

Ethernet: Surviving the Manufacturing and Industrial Environment White Paper

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Over the past several years, Ethernet has evolved from a coaxial cable running at 10 megabits per second (Mbps) to twisted pair running data rates up to 1 gigabit per second (Gbps). For each phase of the evolution, the demands on the media and connector have substantially increased.

To optimize bandwidth efficiency while reducing emissions, the signaling on the wire has gone from Manchester encoding to a ternary encoding scheme such as MLT3. These enhancements have primarily been driven by two key factors: a need for greater data throughput and a need to minimize both internal and external interference.

The migration from 10 Mbps to 100 Mbps was driven by the need to transfer more data within a shorter time. As video and audio find their way into the information stream, the demand for more data in a shorter time has propelled Ethernet into the next evolution of 1 Gbps data rates. Once again we find, through growth, that Ethernet is becoming useful in factory automation applications.

Unlike information networks, industrial control networks place a greater burden on the designers of system components. An industrial control network requires fast and guaranteed (deterministic) throughput to effectively control machines and manufacturing processes. Additionally, some industrial environments require a greater level of performance due to the elevated levels of noise and contaminants common to those installations.

The purpose of this paper is to discuss the testing, test results and requirements of Ethernet physical layer components with respect to these environments.

Industrial Control and Information Systems

Many industrial networks are required to be deterministic and have relatively low-message turnaround times. As the popularity of 100 Mb (Fast) Ethernet increases and component costs decrease, the use of Ethernet for control applications becomes increasingly attractive.

However, there are significant hurdles to overcome when using Ethernet in industrial environments. These can be grouped in two categories: Performance and Materials.

From a performance perspective, cables designed for higher-speed communications don't always translate to higher data rates in industrial environments. Due to operating conditions, it's more important to optimize the *entire* communications channel to yield the maximum possible throughput.

When choosing Materials, office-quality Ethernet products may not be suitable for use in some of the harsher industrial environments. In some instances, cable connector and component construction may need to be modified or optimized for use in some of the more extreme applications.

Additionally, many network and component designs may not be adequate for the high noise levels common to these environments.

The first part of this paper will discuss the levels and types of noise common in industrial and manufacturing facilities.

In general, the higher the data rate the more sensitive the communication system will be to noise. In addition, from an ethernet signaling perspective, the amplitude on the wire is less for 100mb/s systems versus 10mb/s systems. The overall symbol amplitude is greater for 100mb/s however the difference between a bit transition for 100mb/s is only .78 Volts Figure 2 as compared to 2.2 Figure 1 for 10mb/s ethernet. This effectively reduces the s/n ratio for fast ethernet.

Figure 1 Manchester Encoding (10 mb/s)

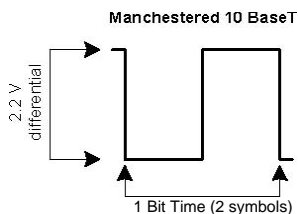
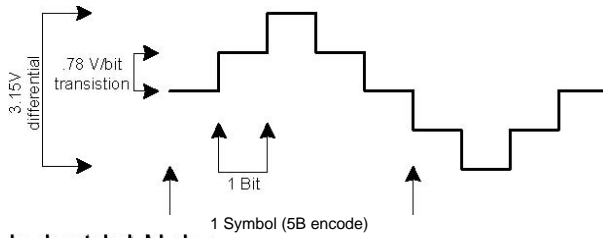


Figure 2 MLT3 Encoding (100mb/s)

MLT-3 Ternary Signaling
(100b/s)



Industrial Noise

An industrial control device must be designed to withstand two different groups of noises **1) Plant floor generated noises** and **2) Noise immunity and emissions as defined by European Communities Directives**. However, a direct correlation between these two entities doesn't always exist.

Products must be designed to withstand the electrical and mechanical noises produced by a plant's floor equipment. These types of noises range from EMI generated by contact arcing and welding processes to RF fields from high power sources like radio transmitters.

Furthermore, historically, control equipment and industrial networks have been designed to survive electromagnetic compatibility (EMC) directives as defined by the European Communities. In addition, products must conform to other local agency requirements such as Under Writers Laboratories, C-TECK and Federal Communications Commission (FCC). The objective of these directives is to protect from external electromagnetic interference (EMI) and to limit electromagnetic emissions. In other words, products should be designed to withstand, external noise and limit potentially disruptive noise emissions.

Table 1 is a list of the European Communities' EMC Directives established to ensure performance in some of the harshest industrial environments.

Table 2 is a list of noise-generating devices common to manufacturing environments.

Table 1 Standards Table 2 Sources of Industrial Noises

Mechanical Requirements	Industry Standard
Vibration (Unpackaged)	IEC 68-2-6
Shock (Unpackaged)	IEC 68-2-27
Vibration (Packaged)	NSTA Project 1A ASTM D999-75
Shock (Packaged)	NSTA Project 1A ASTM D775-80
Electrical Requirements	Industry Standard
ESD Susceptibility	IEC1000-4-2
Temperature	IEC 68-2-1
Humidity	IEC 68-2-30
Radiated Immunity (80MHz to 1GHz)	IEC1000-4-3
Surge Immunity	IEC1000-4-5
ESD Susceptibility	IEC1000-4-2
EFT/B Immunity	IEC1000-4-4
Radiated Emissions (30 MHz to 1 GHz)	EN 55011
Conducted RF Immunity (150 kHz to 80 MHz)	IEC1000-4-6

Safety Requirements	Industry Standard
Dielectric Withstand	UL 508 CSA Std C22.2 no 142-M NEMA Stds. Pub No ICS 3, Part ICS 3-304

Flammability	ASTM Std. D 3874-1979 UL 83 UL 94 UL 746A UL 746C
Specification	Industry Standard
Sealing	IEC529

Type	Noise	Coupling Mechanism
Electric Motors	Surge and EFT	Local Ground, Conducted
Drive Controllers	Conducted and Surge	Local Ground, Conducted
Relays and Contactors	EFT	Radiated, Conducted
Welding	EFT, Induction	Radiated Magnetic
RF Induction Welding	Radio Frequency	Radiated, Conducted
Material Handling paper/textile	ESD	Radiated
Heating	EFT	Local Ground, Conducted, Radiated
Induction Heating	EFT	Local Ground, Conducted, Radiated
Radio Communications	Radio Frequency	Radiated

Note:

EFT (Electrical Fast Transient): Line disturbances caused by switching transients from nearby relays, motors and other switched devices.

ESD (Electro Static Discharge): The transfer of charge between bodies at different electrical potentials. High levels of ESD may upset the operation of an electronic system, causing equipment malfunction or failure.

In most cases, testing has found that the EMC environmental directives are more severe than most actual industrial environments. A good example of this is in the radiated immunity category. 10 V/meter is a common test level for radiated immunity verification of industrial products. However, to produce a 10 V/meter level, it requires roughly 39.6 watts of power from a transmitter located two feet away from the equipment.

$P_a = 39.622$ watts

As demonstrated in this simple relationship, the power of the transmitter is relatively large compared to hand-held cellular telephones at .6 watts or most two-way radios at 3 watts (ERP) effective radiated power. A poorly designed product will experience problems even with low power transmitters such as cellular phones when in close proximity to the equipment.

Noise Coupling (Conducted)

System integrators, plant engineers and machine and automation designers can realize substantial savings in material costs by combining communications, instrumentation and power conductors into a single raceway. However, this cost-saving practice leaves the cabling highly vulnerable to coupled noise (a major noise ingress mechanism).

The impact of combining conductors carrying high dv/dt transients to a communications cable carrying < 100mV signals can be enormous on the system performance. Once again, the coupled voltage (common mode) of a 10 Vrms RF signal is measured in the tenths of volts. Further, for high dv/dt type noises, the coupling of a 2 kV common mode transient can be a magnitude greater than the RF signals (hundredths of volts). In a transformer-coupled system such as Ethernet 100Base-T, the common-mode voltages are not an issue. However, the voltages produced by poor common-mode performance can cause relatively large differential voltages, which can be destructive to communications.

It's worth noting that most commercial Ethernet media access transformers only have an isolation voltage of 1500 volts. The voltage is 500 volts short of the required 2kV needed to pass the IEC surge and electrical fast transient burst (EFT) tests.

Optimizing Throughput

Optimizing throughput for an Ethernet system involves reducing unnecessary traffic caused by things like packet error-induced retransmission and minimizing collisions, and is essential in some critical industrial control applications.

Traffic and collisions in a hub-based system are normally high because the hub consists of virtual connections and broadcast all traffic to one another.

Conversely, a switch effectively minimizes traffic by setting up independent, virtual connections between ports. Therefore, devices will only receive traffic destined to the device connected through the switch port, essentially eliminating the collision domain and establishing a nearly deterministic channel.

Full duplex is another method of optimizing throughput. In full-duplex transmission, data can be simultaneously transmitted in both directions on a single carrier (cable), which implies that the cabling system itself is bi-directional in nature. Full-duplex transmission provides an additional communications channel without having to add an additional cable.

As mentioned previously, optimizing throughput requires that the traffic on the network be minimized. Aside from keeping unnecessary traffic off the network, minimizing the error rate is absolutely mandatory. Ethernet packet errors will cause jitter and

inconsistency in response times. There are two mechanisms that cause unnecessary traffic on the network: 1) collisions and 2) errors.

As discussed, the use of switches (as opposed to hubs) and full duplex communications will effectively eliminate the collision problem. However, errors are more difficult to address because of the different influences and factors which cause them.

For example, in an office environment, most errors are caused by impedance mismatches in the system. Impedance mismatches cause reflections in the signal. Reflections are caused by sudden changes in the impedance within the channel itself. The magnitude of a reflection is a function of the reflection coefficient and can be described in Equation 1 below.

Equation 1 Reflection Coefficient

$$\rho = \frac{Z_{in} - Z_{out}}{Z_{in} + Z_{out}}$$

For a 15% mismatch between a cable and a connector, the following voltage could be present on the wire:

$$E_{refl} = 0.0783 \cdot E_{inc}$$

(VSWR 1)

An impedance mismatch between the cable and connector may cause 78 mV of reflected voltage. This reflected voltage will affect a receiver with a typical 50-mV sensitivity, and the result will be a significant degradation of the signal itself. In fact, the signal-to-noise ratio (SNR) for one impedance mismatch between a cable and connector would be roughly equivalent to the figure below:

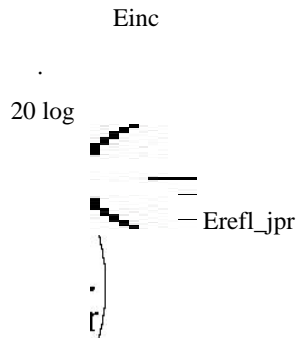
$$20 \log \left(\frac{E_{inc}}{E_{refl}} \right)$$

SN

$$S_N = 23.13 \text{ dB}$$

Signal-to-noise ratio (SNR): A ratio of the amplitude of a desired signal to the amplitude of noise, usually expressed in decibels. This ratio measures the quality and integrity of the signal.

The signal-to-noise ratio for a short cable system with a mismatched jumper cable and mismatched connector would be roughly 7.56 dB, as 6 multiplies the reflected voltage.



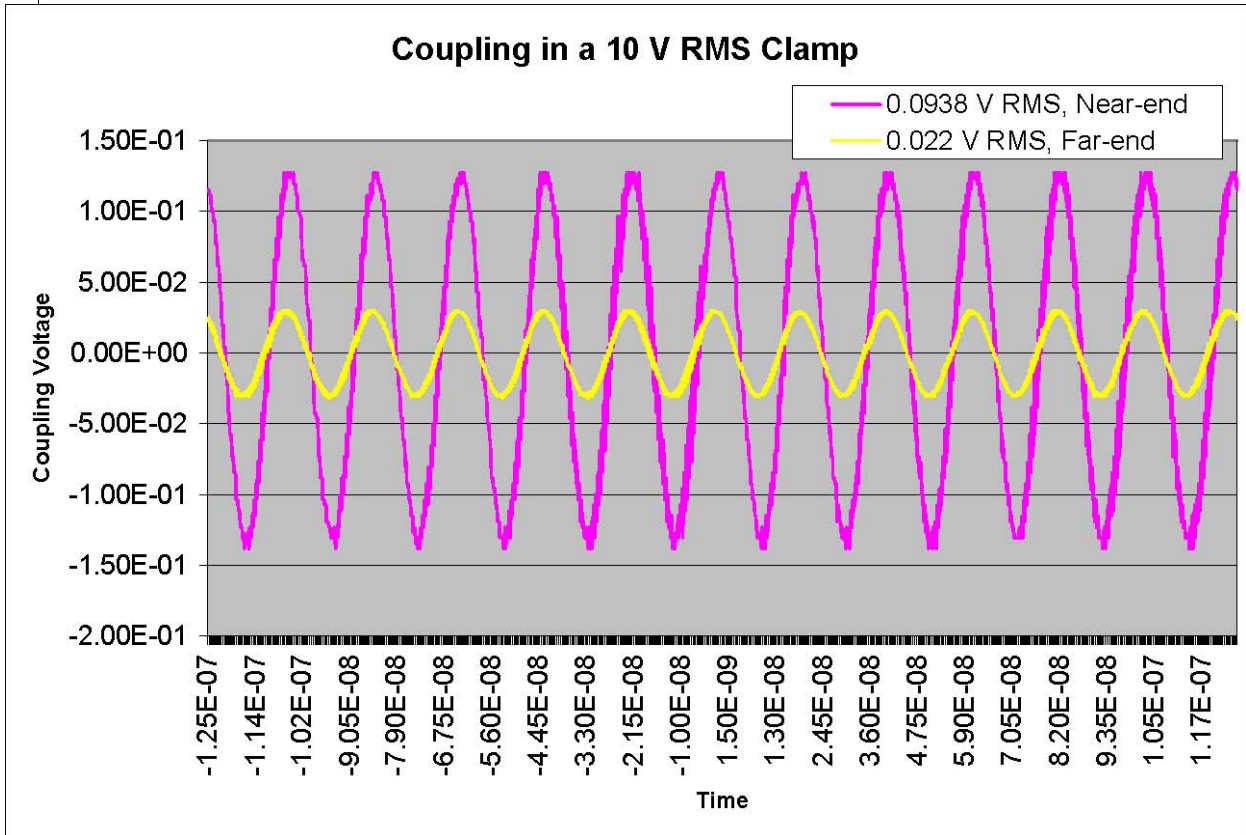
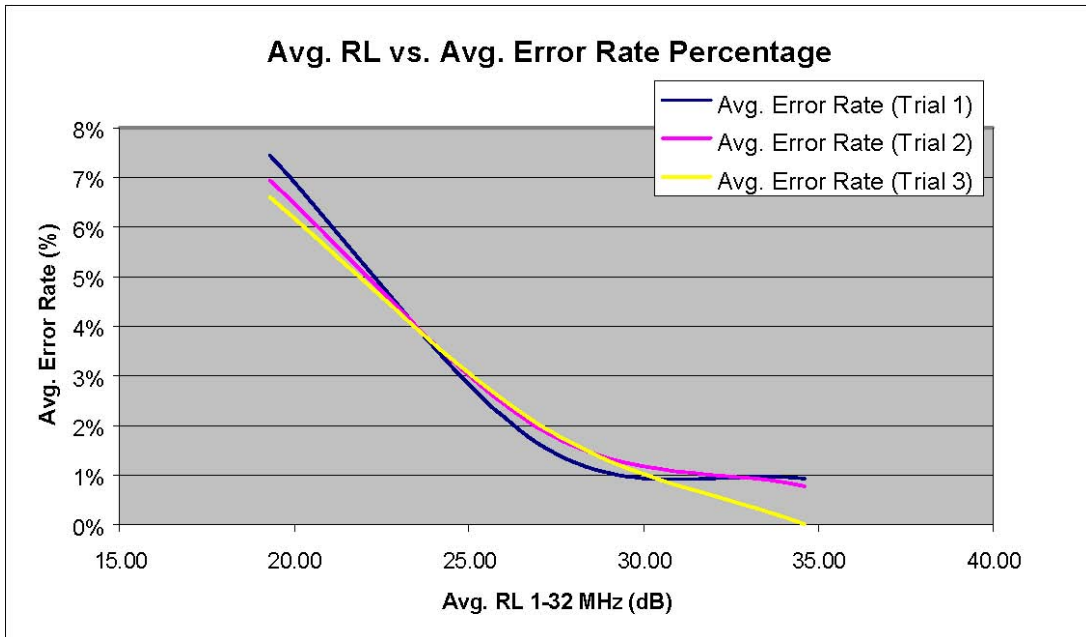
SN

$$S_N = 7.56 \text{ dB}$$

Assuming that all of the reflections are in phase, the sum of the reflected voltages (due to only the +/- 15% impedance tolerance) could be 0.47 Volts. For example, a 10-meter jumper at 85 ohms connected at both ends with connector at 115 ohms could produce reflections at each impedance discontinuity. At ~40 MHz, the reflections will be in phase and added algebraically.

The following graph **Figure 3** demonstrates the effects of impedance mismatch on the link error rate.

Figure 3 Error Rates Caused by Impedance Mismatches (courtesy of Anixter Levels Labs) Figure 4 Noise Coupling High-Performance UTP cable



Common-Mode Noise

Common-mode noise is the voltage (common-mode voltage, or CMV) present on all conductors with respect to ground. Due to the number of common-mode noise sources present in some industrial environments, plant floor communications systems are highly susceptible to common mode noise related problems.

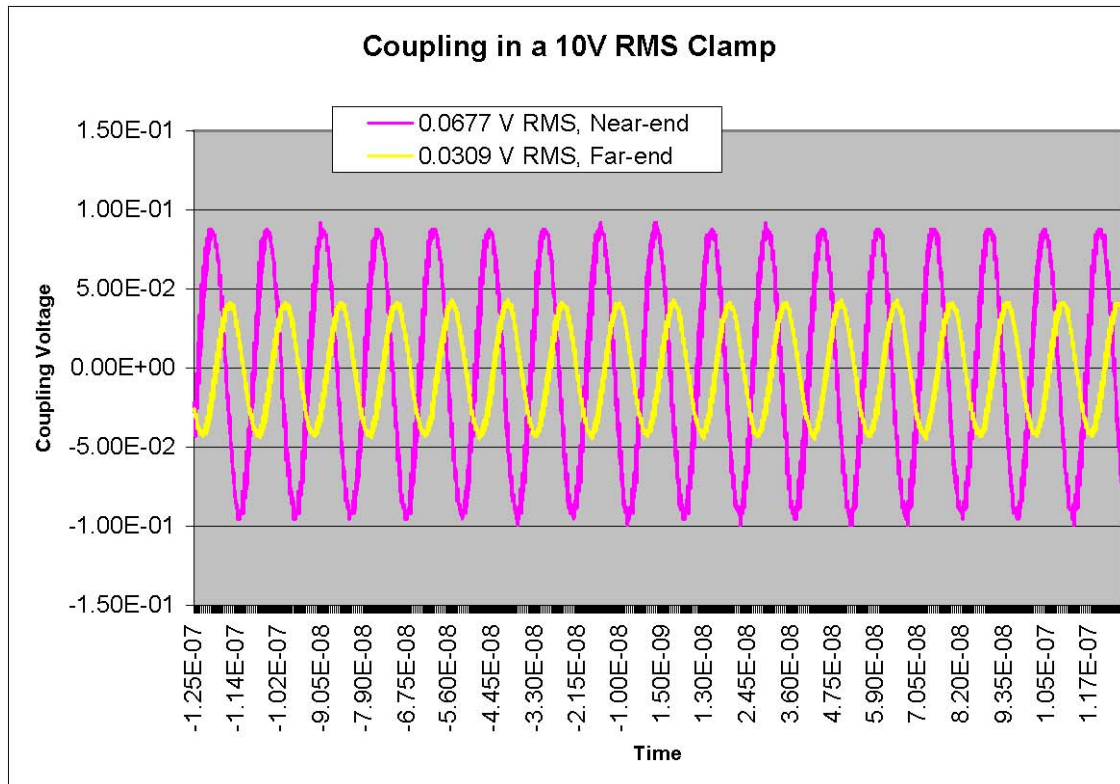
Some sources of common-mode noise include induction heaters noises coupled from adjacent conductors, motor control relays, ungrounded or poorly grounded systems and proximity to power lines.

Consequently, the CMRR (Common-Mode Rejection Ratio) of an industrial cabling system is critical. CMRR is the ratio, expressed in dB, of common-mode noise rejected and subsequently prevented from converting to a differential mode voltage.

The trace in the Figure 4 above is a real-life example of what happens when a 10 V RMS RF signal is applied through a coupling clamp common mode to a cable. The 0.0938V RMS signal is coupled differentially to the near-end of the cable. The CMRR of this cable is roughly 40.6 dB at 40 MHz. With a 13dB link budget and the noise applied at the far end of the cable (receiver) the signal to noise ratio equals 8dB. The reader must remember that these measurements were taken with an optimized cable that has 40.6dB CMRR. Other cables in the same classification measure considerable less CMRR performance levels of 17 dB.

For a shielded twisted pair cable (STP), the CMRR is 43.4 dB. The CMRR for shield-type cables is achieved through use of shield itself. The RF currents are conducted on the shield instead of coupling to the cable's inner conductors. There is some capacitive coupling of noise to the conductors. However, it's much less compared to a non-shielded cable. Note that the overall coupling is lower with the STP cable, and attenuation is about 6dB. This can be attributed to the fact that the noise ingress into the network has a different path/mechanism.

Figure 5 Noise Coupling to STP cables



Evaluating the cable's CMRR using a network analyzer yields approximately the same results. Figure 3, through Figure 8 are compensated CMRR results. Note that all three meet the specification, however the study shows that with careful optimization, un-shielded twisted pairs can approach the performance of shielded designs. Further, standard off-the-shelf UTP cables will not provide as high Common Mode Rejection (CMR) as the industrial optimized UTP cables shown in the accompanying graphs. The CMR

Ref plot represents the performance limit line for the test system used to measure the CMR of the various cables.

Figure 6 High-Performance Cable CMR

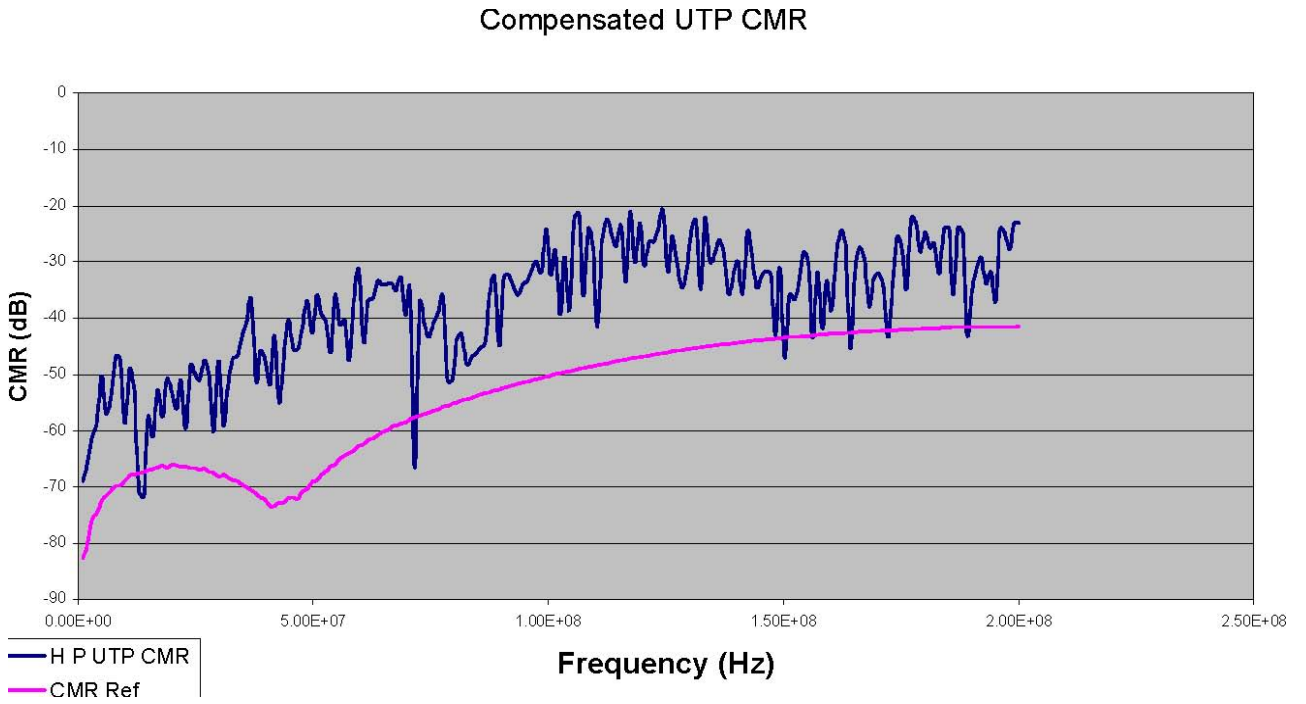


Figure 7 STP CMR

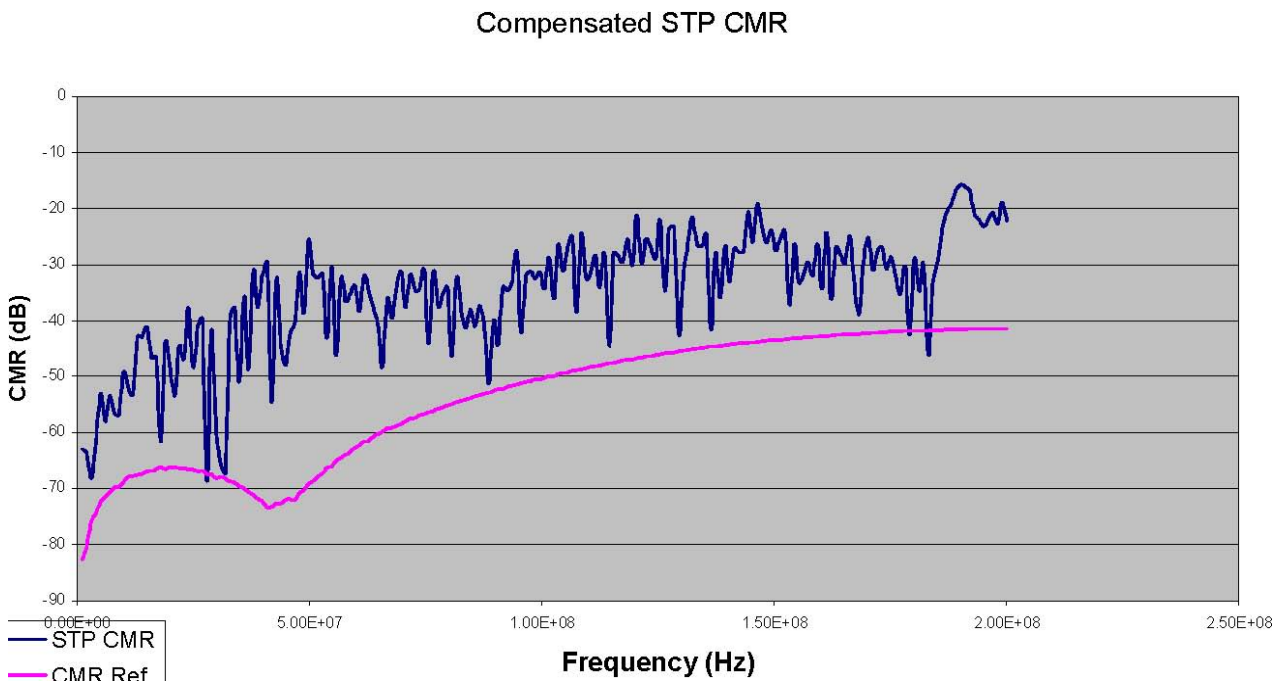
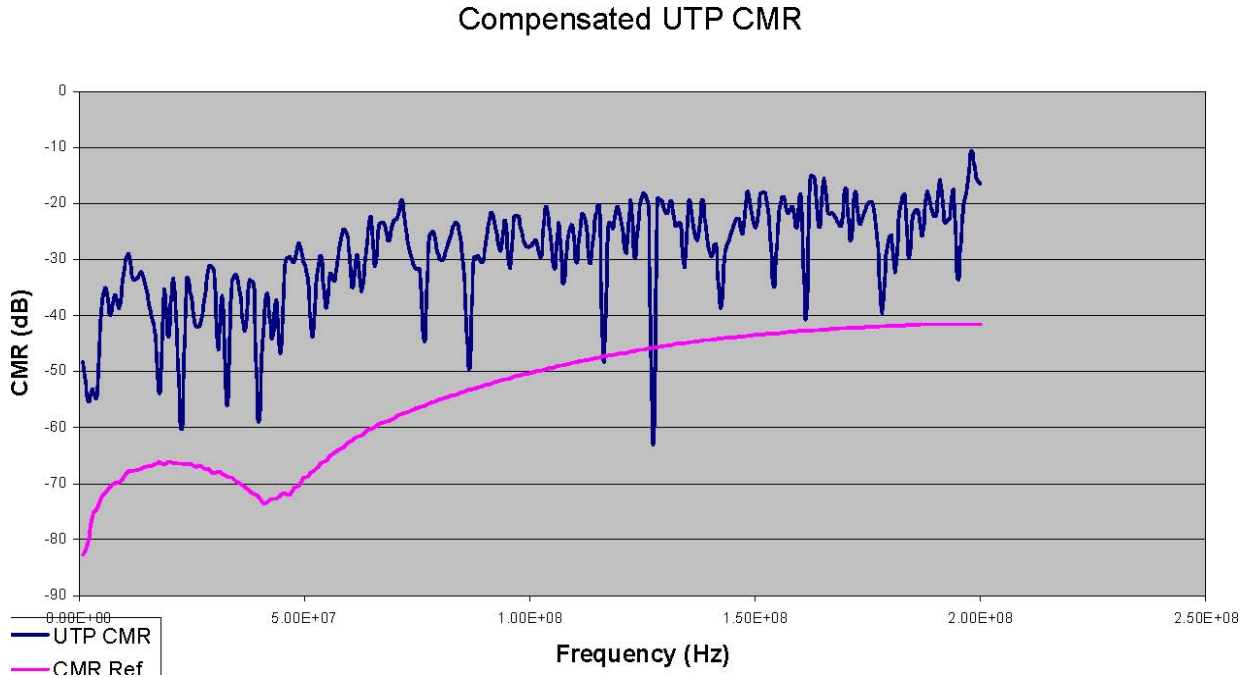
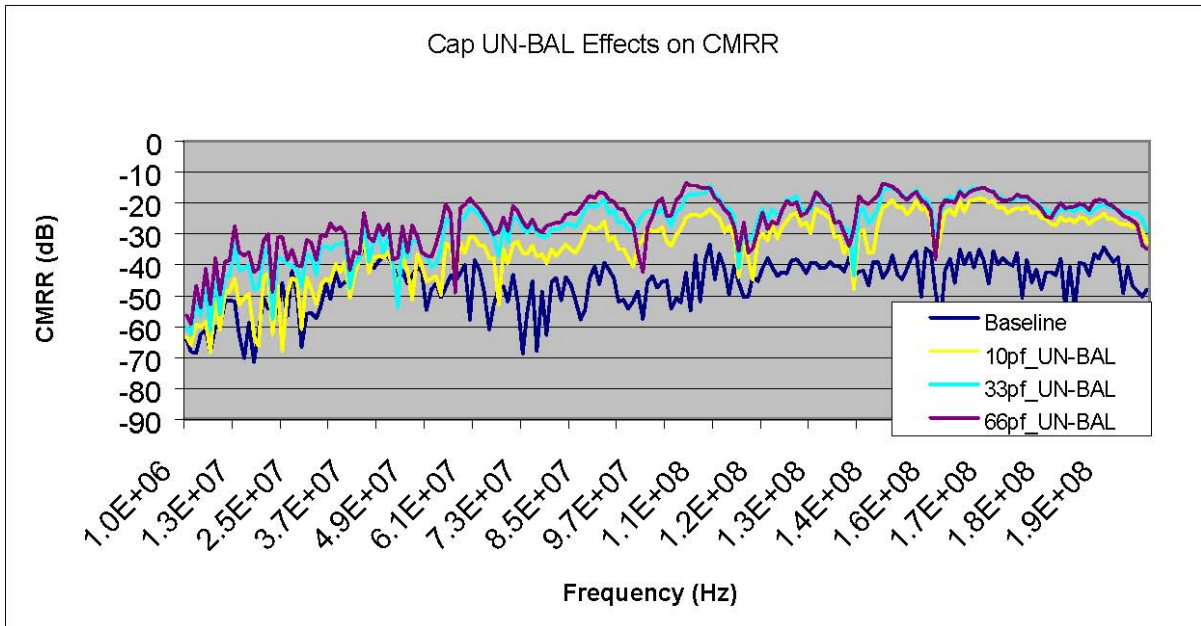


Figure 8 UTP CMR



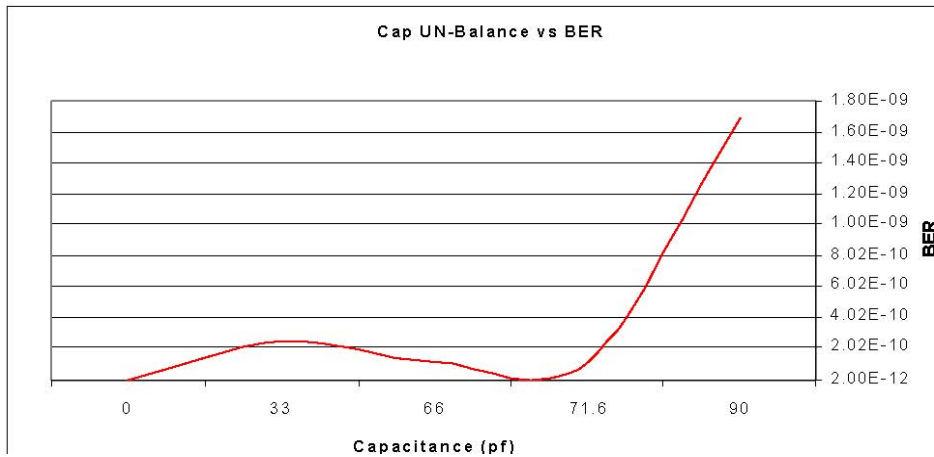
The tests show that CMRR performance of optimized un-shielded twisted pair cables can be as good or better than shielded twisted pairs. The noise coupling mechanism for STP cables are primarily caused by currents in the shield that is capacitively coupling to the pairs. The noise coupling mechanism for UTP is capacitively coupled to the pairs from the test clamp where the CMRR performance is a function of the UN-balances in the link. The cable capacitance UN-balance is major contributor to the overall system, UN-balances. When the same cables are subjected to common-mode signals and the capacitance UN-balance becomes a variable, the amount of differential noise measured is high. Figure 9 shows the CMRR (dB) versus Capacitance UN-balance. The trend is upward (less CMRR) as the capacitance UN-Balance increases.

Figure 9 Capacitance UN-BAL VS CMRR

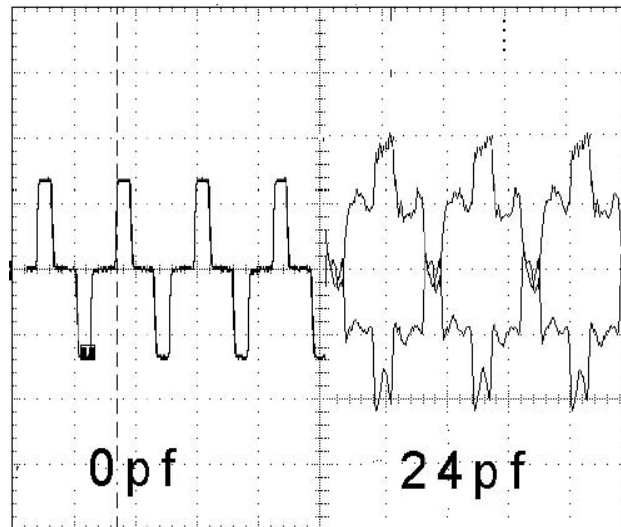


The capacitance UN-Balance affects the link performance in a non-noise environment. The bit error rate (BER) will increase as the capacitance UN-Balance in increased. Figure 10 shows the BER performance as a function of capacitance UN-Balance

Figure 10 BER Versus Capacitance UN-Balance



The increased BER is caused by the distortion in the MLT3 encoded signaling on the wire. **The effect of noise (on the BER performance) will be greater for a poorly balanced system as opposed to a well-balanced system.** That is to say that when common mode noise is applied to a differential system where the system is poorly balanced the amount of differential noise voltage will be greater for a given (fixed) amount of coupling. With 24 pf of capacitance added to the link the waveform is vastly distorted as shown in Figure 11.



Test data suggests that the key to noise immunity, is a highly balanced differential system. Any device, cable, connector, patch panel or jumper that affects the capacitance UN-Balance will have negative effects on the system noise and BER performance. The trace and component layout of a network interface could easily have 10-pf to 20-pf differences in TX+/RX+ and TX-/RX-. Significant degradation to the signal quality could result if compounded by both TX and RX of two different devices connected by TP cables. Figure 11 shows the distortion of MLT3 encoded data caused by 24 pf of capacitance UN-Balance in the differential cable.

Application-level testing with motor drives testing yields different results than lab testing. There are two possible noise mechanisms in a system with motor drives. The most common is “noise ingress through grounds” and perhaps has the greatest affect on the system quality of performance. Noise also couples (capacitively and inductively) to the conductors when the conductors are in close proximity to the drive/motor power conductors.

Testing was performed on a system where the communications conductors (four-pair Ethernet cables) were placed in wire ladder-ways. These cables were placed along side conductors carrying 480 V drive-control voltages connecting the controller and a high-horsepower motor. The differential voltage coupled into the Ethernet cables varied, depending on the type of cable tested.

The picture in Figure 12 shows the cable routing with respect to the drive conductors. Table 3 shows the differential voltages measured on the communications cables. The additional CMRR is referenced to the shielded cable. The shielded cable is used as a reference because this cable provides adequate performance in environmental testing for Ethernet modules.

It’s worth noting that there were no physical layer communications errors during this sequence of testing.



Reiterating what was stated earlier, in comparing the real-world noise levels to the lab EMC testing we find that the noise present in most real-world situations is considerably less. The following Table 3 is a comparison of noise measured in a motor drive controller application-to-noise coupling measured in EFT noise. Although this is only one comparison, other tests have shown that lab testing to EMC directives is usually more difficult to survive than most of the real-world applications. Both field and lab tests show that the higher performance cables (based on EIA/TIA category standards) have greater common mode voltages coupled to the conductors. Cables that exhibit lower CMRRs will have a greater differential noise voltage as seen by the receiver.

Table 3 Comparison Coupled Noise Between Drives and EFT

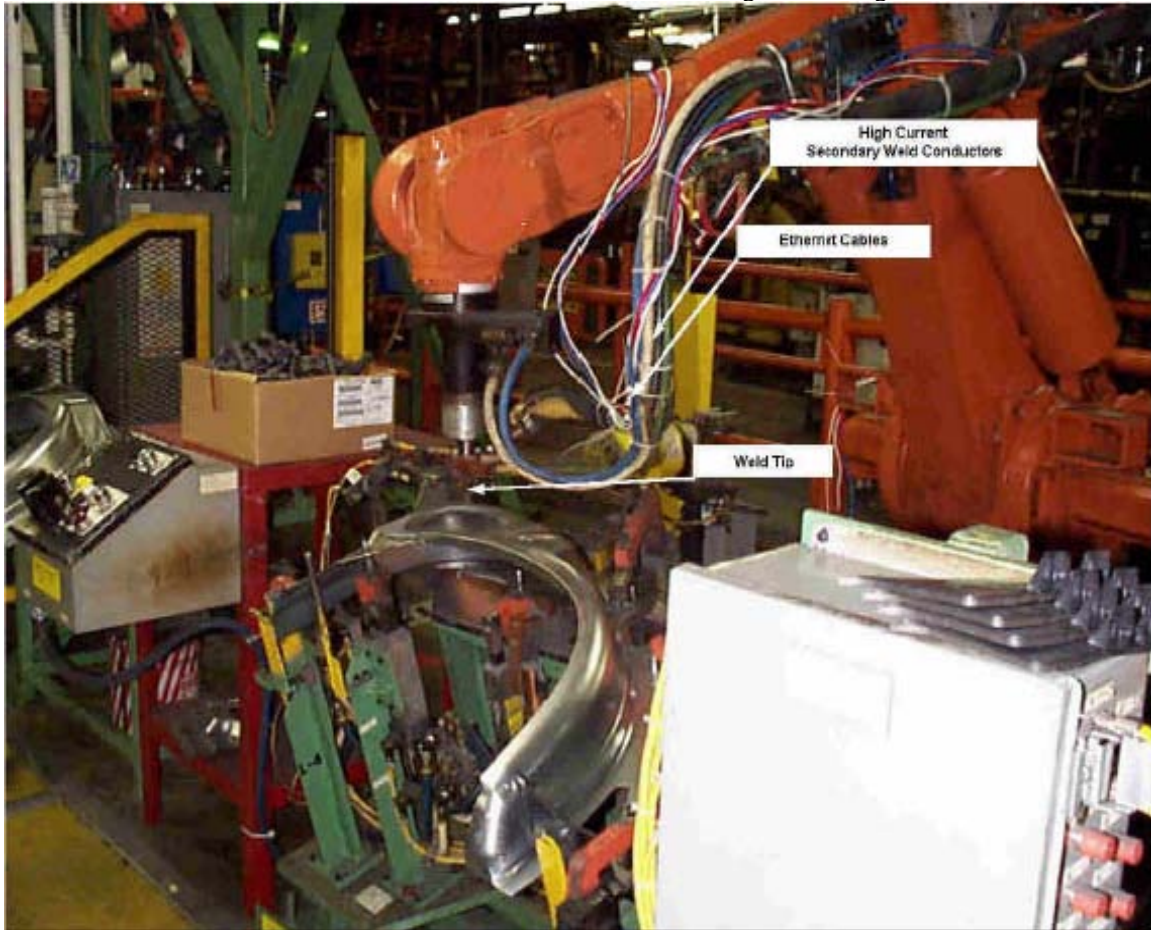
Cable Type	Description	Drives Coupled noise Pk – Pk CM	EFT Coupled Noise pk – pk CM
Shielded (STP)	CAT 5	62mV	1.31V
High Loss Jacket	CAT 5	45mV	1.61V
High Performance	CAT 5E	36mV	1.16V
High Performance	CAT 6	69mV	1.20V

A Case Example of Lab and Real Applications

A test was conducted where different Ethernet cables were installed in a real-world robotic application. This specific application uses a robot to perform a spot welding operation on sheet metal parts, and was selected because of the number of noise mechanisms present. Electro Magnetic Interference (EMI) is generated at the instance of the spot weld arc. In addition, large magnetic fields are generated in the secondary weld conductors during the weld process. Lastly, the motor drives for the robotic arm and conveyors produce conducted noise currents and local ground currents.

The four-pair Ethernet cables were tightly strapped to the high-current secondary of the welding conductors and routed in close proximity to the weld tip. This setup provided both magnetic and radiated noises during the welding event. Figure 13 shows the routing of the cables on the robot arm. A telecommunications analyzer was used to generate 100Mbit NRZ data that was sent to a pair of Fast Ethernet transceivers for encoding and decoding into MLT3 type data. The telecommunications analyzer provided bit-level error detection. The performance statistics were recorded for each of the five cable samples tested. Surprisingly,

zero data errors were recorded for each of the five cables tested during the welding events.

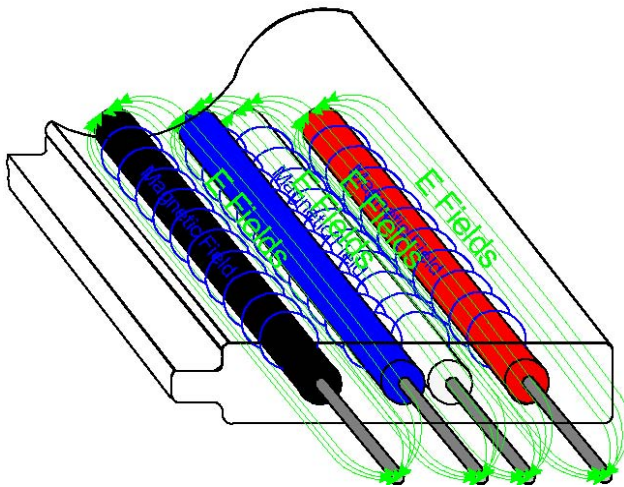


As mentioned earlier, comparisons between real-life application and lab tests (based on European Community standards) indicate that EC based directives are typically more difficult to meet. This does not suggest that the recognized IEC standards are not relevant to typical industrial environments. However, tests proved that the IEC Standards-level noise did represent a more stringent test of the equipment than the real-life applications examined.

The routing of the Ethernet cables in both drives testing and the robotic application testing was in violation of most published wiring practices, including the National Electric Codes in the USA. This was done in an attempt to simulate worst-case conditions, including a marginal cable installation.

The reader should note that the coupled voltages were greater for higher performance cables (based on EIA/TIA category standards) than lower ones. The greater the cable bandwidth, the greater the noise power in the system. For industrial environments, limiting the cable bandwidth can enhance the signal-to-noise performance. If most of the signal energy for Ethernet is below 62.5 MHz, reducing the cable bandwidth to below 100 MHz can provide up to 10-dB increase in the signal-to-noise performance.

Figure 14 Electric Fields Surrounding Conductors



Previous research has found that if shields are not present in a cable, the surrounding environment can effect the cable’s electrical parameters. For example, in Rockwell Automation’s KwikLink system, the two-pair, unshielded, parallel cable has no shield to isolate the conductors from the environment or from each other. However, with careful cable design and selection of materials, a cable can be built that will achieve adequate electrical and mechanical isolation from the environment.

Figure 14 is an illustration of the electric fields with respect to the jacket material of the cable. In this cable design, the jacket material is the same as the primary insulation material. This allows for a uniform dielectric constant within the cable structure. The jacket thickness is roughly .075” and is enough to provide adequate spacing from adjacent material structures that can influence the electrical specifications. A common method for protecting communications cables in harsh environments is to place them in conduit. The electrical performance of a thin-jacketed, unshielded cable, installed in a metallic conduit, will be adversely affected. Figure 15 shows the changes measured in the cable return loss due to the effects of the metal surrounding a 100-meter segment of Ethernet UTP cable.

“Return loss” is another way to describe the mismatch between two impedances. This relationship is expressed in the equation below.

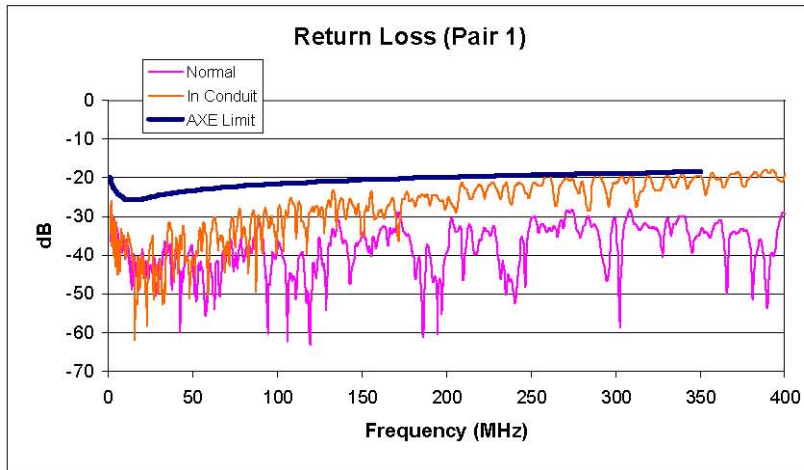
Equation 2 (Return Loss)

$$\text{Return_Loss} = 20 \log_{10} \frac{1}{|\rho|}$$

For the Reflection Coefficient ρ

$$\rho = \frac{Z_L - Z_o}{Z_L + Z_o}$$

Figure 15 Effects of Conduit on the Cable Return Loss (courtesy of Anixter Levels Labs)

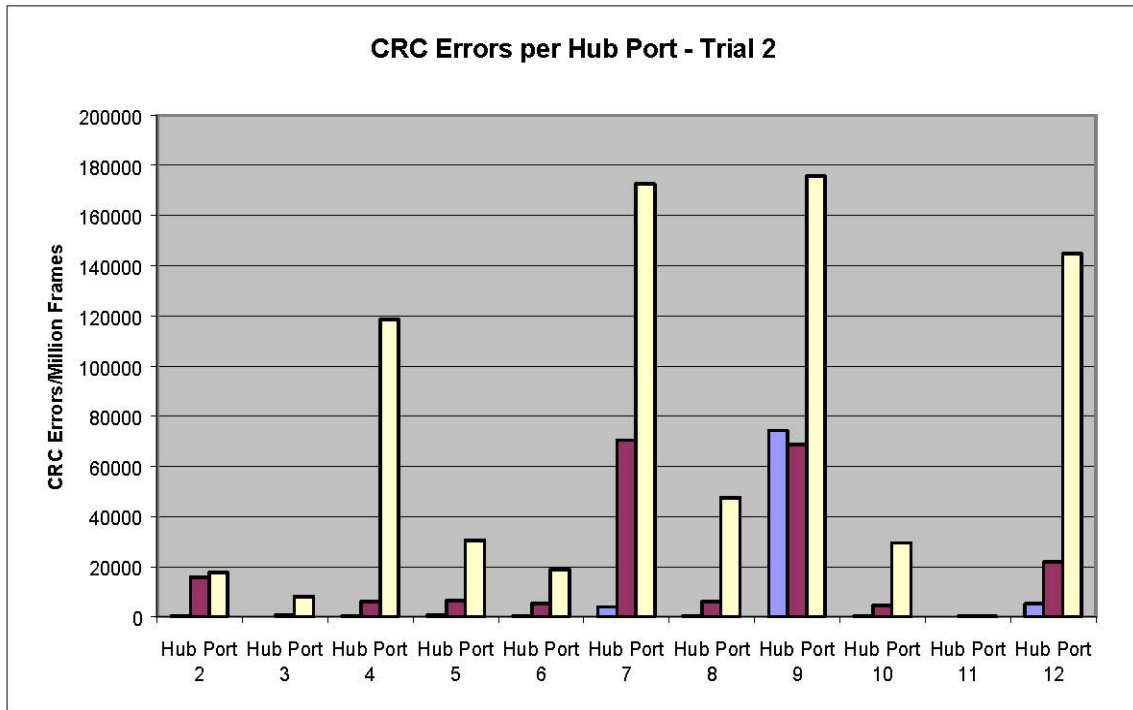


Impedance mismatches (return loss) can adversely affect the link performance. A study was conducted to determine the effects of return loss on communications error rates, and keeping the data errors to a minimum was imperative. A key factor in reducing errors is controlling the impedance of all devices on a segment.

The slight differences in layouts and ground planes within an NIC interface can be large enough to cause performance differences in a hub or switch. As mentioned earlier,, unbalances in the differential TX +/- and RX +/- can adversely affect the channel performance. The packet error rate was measured over three (3) trials and each port of a 12-port device. Note that the packet error rate is different for each port. The error rate increases in the middle ports with respect to the outer-end ports.

This suggests possible significant layout differences between the 12-ports. The layout differences can cause a change in noise currents and temperature offsets that increase in the inner ports. Designers need to pay particular attention to the difference in length between RX+ and RX-, as well as TX+ and TX-. The physical layer ground planes must also be separated from V+ and logic grounds.

Figure 16 Port to Port Performance

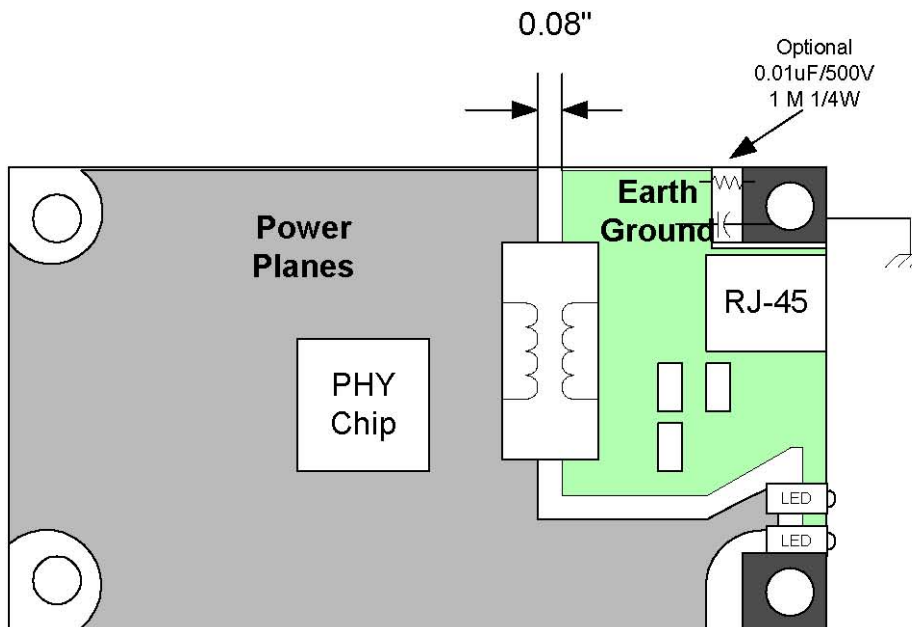


The different classifications of Ethernet nodes are 1) **connectivity devices** such as routers, switches, hubs or gateways or 2) **control type devices** such as I/O, PLCs and sensors. The grounding is different, depending on the node type.

A connectivity device shall be directly grounded to earth via a suitable ground wire.

A control device shall be either left open or connected to earth via a parallel resistor and capacitor. The optional resistor, capacitor values shall be 1 meg ohm +/- 1% - ¼ W resistor and a .01uF capacitor with a 500 V minimum voltage rating. A 1500 V (minimum) network isolation transformer accomplishes isolation between the physical layer and digital circuitry. The power planes and physical layer ground planes shall be separated by 0.08” minimum. This provides adequate isolation (see Figure 17).

Figure 17 Grounding



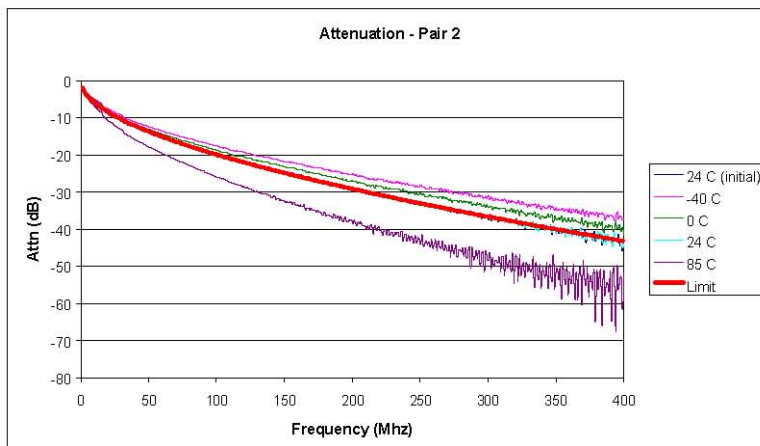
Installation

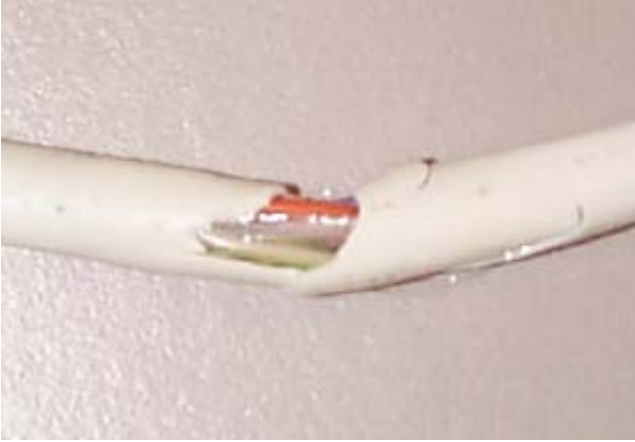
Adequate noise performance can be achieved by maintaining a minimum separation from noise-carrying conductors. The minimum separation rule is 1.5 inches for every 100 V (with a minimum separation of 3” from NEC Class 1 conductors).

Sealing can be achieved by providing cables and connectors made from materials compatible with the operating environment. It is envisioned that various cable designs will emerge that will be resistant to chemicals, weld splatter and UV. In addition several industrial grade connectors will be offered to provide high vibration performance and sealing commensurate with the requirements of industrial applications (IP65 and IP67).

Additionally, high-temperature environments may cause problems with the cables’ electrical performance. As the temperature increases, so does the DC resistance of the copper. This will impact the attenuation of the cable (see Figure 18). Low temperatures will cause PVC jackets to fail, degrading the overall electrical performance of the cable as shown in Figure 19.

Figure 18 Attenuation over Temperature





Connectors

Connectors play a vital role in the overall performance of the Ethernet channel. However, tests have shown that not *all* commercial, off-the-shelf RJ45 connectors designed for Ethernet networks are suitable for industrial environments and their performance in vibration tests vary from manufacture to manufacture.

One of the primary concerns is the effect of vibration and repetitive shock. The connector design must be such that vibration doesn't degrade the contact surface area over time. Additionally, the RJ45 connector contacts must meet some minimum level of specifications common to industrial-rated connectors (specifically 30 micro inches gold over 50 micro inches nickel). Contact surface areas must be optimized for vibration and the lever arm must have enough normal force to minimize movement during vibration.

Several off-the-shelf RJ45 connectors were evaluated in long-term vibration test simulation and exhibited no electrical discontinuity and minimal contact wear. Conversely, other off-the-shelf RJ45 connectors didn't fare as well in identical testing, and quickly fell out of minimum performance specification. It is important to note that fretting due to micro contact movement and oxidation will eventually cause contact failure, and connector designs which minimize contact movement are preferable in areas in which vibration and shock are present.

Sealing an RJ45 for use in industrial areas represents a completely different challenge and can be achieved by providing a face seal around the connector-mating edge and cable entry point.

Conclusions:

Deploying Ethernet into the plant floor requires the next level of communications and cable system performance.

For an office system, latency caused by link errors may go unnoticed. However, in a control system, link errors may lead to jitter which may be unacceptable in some machine or process control applications.

To provide near deterministic performance, which may be mandatory in some control networks, network traffic must be minimized. Minimizing traffic requires optimization of the entire communications network and is accomplished by following proper installation guidelines, selecting the proper materials, reducing the influence of external interference and enhancing the electrical properties of the cabling infrastructure.

While network topology variations, increased wire speeds and the proper selection of electronics can minimize collisions and their effects, it is also important to minimize the number of *errors* caused by either deficiencies in the communications infrastructure or the operating environment itself. Equally important is the isolation of control networks from non-control networks through the use of firewalls and security measures.

Tests show that some industrial operating conditions (noise, temperature, etc.) can negatively affect the

performance of a cabling system and, consequently, increase error rates. In addition, deficiencies in a cabling system's electrical properties, like impedance and common mode noise rejection (CMR) can further add to error rates. As an example, the effects of worst-case impedance and capacitance unbalanced, coupled with the effects of temperature, can degrade system performance by anywhere from 7-14%.

This relationship of increased error rates and decreased performance (throughput) causes an increase in control jitter, which detracts from the network determinism

In initial testing all off-the-shelf shielded and (unmodified) unshielded Ethernet cables examined, failed to meet one or more of the targeted industrial performance requirements .

Because of the presence common mode noise in many industrial environments, the CMR of the system should be as high as is technically and economically feasible. The tests indicate that the Common Mode Rejection Ratio (CMRR) for industrial communications cables should be minimum of 40dB. To achieve high CMRR and minimize residual error rates the capacitance UN- balance of the cable must be kept below 0.5pf / meter, and the cabling system impedance should be controlled to less than +/- 5% from 1 – 32 MHz. Minimizing impedance tolerance helps decrease residual errors caused by signal reflections.

The off-the-shelf cables can meet the capacitance UN-balance of 0.5pf/m but failed to meet the impedance tolerances.

Tests have shown that unshielded Ethernet cables *can be modified and optimized* to provide an acceptable, in-spec performance, which is an encouraging development. The advent of industrially-optimized unshielded cables should serve to offer the industrial user community a lower cost and less complex ethernet cabling infrastructure versus shielded cabling solutions.

Testing has also shown that a cable's ability to meet the industrial operating standards targeted by this study is typically *not* in direct correlation with it's established ANSI/TIA/EIA Category rating.

From a connector perspective some off-the-shelf RJ45 connectors performed adequately when tested against the recognized shock and vibration specifications, yet others did not. The level of performance vs. specification varied among designs. Network and product designers targeting industrial environments should carefully select RJ45 connectors based on their performance versus shock and vibration specification.

Additionally, there are ongoing product enhancements and releases, which directly address the IP65 and IP67 environmental sealing required in many industrial applications.

As mentioned earlier, to further ensure the highest level of determinism and system performance, switches should be employed in lieu of hubs, and careful consideration should be given to the operational/environmental limitations of the electronics selected.

Some electronics are designed for higher operating temperatures and humidity ranges. Conversely, some commercial-grade electronics have operational temperature and humidity ratings that may not be acceptable in some industrial or manufacturing facilities. The selection of electronics is application-dependent, and the applications will vary from facility to facility.

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