.One device failed then others in the network will disturbed 2. All disturbed when adding new device
Star	1.Easy to install 2. One device disconnected will not disturb network 3. Easy to find the error 4. Repairing a device will not affect others or network performance	1. Depend on the central hub, if it breaks, the entire network will go down. 2. Require more cable for each device connects to the hub directly 3. More expensive for cables and installation cost

Figure 5: Basic network topologies comparison

The size of the modules is very relevant in some scenarios where space is limited and less significant in other.

D. Performance

The performance of fieldbuses refers to technical goals that needed to be met. For instance, we focus on: bandwidth, network imposed delay, jitter and synchronization.

As mentioned previously bandwidth is the throughput rate of which data is transferred. Higher bandwidth is needed when large amounts of data needs to be transferred in a shorter time. Excess of bandwidth provides the option to later expand the scale of the system.

Network imposed delay is as explained earlier dependant on multiple things and is most relevant where the speed is critical, for example high speed real-time requirements.

Low jitter needed for high precision synchronisation. Jitter also affects reliability by affecting the bit error rate.

Synchronisation capabilities/features are closely related to jitter but was not included in our fieldbus comparison. Synchronization is needed to perform tasks that require high precision timings from multiple nodes in the system.

E. Reliability

The reliability relates to how dependable the fieldbus is. Reliability is derived from features such as error checking, cabling redundancy and robustness, hard/soft real-time, safety and fault tolerance.

The error checking techniques aim of enable reliable delivery of digital data over unreliable communication channels. We have previously discussed some error detection methods like Cyclic redundancy checking (CRC), Manchester encoding, echo check and Hamming code.

Two common types of cabling redundancy were discussed in the fieldbus comparison and provide protection against line breakage.

Cabling robustness referees to the cablings resilience against electromagnetic interference for example fibre cabling is have very high resilience.

Real time was defined previously in the fieldbus comparison section. Many scenarios require real time capabilities that can reliably meet communication deadlines.

Safety is the ability to limit the risk and the impact of failure to an acceptable level. Avizienis et al. (2004) pointed out that safety is an absence of catastrophic consequences on the users and the environment. In this research, SIL is used as a standard way of measuring safety. Measuring to what degree the fieldbuses meet all the requirements of SIL, in order to reduce the risk. SIL takes in account some qualitative factors such as development process.

Fault-tolerance is closely related to safety. It is the ability to detect and respond gracefully to unexpected hardware or software failure for example the ability to continue operation in the event of a power failure.

F. Usability

This term reflects a capability of fieldbus to be understood and used effectively.

The documentation, for example, can be a fieldbus application guide. It has been prepared to aid understanding of the application considerations of fieldbuses and usually begin with a brief overview of the topologies. The main part of the guide should provide practical guidance for the planning, design and installation of the corresponding fieldbus.

Installation time is increasingly important with the quantity of installations. The install time depends on many factors, like personal experience, but can be decreased by plug and play like features or intuitive devices that are fast and easy to put together with few rooms for human errors. For example, the Foundation Fieldbus (FF) recommended using device couplers and power conditioners to reduce the installation time.

Diagnostics is the monitoring and surveillance available in the system the ability to provide information about states and conditions.

Maintainability refers to how easy a system is to maintain over time. It depends on many factors including the specific systems setup and is hard to compare in technical terms.

Modifiability includes features that make it easier to change a system. Both application and setup, similar to maintainability there are many influencing factors that affect the modifiability for example topology.

G. Transport Mechanism

Transport mechanism presents how the data gets delivered in the system.

Having a suitable communication method is relevant when developing the application for the system. However the transport mechanism includes much more, fieldbuses include many different kinds of messages: events, diagnostics, service data object (SDO), process data object (PDO) and different message prioritization capabilities.

Thomesse, J. P., & Chavez, M. L. (1999) explains further concepts:

- Static vs. dynamic scheduling
- Centralized vs. distributed MAC (Media access Control) protocols
- Synchronous and asynchronous data traffic
- Periodic, aperiodic and sporadic data traffic
- Deterministic and non-deterministic systems
- And blocking messages.

These where reviewed and considered, and have a big impact on a system. However, in this study we will not elaborate these concepts in detail.

The transmission affect these capabilities, using switches and full-duplex will allows the protocol to make more efficient use of the available resources (e.g. Bandwidth).

H. Interoperability

Interoperability is the ability of one piece of equipment to work within an existing system. For example, fieldbuses with open standards make the communication possible between heterogeneous systems from different vendors that exist for different OSI layers.

Many new devices still use very old electrical stands like EIA/TIA-232 making support for these relevant.

V. SCENARIO ANALYSIS APPLYING THE QUALITY MODEL

A. Introduction

The spectrum of scenarios where fieldbuses are applicable is very large, from overall low requirements in safe environments like a small fire control system or a tailgate of a truck, to overall high requirements where a breakdown can cost more than any fieldbus system like an oil platform, an air plane or a nuclear power plant.

In the following section we take a look at two specific scenarios where fieldbus technology was implemented.

B. Senario1: Forest Harvester

This scenario is based on a real case from a company in Sweden. They were choosing a new fieldbus for their system in a forest harvesting machine. The system is mounted on a mechanical crane cutting down trees and cutting of the branches. The system is measuring the length of the tree and the thickness throughout the whole tree as the branches are cut. The process is fast and creates intensive data in bursts. The measurements are sent to a computer inside the vehicle where it is used for calculating the best way to cut the trees relative to current orders. The scenario requires durable cabling because the moving arm the cables will bend back and forth, so preferably a cable that gives minimal loss of performance when exposed to this treatment. The system will be exposed to a lot of mistreatment being used outside in the forest with different temperatures and a lot of shaking from falling trees, cutting branches and moving in the forest. The data is used immediately and needs to be sent in real time requiring sufficient bandwidth with consideration to the possible performance loss in the cable.

To sort out this block of requirements and find appropriate fieldbuses with aid of the quality model we look at each category in the model and what this scenario requires from that category.

First we examine the physical characteristic. The number of nodes and distance between nodes are both low. Cabling durability is however the most important attribute of this category in this scenario. A cable with high durability towards this scenarios kind of mistreatments is required to give the system a longer lifetime. This eliminates any fieldbus that use known sensitive cabling. A test to ensure the resilience of the cable may be needed. The topology options are fairly flexible most common topology could all be used linear, mesh, star or ring. Similarly there is sufficient space on the crane head that most modules will fit in terms of size.

The performance requirements are fairly high. Low delay, low jitter and synchronization are all desired but mainly the bandwidth limits the suitable fieldbuses to those able of at least 10Mbit/s preferably more, considering the possible performance loss in the cable.

Regarding the reliability consider if cabling redundancy is needed, what level of safety is required, and what amount of error checking will be implemented.

Continuing the usability requirements are low, the system is unlikely to be modified or regularly maintained. Diagnostics could be considered. And any install time difference would be neglectable because of the low quantity, less than one thousand machines per year.

The transport mechanism provides many options in terms of the communication method, data traffic and scheduling etc. That is not covered in this study.

Interoperability with the system inside the machine is required, this can be solved in multiple ways; custom solutions, adapter card etc. How it is going to work together with the other system should be investigated when choosing the fieldbus.

This leave the choice fairly open the main limiting factors being the cable, the bandwidth and the desired reliability features. This makes most of the high speed Ethernet fieldbuses valid options. The final decision depending on preference of different things like transport mechanism, cabling redundancy and cost.

C. Senario2: Wind Turbine Control System

In this scenario we have referenced Solutions for Wind Turbine Systems (2009) to create the requirements.

The scale of this scenario is much larger with many more requirements limiting the options of suitable fieldbuses. Firstly looking at the physical characteristic the system requires a high number of nodes (per segment and in total) and communications over long distances. And high flexibility in the topology is needed. This directly limits the possible options down to a few fieldbuses.

Performance requirements are overall high mainly bandwidth and network imposed delay.

In terms of reliability the system must be resilient to electromagnetic interference from power cables and a power generator close by. Furthermore the environment exposes the system to shifting temperatures, vibrations from wind and high risk for lightning strikes. This requires there to be surge protection devices available to protect against data loss and damage to the system. Extensive testing is required simulating the extreme environment.

High reliability, safety and fault tolerance is of great importance for minimum downtime and requirements on a minimum lifetime of 20 years.

Remote management and comprehensive diagnostics are required. Also simple and fast setup is important, being able to prepare the equipment in advance to be able to quickly set-up the system in the field.

The transport mechanism and structure is a very important aspect in this scenario with many variables/ decisions affecting the whole system. For example a deterministic check-in/update system for each satiation could be used.

In addition the system should preferably be interoperable with several other systems, a wireless GSM/GPRS system and a control system connected to the internet. Otherwise it will require custom solutions.

From the fieldbuses in the comparison this leaves only a few mainly; EtherCAT, Profinet, FF (HSE) and possibly Ethernet PowerLink.

VI. RELATED WORK

Piggin, Young and McLaughlin (1999) reviewed current and proposed fieldbus standards that affect Europe. Relevant technologies and the formation of standards are shown. The standard IEC 61158 had not published yet that time. Conversely, this paper based on IEC 61158 and our research range is not only limited in standards but also going in-depth in attributes comparison and establish a fieldbus quality model for helping us to choose target fieldbuses.

Thomesse (1999) provided a synthesis of the different fieldbuses. The paper describes end-user requirements for fieldbuses, main traffic characteristics. Moreover, the property of interoperability is given, from the viewpoint of the reasons that may lead to an incompatibility between devices. This paper introduced fieldbus history in detailed which in contrast, we were not involve too much, since we put more attention on current situation of fieldbuses and their future trend.

Diehich and Sauter (2000) gave a broad picture about evolutionary history of fieldbus systems, explained the driving forces behind the development of fieldbus systems: cabling reduction, remote monitoring and maintenance of automation systems. Felser and Sauter (2002) reviewed the evolution of international fieldbus standards in the area of industrial automation. In this paper, however, we did not provide anything about evolution or history of fieldbuses, instead concern more on practical application, and let users choose suitable fieldbuses easier by using the fieldbus quality model.

Thomesse (2002) presented the main concepts of the quality of service by introducing its characteristics, requirements, parameters and management from both user and provider point of views. This paper also defined basic quality metrics of service quality. These metrics inspired us on comparing attributes of fieldbuses. We were not only focusing on quality of services, but also came up with more classical notions such as physical characteristics, transmission mechanism and electrical features, in order to provide a comprehensive comparison.

Through the literatures, we noticed that authors all reached a consensus: The fieldbus technology covers a very large spectrum of techniques and applications. However, since the fieldbus technology has been developing continuously, some “future outlook” in their papers are already came true (e.g. IEC 61158, combine fieldbus and Ethernet). Besides, since we found these papers in same researching field, some of these papers are overlapping, especially on the part of historical evolution, OSI model specification and end-user requirements. Our work presented not only these concepts but also a comprehensive comparison of different fieldbuses’ attributes and an original quality model based on fieldbus attributes to analysis scenarios in real industry.

VII. CONCLUSION

This paper has provided an exhaustive fieldbus attributes’ comparison and a suggested fieldbus quality model, to aid in evaluating and comparing fieldbus quality in the practical scenarios. With the aid of the proposed quality model we can see that each category posses several questions simplifying the task of finding out what type of fieldbus are suitable.

Fieldbuses are numerous today, the whole fieldbus market is diverse and the industry lack of a uniform standard can be seen as a result of vastly differing requirements and the need for focused solutions. In this research, we have chosen nineteen representative fieldbuses which applied in four different application areas: process, building automotive and industrial automation.

In order to conduct fieldbus attributes’ comparison in a uniform way, we have integrated the results of various literatures, then defined a comparison table which based on their general, physical and electrical characteristics that display during the fieldbus life-cycle. In this comparison table, we have defined fourteen criteria to elaborate these characteristics.

The result of the comparison has shown the data sheet of all the attributes. Through figure-3, we found the advantages of fieldbuses without Ethernet empowered (e.g. Profibus, DeviceNet, and J1939) are simple wiring, meet real-time requirement and reliable, fieldbuses which based on Ethernet (e.g. EtherCAT, Profinet, and HSE) even have more significant advantages: high transfer rates, strong anti-jamming capability and excellent compatibility for different vendors. On the other hand, when we were analyzing the scenarios, for instance, in automotive and building automation, we realized that manufacturers’ demands focus on high security and reliability, they also preferred target fieldbuses have a good price and durable.

A major strength of the concept formulated in this paper, is its comprehensive nature. This enables the crucial notions of physical characteristics, performance, reliability, usability, transport mechanism and the interoperability to be put into perspective. The fieldbus quality model is central to the understanding and mastering of the various attributes that may affect the fieldbus system, it enables a systematic presentation of these attributes, and preserving their specificities.

The best practice is testing the fieldbuses in real life industrial working, thus we introduced two scenarios, which respectively is forest harvester and wind turbine control system, we discussed in-depth which kind of fieldbuses are suitable by analyzing their requirements, illustrating and comparing how these characteristics affect the fieldbus system. An interesting side note is that some of the Ethernet based fieldbuses could be suitable in both of the examined scenarios even thou they are significantly different. This shows the flexibility of Ethernet based technology and may be part of the market trending towards these.

For the limitation of researching scope, not all the aspects have been treated. One is different physical layers, because of numerous solutions; it cannot be seen as a key aspect if we concentrate more on their applications.

Through this research, we have provided an analysis of fieldbus attributes and a quality model to support the selection of fieldbus. This knowledge will guide future improvements in fieldbus industries.

VIII. FUTURE WORK

This paper has enabled us to determine some of the possible future research directions.

Improving the quality model, there were many options when designing the model and suggestions for changes. Several additional aspects could be considered for improve the quality model.

When comparing fieldbuses we found that many things are very depending on the network setup making them very difficult to compare. For example cycling time which is often used instead of network imposed delay to measure the speed of a buss, depends on many things like the byte load per node, number of nodes, type of message, distance between nodes and topology. A series of standard testing scenarios could be used to compare easily compare the fieldbuses performance in those scenarios. For example

- Block transfer of 128 bytes 1 node
- 16 nodes with 256 byte load per node, linear topology

And so on, you would need a range of scenarios to test because the protocols/technologies scale differently with size of the message number of I/Os and so on. This can be seen in Prytz, G. (2008)'s performance analysis of EtherCAT and PROFINET IRT where the scaling of EtherCAT and PROFINET IRT is demonstrated. With this kind of standard test one could easily compare the performance strongpoints of each fieldbus.

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Comparison Table

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Glossary

1. Spur: means each fieldbus device connects via a drop on the segment. The spur lengths for bus topology are dependent on the number of devices / nodes on the fieldbus. The specific data for max number of nodes can refer the appendix.
2. Heterogeneous: In a distributed system there are many different kinds of hardware and software working together in cooperative to solve the problems.
3. MAC: Media access control (MAC) is a sub-layer of the data link layer (Layer 2) in the OSI model. MAC is responsible for the transmission of data packets to/from the network-interface card to/from another remotely shared channel.

Appendix

Fieldbus \ Attributes	Application Target	Bus/ Net	Real-time	Electrical Characteristics	Safety	Max no. of nodes	Network Imposed Delay	Jitter	Max Bandwith	Max Distance	Transmission	Error Checking	Cabling redundancy	Topology	Communication methods	Power from network	OSI Layers / Layers	Reference
EtherCAT	Process Automation	Net	Hard	EIA/TIA-232 EIA/TIA-422 EIA/TIA-485	SIL 3	65536	≤ 100 µs	≤ 1 µs	> 100 Mbit/s	100m (CAT 5) 100 km (Fiber optic)	Full-duplex	32 bit CRC	Y	Linear, ring, tree, star, or daisy-chain	Master-Slave	N	1,2,7	EtherCAT – the Ethernet Fieldbus (2012) High speed industrail Ethernet for semiconductor equipment (2006)
Ethernet/IP	Process Automation	Net	Soft	EIA/TIA-422 EIA/TIA-485	SIL 3	Almost unlimited	10000 µs	0.1 µs (100 ns)	10 Mbit/s, 100 Mbit/s	2000m	Full-duplex	32 bit CRC	Optional	Star, bus	Master-Slave		7	INDUSTRIAL ETHERNET (2004) by Perry S. Marshall, John S. Rinaldi
PROFInet	Process Automation	Net	Hard	EIA/TIA-232 EIA/TIA-485	SIL 3	255	< 250 µs	< 1 µs	100 Mbit/s	100m (copper cable)	Full-duplex	16 bit CRC	Optional	Star, linear, tree, ring	Master-Slave		1,2,3,4,7	PROFINET(2010): Answers for industry by Siemens.
DeviceNet	Process Automation	Net	Hard	EIA/TIA-232 EIA/TIA-485	SIL 3	64	2000 µs	≤ 0.01 µs	0.5 Mbit/s (500 kbit/s)	500m (baudrate dependent) 6 km with repeaters	Full / Half-duplex	CRC check	N	Linear (trunkline/dropline)	Master-Slave, multi-master		1,2,7	ODVA (2009), Devicenet Overview by ODVA (2004)
Zigbee	Building Automation	Net	None	EIA/TIA-232 EIA/TIA-485		65540 (pro)			0.24 Mbit/s (250 kbit /s)		Half-duplex	16 bit CRC		Star, peer to peer, mesh	Transmitter-Receiver		1,3,7,MAC	ZigBee – WiFi Coexistence by Sheneider (2008), Performance evaluations of ZigBee in different smart grid environments (2012)
BACNet	Building Automation	Net	Hard / Soft	EIA/TIA-232 EIA/TIA-485	SIL 3	255	10000 µs	Depends onLANs	Ethernet(10 to100 Mbit/s) ARCNET(0.156 to10 Mbit/s) MS/TP(9.6 to78.4 Kbit/s) LonTalk2(4.8 to1250 Kbit/s)	1200m (at low speed)	Full / Half-duplex	8 bit CRC	Y (for Ethernet-based)	Star, Bus, distributed star	Master-Slave / Token passing	N	1,2,3,7	Raising BACnet to the next level (2009), BACnet® Information Guide by Siemens(2009)
KNX	Building Automation	Net	Hard / Soft	EIA/TIA-232 EIA/TIA-485	SIL 3	256, (57600 for complete system)	Depends on transmission media	Depends on transmission media	10/100 Mbit/s (Ethernet), 9600 bit/s (twisted pair)	700 m	Half-duplex		Y (for Ethernet-based)	Tree, line,star	Peer-to-Peer		1,2,3,4,7	Simulation of a KNX network withEIBsec protocol extensions (2008)
Modbus RTU/ASCII	Building Automation	Net		EIA/TIA-232 EIA/TIA-422 EIA/TIA-485		250 nodes per segment			300 bit/s - 38.4 kbit/s	350m	Half-duplex		N	Line, star, tree	Master-Slave	Optional	1,2,7	MODBUS over Serial Line Specification & Implementation guide (2012), Introduction to MODBUS Technical Tutorial (2002)
Modbus PLUS	Building Automation	Net				64 /segment with bridge capabilities			1 Mbit/s	500m /segment	Half-duplex	16 bit CRC		Linear	Token passing			
CANOpen	Automotive	Bus	Hard	EIA/TIA-232 EIA/TIA-485	SIL 3	127	≤ 1000 µs		1 Mbit/s	25-1000m (baud rate dependent)	Half-duplex	CRC check	N	Linear (trunkline/dropline)	Producer-Customer	Y/N (power supply tap)	1,2,7	Canopen communication protocol (2009), High Precision Drive Synchronisation with CANopen (2002)
J1939	Automotive	Net		EIA/TIA-232	SIL 2	30 (J1939 / 11), 10 (J1939/15)			0.24 Mbit/s (250 kbit /s)	40m	Half-duplex	16 bit CRC		Linear	Transmitter-Receiver		1,2,3,4,7	Technical manual for J1939 by Kubler (2009), Surface Vehicle Recommended Practice (2009)
FlexRay	Automotive	Net	Hard	EIA/TIA-485	SIL 4	22 nodes (bus), 22 / 64 nodes (star), 64 nodes (hybrid)			2 Channels: 5 MBit/s, 10 MBit/s	24 m	Full / Half-duplex	11 and 24-bit CRC	Y	Bus, star, hybrid	Autonomous, Master-Slave		1,2	Next Generation Car Network- FlexRay (2006)
Linbus	Automotive	Net	Soft	EIA/TIA-232 EIA/TIA-485		17 (1 master+ 16 slaves)			20 kbit/s (20,000 bit/s)	40 m	Half-duplex	2 bit checksum	N	Daisy-chain or Bus with shunt	Master-Slave		1,2,7	Comparison of FieldBus Systems, CAN, TTCAN, FlexRay and LIN in Passenger Vehicles (2009)
Profibus DP (high speed bus)	Industrial Automation	Bus	Hard	EIA/TIA-232 EIA/TIA-485	SIL 3	126 (per network), 32 (per segment)	< 2000 µs	≤ 8 µs	12 Mbit/s	100m between segments	Half-duplex	HD4 CRC	Optional	Star, bus, ring	Master-Slave, peer to peer	N	1,2,7	PROFIBUS: The perfect fit for the process industry (2008), PROFIBUS Installation Guideline for Planning(2009)
Profibus PA (low speed bus)	Process Automation				SIL 3	32 (per segment)			0.03 Mbit/s (31.25 kbit/s)	24 km (fiber) baud rate and media dependent		HD4 CRC	N	Bus, tree, point to point		Y		
Foundation Fieldbus (H1: low speed)	Process Automation	Net	Soft	EIA/TIA-485	SIL 3	240/segment, 65,000 segments	<100,000 µs		0.03 Mbit/s (31.25 kbit/s)	1900 m	Half-duplex	16-bit CRC	N	Tree, daisychain, star	Master-Slave, Publisher-subscriber, Event notification	Y	1,2,7	Foundation Fieldbus Overview (2003), Fieldbus Foundation –India Marketing Committee (2007)
Foundation Fieldbus (HSE)	Process Automation		Hard		SIL 3	IP addressing - Almost unlimited			100 Mbit/s, 1Gbit/s	100m @ 100Mbit/s, 2000m @ 100Mbit/s with fiber	Full-duplex	CRC	Optional	Bus,star, tree ,ring, mesh		N	1,2,3,4,7	
Ethernet PowerLink	Industrial Automation	Net	Hard	EIA/TIA-232	SIL 3	240	< 200 µs	< 1 µs	100 Mbit/s	1500 m	Half-duplex	32 bit CRC	Y	Star, tree, ring, or daisy chain	Master-Slave	N	2,7	Sigma-5 Powerlink by YASKAWA (2011)
WorldFIP	Process Automation	Bus	Soft	EIA/TIA-485	SIL 3	256	20000 µs	< 1 µs	2.5 Mbit/s	40 km	Full-duplex	16-bit CRC, data "freshness" indicator		Bus	Master-Slave	Y	1,2,7	WorldFIP JCOP Meeting (2001)