Commissioning cabling infrastructure for OT networks

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Abstract

All Ethernet applications require the transmitted data to reach receivers without excessive loss of signal or interference from electrical noise. If the signal-to-noise ratio is too high, applications like EtherNet/IP™ will not function correctly, and data may be lost or require re-transmission. By employing good commissioning practices, one can ensure that the cabling installation will support traditional Ethernet physical layer requirements like 100/1000BASE-T as well as Single-Pair applications such as 10BASE-T1L and [1]Ethernet-APL™.

This paper will describe key aspects of a quality commissioning practice:

- standards for specification of OT network wiring systems including power delivery
- common network topologies and wiring practices
- specific commissioning tests for point-to-point links to identify non-compliant cable or connectors, as well workmanship issues
- measurement properties and associated industry standards for physical infrastructure
- and re-purposing legacy fieldbus cabling for industrial Ethernet

Keywords
Industrial Ethernet, acceptance testing, commissioning, network infrastructure, cabling, field test

Definition of terms

APL – Advanced Physical Layer (a.k.a. Ethernet-APL™)
Ethernet – the entirety of data transmission requirements comprising the IEEE 802.3 standard
IEC – International Electrotechnical Commission
ISO - International Organization for Standardization
IT network – information technology networks connect personal computers and servers for the exchange of information and storage
OEE - Overall Equipment Effectiveness, a measure of manufacturing productivity
OT network – operations technology networks are control networks that monitor and control the profit-making assets of a business. (R. Voss)
RPI - Requested Packet Interval rate. The RPI value is the rate at which a controller attempts to communicate with a module or I/O device.
RTE – real-time Ethernet (reliable communication cycle times < 10 ms down to microseconds)

Current context for industrial cabling infrastructure

2020 market research data provided by HMS Networks[2] indicates that new installations of all types of fieldbuses are in decline, and wireless installation rates are stable, The Industrial Ethernet market share has reached 64% of all new installations, up from 59% in the previous year.

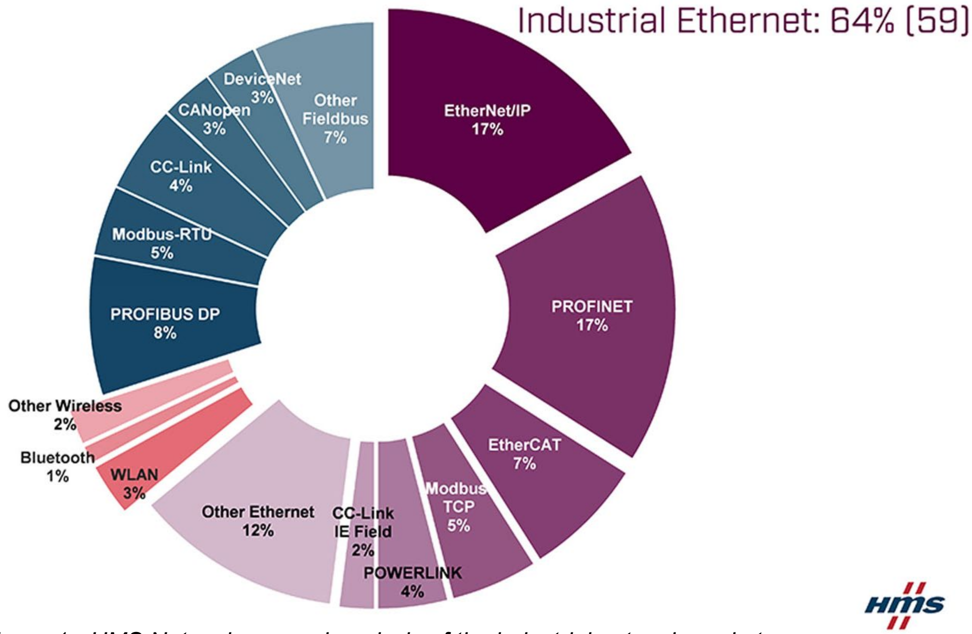

Figure 1 - HMS Networks annual analysis of the industrial network market (new installed nodes within factory automation globally)

Note: EtherNet/IP and Profinet are the dominant Industrial Ethernet variants with 17% market share each.

Recent research conducted by Fluke Networks (a business unit of Fluke Corp.) has found that greater than 50% of problems operating industrial ethernet can be traced to cabling problems. Data for the study came from reviewing industry reports, interviewing facilities staff, controls engineers, equipment manufacturers, and system integrators. The research covered a broad mix of primary users, systems, and industrial network types. This finding is also corroborated by recent findings of the International Society of Automation (ISA) [3] where more than half of failures in the industrial network were found in the data-link and physical layer.

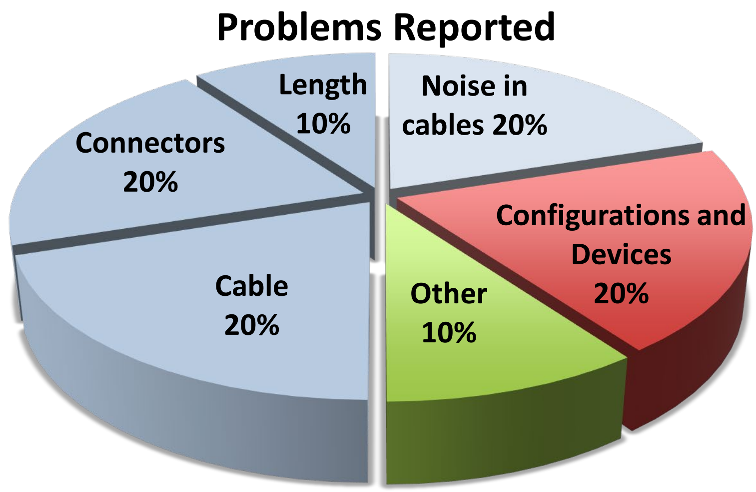

Figure 2 - results from Fluke research

What follows is a short list of the most common defects:

- Wrong cable used for the application
- Needed to re-terminate cables on-site (too long)
- Cables damaged during installation or operation
- Connectors wired incorrectly
- Wire-pair separation causing noise ingress
- Poorly bonded cable shielding

The potential downtime from these types of defects directly affects OEE and can be costly for the end user. Our experience, and that of our partners in the cabling industry, shows that plants with best-in-class OEE (those at the 90%+ level) do more planning, specification, and testing for data-link and physical layer reliability. Put another way, if one doesn't baseline the performance of the original cabling installation, one won't know the capacity of the system to grow or support future upgrades. This is especially important when you consider the likelihood that the active hardware in the network will typically be replaced 4x over the life of the cabling.

In summary, installation of Ethernet connected industrial devices are increasing along with the need for more real time data. Using a disciplined approach to planning and deploying the network physical layer can reduce risks and improve long-term process reliability. System baseline testing will improve your knowledge of the system capacity and workmanship, and leads to reduced troubleshooting costs for both for the system integrator and those responsible for system maintenance and future upgrades.

Standards for specification of OT network wiring systems

Network Physical Layer standards defined by the Telecommunications Industry Association (TIA)

TIA is recognized across multiple "premises" by IT organizations in North America as the standards making body for network design and deployments. If you are sitting in a commercial building today your network is extremely likely to be distributed following the *commercial* standard – accordingly data centers, healthcare and Industrial premises also have unique standards. These standards make systems consistent, predictable, and easier to manage the changes needed to accommodate growth and improvements in the network.

The primary TIA standards for Information and Communications Technology (ICT) are found in the **TIA/EIA-568** series. This group of cohesive standards defines copper and fiber optic cabling types, distances, connectors, cable system architectures, cable terminations, installation requirements and methods of testing installed cable. And perhaps most importantly, they define cabling transmission performance and noise immunity necessary to assure reliability in the various premises. In all cases the TIA standards define cabling and infrastructure in support of IEEE 802.3 Ethernet (LAN, MAN).

The TIA standard most relevant to OT networks is the **TIA-1005-A** standard for industrial premises. This standard is referenced directly from the 568-series parent documents and concerns itself with specific differences necessary for industrial applications. Specific examples being:

- Additional cabling transmission performance and noise immunity requirements
- Requirements for utilizing the M12 connector form factors
- Allowance for greater number of connectors per channel (max. 6 connector channel)
- Definition of MICE component ratings (Mechanical, Ingress, Chemical/Climatic, Electromagnetic).

Environmental elements and severities			
Mechanical	M_1	M_2	M_3
Ingress	I_1	I_2	I_3
Climatic	C_1	C_2	C_3
Electromagnetic	E_1	E_2	E_3

Figure 3 – M.I.C.E. levels

TIA standards are also largely harmonization with the IEC and ISO standards bodies in Europe. Nearly all of the concepts and requirements described so far are also found in ISO/IEC standards.

Network Physical Layer standards defined by the ISO and IEC

Much the same as TIA standards, the ISO/IEC standards define cabling, infrastructure, and management in support of IEEE 802.3 Ethernet (LAN, MAN). The primary standards for Information and Communications Technology (ICT) infrastructure are found in the **ISO/IEC 11801** series. Like the TIA standards this series defines copper and fiber optic cabling used across multiple "premises". The primary standard applied to industrial premises is **ISO/IEC 11801-3** which should be specified in support of any of the primary industrial Ethernet protocol types (e.g. Profinet, EtherNet/IP, Modbus-IP). Other standards of interest, but not necessary for commissioning practices, are the IEC 61784-1 & -2 fieldbus profiles. Of special interest are the Real-Time Ethernet communication profiles (RTE) defining solutions that are able to run in parallel with other IEEE 802.3 based applications.

Three additional ISO & IEC standards that have particularly useful guidance and specifications for commissioning are:

ISO/IEC 14763-2 - defines planning, installation, and acceptance testing of 11801 standards compliant infrastructure

ISO/IEC 14763-3 – specifically defines testing of optical fiber cabling

IEC 61918 – defines installation of communication networks in industrial premises

IEC 61918 is specific to the installation of cabling within and between the automation islands. It deals with the roles of planner, installer, verifier, acceptance test personnel, and gives comprehensive guidance.

Network topologies and wiring practices

Figure 4 depicts the universal TIA model for naming the parts of a network cabling system. This is a physical infrastructure model for cabling and connectivity design that is flexible and scalable.

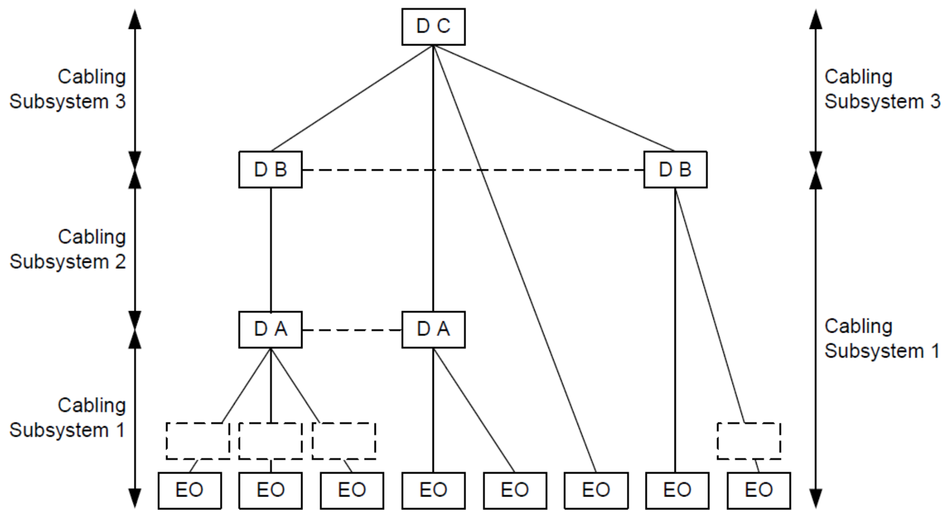

Figure 4 – Structured cabling for industrial premises

Conceptually it starts at the bottom where “EO” indicates an equipment outlet. Then there are two, and sometimes three sets of patching systems or “distributors” on the way up to the network core at the top. From the bottom up these are depicted as “DA” (Distributor A), “DB” (Distributor B) and “DC” (Distributor C). Distributor C is the link patching that is collocated with the actual network core equipment.

In actual practice, cabling subsystems also start at the bottom and move up toward the network core. The collection of links that connect the edge-equipment outlets is “Cabling Subsystem 1”, then moving up you have Subsystem 2 (intermediate distribution) and Subsystem 3 attaching the network core. Within the distributors are where the patching interconnects occur (a.k.a. cross-connects). This provides a testable and scalable plant floor cabling infrastructure that lends itself to good commissioning practice and testability for any incremental moves-adds-and-changes.

You will also notice the model is quite flexible, allowing structured cabling to be implemented across various network topologies that often include fail-over redundancy. One can see that different portions of the network may have multiple cabling subsystems or none at all (like the EO third from the right). The example on the far right side of the diagram, with only one distributor between the equipment outlets and the core, just implements Subsystem 1 and 3. Also note that Subsystem 1 is usually copper media and Subsystems 2 and 3 are usually some kind of fiber optic medium. The reason fiber links are often broken into two subsystems is that these could be very different kinds of fiber links (e.g. single-mode, multi-mode, or trunked fiber) depending upon distances and environments in the plant.

The TIA 1005-A is a premises standard for the industrial building, and we can describe directly where that structured cabling model fits within the typical **Plantwide Ethernet Levels**.

At the top of the Manufacturing Zone (aka factory floor) network Level 3 corresponds to structured cabling Subsystem 1. Level 2 Distribution Frames or intermediate distributors (switches on the plant floor) correspond to structured cabling Subsystem 2. And the Levels 1 and Level 0, industrial switches in the Access Layer, in turn correspond to structured cabling Subsystem 1. The later are typically deployed in control panels or within network zone enclosures in the Cell Area, automation island, or on-machines.

One final consideration when implementing structured cabling topologies like TIA 1005-A are the M.I.C.E. level considerations. Whatever particular path one may be on, it's going to be important to take a look at updating how the plant is laid out for future growth and apply the standards appropriate to the various environments.

Most quality cabling suppliers provide suitable guidance about products rated to withstand the severity associated with the M.I.C.E. elements. Keep in mind that environments may change over time, and one should allow consideration for the worst-case use in a particular area. It's also possible to use the M.I.C.E. concepts, and product guidance, along with the structured cabling approach, to control costs. A specific example is to utilize commercial-grade components as much as possible in the M.I.C.E. Level 1 environments.

Installation testing practices

Let's start by describing why we test cabling during the commissioning process. The world has almost 30 years of network testing experience now (both IT and OT). These tend to be the major motivations for testing:

- To be sure that the installed cabling has the performance the customer is paying for and is free of defects.
- An untested cable is a *source of uncertainty*. The cabling may appear to be working, but does it have the margin for continued reliability? Can it support growth in the network and modernization of the edge devices?
- Experience has shown that tested networks:
  - Reduce New Machine Start-up Time – one can eliminate the cabling as the source of any start-up errors
  - Reduce CRC/FCS errors that lead to re-transmissions and latency problems (RTE)
  - Reduce intermittent *production down-time* due to material defects or workmanship
  - Have a longer service life due to verified design margins
- And if you are an installer or machine builder, it helps you *get paid faster* and leads to higher customer satisfaction.

It then becomes important to specify installation testing. As an example, ODVA has required cabling performance tests for some time now (EtherNet/IP Network Infrastructure Guide – ODVA Pub 35) [4]

> *"Each cabling segment (consisting of cable and connectors) must be tested to confirm that, after installation, the segments all conform to The EtherNet/IP™ Specification* for performance*." (*The CIP Networks Library, Vol. 1 and 2)

Including standards references for **TIA 568, 1005-A, and 1152-A** (or ISO/IEC 11801 and associated installation requirements) in any bid specification for materials and installation is key to getting the necessary assurance from the commissioning process.

Returning to the TIA model and the definitions for a cabling subsystem; the testing methods are defined within the TIA 568 series common standard – **TIA 568.7-C** for copper cabling and **TIA 568.3-D** for fiber optic cabling. Cable installation testing is typically be done just prior to commissioning stage in most projects. Channel testing that verifies cable and connectors should be done at each cabling subsystem level. This includes Subsystem 1, the field Level 1 & 0 connections. (See Figure 5.)

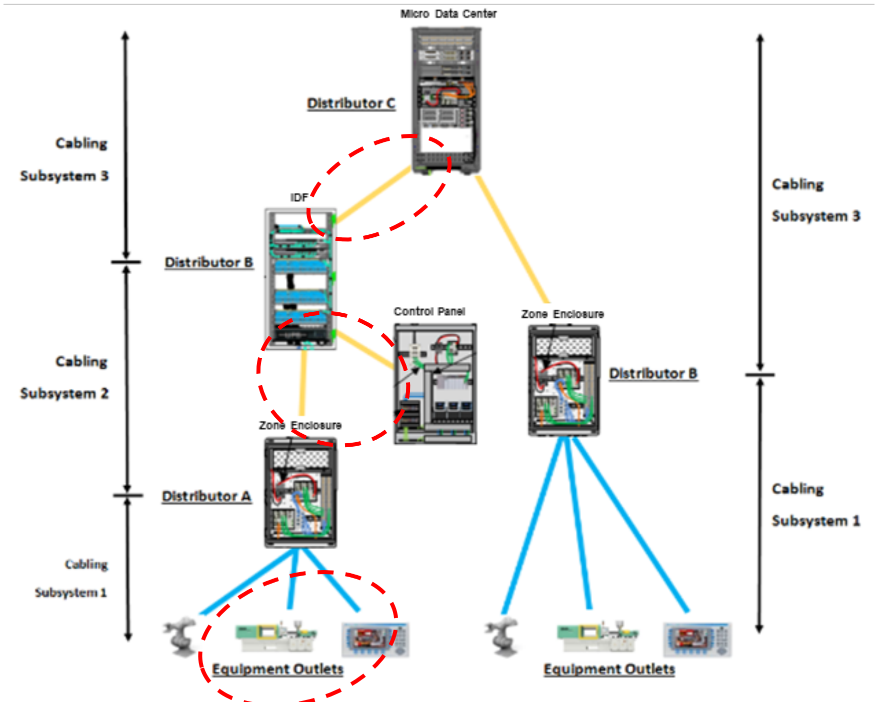

Figure 5 - TIA 1005 Model shown with industrial enclosures

Modern hand-held cabling testers, in use today, demonstrate varying levels of simplicity, sophistication, and basic accuracy. At the simple end of the spectrum are testers that perform wire-tracing, length measurements, and indicate a pass/fail result for transmission at some maximum data rate. These testers are very useful but are not sufficient to demonstrate conformance to standards or to calculate system margins.

At the more sophisticated end of the market are testers that perform full frequency analysis with high accuracies which are capable of guaranteeing standards compliance. These higher-end testers typically employ a graphical user interface (see Figure 6) and features to aid more detailed trouble-shooting for any failed links. The testers typically come pre-programmed with the necessary standardized tests and associated pass/fail criteria and are fairly intuitive to operate. Some can even be remotely configured by project managers, in advance of commissioning, to assure all specified tests are applied correctly. In all cases the test results can be saved and used to document the system baseline performance.

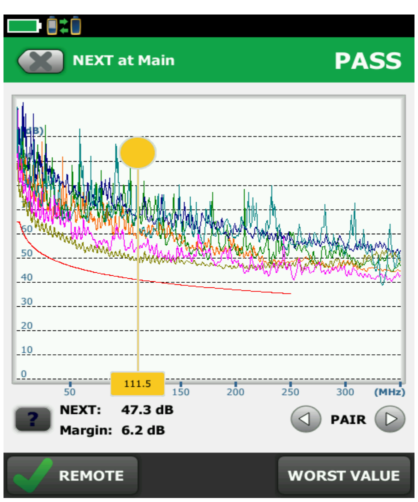

Figure 6 – tester GUI displaying full frequency performance and quantified margin-to-passing

Standards-based measurement properties

Here we will describe the standardized parameters that need to be measured to assure long-term system performance. The capacity of a cabling system to support high-speed data is based on measurements of signal and noise. Continuity testing, or wire-tracing, while necessary, is not sufficient assurance for even the slowest Ethernet. Signal strength, or loss, is measured as attenuation; a.k.a. **Insertion Loss**. Noise is measured with two parameters, **NEXT** and **Return Loss**. Putting these measurements together one gets a total picture of the Signal to Noise Ratio (SNR). The greater the frequency where we can maintain a positive SNR, the faster and farther our devices can communicate.

Wire-tracing or Wire-map Testing
Typically an automated test to sequentially check the continuity of all wire-pairs and the correct isolation of all combinations of wires and wire-pairs. Test results are typically straight forward. (see Figure 7.)

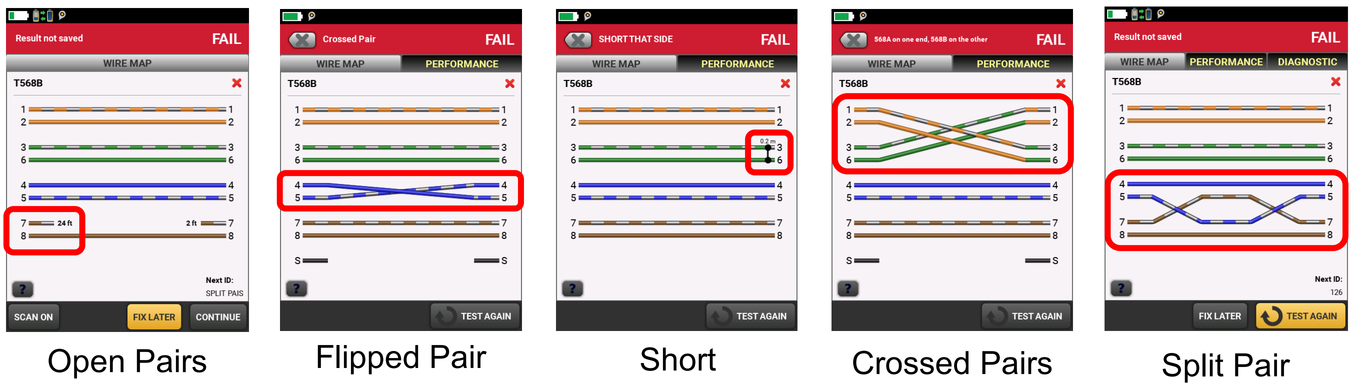

Figure 7 – Most common wire-map failures

Wire-map testing is typically accompanied by cable length measurements as well as resistance measurements of the wire-pairs and individual conductors, both of which can cause a test failure for certain standards. All are quite important for the implementation of PoE power delivery.

Signal Strength – Insertion Loss Testing
Insertion Loss is measured in units of decibels (dB) and indicates the signal loss down the cable into a calibrated load. Signal Loss will typically increase with cable length, transmission frequency, and ambient temperature. Note: the various communications data rates have different frequency and signal strength requirements (e.g. Gigabit Ethernet requires an upper test frequency of 100 MHz, 10 Mb single-pair Ethernet only 20 MHz). It is most prudent to choose a cabling category for the maximum application speed and then test the cabling to those performance minimums. This will guarantee the worst-case transmission performance. The cabling category is easily specified in the tester.

Noise – Return Loss Testing
Return Loss is also measured in units of decibels (dB) and indicates the reflected signal on a single wire-pair; a kind of echo if you will, that cannot be avoided in practical applications. The name Return Loss sounds like an attenuation measurement i.e. a signal loss measurement. However, it's the actually the level of reflected transmission energy in the cable that shows up as noise in the receivers after reflection. So high amounts of loss are a good thing, because it's a loss of reflected energy noise).

Low Return Loss can be found due to defective or damaged cabling, wire-pairs being separated, water in the cable, and sometimes just choosing the wrong cabling with incorrect impedance characteristic.

Noise – Near-end Cross-talk (NEXT) Testing
NEXT, also indicated in dB units, is a measure of unwanted signal found on another wire-pair when a test signal is applied to an adjacent wire-pair. (see Figure 8.) Put simply, Near-end Cross-talk is the

measurement of noise coming from the other pairs within a multi-pair cable. (Obviously, this does not apply to single-pair cables.)

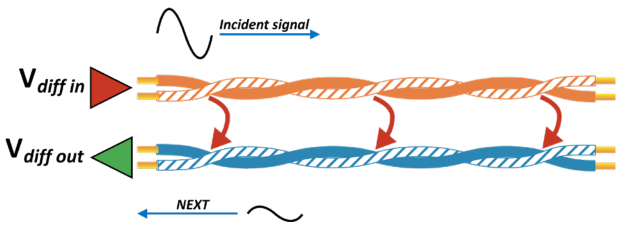

Figure 8 - Near-end Cross-talk (NEXT)

NEXT noise is increased by some connector geometries and pin configurations, defective or damaged cable or connectors, untwisting wire-pairs, or just choosing the wrong category of cable or connectors.

SNR - Attenuation Cross-talk Ratio (ACR) Testing
ACR is a derived parameter, displayed in units of dB, and indicates a signal-to-noise ratio of a given pair. ACR values are obtained by subtracting insertion losses from cross-talk measurements across the frequency range of interest. It is typically measured at the near-end and the far-end of a cabling channel. Higher ACR values on a cable at higher frequencies will support faster communications. Therefore higher category cable has more stringent requirements.

Shield Integrity and Cable Balance (TCL) Testing
CRC errors can slow down or even crash a network. These errors occur when data packet checksum values generated by transmitting devices don't match those calculated by the receiving device. The network operator may not know they are happening. Devices will 'throw out' a defective frame and re-try many times. A few bad frames can cause some machines to shut down, and this is especially true for high RPI applications. These errors can be caused by internal noise products or external interference. The possibility for external interference is why we want to recommend these last two test types.

Susceptibility to electromagnetic interference (EMI) can also be tested during acceptance testing. Cabling is designed to meet certain noise rejection characteristics, and some of these parameters can be tested after the cabling has been routed, pulled, and terminated. These tests are not required by standards, they likely take just one or two seconds of extra test time during an auto-test, but they are well worth it.

Shield Integrity testing measures the shield continuity on shielded network cabling. However this is not a typical DC continuity test. This is a radio-frequency test of the shielding all the way through the link regardless of any grounding connections presented along the way. If the shield does not follow the path of the cable along its entirety an open shield will be reported.

Twisted-pair Ethernet cable is inherently balanced and differential mode signaling takes advantage of this characteristic to reject common-mode noise, like EMI. When common-mode noise is coupled equally onto the two conductors in a perfectly balanced twisted-pair, very little energy will be detected by the differential receiver. This is called common-mode rejection. Well-constructed and properly installed cabling will reject EMI to a high degree. However, installed balanced twisted-pair cables are never "perfectly" balanced, which is why we have test parameters for balance specified in industry standards. The two balance measurements that indicate noise rejection performance are Transverse Conversion Loss **(TCL)** and Equal Level Transverse Conversion Transfer Loss **(ELTCTL)**. In field testers these are implemented as optional choices for an automated commissioning suite.

Re-purposing legacy cabling for industrial Ethernet

Here we must confine our conclusions to Single-Pair Ethernet and the use of existing controls cabling (I/O), which is also single-pair wire. IEEE 10BASE-T1 (10SPE) popularly known as Single-Pair Ethernet was designed to take advantage of a lot of existing low-voltage wiring. (It must be balanced twisted-pair of course.) *However* not all field bus cabling was designed with the frequency range and performance required for 10SPE, and even if it was, and it functions fine for the current use, wear-and-tear, workmanship and terminations must be considered before connecting new Ethernet devices. The use of shielded wiring and/or well-balanced cabling being chief among them, especially where MICE considerations must be taken into account. (Examples being; long runs in open space and cabling densely packed in closed spaces or near higher voltages, motors, VFD, etc.)

That said, there is much potential for high quality, recent vintage, control cabling to perform well for SPE traffic. The quickest and most certain way to tell is to test it. Certification tests provide high accuracy, total parametric coverage, and the highest level of assurance. Verification tests typically cover less parameters, have slightly reduced accuracy, but provide reasonable assurance. Also one doesn't necessarily need to test every link under consideration. Statistical sampling is recommended for reuse of large populations of cabling (given that the supplier and age is fairly uniform). Examples exist in the cabling standards for the use of Statistical Sampling methods. The best example being the **ISO/IEC 14763-2** Cabling planning and installation standard recommendations, which are consistent with **ISO 2859-1** for the attainment of statistically acceptable quality levels (AQL).

In summary

- Fieldbuses are in decline; Industrial Ethernet is now estimated to be more than 60% of newly installed nodes and SPE/APL are rolling out to wire the remaining edge devices
- It is recommended to review your organization's internal standards for the network physical layer and specify the latest norms for Industrial Ethernet
- It is recommended to utilize the M.I.C.E. concept to improve designs and mitigate environmental factors in advance
- Greater than 50% of problems operating industrial ethernet can be traced to cabling problems
- Assessment tests are a recommended best-practice that can catch most common defects and provide the greatest assurance over the lifetime of the network

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