Ethernet Cable for Industrial Environment

Lu Li

Alpha Wire
711 Lidgerwood Ave.
Elizabeth, NJ 07207, USA

Abstract — As the demands for reliable, real-time automation and process control in industrial environments increase, an Industrial Ethernet cabling system quickly becomes the most attractive solution. Cables used in industrial environments must be designed to work in harsh environments of temperature extremes, humidity, and vibration. Many times this can exceed the ranges for information technology equipment intended for installation in controlled environments. The many options for designing such a rugged cable with supreme performance working on the factory floor merits discussion. This paper introduces the basic concepts and special considerations for the Industrial Ethernet cable design.

Index Terms: Industrial Ethernet, Industrial Environment, Network Cable, Factory.

I. INTRODUCTION

A high demand exists in the industrial environment for the Ethernet family of computer network technologies for automation and process control. By using standard Ethernet, automation systems from different manufacturers can be interconnected throughout a process plant. Industrial Ethernet takes advantage of the relatively larger marketplace for computer interconnections to reduce cost and improve performance of communications between industrial controllers. Some of the advantages of using Ethernet as the link-layer protocol over one of the open or proprietary protocols such as Modbus®, Profibus®, CANopen™, DeviceNet™, and FieldBus® commonly used in conjunction with PLCs (Programmable logic controllers) are:

- Increased speed, up from 9.6 Kbit/s with RS-232 to 1 Gbit/s with Gigabit Ethernet over Cat5e/Cat6 cables
- Increased distance
- Ability to use standard access points, routers, switches, hubs, and cables, which are immensely cheaper than the equivalent serial-port devices
- Ability to have more than two nodes on link, which was possible with RS-485 but not with RS-232
- Peer-to-peer architectures may replace master-slave ones
- Better interoperability

However, moving Ethernet from an office environment into the industrial world is not as easy as one might think. The office environment offers its cabling system a relatively safe harbor, whereas industrial applications are often subject to harsh and hazardous environments. Examples of applications that take place in this kind of environment are oil, gas and petrochemical plants, water and wastewater facilities, wind farms, and mining. Such environments require the Ethernet cable to resist temperature extremes, humidity and moisture, dust and mud, oil and solvents, corrosive chemicals, mechanical vibration, EMI interference, etc.

In order to meet Industrial Ethernet cabling demands, some cable manufacturers have introduced a so-called "Industrial Ethernet" that is essentially the commercial off-the-shelf (COTS) Ethernet cable covered by an extra jacket. This kind of Ethernet cable has certain rugged qualities, but is usually oversized due to the

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Dr. Lu Li holds the title of Product Engineer at Alpha Wire. He has extensive development experience of networking cable for industrial and commercial environment, transmission lines for power systems, and communication, control, and instrumentation cables for other specific applications.

dual jacket construction. This larger cable is not convenient for installation and extremely inflexible when compared the common COTS cable with the same construction. Another huge disadvantage of such cable is that the temperature rating is still limited by the COTS cable itself.

To provide a complete solution to the above mentioned requirements, a special cable customized to the industrial environment must be designed using the current available technologies.

II. CABLE DESIGN FOR INDUSTRIAL ETHERNET

A typical Ethernet cable construction is shown in figure 1. The cable consists of either two or four twisted pairs surrounded by a metal shielding (for shielded cable only) and covered by a jacket. For Cat6 and above, a cross-filler is often used as well.

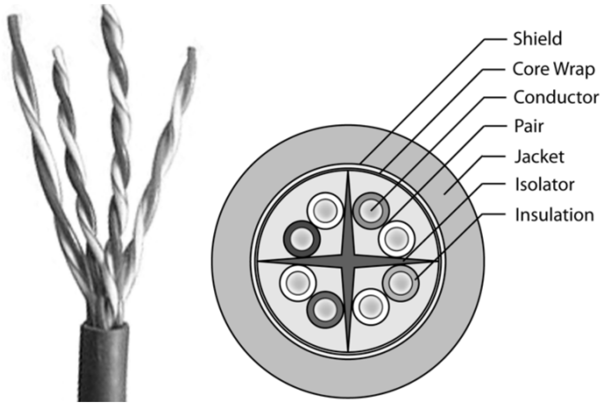

Figure 1. A typical Ethernet cable

The Telecommunications Industry Association (TIA) has developed voluntary, consensus-based industry standards for a wide variety of ICT (information and communication technologies) products, and currently represents nearly 400 companies. Its TIA-568-C.2 specifies the standards for Category cables such as Cat5e, Cat6, Cat6a, and Cat7. The following sections use Cat5e industrial Ethernet cable as a sample to describe the design method according to this standard.

(1) Conductor Drawing

Typically, oxygen-free high conductivity (OFHC) copper is selected as the conductor material for Ethernet cables. This kind of material has 99.95% minimum copper content and an average annealed conductivity of 101%. Depending on the Ethernet cable type, bare copper and tinned copper are often used for category cables. The copper conductor size and stranding construction determine the DC resistance, insertion loss (previously called attenuation), and other related electrical parameters. Generally speaking, 26AWG to 22AWG conductors are used for this type of design. A slight variation on the size is usually adopted to meet the insertion loss while keep the cable light and flexible.

For the primary extrusion line with the capability of drawing the copper rod down to the desired wire size and annealing process, proper cleaning and maintenance should be taken into serious consideration. Any imperfections, such as dirty capstan and defective dies, will cause the periodical defects on the copper wire resulting in impedance variation and return loss failure.

For the patch cable production, a stranded tinned copper (sometimes stranded silver plated copper is used to increase the conductivity) conductor is often used to maximize the flexibility of the final cable. Due to the complexity of the stranded conductor manufacturing process, the Ethernet cable manufacturer usually purchases the off-the-shelf stranded conductor for primary extrusion. A thorough examination on the purchased conductor is strongly recommended before putting it into production.

(2) Insulation Extrusion

Depending on the flame resistance requirements, polyolefin (polyethylene and polypropylene) and fluorinated ethylene propylene (FEP) are commonly used as insulation material. These materials have good dielectric constant and dissipation factors which are critical to Ethernet cables' electrical performance including impedance and insertion loss.

It should be noted that both dielectric constant and dissipation factors are frequency dependent. Meaning, to make the cable Cat5e, Cat6, Cat6a, or Cat7 compliant, a different grade of the aforementioned materials should be considered since the operating frequency spans of these category cables are different.

Eccentricity is a critical parameter at the extrusion stage. High eccentricity is the root cause of impedance irregularities by means of the unstable mutual capacitance when the conductors are twisted into a pair.

A desired eccentricity should be kept within 3% for a decent product.

In order to keep the impedance centered at 100 ohms for higher category cables, a foaming technique is usually adapted for insulation extrusion. Chemical foaming and gas injection foaming are two commonly used methods to achieve this purpose. However, foaming also adds another dimension of complexity to the design due to the fact that foaming causes unpredicted insulation crushing at the twisting and cabling process. Some designs put a thin layer of skin of the same material on top of the foamed insulation to strengthen the crushing resistance, but the process capability and complexity of quality control make this technique difficult to use.

(3) Pair Twisting

Pair twist is a very important process during the cable’s production because almost all of the major electrical characteristics are determined at this stage. Design-wise, the twist lay length is the main concern. Each pair’s lay length affects not only each individual pair’s impedance, signal transmission delay, and time skew, but also the crosstalk between pairs. Process-wise, the twisting not only determines how balanced the insulated conductors are (electrically determines the resistance unbalance, capacitance unbalance, differential and common mode performances such as TCL and TCTL), but also influences cabling since an imperfect twisting can exaggerate the flaw caused by cabling process itself.

Because the signals with different frequencies travel in twisted pair, a certain signal will have the same (or harmonic) frequency as the pair’s intrinsic frequency determined by the twist lay length. So the energy coupled between pairs at this frequency will be accumulated, causing a spike showing on the crosstalk graph. Figure 2 shows a typical crosstalk in dB with spikes on a logarithm scale for an unshielded Cat5e cable. The straight line is the specification in TIA-568-C.2, while the waves stand for multiple measurements of the near-end crosstalk between the blue and orange pairs.

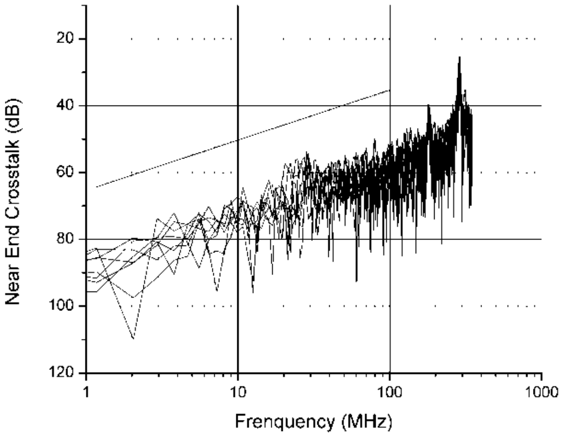

Figure 2. Typical Near-End Crosstalk

The location of spikes in frequency domain can be predicted at the design stage using the intermodulation theory. The intermodulation method uses the intrinsic frequencies of each pair and signal transmission speed to calculate the frequency at which the dominant spike shows. Due to the existence of harmonic frequencies other spikes with decreasing amplitude can also be seen symmetrically distributed on both sides of the main spike. Under certain conditions, one may observe the minor spikes shown asymmetrically on the left side (lower frequency) of the main spike. This is due to the mirror effect of the ground plane at zero frequency. As this is beyond the scope of this paper, it will not be discussed in detail herein.

The amplitude of spikes can be simulated by finite element analysis. There are several commercial software packages available on the market, but neither of them can show results in a reasonable time frame due to the hardware limitations of current computer systems. Selecting a set of lay lengths of existing successful products as the starting point combined with calculations result are the practical approach for cable designers.

An electronic controlled twiner is ideal for the twist lay length and tension adjustment to ensure a balanced construction of the pairs with desired lay. Back twist technique is also used to reduce the twist tension, particularly for solid conductors.

(4) Cabling

Cabling can be as simple as bunch bundling four pairs in sequence for lower category cables or as complicated as adding filler with all kinds of shapes, isolation tapes (usually clear Mylar tape), and drain wires (usually stranded tinned copper wire) all together as in the higher category cables. Various filler designs have been seen in the network cable industry, but the goal stays the same: minimize the crosstalk between pairs. Although all kinds of material can be used as the filler, a rule of thumb is to use a material that has similar or better characteristics than the insulation material. The major purpose of using an isolation tape is to segregate the pairs from the drain wire and shielding tape/braid to avoid hipot failure. At the same time, it pushes the drain wire and shielding tape/braid away from the pairs to help electrical performance.

Another design variable to help the overall electrical performance is using variable cabling lay length. Occasionally the intrinsic frequency of cable lay length will inter-modulate with the pairs’ frequency to cause cabling spike showing on the return loss data graph. By using the variable cabling lay, one can spread out the cabling spike into a range of frequencies. In other words, the energy with higher amplitude at one frequency can be redistributed to many frequencies with lower amplitude.

(5) Braiding

Braiding is not common for typical Ethernet cables, but for industrial-grade Ethernet cables, braiding is an excellent way to minimize low frequency EMI and add extra mechanical protection to the cable. With the possibility for cable abuse on the factory floor, a braid will also assure the grounding continuity for the low frequency machine noise and high frequency electromagnetic influence.

That being said, the braiding is an extremely difficult process with a high potential to jeopardize electrical performance. An uncontrolled braider tends to introduce variable tensions when the pay-off bobbins have less and less material left. Thus, the braiding process is of utmost importance in manufacturing a successful Industrial Ethernet product.

(6) Jacket Extrusion

Jacket extrusion involves covering the cable core with thermoplastic material for mechanical protection and adding shielding material for EMI protection required for the shielded cables.

For a foil shielded cable, Aluminum/Mylar tape is usually applied with drain wire at this process rather than at the cabling process; if the drain wire is spiral applied or foil tape faces out, other equipment not convenient to operate at a jacket extrusion line is needed. A tape folding guide and a series of closing dies are arranged in sequence to apply the shielding tape with 100% coverage while keeping the desired tightness. Improper tightness can vary the impedance by 3ohms or more.

For a foil/braid shielded cable, jacket extrusion involves only one process – jacketing - because the foil/braid process has to be done separately. However, a paper tissue might be applied at this stage to keep the jacket material from intruding into the braid interstices. Using paper tissue will give the jacket a tube or semi-tube configuration versus a pressure-extruded configuration.

Besides the aforementioned jacketing considerations, the most critical design for Industrial Ethernet cables is the jacket compound.

Common Ethernet cables use PVC or similar compounds as jacket materials. Such compounds work well for office buildings or data centers with clean and stable cable conduit, temperature controlled environments, and electromagnetic noise-free surroundings. The industrial environment has a different scenario – vibration, chemical spills, solvent emergence, EMI, temperature variation, etc. In this uncontrolled environment, a PVC jacket is simply not acceptable.

FEP is an option as the jacket material, but due to the raw material cost and stiffness, it has never been seen as a practical solution for Industrial Ethernet products.

As a result, a proprietary TPE (thermoplastic elastomer) was developed at Alpha Wire for the industrial environment. It resists temperature extremes, humidity and moisture, dust and mud, oils and solvents, corrosive chemicals, mechanical vibration, and EMI interference. This TPE compound not only has similar electrical characteristics as PVC, but also has three times the flexibility versus ordinary PVC, which benefits the industry in cold climates. Figure 3 and figure 4 show the characteristics of the newly developed TPE having similar properties as the ordinary PVC.

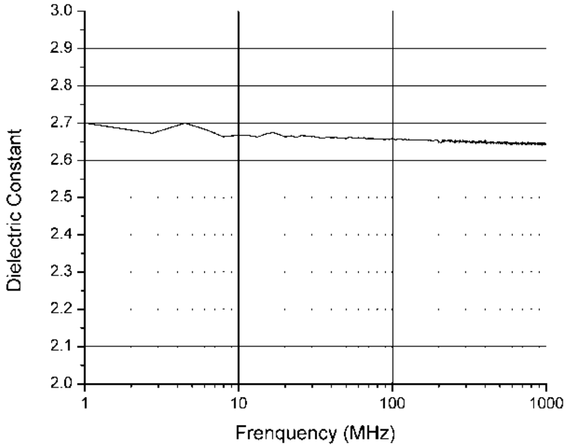

Figure 3. A proprietary TPE's dielectric constant

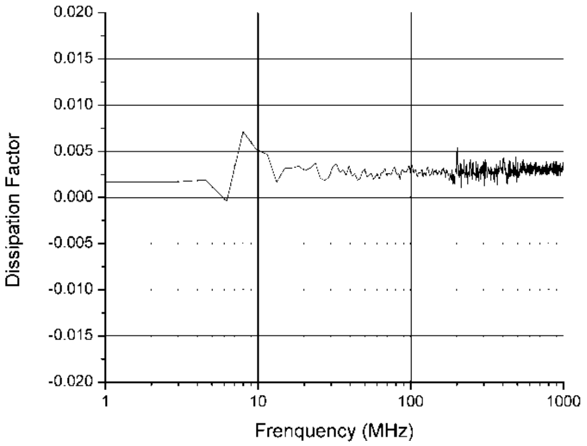

Figure 4. A proprietary TPE's dissipation factor

Table 1 shows the physical properties of commonly used PVC and TPE jacket compounds. These special features of the proprietary TPE compound make it an ideal candidate for the industrial Ethernet.

Another aspect in the design stage for the jacket is wall thickness. A thin wall can increase flexibility and benefit installation, but make the cable prone to damage. For category cables having alien crosstalk requirements, jacket wall thickness plays a major role.

Table 1. Comparison between TPE and PVC

PROPERTIES (Resistance)	**TPE**	**PVC**
Abrasion	Good	Good
Heat	Excellent	Good
Weatherability	Excellent	Good
Flame	Excellent	Excellent
Water	Good	Good
Acid	Excellent	Good
Alkali	Excellent	Good
Aliphatic Hydro.	Poor	Good
Aromatic Hydro.	Poor	Poor

III. CABLE DESIGN EXAMPLE AND RESULTS

As an example to illustrate all the basic concepts and design considerations mentioned above, an industrial grade -50°C to 125°C, foil/braid shielded Cat5e CMR rated cable design is demonstrated here.

A 24AWG (0.2mm^2) solid bare copper wire was selected as conductor. The wire was drawn down from a high quality copper rod to the 24AWG range to meet the DC resistance and low frequency insertion loss requirements, all while maintaining flexibility by minimizing the conductor diameter.

Solid FEP was extruded over the copper wire as insulation to meet the temperature requirement and to maintain high performance in all other electrical parameters. Since the electrical performance can be met using the solid FEP, no foaming is needed. Plus, solid FEP is smaller in size and contributes to the robustness of the cable.

Eight colored insulated conductors were twisted separately into four pairs with different lay lengths. The lay lengths for the blue, orange, green, and brown pairs are 0.750", 0.538", 0.900", and 0.625" respectively. Back twist and tension control were adapted during twist process.

At cabling the four pairs were bunched in sequence into a cable core with a fixed cable lay. No filler was used due to the crosstalk requirement of Cat5e cables.

Before jacketing, the cable core was foil shielded with a drain wire applied spirally under the foil tape before applying braid over the foil shield. The tension was monitored at this process to ensure electrical performance would not be jeopardized.

The braided cable core was jacketed using the TPE material. Paper tissue was used to prevent the jacket material from embedding into the braid.

Eight 100 meter samples were tested according to the TIA-568-C.2 standard. Blue pair's DC resistance, DC resistance unbalance, and capacitance unbalance (pair to ground) are shown in Table 2. Blue pair's impedance is shown in figure 5, insertion loss in figure 6, return loss in figure 7. Blue and green pairs' near end crosstalk is shown in figure 8.

Table 2. Test results for DC parameters of blue pair.

	DC Resistance (ohm)	DCR Unbalance (%)	Capacitance Unbalance (pF)
Spec.	9.38	5	330
Test	8.42	1.89	27.33

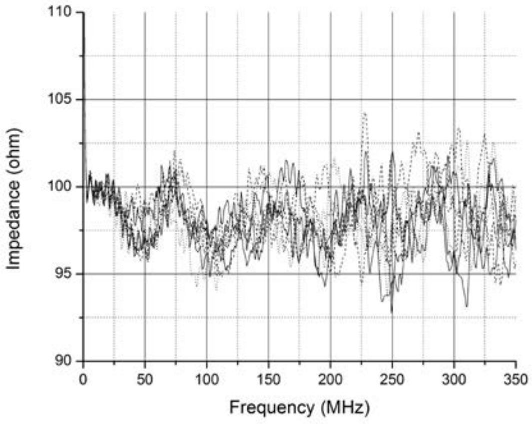

Figure 5. Impedance of blue pair

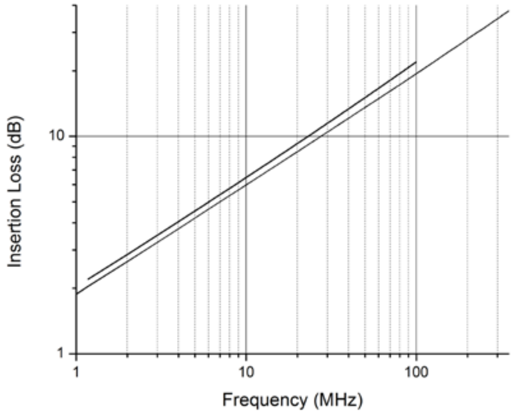

Figure 6. Insertion Loss of blue pair

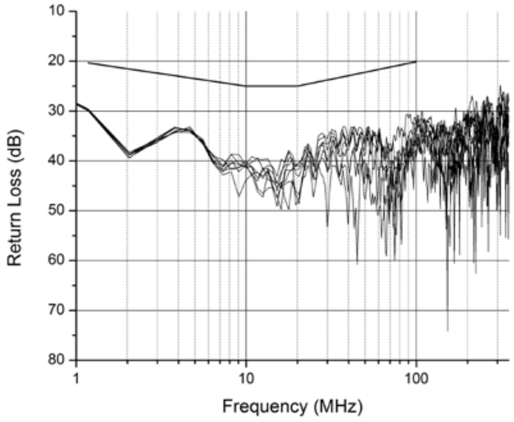

Figure 7. Return Loss of blue pair

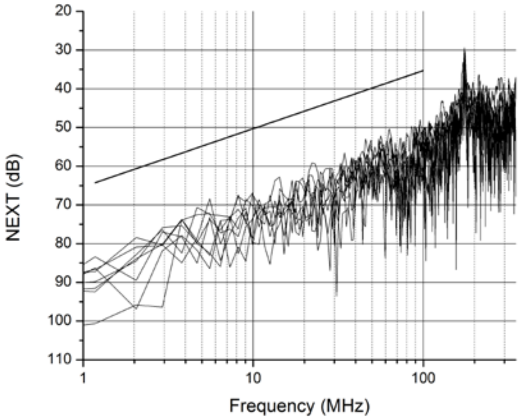

Figure 8. Near End Crosstalk between blue and green pairs

All other test parameters such as mutual capacitance, structure return loss (SRL), power sum near end crosstalk (PSNEXT), far end attenuation to crosstalk ratio (ACRF), power sum far end attenuation to crosstalk ratio (PSACRF), surface transfer impedance, propagation delay, and propagation delay skew are also within limits.

IV. CONCLUSIONS

This technical paper introduces the basic design concepts of Ethernet cable customized for industrial environments. Special considerations for conductor selection, insulation extrusion, twisting, cabling, braiding, and jacketing process are discussed. A customized jacket compound for industrial environments is introduced. To help to understand how the industrial Ethernet cable should be designed, this paper uses an industrial grade Cat5e cable as an example to illustrate the design workflow. The test results of this design showed the compliance of current TIA-568-C.2 standard. Alpha Wire’s Xtra-Guard® Industrial Ethernet Cat5e cable not only meets all the specifications in the standard, but also exceeds the general requirements in a typical industrial environment.

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