Santa Clara County Traffic Operations System (TOS) – Technology Evolution

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ABSTRACT

In the nine years since the Santa Clara County Traffic Operations System (TOS) was conceived the ITS technology landscape has changed considerably. This paper will compare the ITS "state-of-the-art" of 1996, 2000, 2005 and the future in the areas of telecommunications architecture, communications protocols, video transmission and infrastructure management. As construction on the Santa Clara TOS project nears completion, the paper will present a brief overview of emerging technologies that have the potential to be adopted by Santa Clara County TOS in the not too distant future.

KEYWORDS

Telecommunications Network Architecture, Fiber Optic Cable, RF Modulation, Course Wavelength Division Multiplexing (CWDM), Ethernet

SANTA CLARA COUNTY TOS PROJECT OVERVIEW

Santa Clara County covers 13 cities that form the bulk of what is commonly referred to as Silicon Valley. Within the county, the Interstate and State highways are controlled and operated by the California Department of Transportation (Caltrans); the County operates a system of limited access expressways, that generally have at-grade signalized intersections; and the Cities operate signals on City-owned streets. There is a high level of inter-agency cooperation at an operational level, and most of those agencies are developing the technology to actively integrate the traffic signal and CCTV systems.

In 1996 work began on a feasibility study of ways to develop an enhanced Traffic Operations System (TOS). The goals of the TOS project are to improve the flow of all modes of traffic on the expressways, and to improve the response to incidents and accidents. In 1998 the County first constructed a Traffic Operations Center (TOC) and, in association with the Silicon Valley Smart Corridor project, installed fiber optic cable to a small number of intersections and CCTV cameras. Detailed design on the TOS project began in 1999. This project is expanding the fiber optic communications network to cover 64 miles of County expressways, and install 397 fixed CCTV cameras and 16 Pan-Tilt-Zoom cameras at 131 intersections. Construction began in 2001 and is expected to be completed in 2006.

1996 - TOS CONCEPT DESIGN

The original feasibility study, finalized in January 1997, recommended deployment of a fiber optic cable network along the expressways, primarily to support the analog video system and to provide direct communications between the TOC and ITS field devices. The analog video system required a high bandwidth communications network for simultaneous transmission of 480 camera feeds over distances of up to 9 miles. The initial study assumed a basic star network topology with one dedicated fiber strand supporting communications between the TOC and each of the field devices. Expecting technology advances to occur, CCTV camera and transmission technology recommendations were not made at the time.

2000 – CONCEPT REVIEW & DESIGN

By 2000, digital technology was more readily available for ITS applications. An extensive review of the concept design was undertaken to assess the applicability of the new technology. As part of the evaluation process, Santa Clara County and DKS study team members examined video and data communications architectures at: San Diego Caltrans/CHP TMC; City of Stockton Traffic Operations Center; and several vendors of CCTV and digital communications equipment; City of San Jose. At this point the original star network topology was changed to a hybrid topology that combines star and ring topologies. Under this scheme the TOC and four Communication Hubs would be connected through a ring while individual signalized intersections would be connected to a Communication Hub in a star topology. Figure 1 provides a high level illustration of this topology.

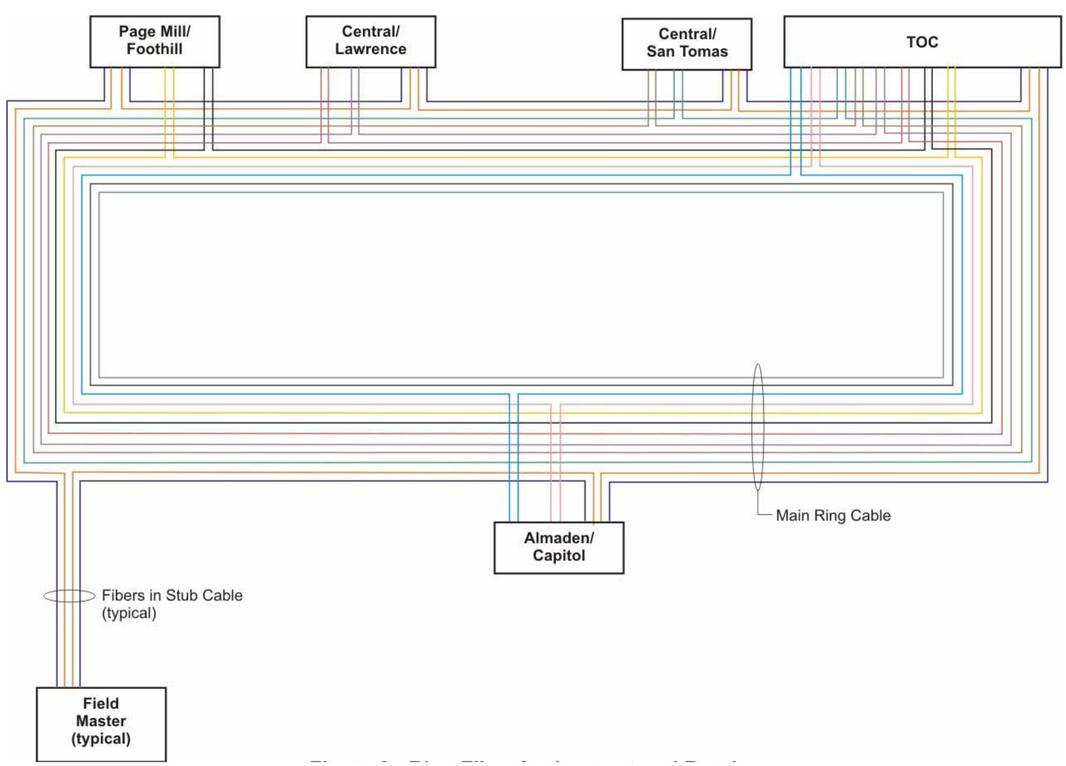

Figure 1 – TOS Fiber Ring Assignment and Routing

VIDEO TRANSMISSION

The study team conducted field observations of other systems that employed analog and digital transmission, comparing color, refresh rate and ease of use of PTZ controls. At the time it was concluded that analog transmission was most appropriate. The analog-based systems investigated consistently had high picture quality, while the digital systems had variable quality. At the time, the following conclusions were reached:

- The analog systems maintained full motion video in either color or black and white, which was comfortable to watch, and would be suitable for use with a video detection unit at the TOC;
- The digital systems observed had variable frame rates, resulting in jerky pictures, which made it difficult for operators to distinguish between stopped traffic and moving but congested traffic;
- To provide full motion (30 frames per second) with adequate resolution for traffic management required high bandwidth (approximately 143 Mbps);
- The digital systems required relatively expensive digital encoding and decoding equipment for each video signal;
- Analog systems had no appreciable signal delay, enabling accurate PTZ control. With the digital systems, if bandwidth becomes constrained, the frame rates become variable, resulting in poor control of PTZ cameras, because of the inherent latency and sometimes variable delay in the system, which makes the task of the operator more difficult and time consuming, especially during emergencies when camera pre-sets may not be applicable; and
- Color analog video was of constant quality, while the digital systems had relatively poor and variable color rendition, which makes the image less distinguishable and harder to watch for extended periods. The quality of the color and smoothness of picture motion is dependent on the amount of movement on the screen and the number and complexity of pictures being compressed onto one line.

VIDEO LINKS BETWEEN INTERSECTIONS AND HUBS

The choice of signal format between individual intersections and hubs is constrained by the severe environmental and size requirements for the intersection equipment. The equipment must be very compact and able to operate at ambient temperatures as high as +65°C.

At the time, four channel video transmitters were recommended. This could have been done through frequency modulation (FM), amplitude modulation (AM), wavelength division multiplexing (WDM), or any combination thereof. After evaluating the available alternatives, the Conceptual Design settled on a RF solution which included the use of transmitters that first frequency modulated the video signal on a subcarrier, then used the subcarrier signal to amplitude modulate that output to a laser diode.

At the time equipment capable of carrying four video signals over a common fiber was available, using two different approaches:

- RF Modulation: All fixed cameras at an intersection are transmitted to the Communications Hub using Frequency Division Multiplexing equipment. In this approach one channel would be allocated to each intersection's fixed CCTV cameras. On a separate channel, PTZ camera video and data is transmitted to the Hub using a separate Video Optical Transceiver. At the Hub, the PTZ video signal is transmitted to the TOC with other fixed video camera signals using an analog RF Combiner and Optical Transmitter. PTZ data is sent to the TOC via a separate data multiplexer/demultiplexer pair. Figure 2 illustrates this approach.

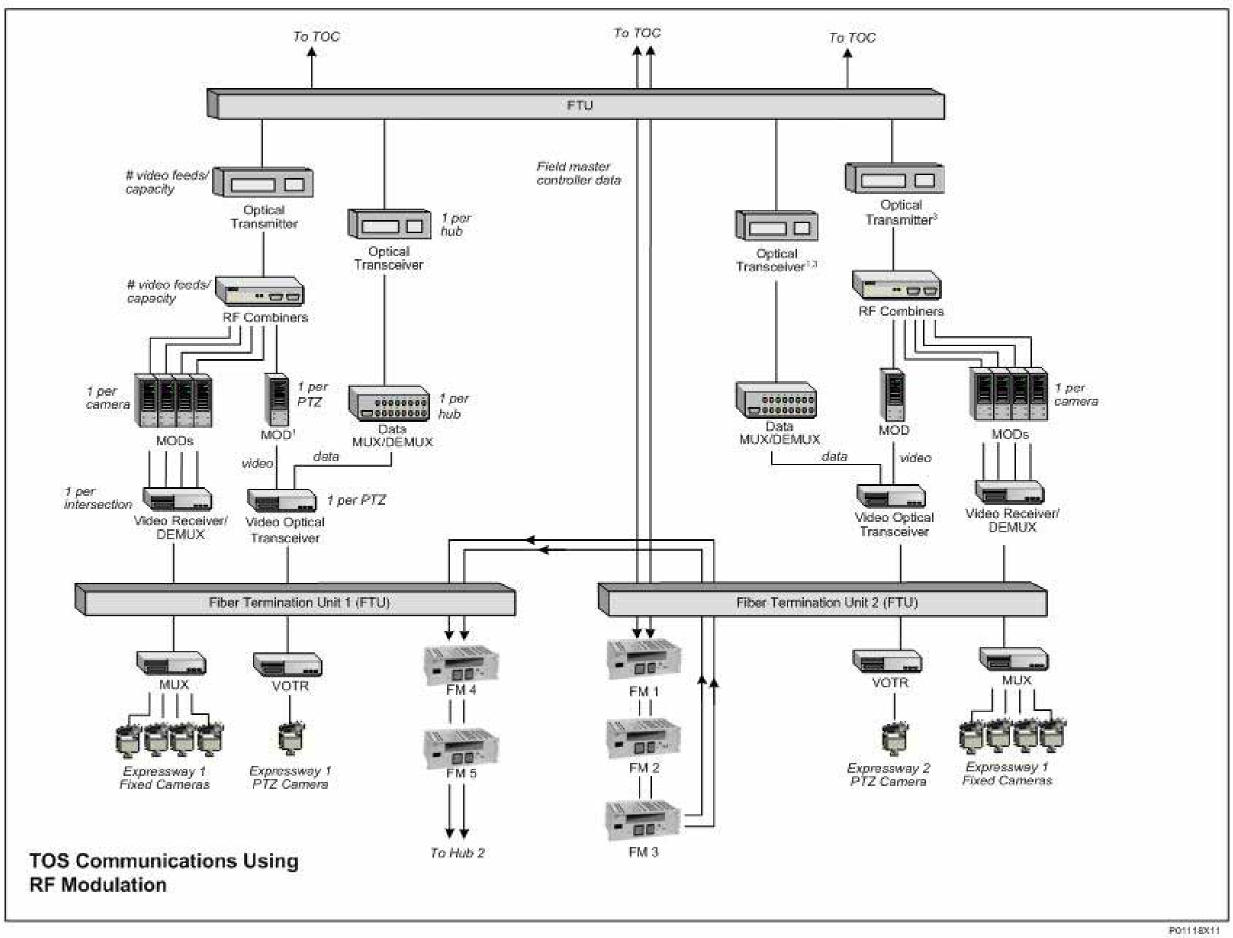

Figure 2 – TOS Communications Using RF Modulation

- Multiplexing: This approach is similar to RF Modulation however the RF Combiner function is performed instead by Frequency Division Multiplexing equipment and Optical Transceiver which can be either analog or digital. Figure 3 illustrates this approach.

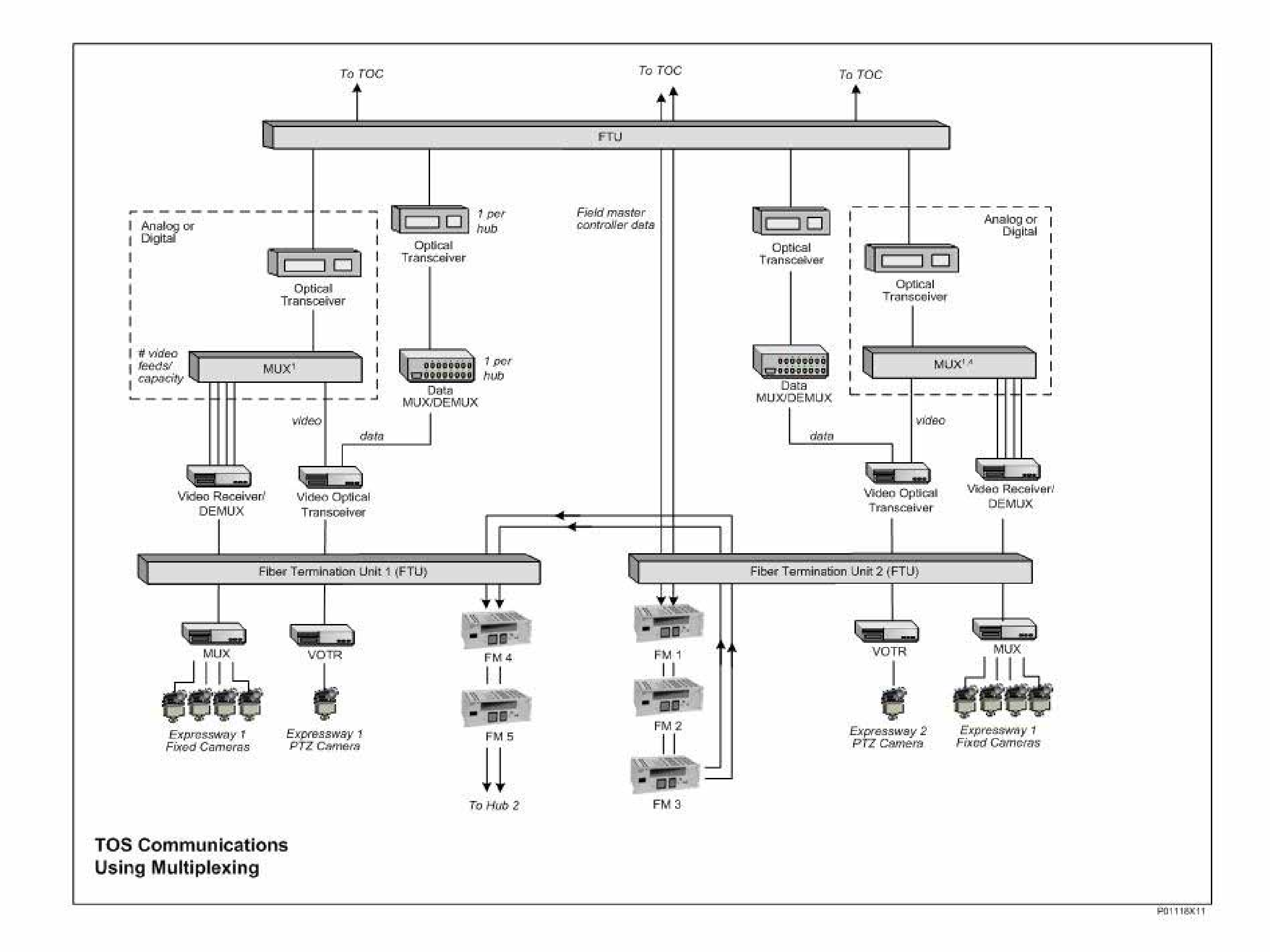

Figure 3 – TOS Communications Using Multiplexing

Both approaches were deemed adequate for Santa Clara County's system.

LINKS BETWEEN COMMUNICATION HUBS AND TOC

Deploying a network topology where each traffic intersection communicated directly with the Traffic Operations Center presented several significant drawbacks. First, the large distances, in some cases over fifteen miles, between individual intersections and the TOC resulted in unacceptable or barely passable signal margins. Second, such a topology would not be fault tolerant with respect to accidental cable cuts. Furthermore, it would require at least one fiber per intersection or PTZ camera site to be routed to the TOC and would require the equipment at the TOC to deal with approximately 400 separate video baseband feeds.

In order to partially address these issues, the design team recommended the establishment of Communication Hubs that would be placed at strategic locations. The Hubs would function as a congregation point for regenerating the signal levels prior to transmission to the TOC. The issue of reducing the number of fibers and associated RF modulators in the TOC was to be addressed by combining the camera feeds from each intersection into one 2x2 image before modulating the signal. However, using such a device would mean that all four displays would always have to be viewed together, and a full-screen view of one camera would not be possible.

The modulators would be set up for normal analog cable television channel frequencies extending from 55.25 MHz (channel 2) through 547.25 MHz (channel 78), giving a total of 77 channels per fiber, with all frequencies per EIA-543 "Standard" channel plan. Where more signals are required than can be accommodated by the plan, a second set of modulators would be used, duplicating as many channels as required. These were standard pieces of equipment in common use in the cable TV industry at the time. Depending on the degree of redundancy desired, the output of a single transmitter can be split to feed signal to the TOC via the clockwise and counter-clockwise directions around the ring or, for a higher degree of redundancy, the signals can be fed to two separate transmitters. In either case, the optical output power may be as high as +17 dB at 1550 nm. While it is anticipated that this will be adequate for routing either way around the ring, that will obviously depend on the final routing. Should it not be adequate in one direction, an optical amplifier can be added wherever required.

The proposed configuration between each hub and the TOC is a "sheath ring", meaning that one dedicated fiber for each set of modulators extend from each hub to the TOC clockwise around the ring and another dedicated fiber run counter-clockwise around the ring.

CONCEPT DESIGN RECOMMENDATIONS

Ultimately the Concept Design Review report recommended RF Modulation as illustrated in Figure 1. From the point of view of the fiber requirements:

- Two fibers would "drop and repeat" from data transceiver to data transceiver around the ring in a configuration and will carry both signal information and PTZ control information in RS-232 format. Should it be desired to separate the signal information from the PTZ control signals, two additional fibers will be required.
- In each portion of the ring, one fiber would be dedicated to video transmission for each set of modulators for each hub. Since each of the four proposed hubs on the ring will potentially originate more than 80 video feeds, two fibers will be required from each hub to the TOC each way around the ring. At some future time, these feeds could be configured to be self healing through the route-redundant path from hub to TOC and the automatic selection at the TOC of the surviving feed in the event of a cut.

In total, therefore, 10 active fibers will be required throughout the extent of the ring to interconnect the hubs and master controllers, assuming all data is handled on a common pair. The fibers are assigned as follows:

- The two outer fibers are the drop-and-repeat data ring
- The next two fibers carry the two sets of channels from the Central/San Tomas hub
- The next two fibers carry the two sets of channels from the Central/Lawrence hub
- The next two fibers carry the two sets of channels from the Page Mill/Foothill hub
- The next two fibers carry the two sets of channels from the Almaden/Capital hub
- The two inner fibers are spares

TECHNOLOGY EVOLUTION

The Concept Design Review recommended an analog video transmission strategy based on analog's superior video quality. However in the year following issuance of the Concept Design Review in December 2000, a number of factors changed resulting in a reevaluation and subsequent reversal of the initial design recommendation. These factors included:

- Technology trend: Most RF Modulators supported 77 channels on a single fiber strand. The prospects of increasing the channel capacity appeared remote based on informal surveys of equipment manufacturers.
- Fiber Optic Cable Requirements: Routing all 480 analog video signals to their respective Communication Hub using RF Modulators required substantially more fiber optic cable compared to multi-channel digital multiplexers.
- Physical Space Requirements: Each one channel RF modulator required 1U of rack space. The TOC Equipment Room could not accommodate this equipment.
- Signal Quality: The digital multiplexers output an analog video signal with quality comparable to that transmitted by a RF Modulator.

2001 – REVISED DESIGN

Instead of using modulators, demodulators and RF Combiners to carry out Communications Hub-to-TOC communications, digital multiplexers and demultiplexers using Course Wavelength Division Multiplexing techniques were introduced into the ITS market in late 2001 and early 2002.

Wavelength division multiplexing (WDM) techniques send multiple colors of light down a single fiber strand. Each color is a separate, signal-carrying channel. Thus, if one fiber using one color of light can carry a certain amount of data, that same fiber using eight colors of light can carry eight times as much data. Several large WDM systems designed for telecommunications applications can place 80 or more colors of light on a single fiber. As a protocol-independent technology, WDM can be used for FDDI, Ethernet, ATM, and other network architectures. These high-capacity systems could effectively multiply existing capacity by one or two orders of magnitude - offering plenty of bandwidth.

Coarse Wavelength Division Multiplexing (CWDM) is an implementation of WDM technology for short-to-medium haul networks. CWDM systems use 10 to 25nm spacings and operate between 1300nm and 1610nm. CWDM systems have extremely low laser drift which eliminates the need for cooling equipment, and result is lower equipment cost. CWDM systems have between 8 and 16 channels, each operating between at a minimum of 156Mbps, which can deliver bandwidths ranging from 1Gbps to over 100Gbps.

Santa Clara County applied this technology by deploying 4 channel video/data multiplexers at each CCTV location. At each Communication Hub inbound video and data signals are demultiplexed with 4 channel units, then multiplexed with a higher channel multiplexer (8, 16, 32 or 64) for transmission to the TOC. The CWDM cards used operate at nine separate wavelengths, eight (1470nm through1610nm) are dedicated for video and one (1310nm) for serial data. A block diagram showing the revised system layout is provided below.

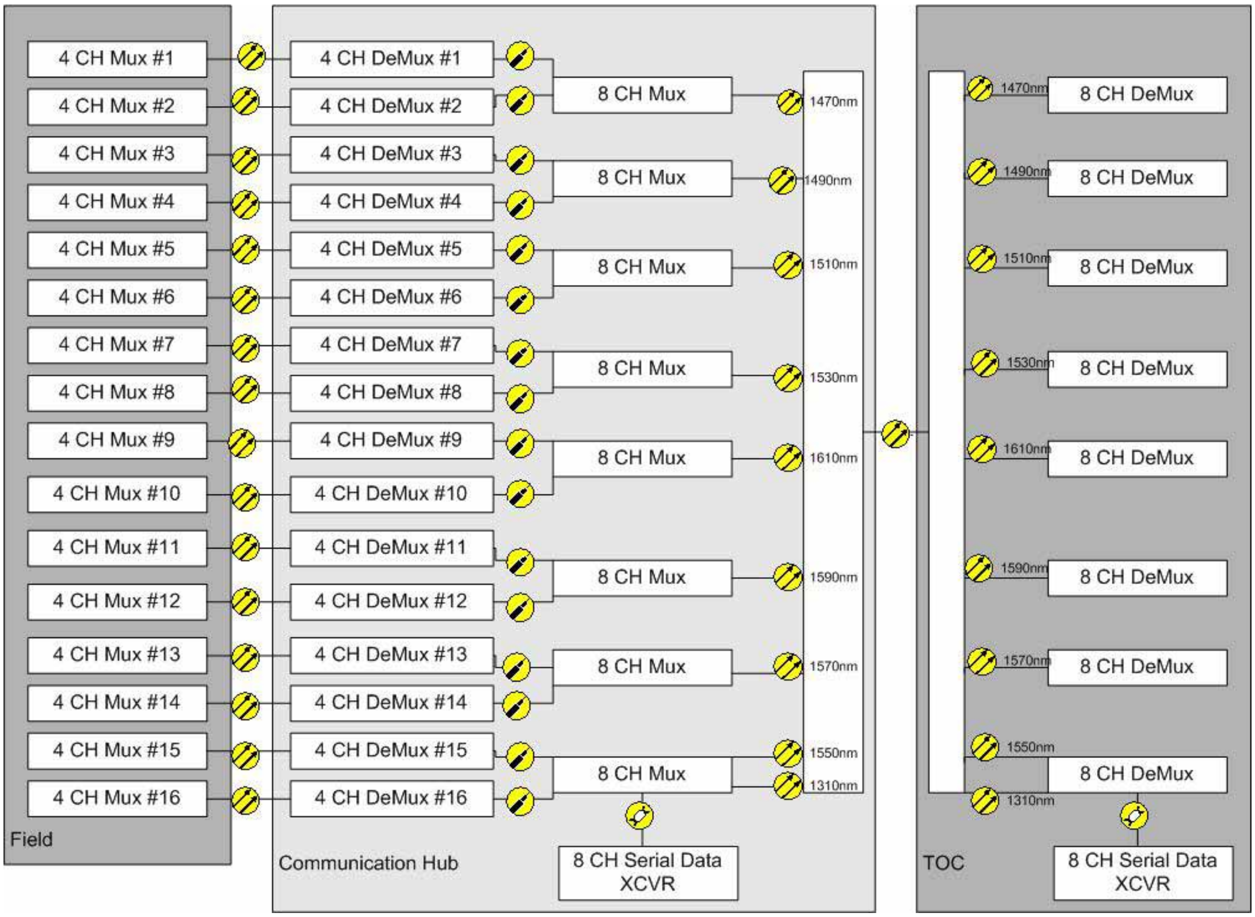

Figure 4 – Digital Transmission of Analog Video System Layout

Digital transmission using Course Wavelength Division Multiplexing (CWDM) was recommended, and subsequently included in the detailed engineering design, for the following reasons:

- Digital transmission offers true broadcast quality video that exceeds RS-250C Short-Haul Transmission and is superior to RF Modulation. Digital video performance is constant over the rated range of the equipment and is not subject to waveform distortion found when transmitting RF modulated waveform signals over a long distance.
- No video compression is utilized, so the video is transmitted in real time with zero latency, at the standard frame rate of 30 frames per second, and with none of the pixelization associated with MPEG-1 or other compressed video systems. This matches the quality of RF Modulation.
- Reduced component parts enhance the overall Mean Time Between Failure. RF Modulation uses two components to perform the same function as a multiplexer/demultiplexer.
- Cost estimates obtained in early 2002 showed the total cost of deployment of a digital system to be approximately 6% less compared to an analog system deployment.

- Using CWDM cards that operate on 9 separate wavelengths (one for data and eight for video) in combination with 8 Channel Multiplexers selected by the County allowed for the transmission of up to 64 video signals on a single fiber. Subsequent technological improvements have resulted in the introduction of CWDM cards that operate on 17 separate wavelengths (one for data and sixteen for video). When used in combination with 8 Channel Multiplexers, transmission of 128 video signals on a single fiber is possible.
- The digital transmission equipment is easily mountable in standard 19" equipment racks and offers takes up significantly less physical space compared to RF modulation equipment. If an analog system were to be deployed, Santa Clara County would be forced to physically expand their TOC Equipment Room. Such expansion is not necessary using digital transmission equipment.

CONTINUED EVOLUTION

Aside from the shift in communication strategies, several technologies have been introduced into the ITS marketplace since completion of the original Traffic Operations System Feasibility Study in 1996. Santa Clara County has incorporated two into the TOS program – Cable Management Software and Digital Encoding.

As a stakeholder of the Silicon Valley Intelligent Transportation System (SV-ITS) along with Valley Transportation Authority (VTA); Metropolitan Transportation Commission (MTC); Caltrans; and the cities of San Jose, Santa Clara, Milpitas, Fremont, Campbell, Cupertino; and the Town of Los Gatos, Santa Clara County has shared their fiber optic cable infrastructure with other stakeholders. Until recently, all fiber optic cable has been tracked by manually updating AutoCAD files. This technique has proven to be labor intensive and prone to errors. In its place Santa Clara County has implemented a Cable Management Software application that has significantly reduced the staff time required to track the current status of individual fiber strands. With a few mouse clicks, County transportation management staff can determine every end device connected to individual fiber cables and fiber strands. By working with off-the-shelf Geographic Information System (GIS) software, this information can be plotted on either a map or aerial photograph. In the event of a fiber break or other system outage, County staff are able to quickly identify the affected intersections and implement measures to reroute network traffic. By working closely with other SV-ITS stakeholders, most notably the City of San Jose, Santa Clara County has established common naming conventions for all fiber optic equipment and end electronics connected to the network. This allows the County to share its database with other stakeholders and improve the degree of interagency cooperation which is critical to the overall success of both the County's TOS program and region's SV-ITS program.

Santa Clara County has established a web site (www.511sccexpressways.info) for view selected CCTV camera images on the Internet. By encoding analog CCTV camera feeds from the existing Matrix Switch as Motion-JPEG images and transmitting those video streams onto the Internet using a Video/Web Server, the public is able to access these images for trip planning purposes. The initial deployment includes 48 CCTV cameras but can be increased in the future.

2005 – EMERGING TECHNOLOGIES

One of the biggest strengths of the TOS network is their fiber network. By designing a fiber optic ring that provides 12 strands of single-mode fiber optic cable to every signalized intersection in the Santa Clara County Expressway System, the County has the flexibility, capacity and geographic coverage to adopt new end electronics when and where appropriate. With little or no modifications to the network topology, Santa Clara County TOS fiber optic plant is positioned to deploy Ethernet communications and digitally encoded video at the controller cabinet if necessary.

If we were to start from scratch using today's technology, the TOS network would most likely employ Ethernet communications protocols throughout. Field-hardened Gigabit Ethernet (GigE) switches would be deployed in each traffic controller cabinet giving the County 1000 Mbps of bandwidth to support the various field devices. Instead of analog CCTV cameras with serial PTZ data, CCTV cameras and PTZ data would be encoded at in the traffic controller cabinet using field-hardened MPEG-2 or MPEG-4 encoding hardware. Alternatively, IP cameras which output MPEG-2 or MPEG-4 video streams are being introduced into the ITS market and will become a legitimate deployment option in the near future.

SUMMARY

Although technology advances in the ITS industry since 1996 have been dramatic, the original Santa Clara County TOS system design remains relevant. By prudently applying end electronics that increase the efficiency of the fiber plant and improve the overall operation of the network, Santa Clara County has positioned itself to take full advantage of their existing resources to improve traffic conditions along the expressway system.

Fiber optic cable in the ground is an investment. Over time, end electronic equipment will depreciate and be replaced by equipment that will provide increased capacity over the fiber optic cable.