Using Copper Wires for ITS Networks:
It's not only for Fiber Optics and Wireless Systems

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ABSTRACT

The paper will present the old, new and upcoming technologies for communications over copper wires that are, or will be very useful for ITS networks. The discussion will focus on the design and implementation of various ITS communications applications that are being demonstrated using copper wires, and will illustrate specific situations where there are immediate benefits over fiber optic and wireless systems. Some of the issues that are addressed include bandwidth and distance limitations, ease of installation, equipment configuration and costs. With such a multitude of products available or soon to be available, this method of communicating with ITS field devices is poised to save agencies a significant amount of money. The paper will also the possible configurations for integrating Ethernet using copper, fiber and wireless systems into a seamless, high capacity system, and how the use of standards as they apply using copper wires to both circuit and packet-switched networks including EIA-232, EIA-422/485, VDSL, G.SHDSL, HDLC and Ethernet.

KEYWORDS

Ethernet over copper, ITS, G.SHDSL, NTSC, Internet Protocol (IP), Ethernet, Wi-Fi, packet-switched, NTSC, dB, Free Space Loss, multiplexing, twisted wire pair, IEEE.

INTRODUCTION

It has become common for ITS designers to utilize fiber optics for any high speed, long distance transport of data for ITS networks. This included both video (analog and digital) and data communications under both circuit and packet-switched network technologies. The use of wireless solutions is also taking the ITS world by storm. This includes varying topologies and technologies. However, a vast majority of the existing, or legacy traffic signal systems utilize an installed base of copper twisted pair wires as the primary medium for communications with field devices like traffic signal controllers. Until recently, it was thought that in order to provide feasible communications with modern ITS field devices, the use of fiber optics was the only real option, and that the installed base of twisted pair wires could only be used for very low bandwidth, serial communications (e.g., 1200 baud). Moreover, the sweeping trend is towards packet-switched technologies including Internet Protocol and Ethernet making a further case to migrate towards an all-fiber infrastructure to meet the ever increasing bandwidth demands.

Then along comes the father of innovation and technology: the manufacturers hoping to capture previously untapped markets. Why not implement technologies that can utilize what's already in the ground and transport the new forms of data? While it has taken several years and a few international standards, newer technologies such as G.SHDSL, are making the upgrade of legacy traffic signal systems more cost effective by utilizing the existing communication infrastructure.

With the quickly growing trend to install Ethernet drivers and ports in nearly every ITS device, agencies are poised to take advantage of these new devices without the need to install new communications infrastructure. Also, given that Ethernet is a packet-switched protocol, there are several layers of complexity that are removed when operating and maintaining ITS networks, especially with the remote monitoring and diagnostic capabilities of Ethernet. These factors, coupled with the savings associated with using the existing communications infrastructure, make Ethernet over copper a very practical and cost effective approach to upgrading one's ITS system.

The following sections describe in some level of detail these new technologies and the appropriateness of their use for traffic management systems.

TECHNICAL CHALLENGES TO OVERCOME

Copper twisted wire pair cable, or traffic signal interconnect cable, (hereinafter referred to as twisted pair) has historically been the transmission medium of choice for traffic signal systems transporting mainly serial-based data in long-reach circuit-switched networks. This has been adequate for many years, and has resulted in a large installed base of copper interconnect. As the need for more bandwidth is realized, the main limitations of copper-based networks begin to unfold, namely transmission distance and bandwidth. The following sections describe in more detail these limitations, and the different ways in which new technologies are overcoming them.

Distance limitations

Twisted pair, fiber optic and wireless networks have differing performance characteristics when transporting both analog and digital data. In particular, the transport of analog video (National Television Standards Committee – NTSC) signals presents some interesting challenges.

Twisted Pair

The reduction of signal strength during transmission (i.e. attenuation) through a twisted pair cable varies with frequency, resistance, inductance, capacitance and leakage conductance. Taken together, these factors make up the attenuation which is measured in signal loss (decibels, or dB) whether it be total attenuation on a link or on a per-unit of distance measurement. Twisted pair with gauges between 19 American Wire Gauge (AWG) and 24 AWG are the most widely deployed in the USA for traffic signal systems. The typical attenuation for these wire sizes is 0.71 and 1.27 dB per kilometer for 19 AWG and 24 AWG respectively.[1] The wire sizes increase with lower gauge numbers, thus, there is more copper material available for the electrical signals to employ during transport. With all other factors being equal, electrical signals attenuate less and travel further while traveling through lower gauge copper wire.

The methods available to reduce the attenuation and increase the transmission lengths of copper cable include increasing the conductor diameter, using signal amplifiers/repeaters, and using carrier equipment to perform some form of modulation such as Frequency and Time Division Multiplexers.

In practice, coaxial cable has traditionally been used for NTSC video transmission at the local intersection (i.e. 500 to 1000 feet maximum) only. Then, the use of copper twisted pair was initiated for short haul distances using intermediate repeaters and amplifiers. It still had limitations on the number of repeaters and thus was not used extensively for medium haul distances (i.e., several miles).

Fiber Optic Cable

Fiber optic cable uses strands of glass slightly wider than a human hair to transmit light in the infrared band. There are two distinct types of fiber optic cables: single mode and multi-mode fiber. In single-mode fiber, shorter wavelengths of light travel along a single path, and in multi-mode fiber, longer wavelengths of light inside the core travel along multiple paths, or modes of light. Single-mode fiber has a very thin core which is used together with a laser diode for long range, high speed communications. The multi-mode fiber optic cable is somewhat coarser, allowing for less refraction back into the core which leads to lower data rates and shorter ranges (up to 2 km in some cases).

Like copper wire, attenuation within fiber optic cable is measured in dB/km, or total dB. Single mode fiber optic cables typically have an attenuation of between 0.25 dB/km and 0.40 dB/km. Multi-mode fiber optic cables typically have an attenuation of approximately 3.5 dB/km.

In previous practices, single mode fiber optic cable was typically deployed as a network backbone medium which required high bandwidth carrying capacity over medium to long haul distances. In today's ITS networks single mode fiber is deployed for all types of segments including drop and distribution segments in addition to backbone and trunk segments. Whereas copper twisted pair was and continues to be traditionally used to transmit native NTSC video signals for a few hundred feet, or serial data for up to 14 miles at the lowest bit rate (1200 baud). For reference, single mode fiber optic cable can transmit NTSC video signals up to 20 miles without the use of optical amplifiers/repeaters, due to the combination of low lightwave attenuation and large optical budgets.

Wireless Networks

In wireless networks there are a number of factors that impact the distance achieved by the communications system. However, the factor that describes the signal strength loss due to the communications medium is Free Space Loss (FSL). Free Space Loss is dependent upon the distance between antennas as well as the operating frequency and is represented by the following formula:

Free Space Loss (dB) = 32.44 + 20 log (Distance in Kilometers) + 20 log (Frequency in Megahertz, MHz) [2]

Using the two most common license-free frequencies that are capable of supporting higher bandwidth ITS applications (2400 MHz and 5800 MHz), the Free Space Loss calculations at distances between 5 and 20 kilometers are presented in Table 1 below.

Table 1
Calculated Free Space Loss

	2400 MHz		5800 MHz	
Distance (km)	**FSL (dB)**	**FSL/km**	**FSL (dB)**	**FSL/km**
5	94.02	18.80	121.69	24.34
10	100.04	10.00	127.71	12.77
15	103.56	6.90	131.23	8.75
20	106.06	5.30	133.73	6.69

In practice, wireless transmission of NTSC video signals is not the most cost effective for deployment in ITS networks for a number of reasons. First, while the license-free frequencies analyzed above are capable of transporting high bandwidth data, they require a dedicated wireless link to support the transmission of pure analog video. Second, the equipment needed to support analog video transmission modulated to different frequencies is prohibitively expensive and not built for deployment in a traffic control cabinet, e.g., outdoor installations.

Ethernet Communications

Over the last few years there has been an ever increasing trend to utilize Ethernet as the primary communications protocol for ITS networks in the center-to-field area. Ethernet is a communications protocol defined by the Institute of Electrical and Electronic Engineers (IEEE) 802 family of protocols. It is a Layer 2 (Data Link) protocol that defines interfaces down to Layer 1 (Physical) making it capable of operating with a wide range of physical media including twisted pair, fiber optics, and wireless.

Listed in Table 2 below are some standard segment lengths for transmitting Ethernet data packets according to the IEEE 802.11b (wireless) and 802.3 (fiber optic cable and twisted pair).

Table 2
Standard Segment Lengths

Medium	**IEEE Standard**	**Maximum Distance**
Wireless	802.11b	100 m
Fiber Optics[1]	802.3	2000 m/5000m
Twisted Pair	802.3	100 m

1. 2000 meters is for multi-mode. There are no standards for single-mode. 5000 meters is for gigabit transmissions.

The distances listed above are the maximum specified according to IEEE standards. In particular, the 100 meter distance for twisted pair is based on the minimum Ethernet frame size (64 bytes) and the round trip propagation delay. Through the use of DSL technology (described below), this distance can be extended. However, this now places the system outside the bounds of a standard Ethernet communications system.

Several factors can impact the actual distances achieved in practice. Wireless transmission distances are most commonly affected by the lack of line-of-sight between transmitter and receiver. Operating at either 2.4 or 5.8 GHz, wireless network interface cards and access points are capable of transmitting through thin walls and small trees but not through metal objects, thick brush and cinder block walls. However, under typical situations (e.g., in offices or homes), the standard distances indicated above should be achieved.

Fiber optic transmission distances can be negatively impacted by refraction. Refraction occurs when light pulses are sent off the outer portion of the fiber optic cable known as cladding instead of remaining in the core located at the center. This condition can be minimized through the use of single mode fiber optic cable which has a thinner core and results in light traveling in a straighter line for a longer distance compared to multi-mode fiber cable. However, in practice, distance well in excess of the standards can be achieved.

Unshielded or ungrounded twisted pair is susceptible to Electromagnetic Interference (EMI), which can negatively impact the actual transmission distances. When multiple pairs are deployed in close proximity to each other, EMI can result in an intermingling of electrical signals between adjacent pairs. This condition is referred to as crosstalk.

Through the use of Digital Subscriber Line (DSL) technology, government agencies are able to deploy high bandwidth ITS field devices such as digitally encoded analog video signals using their existing copper twisted pair infrastructure. DSL is a circuit switched technology that requires a dedicated connection between transmitter and receiver.

Since DSL equipment only carries Ethernet frames and is not responsible for Ethernet control signals, it does not support Ethernet redundancy measures such as Spanning Tree Protocol (STP). Therefore, if a cable cut occurs, communications with affected locations will be unavailable until the physical medium is repaired or manually rerouted. Automatic failover is not possible with DSL.

There two types of DSL service commonly deployed in the United States – Asymmetric Digital Subscriber Lines (ADSL) and Symmetric High Bit-Rate Digital Subscriber Lines (SHDSL). ADSL provides significantly lower upstream data speeds compared to downstream speeds and is commonly deployed by telecommunications providers to their residential broadband customers. SHDSL delivers an equal amount of bandwidth in each direction and is a better candidate for ITS networks. According to ITU Specifications G.991.2 and G.992.1, ADSL and HDSL provide transmission distances on a single copper twisted pair of up to 15,000 feet (4,570 m) and 23,000 feet (7,010 m) respectively. Although the bandwidth achieved using HDSL equipment decreases as transmission distances increase, HDSL has proven to be a viable option for supporting high bandwidth ITS applications such as digitally encoded MPEG-4 video. In the following section, the bandwidth aspect will be discussed in greater detail.

Bandwidth Limitations

Initial ITS networks deployed in the United States in the early to mid 1990's utilized analog CCTV cameras in the field with fiber optics as the communications medium. Fiber optic cable was the medium of choice because of its ability to carry the video signals further without the need for repeaters. At the time of deployment for early ITS networks, video encoding technology for digital networks was not developed to a level where deployment in the field was practical.

In the last ten years, MPEG-2 and MPEG-4 technology has advanced to a point where video encoders deployed in traffic controller cabinets can produce video data streams that are of comparable quality to a standard NTSC signal. With nominal bandwidth requirements ranging from 4 Mbps to 10 Mbps for digital encoders to produce video at near full frame rates - 29.99 frames per second - deployment using alternate communications media has become a possibility.

IEEE 802.11b “Wi-Fi” provides up to 11 Mbps maximum. However, actual bandwidths achieved in the field are typically between 5 Mbps and 6 Mbps. These levels are acceptable for supporting MPEG-4 video streams. As discussed previously, the native transmission distance of “Wi-Fi” is 100 meters which is not acceptable for ITS field deployments. However, with the application of high-gain antennas, proprietary protocols and favorable geographic field conditions, “Wi-Fi” can achieve actual transmission distances of between three and five miles.

As discussed previously, SHDSL equipment is available that can support high bandwidth applications over distances of several thousand feet. SHDSL is an International Telecommunications Union – Telecommunications (ITU-T) standard that stipulates performance ranging from 192 Kbps to 2.3 Mbps over one pair and 384 Kbps and 4.6 Mbps over two pairs of copper. Actual transmission distance depends upon the number factors, most notably the number of available copper twisted pair and the gauge of wire deployed in the field.

In February and March 2005 the City of Livermore and DKS Associates conducted a 60 day field trail comparing two G.SHDSL equipment manufacturers to determine the viability of deploying this technology to support high bandwidth ITS field devices using the City of Livermore’s existing twisted pair traffic signal interconnect.

It was discovered that each manufacturer claimed different performance metrics even for the same type of twisted pair and number of pairs. On a good note, the actual performance metrics obtained during the field trial was comparable to the claimed metrics provided by each manufacturer.

Comparing the two products using the same gauge of copper cable (24 AWG), transmission distance (9,500’, 15,000’, and 19,000’) and number of pairs (1 and 2) yielded the following results:

At 9,500’ bandwidths averaged 4.35 Mbps and 8.2 Mbps using 1 and 2 pairs, respectively.
At 15,000’ bandwidths averaged 2.65 Mbps and 4.45 Mbps using 1 and 2 pairs, respectively.
At 19,000’ bandwidths averaged 1.3 Mbps and 2.2 Mbps using 1 and 2 pairs, respectively.

Figure 1 below presents some typical performance metrics of Ethernet over copper devices for a 24-gauge twisted pair cable.

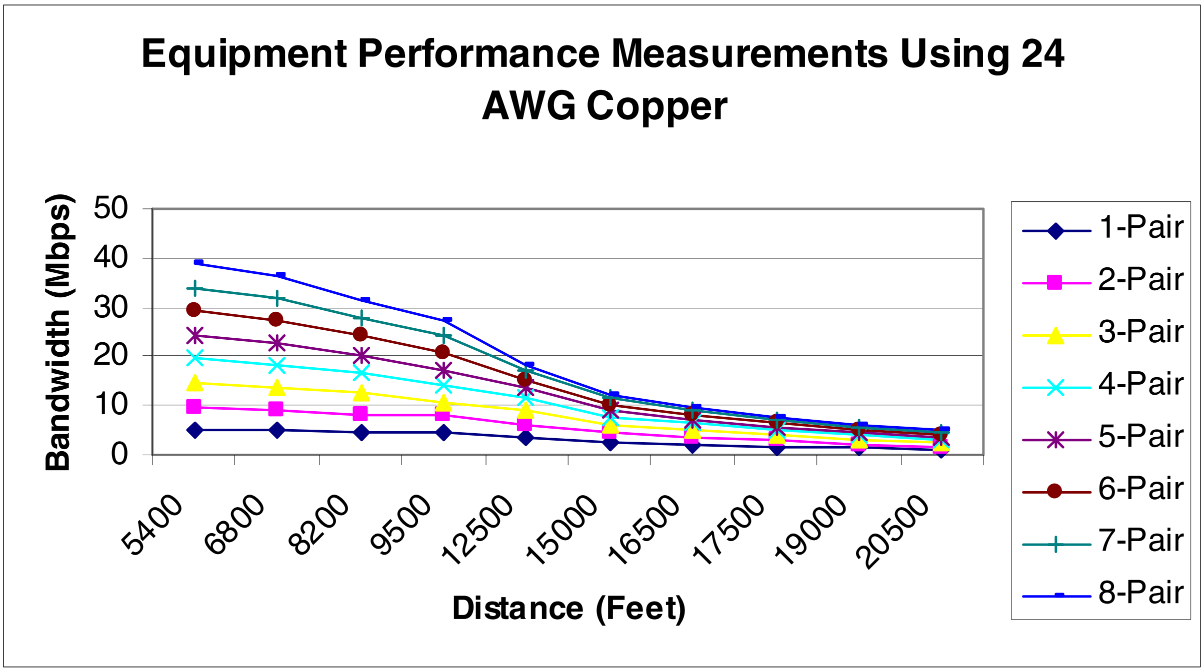

Figure 1 - Typical Performance Metrics for Ethernet over Copper

Fiber optic cable remains the optimal physical medium to support CCTV video cameras. However given the relatively large amount of copper twisted cable already deployed by state and local governments for traffic signal control, technologies such as HDSL allow ITS system operators to deploy high bandwidth ITS field devices in the short term without incurring the sizeable costs associated with constructing fiber optic cable infrastructure.

INNOVATIONS

This section discusses the newest technical innovations that make it possible to utilize twisted pair for many different high bandwidth ITS applications that were not possible before. Historically, ITS applications have been operated with low bandwidth, low latency requirements predominantly geared for the circuit-switched, serial communications world. With the advent of the Internet and graphical user interface systems, the need for increased bandwidth and flexibility associated with packet-switched systems became more apparent. Still yet, other applications such as analog (NTSC) video have use for transport over twisted pair, which in the past have relied on amplifiers to stretch the long distances required for ITS networks. Newer systems have been able to double and even triple the reach of analog video systems over twisted pair.

Digital Subscriber Line (DSL)

Perhaps the most notable innovation for ITS is the development and implementation of the G.SHDSL (or G.991.2), the first international DSL standard. Using pulse amplitude modulation (PAM) line encoding, G.SHDSL requires only one twisted pair for the same or higher data bit rates and can extend up to 40 percent further in comparison to the older SHDSL with 2B1Q line encoding. What this means for ITS is that using twisted pair interconnect cable, an ITS application such as IP video can utilize this technology for transport for up to 2000 feet more than was possible before.

NTSC (analog) Video

For many ITS networks, the transport of analog video presents an interesting challenge. First, because it is a baseband technology, transport of other signals is not possible without some form of modulation that utilizes multiple carrier waves along the same medium. Also, since the signal is an analog waveform, it requires a high bandwidth (frequency) which results in shorter transmission distances due to the impact of attenuation. In order to transmit the signal further distances, frequency modulation and wavelength multiplexing within optical fiber is typically used. For medium haul distances, twisted pair is used. Previously, distances much less than a mile have been achieved before some form of amplification is required. Transmission distances of over seven miles in some cases (seven amplification points) have been achieved with little degradation in video quality.

New innovative transmission techniques can transmit NTSC signals over twisted pair nearly 2.5 miles (13,000 feet) without the need for amplification or repeaters. New approaches including the use of proprietary amplification, frequency equalization, and potentiometers to trim video level and peaking, the video signals can be pushed to extended distances by optimizing the video signal performance between transmitter and receiver. This has resulted in a 60% improvement in transmission distance. While this is still far less than a typical reach using optical fiber, the significant cost savings associated with utilizing existing twisted pair instead of installing new fiber makes this option very attractive.

COSTS AND BENEFITS

This section will analyze various technologies that can provide Ethernet connectivity along various City corridors. For purposes of this section, the costs and benefits of these technologies will be evaluated along an arterial roadway located in the City of Livermore.

North Canyons Parkway

North Canyons Parkway is a four-lane arterial roadway located in the northwest corner of the City. The arterial currently serves Las Positas College, a Costco wholesale warehouse, and numerous residential, industrial, and commercial properties. The typical ADT along the arterial is 26,000 vehicles per day and is approximately 6000' in length. The roadway borders the City of Dublin and is accessed from Interstate 580 at Airway Boulevard. A western connection from Dublin, an interchange on Interstate 580 at Isabel Avenue, college expansion, and residential and commercial developments are all planned in the next 20 years. The City's traffic model predicts buildout volumes to reach 45,000 vehicles per day in 2025.

The corridor currently employs six (6) traffic signals. Six-pair copper interconnect was installed as each signal was constructed in the past. The original system ran Multisonics 820A controllers with an On-Street Arterial Master (OSAM) located within the corridor. A phone drop provided communications between the OSAM and City Hall. In 2004, the Multisonics 820A controllers were replaced with Naztec 2070 Controllers utilizing their proprietary software. The OSAM was removed and the phone drop was disconnected.

The corridor is isolated from the rest of the City due to the lack of connection to other City arterials. The City had a desire to reestablish connectivity along the corridor in order to coordinate the corridor during the AM and PM peak hours. In addition, the City wanted to install a CCTV camera adjacent to Interstate 580 to monitor traffic conditions along Interstate

580 and North Canyons Parkway. The City also desired to install devices that could utilize Ethernet Protocols for its TOC expansion. The Naztec 2070 controllers come equipped with an Ethernet port and are IP addressable. Wireless Ethernet will link the corridor to the TOC, located about 5 miles away. With the exception of the 2070 controllers and proposed CCTV camera, the City does not have any other Ethernet-ready devices along the corridor.

Costs and Benefits

The City identified three options to provide Ethernet Connectivity:

- Replace existing copper interconnect with fiber-optic cable and install Ethernet-over fiber communications devices.
- Install wireless communications devices along the corridor.
- Install Ethernet devices along the existing copper interconnect.

Option 1 – Fiber-optic Cable Installation

In order to install fiber-optic cable at each intersection, extensive modifications to the existing interconnect system was necessary. The conduit system was in good shape and was installed within the last 15 years, so staff determined that it would cheaper to modify the existing system rather than constructing new conduit and pull boxes. In addition, each traffic signal controller cabinet required a fiber Ethernet Switch. Each switch is able to link up to six (6) IP addressable devices in an intersection utilizing single mode fiber optic cable.

The fiber installation would support long term expansion along the corridor and would allow the City to implement a variety of Ethernet devices in the future, including additional CCTV cameras, video detection systems, etc. Ultimately, the fiber will be linked directly to the City's TOC when the Isabel Interchange is constructed. Until that time, fiber capabilities would be limited by the quality of the wireless link between the corridor and the TOC.

This project would require staff time to design, advertise, and oversee the construction. Design to final construction would take about nine months to a year to complete. The engineers estimated cost to design, advertise, construct, and oversee the project would be about $120,000.

Option 2 – Wireless Communications

Due to the existing line-of sight issues and surrounding topography, exclusive wireless technology in each traffic signal controller cabinet was ultimately not achievable and therefore not analyzed.

Option 3 – Ethernet over Copper

By utilizing Ethernet over copper devices along the corridor, the City could utilize the existing copper interconnect, which would eliminate the need for the construction or modification of existing facilities. Once the devices are ordered and received, a typical installation would take between 3 hours to 2 days.

The devices are ideal to bring back traffic signal controller data and a small number of CCTV cameras or video detection cameras. However, the system would need to be modified in the future to provide expanded video monitoring and detection capabilities ultimately planned for the corridor. In addition, the switches come with one or two Ethernet ports for various devices. In order to add more Ethernet ready devices, a hub or switch would need to be installed in the traffic signal controller cabinet. Typical field hardened hubs and switches can cost $99 and up.

An unmanaged Ethernet over copper device is a simple plug-and-play device designed to provide up to 10 MBps of bandwidth. The user can configure the device through a series of dip switches designed to be extremely user friendly. The unmanaged device is not IP addressable and cannot be accessed remotely for setup and configuration purposes. The cost to install the devices (including engineering oversight and vendor installation costs) would be about $13,000.

A managed Ethernet over copper device is a robust device designed to provide up to 10 MBps of bandwidth. Enhanced devices are available that can provide up to 40 MBps of bandwidth. The device is IP addressable, allowing the user to remotely access the unit through proprietary software as well as through a standard Internet browser. The user can modify a variety of parameters to provide optimum performance. The device is also designed to measure interconnect continuity, which can be useful in troubleshooting troublesome interconnect. Because of their robust nature, the devices require additional effort to install and configure. The cost to install the devices (including engineering oversight and vendor installation costs) would be about $19,000.

Conclusions

Based on the ease of installation and the inexpensive cost, the City determined that Ethernet over copper devices would be ideal along the corridor. The City evaluated both the managed and unmanaged devices and decided to install the unmanaged devices along the corridor. In the future, the City will take advantage of future construction projects adjacent to the corridor to construct a fiber optic interconnect system that can meet the City's need for.

In addition to this corridor, the City has installed a mix of managed and unmanaged devices along other corridors in the City. Currently, the City has installed 16 devices and plans to install up to 20 more in the near future. These devices provide IP connectivity to a variety of devices, including traffic signal controllers, CCTV cameras, video detection systems, battery backup systems, conflict monitors, and emergency vehicle preemption devices.

USE OF STANDARDS

When deploying copper wires for ITS networks, it is very important to consider the use of standards-based products. This was an issue a few years ago when Ethernet Extenders first hit the market, where proprietary technologies were developed. Given the maturity of the DSL family of technologies, most importantly symmetric DSL (G.SHDSL), an international standard, the most recently introduced products are now standards-based. The on-going challenge is the ability for different products from different manufacturers to interoperate. This appears to be the next step in the process.

One challenge for extended Ethernet transport over copper wires is interfacing DSL and IP packets. Many products utilize High Level Data Link Control (HDLC), a Layer 2 protocol which interfaces DSL signals with the Ethernet Media Access Control (MAC) and the

Ethernet framing drivers. The main issue is that the specific techniques that manufacturers use to extend the reaches of DSL signals are very much proprietary to each vendor. This is why one must use the same vendor's products on each end of a communications link. The future goal is now to better enable interoperability amongst different vendor's products by offering a common interface. The high level block diagram shown in Figure 2 below illustrates the various firmware/software interfaces of a typical Ethernet over copper device including the portion that represents the proprietary interfaces.

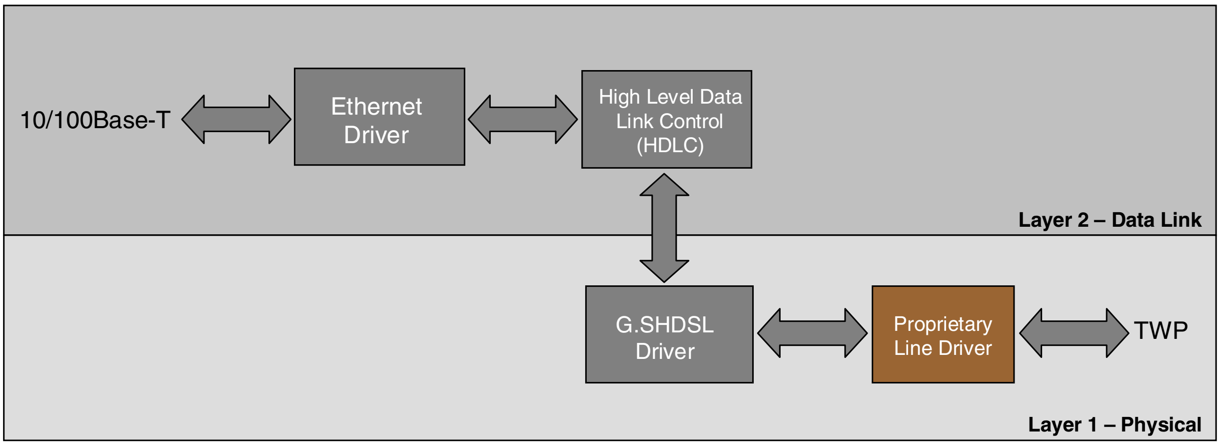

Figure 2 - Ethernet over Copper High Level Block Diagram

SUMMARY

In summary, the use of copper signal interconnect has been a mainstay for traffic signal systems given the ability of serial Frequency Shift Keying (FSK) modems to transport signals at low to medium baud rates over long distances (up to 14 miles at 1200 baud). With the installation of higher bandwidth devices such as CCTV cameras and higher end traffic controllers (ATC 2070), the use of the same copper wires has been prohibitive until recently. For analog-based CCTV systems, a new generation of signal repeaters (amplifiers) are capable of transmitting NTSC signals distances more than three times longer compared with an installation without regeneration. For digital-based systems, using DSL, HDLC and Ethernet technologies, the ITS industry is poised to increase their return on investment in the installed base of signal interconnect to carry high bandwidth data for medium haul distances.

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Joshua Pack, P.E, has over 7 years of experience in the design and operation of traffic signal systems. He is currently an Associate Transportation Engineer with the City of Livermore, CA (USA). Prior to the City of Livermore, he worked in both the private and public sector and has extensive experience in the design and construction of traffic signal and ITS infrastructure.

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REFERENCES

[1] Freeman, Roger L., Telecommunication Transmission Handbook (3rd Ed.), 1991, p 78-80.
[2] Freeman, Roger L., Telecommunication Transmission Handbook (3rd Ed.), 1991, p 210.