Design Choices in Fiber Optic ITS Telecommunications Networks

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ABSTRACT

Designing a fiber optic communications network for Intelligent Transportation Systems (ITS) can be an overwhelming responsibility for decision-makers without previous experience in the field of communications network design. There are nonetheless basic guidelines which, if followed, can help to ensure that the proper choices are made in assessing and selecting the appropriate network design. The following paper proposes a basic framework with guidelines that serve to facilitate fiber optic communications network design for traffic engineers and end-users. The three key elements of this framework can be summarized as follows:

- Developing a set of criteria that must be addressed by the chosen fiber optic communications network design; and

- Understanding the basic network design architecture options available;

- Selecting the network architecture that best addresses the established list of criteria.

This paper addresses each of these elements in turn.

DEVELOPING A SET OF CRITERIA FOR YOUR ITS COMMUNICATIONS NETWORK

The first step towards selecting an appropriate network design involves understanding both current and future demands that will be made of the network. The requirements of a network are fundamentally driven by the ITS Services that will deployed over the infrastructure. For example, Variable Message Signs (VMS), Traffic Loop Counters, and Video Surveillance Cameras with Pan, Tilt and Zoom (PTZ) control represent possible ITS Services to be deployed in a network. Although no two ITS projects are likely to have exactly the same requirements, there is a common set of characteristics that one can identify for networks and their services that help clarify design goals. These characteristics are listed as follows:

- Quality of Service (QoS)
- Reliability and Availability
- Maintainability
- Scalability and Fiber Efficiency
- Cost
- Standards Compliance

These characteristics are not independent of one another and trade-offs are invariably made between them. For example, a higher QoS typically results in higher costs, thereby making it difficult to achieve a network with a low cost per video channel. As such, it is critical to understand which characteristics will take precedence in priority and which trade-offs are most acceptable.

Quality of Service (QoS)

ITS services such as Variable Message Signs (VMS), Traffic Loop Counters and Pan/Tilt/Zoom (PTZ) control of video surveillance cameras are accomplished through communications equipment found by the roadside. This equipment typically communicates with the Traffic Control Center through low speed, asynchronous data communications requiring data speeds of around 9600 bits per second (bps). Video surveillance equipment, on the other hand, requires a much larger “pipe” to effectively transfer video signals back to the Traffic Control Center. The size of the “pipe”, or the communications bandwidth required per video camera signal, directly affects the quality of the video signal seen back at the Control Center. The quality of these images can be critical (particularly in times of inclement weather) in emergency situations requiring specific action under visibly identifiable circumstances (e.g., instructing the dispatch of Ambulance services if deemed necessary, etc.). This need is further compounded during harsh weather conditions in which visibility is somewhat blurred. Thus, in general, the Quality of Service required will be high for video surveillance. This requires that all communications equipment between the camera and the Traffic Control Center conform to an acceptable specification (e.g., EIA/TIA 250C Medium Haul video quality specification) that will implicitly dictate the quality of the image at the Traffic Control Center. A similar analysis is required for every piece of terminal equipment in the network representing a specific ITS Service so that the Quality of Service is understood for each service.

Reliability and Availability

Reliability refers to how often a single piece of equipment fails, whereas availability refers to how often the overall network solution fails to achieve its intended use. For example, all the components of a fiber optic multiplexer may function well without breaking down (*reliability*). By designing a redundant fiber optic transmitter into the multiplexer, however, even if the primary transmitter should fail, the network continues to remain available by virtue of the redundant transmitter, thereby maximizing network *availability*.

In any given ITS project, reliability and availability are fundamental requirements since equipment that is problematic can endanger the public’s safety. The availability of roadside emergency telephone service, for example, needs to equal that of emergency 9-1-1 telephone service. Similarly, a network that is out of operation frequently does not allow personnel back at the Traffic Control Center to dispatch ambulance services in a timely fashion in the event of serious accident. A praiseworthy communications network design is ensured by (a) selecting equipment that has a proven track record of reliability in harsh environments; (b) selecting equipment for which the calculated Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) meet or exceed that required by network administrators; and (c) designing availability into the network. The latter can be accomplished, for example, by having redundant communication links back to the Traffic Control Center in the event of a primary link failure.

Maintainability

An ITS network, by its very nature, is a Wide Area Network (WAN) that typically covers a large area. Due to its expansive nature coupled with the need to repair problems very quickly, ease of maintenance is essential. The most common solution to this problem is computer-based Network Management Systems (NMS) that can remotely monitor and configure the communications network equipment from the Traffic Control Center. The effectiveness of an NMS will depend on how far into the network the NMS capabilities extend. Ideally, the NMS should extend its reach right out to the "edge" of the network. Beyond network management, however, it is important to keep the complexity of the design and the amount of equipment required to a minimum, thereby minimizing the effects of equipment failures on the network.

Scalability

Relative to other industries, ITS today remains in its infancy, though momentum in deploying services is increasing at a significant rate. As such, a competent ITS communications network design will take into account the need for future growth, or "scalability", as the number of ITS Services deployed over the available communications infrastructure will undoubtedly increase over time. Scalability in a communications network design manifests itself in two ways. Firstly, the design should incorporate modular communications equipment that can have communications bandwidth added as the need arises. Secondly, regardless of the number of fibers available to the designer, the design should attempt to minimize the use of fibers. This is because dark fibers (i.e., fibers not used but available) can be used in future expansions for purposes not yet apparent.

Cost

Cost-effectiveness is a primary consideration of most end-users. As such, it is critical to strike up a balance between the other criteria and cost, so as not to compromise the network design while keeping it affordable. Many network designs largely overlook other criteria in the interest of finding the lowest-cost solution. This results in networks that are often unreliable and very difficult to scale to accommodate future growth. Equally important is the need to consider the life-cycle costs of maintaining a network. These costs are directly related to two implementation issues. The first is the quality of the installed equipment. Problematic equipment requires expensive maintenance work. Often the equipment must be replaced, reversing any cost savings realized in the initial purchase. The second issue that affects maintenance costs is the inclusion of a Network Management System in the initial installation. Network Management Systems must have the capacity to remotely monitor and configure the deployed communications equipment. This is particularly important in view of the fact that the annual cost of maintaining an *unmanaged* network will range from 10% to 15% of the deployment cost of the network.

Standards Compliance

Transportation agencies hope that the systems they deploy will be capable of exchanging information with networks deployed by others. As such, adherence to industry-recognized standards is necessary. The NTCIP, or National Transportation Communications for ITS Protocol, is being developed to ensure that inter-network connectivity is through industry standard interfaces, even if proprietary communications are used within an ITS network.

In addition to NTCIP, it is important for all equipment to meet prevalent standards for safety and EMI interference (FCC, etc). This will ensure that the equipment is safe for use by network administrators and is unlikely to cause failures in other equipment installed alongside it.

NETWORK DESIGN OPTIONS

The second component of the network architecture assessment framework involves understanding the technological choices available in implementing a fiber optic network. For illustrative purposes, we will consider different network design options for implementing a network consisting of the following elements:

- 100 video cameras with PTZ (20 cameras feeding into each of 5 remote multiplexers);
- 200 traffic loop counters (data);
- 50 ramp meters (data);
- 25 emergency telephone lines (voice);
- 50 Variable Message Signs (VMS) (data);
- 5 Highway Advisory Radio (HAR) channels (voice);

Five generic network design options will be considered. These are as follows:

1. Separate Video and Voice/Data Networks
    - CCTV and T1
    - CCTV and SONET
2. Integrated Networks for Video, Voice and Data transmission (over a unified path)
    - CCTV and T1
    - Digital Video over SONET
    - Hybrid CCTV/SONET

Separate Video and Data/Voice Networks

A conventional approach to ITS network design is to deploy video on a separate network from that used to transport voice and data. Older networks simply used point-to-point video transmission equipment to carry one channel of video all the way back to the Traffic Control Center on one fiber. This was extremely wasteful of the tremendous bandwidth available on fiber and was very difficult to scale. As such, point-to-point video multiplexing equipment that combines several signals onto one fiber is used. Data and voice communication is typically through point-to-point T1 channel banks (and/or T1 carried on fault-tolerant SONET [Synchronous Optical NETworks] or SONET-like rings).

Separate CCTV and T1 Network Solutions

A traditional point-to-point CCTV and T1 approach using multiplexers to concentrate video and data signals is illustrated in Figure 1. The T1 channel banks are equipped with low speed data and voice interfaces, and integrate all such low-speed signals into a standard, electrical T1 signal at 1.544 Mbps. The CCTV video communications equipment is distinct from the digital T1 equipment and generally uses a network of proprietary analogue Frequency Division Multiplexing (FDM) technology over fiber optic cable due to the high bandwidth and transmission distance requirements. Transmission redundancy is usually built into the video communications equipment. T1 channel banks for data and voice are usually not equipped for transmission redundancy and will generally require external T1 Automatic Protection Switch (APS) equipment. CCTV video multiplexers traditionally provide the best video quality (broadcast quality) for the lowest price.

The multiplexed video signal that arrives at the Traffic Control Center feeds into a demultiplexer to recover the composite signal. The resulting individual video signals are fed into a video matrix switch for distribution to the appropriate video monitors. As the network grows, the video switch becomes a bottleneck since the number of video sources may eventually exceed the capacity of the switch. For network expansion, more physical fibers are required between the remote video multiplexers and the Traffic Control Center. This can be unbearably expensive in situations where additional fiber plant must be put into the ground. Network expansion costs can be significantly eased if the video concentration multiplexers are modular and can have a high number of video channels integrated as required.

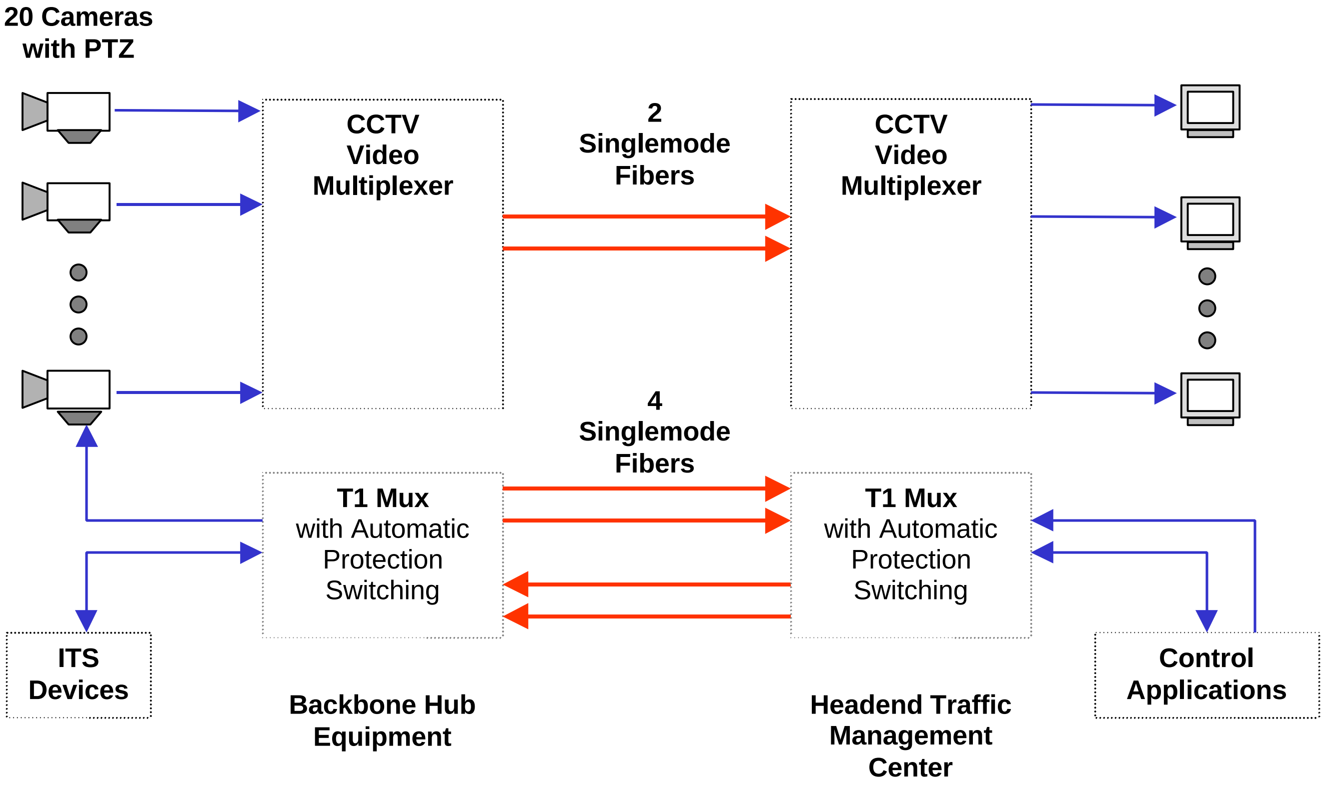

Figure 1. One fifth of the required equipment for the Separate CCTV and T1 Networks. This configuration would be replicated five times to give the required network for 100 cameras. As such, the total number of backbone fibers using this design will be 5 x 6 = 30 fibers.

CCTV and SONET

A second separate network configuration involves the same point-to-point CCTV approach with fault-tolerant transport for voice/data over T1 via a SONET backbone network, as illustrated in Figure 2. SONET equipment is based on standards that have emerged from the telecommunications world. Multi-vendor interoperability is ensured in particular when the equipment adheres to SONET Interoperability Forum (SIF) standards, which are endorsed by most major telecommunications equipment suppliers[1]. Low-speed communication devices feed into T1 channel banks and get integrated into T1 signals before being fed into the SONET equipment.

A CCTV and SONET network reduces the requirement for optical fibers in the backbone network from 30 for the CCTV and T1 network to 14 while maintaining broadcast quality video and fault-tolerant, redundant network paths. The remaining SONET capacity can be used to add more T1 channels over time as the need arises. Furthermore, if another field node should be required in the future, it can be easily inserted into the existing physical SONET data ring without requiring additional cabling to the Traffic Control Center as would be the case in a T1 data/voice network.

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[1] The SONET Interoperability Forum (SIF) is an open industry forum committed to accelerating the deployment of SONET technologies and is sponsored by the Alliance of Telecommunications Industry Solutions (ATIS). Members include Nortel, Positron, Lucent, Alcatel, Tellabs, Fujitsu, Bellcore, and DSC Communications.

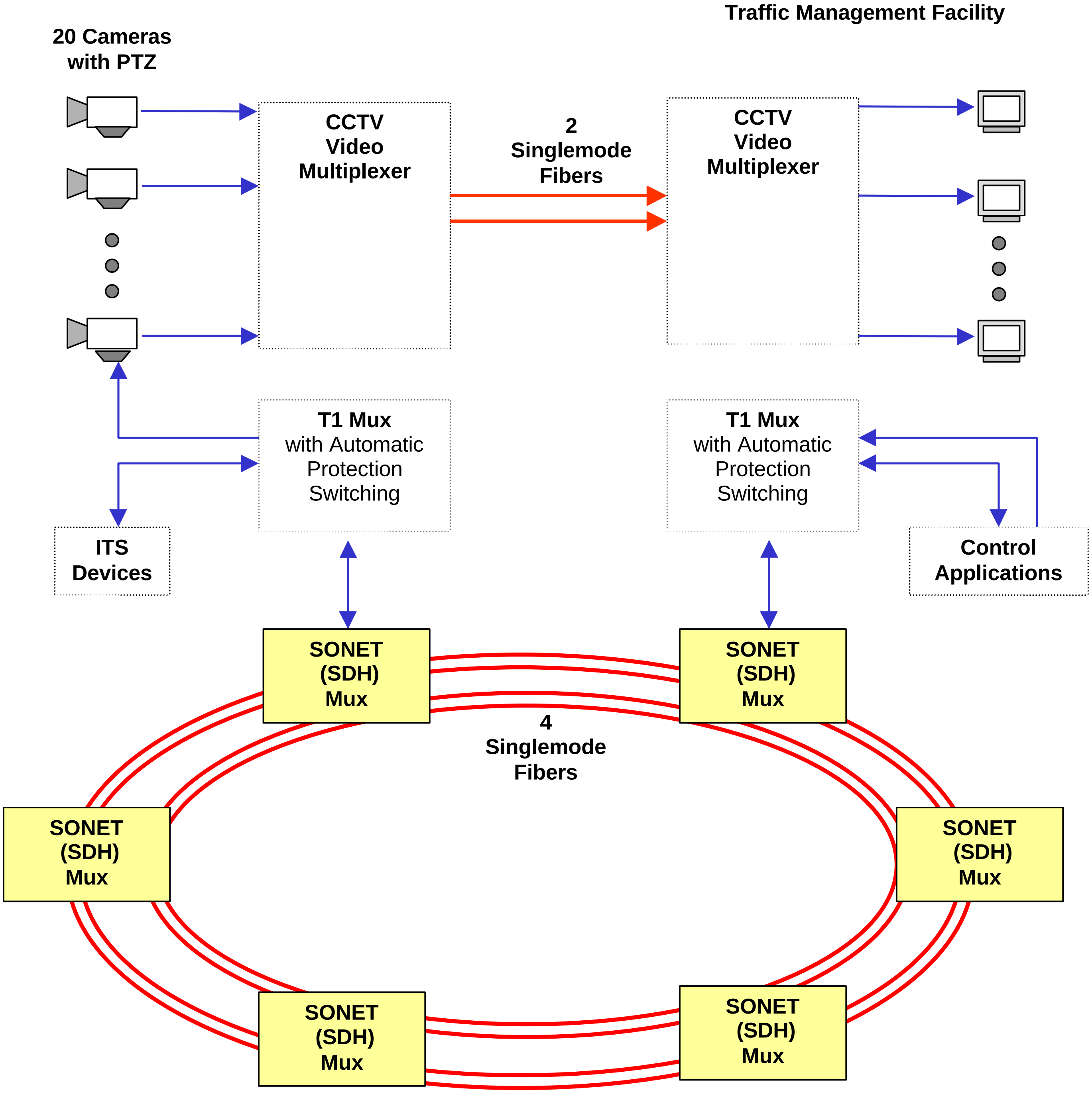

Figure 2. One fifth of the required equipment for the Separate CCTV network and entire SONET network is shown above. The video communications network would be replicated five times to give the network required for 100 cameras. As such, the total number of backbone fibers using this design will be (5 x 2 fibers per CCTV node) + (4 fibers for SONET ring) = 14 fibers.

Integrated Network Solutions

Integrated network solutions for video, voice and data are attractive due to the efficient use of available optical fibers in the backbone segment of the network. This is particularly advantageous where the number of fibers installed in the ground is limited. In general, although using one path for video, voice and data is ideal, it is important to keep in mind the effects on cost and Quality of Service for each specific configuration.

CCTV with T1 Transport

A similar network topology to the separate video and data network already discussed is one in which the CCTV video signals are combined with an embedded high speed digital link for voice and data as shown in Figure 3. The key difference in this case is that the fiber optic transmission link previously used for video only is now used for the integrated transmission of video, voice and data. This requires that the communications equipment be capable of bi-directional data transmission for the T1 voice and data signal. Transmission redundancy for fault-tolerance should also be built into the video multiplexing equipment, hence eliminating the previous need for Automatic Protection Switching equipment. Although this network topology is very similar to the separate video and data network, it has the advantage of requiring only 20 optical fibers in contrast to the 30 for the separate CCTV and T1 networks.

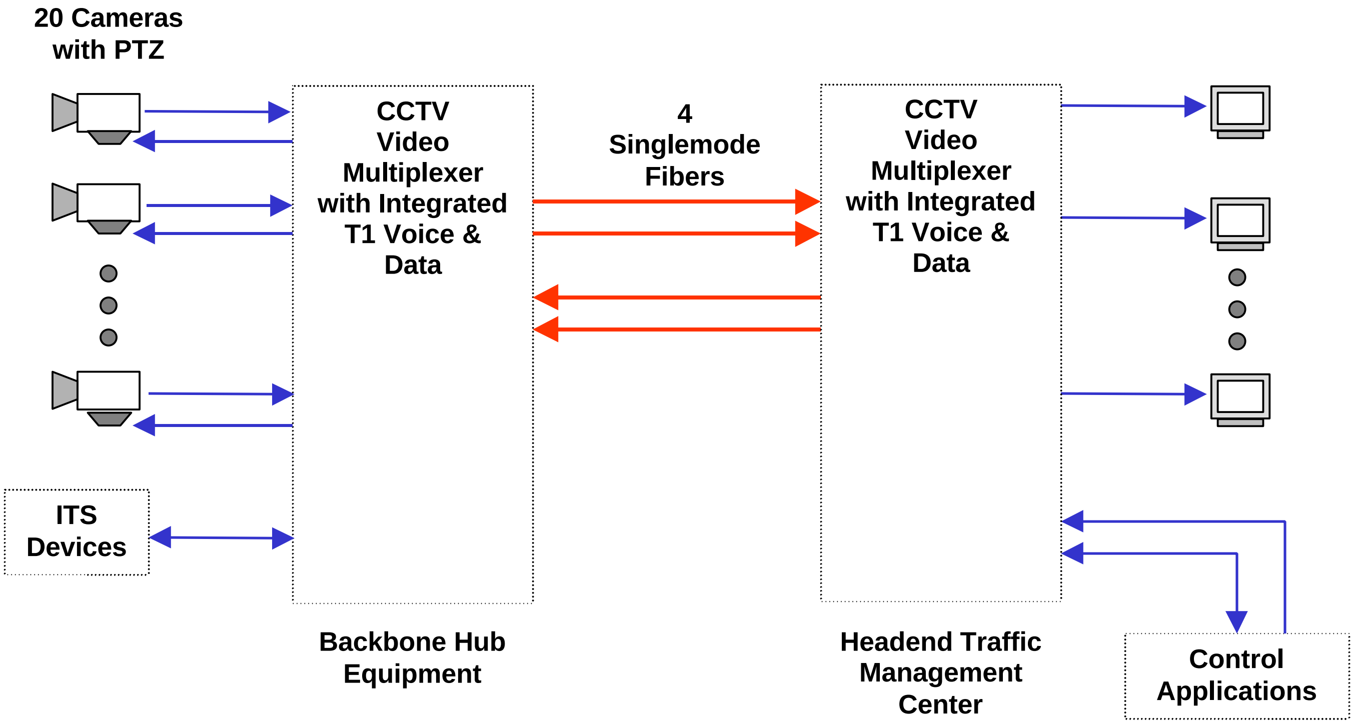

Figure 3. One fifth of the required equipment for the Integrated CCTV and T1 Transport. This configuration would be replicated five times to give the required network for 100 cameras. As such, the total number of backbone fibers using this design will be 5 x 4 = 20 fibers.

Digital Video over SONET

A completely digital solution is ultimately desirable due to the fact that the same “pipe” serves all three information formats (video, voice and data) interchangeably. Digital transport of all information on the network facilitates interoperability with the deployed networks of other agencies. Additionally, the Public Switched Telephone Network (PSTN) can be used to relay information digitally between Traffic Control Centers or to disseminate video images to the public over the Internet (for example).

Public telecommunications networks have been designed around the need to transport voice. The saying that “a picture is worth a thousand words” is true in electronics. Voice is digitized for uncompressed 64 Kbps transmission over telephone lines. In contrast, uncompressed digital video requires about 135 Mbps in bandwidth. Video requirements therefore tend to monopolize the communications bandwidth in an all-digital network. As such, digital video signals are usually compressed before they are transmitted. Video compression techniques, however, are all “lossy” (i.e., don’t capture all the information), which results in degradation of the video signal. In fact, to achieve broadcast quality video at the Traffic Control Center would require a very expensive network solution that allocates excessive bandwidth to the video signals. The most common video compression schemes are summarized in Table 1 below along with their quality at given data rates.

Table 1. Video Compression Comparison

Compression	Data Rate	Data Rate Required for VHS movie quality
MPEG-2	1.5 to 100 Mbps	3 Mbps
MPEG-1	0.4 to 1.5 Mbps	1.15 Mbps
M-JPEG	1 to 25 Mbps	10 Mbps
H.261	64 to 1920 Kbps	Barely possible

SONET is the key network backbone technology being deployed today for ITS data networks. This is for good reason, as it inherently provides excellent scalability, network management facilities and fault-tolerance. High-quality digital video transmission over SONET as yet still comes at a premium cost, however, as a result of the huge bandwidth consumed by digital video and the increased cost of using video encoders and decoders (or codecs[2]). For lower quality full-motion video, a minimum T1 data rate (i.e., 1.544 Mbps) per video channel using H.261 codecs has been the most cost-effective solution to date. To backhaul 100 video channels using H.261 (with very little capacity left over for voice or data) would require a bandwidth of approximately

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[2] An encoder takes an analog video signal, digitizes it, and compresses it using the compression algorithm built into it. A decoder does the inverse.

155 Mbps, or a SONET OC-3 network. Adding voice and/or data to the network would push the bandwidth requirements to the next level of the SONET hierarchy, or OC-12 (at 622.08 Mbps). For Super VHS quality video, MPEG-2 at 6 Mbps per video channel is required. This is equivalent to dedicating four T1 channels per video signal. Hence for 100 video channels, a minimum capacity of 400 T1's or 618 Mbps is required. This corresponds to a SONET OC-12 data rate. Adding any significant amount of voice and/or data requirements would push the bandwidth requirements to the next level of the SONET hierarchy, or OC-48 (with a 2488.32 Mbps capacity). As both OC-12 and OC-48 networks are relatively expensive to implement, OC-3 networks are usually implemented and a compromise on video quality is accepted.

A SONET network as illustrated in Figure 4 provides the most efficient use of existing fiber. Given SONET's extraordinary capacity, network growth can typically be accomplished on existing optical fibers with the odd exception being for very large networks. Higher speed SONET equipment (e.g., OC-48) that is interoperable with the existing equipment can be deployed at a later stage should the current equipment capacity ever be exceeded (provided the vendor's equipment allows such an upgrade).

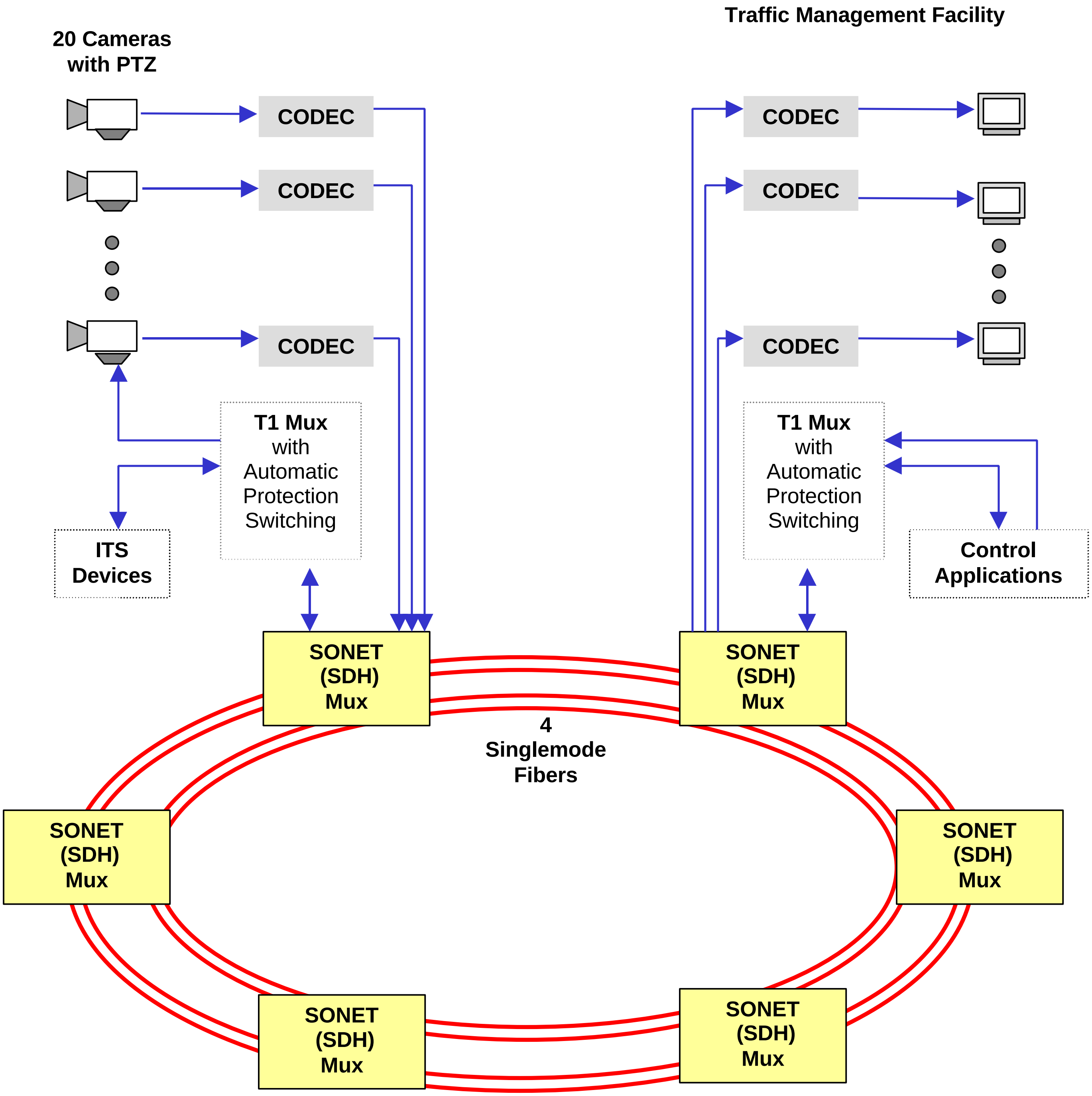


Figure 4. One fifth of the required CODEC and T1 equipment required for the network implementing digital video over SONET. Note that the only fibers required are in the backbone segment assuming that the cameras and CODECS are within reasonable distance of the SONET multiplexers. Therefore the total number of fibers required is 4.

The Hybrid CCTV/SONET Network

An integrated network design alternative which draws on the strengths of each of the previously discussed architectures is represented by the hybrid solution of Figure 5. It employs each of the following elements:

- A SONET data/voice backbone for high fault-tolerance, efficient optical fiber usage, interoperability with other SIF-compliant SONET-based deployments, and graceful migration to digital video as video compression technology becomes more cost-effective. The SONET equipment is used primarily for voice and data services.

- CCTV video communications equipment for high quality, full-motion, low-cost video.

- Optical integration of the CCTV Video and SONET signals through Wavelength Division Multiplexing (WDM) technology; this state-of-the-art technology allows the integration of two distinct optical signals (operating at different wavelengths) for transport over a single optical fiber.

The hybrid network offers the flexibility of having both low-cost, broadcast quality video circuits and digitized video over SONET when required (note that Figure 5 assumes no digital video in order to achieve the lowest cost solution). This solution prevents the SONET network from becoming rapidly congested (which might otherwise happen owing to the large bandwidth requirements of digital video). The SONET network can now be optimally used for ITS and other municipal data and voice requirements.

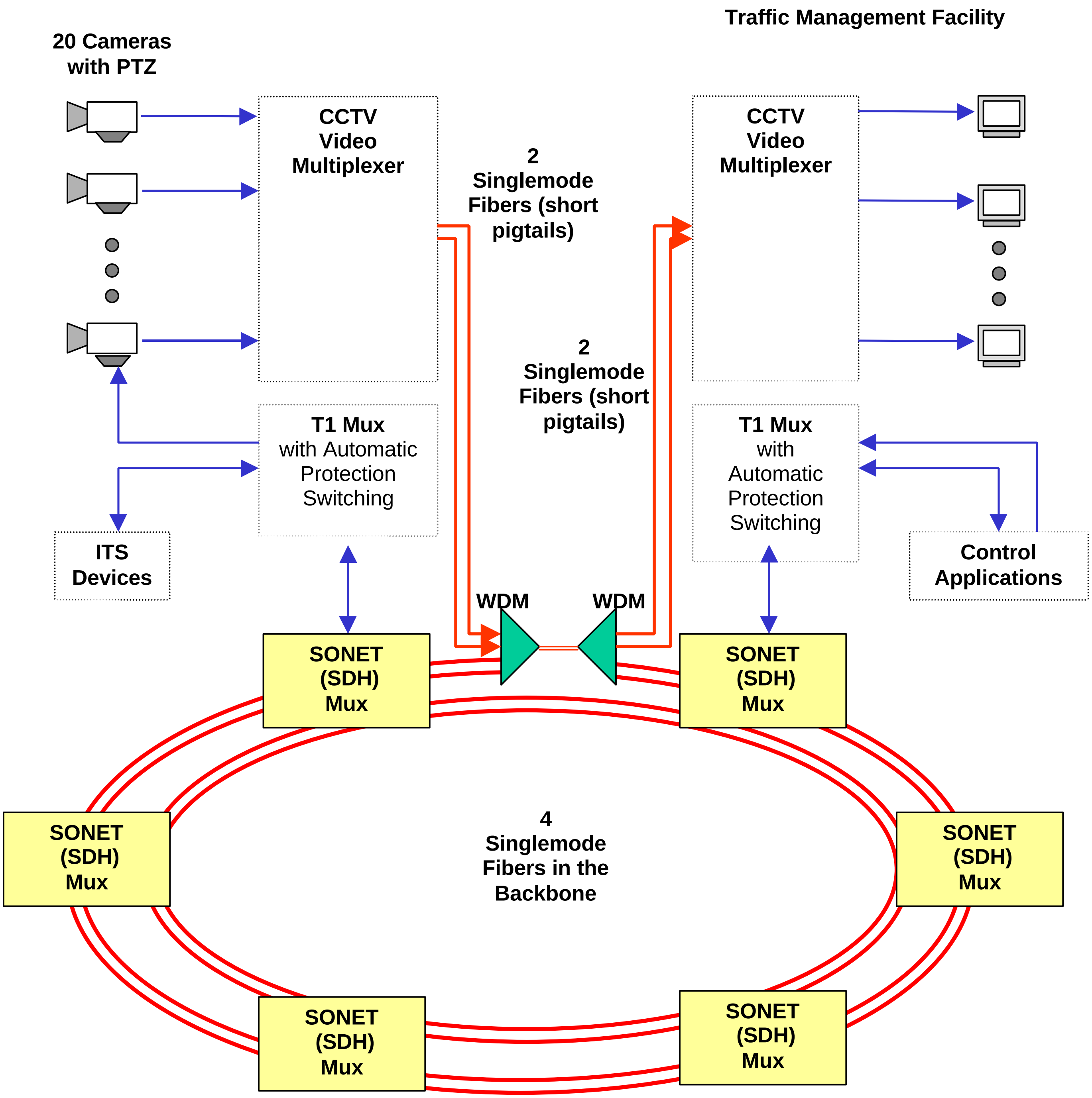


Figure 5. A partial representation of the Hybrid Network architecture (the CCTV and T1 multiplexing equipment would have to be replicated at each SONET node to give the network required for 100 cameras). Since the CCTV multiplexing equipment is optically integrated with the SONET signal, the total number of backbone fibers required equals the SONET ring backbone = 4 fibers.

NETWORK DESIGN COMPARISONS

The five categories of networks discussed are contrasted in Table 2 on the following pages using the previously determined list of criteria. Additionally, the estimated costs of deploying the networks are contrasted in Figures 6 through 8. These charts illustrate each of the following:

- Total cost of the equipment for each network design (Figure 6);
- Breakdown of costs attributed to different ITS Services in the network (Figure 7);
- Efficiency of optical fiber usage (Figure 8).

It is important to note that the costing was done using confidential vendor price lists made available to the authors. As such, the cost comparisons represent rough approximations. Nonetheless, they serve as an indication of the relative costs involved in deploying the competing technological alternatives being discussed.

Other notes of interest with regards to the pricing comparisons:

- The network designs are numbered from 1 to 7. Note that Networks 5 and 6 have not been previously discussed and included remotely switched camera signals for the purposes of reducing the bandwidth required in the backbone segment of the network. These network designs require additional video switches, all of which have been factored into the costs shown.

- The equipment costs for low speed data and voice are those of the T1 channel banks only. The video costs are those for either the CCTV equipment or the digital video encoders, decoders, switches, inverse multiplexers and the SONET equipment. The SONET equipment is factored under the cost of video for simplicity since the video dominates the SONET bandwidth at a ratio 20:1 in some cases.

- The fiber usage factor is based on the number of remote node sites (five in each case with 20 cameras at each site) divided by the number of *backbone* fibers.

- The cost of laying fiber plant is not considered in these cost comparisons, as it is assumed that the required fiber plant is already available.

Analysis of Cost Comparisons

As expected, Figure 7 clearly shows that video services are the key driver of cost in every network design, with the allocation ranging from 50% to 90% of the overall deployment cost. Hence particular attention must be paid to the design of the video communications portion of a network if cost is a paramount concern.

Figure 6 illustrates the relative costs of the network designs. The following observations are of note:

- Networks 1 and 2 provide full-motion, high quality video and have the lowest cost per video channel. Network 2, however, additionally provides more efficient fiber usage (as shown in Figure 8) and the fault-tolerance of SONET equipment at a relatively low incremental cost.

- Network 3 offers a slight increase in the cost of the video transmission largely because the video communications equipment is providing bi-directional, redundant T1 transmission (requiring 4 optical fibers). While there is a slight increase in the cost of equipment for Network 3 over Networks 1 and 2, the efficiency of fiber use increases dramatically.

- Network 4 costs about three times more than Network 3 with a decrease in video quality. This can be attributed to the expense of video encoders in the field and video decoders at the Traffic Control Center. The 100 video signals back hauled to the Traffic Control Center require OC-12 SONET equipment (versus far less expensive OC-3). This cost can be significantly reduced (by about 40 %) by providing 20:10 remote switching capability. Network 5 is the result of integrating such remote switching into the design. This Network 5 design reduces the number of video codecs required in addition to minimizing the SONET capacity requirements to OC-3.

- Network 6 has the highest per channel video cost and total network cost of all designs considered. This is due to using MPEG-2 codecs and inverse T1 multiplexers in addition to the OC-12 SONET equipment. This cost also includes a 20:10 remote video switch, without which OC-48 SONET equipment would have been required (increasing costs by at least a factor of three). In spite of the high costs, the video quality is akin to Super VHS (as opposed to full-motion broadcast quality video). The difference between Super VHS and broadcast quality becomes particularly noticeable when the video signals are forced to travel through expansive video distribution networks. Nonetheless, digital video offers the potential for the transportation agency to disseminate the video signals more readily through the digital Public Switched Telephone Network (PSTN).

- The hybrid solution as represented by Network 7 is significantly less expensive than the proposed digital video solutions and appears to strike a balance between cost and features. Network 7 is only marginally more expensive than the lower-end solutions but offers

SONET backbone, fiber usage efficiency, and the ability to gracefully migrate towards digital video solutions as they become less expensive over time.

TABLE 2: NETWORK DESIGN COMPARISON MATRIX

	Quality of Service (Video)	Reliability	Maintainability	Scalability	Fiber Efficiency (No. Required)	Cost	Standards Compliant
SEPARATE NETWORKS							
CCTV and T1	Highest Quality	Redundant Links for Video and redundant links for Voice/Data Networks	Network Management Systems are available on all of the solutions and should always be deployed to minimize ongoing maintenance costs.	Can be scaled provided that the video comms equipment is modular.	30	See Accompanying Charts on Cost Comparisons.	Al Network Designs are fully NTCIP-compliant with standard UL and FCC approvals.
CCTV and SONET	Highest Quality	Redundant Links for Video and SONET networks		Can be scaled upwards provided that systems are modular; SONET	14		
INTEGRATED NETWORKS							
CCTV and T1	Highest Quality	Redundant Links for integrated Video, Voice and Data Network		Can be scaled provided that the integrated comms systems are	20		
Digital Video over SONET	Passable; depends on established criteria	Redundant Links inherent to SONET		SONET highly scalable	4		
Hybrid CCTV/SONET	Selectable; Hybrid of Highest Quality and Digital Video Quality	Redundant Links for integrated Video and SONET		Can be scaled upwards provided that video comms equipment is modular; SONET	4		

Figure 6: Network Cost Comparisons

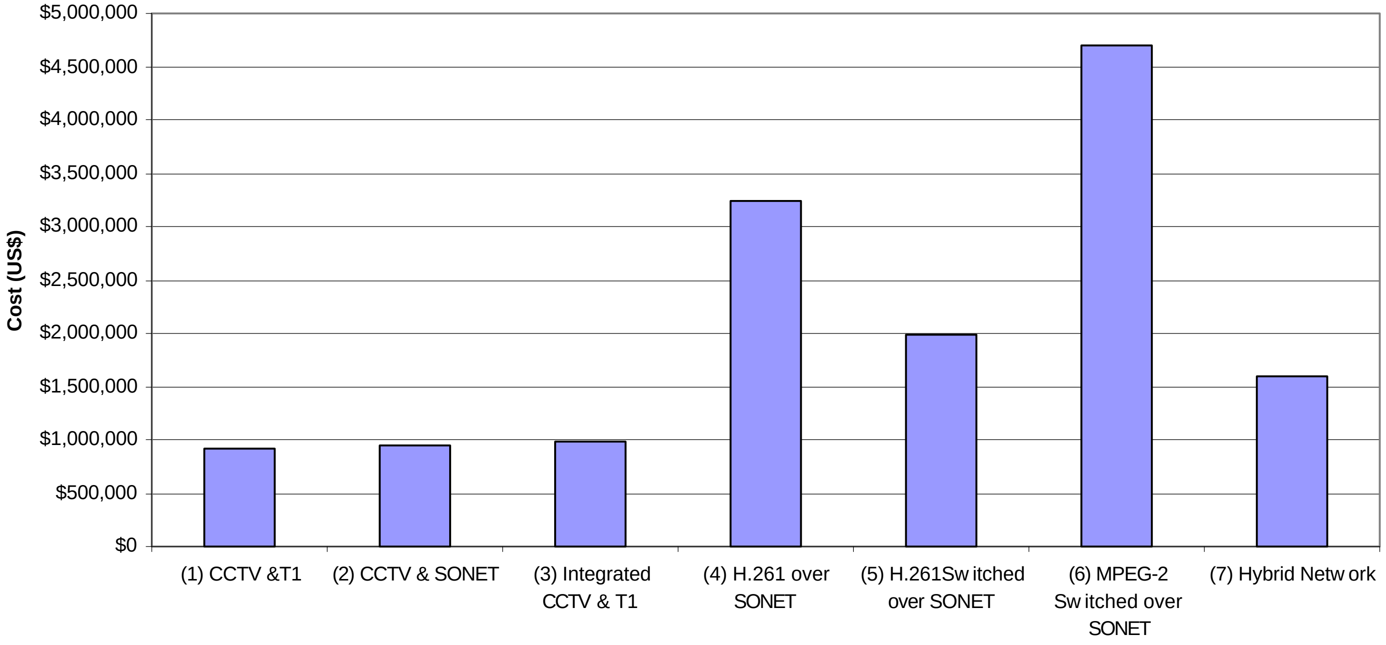
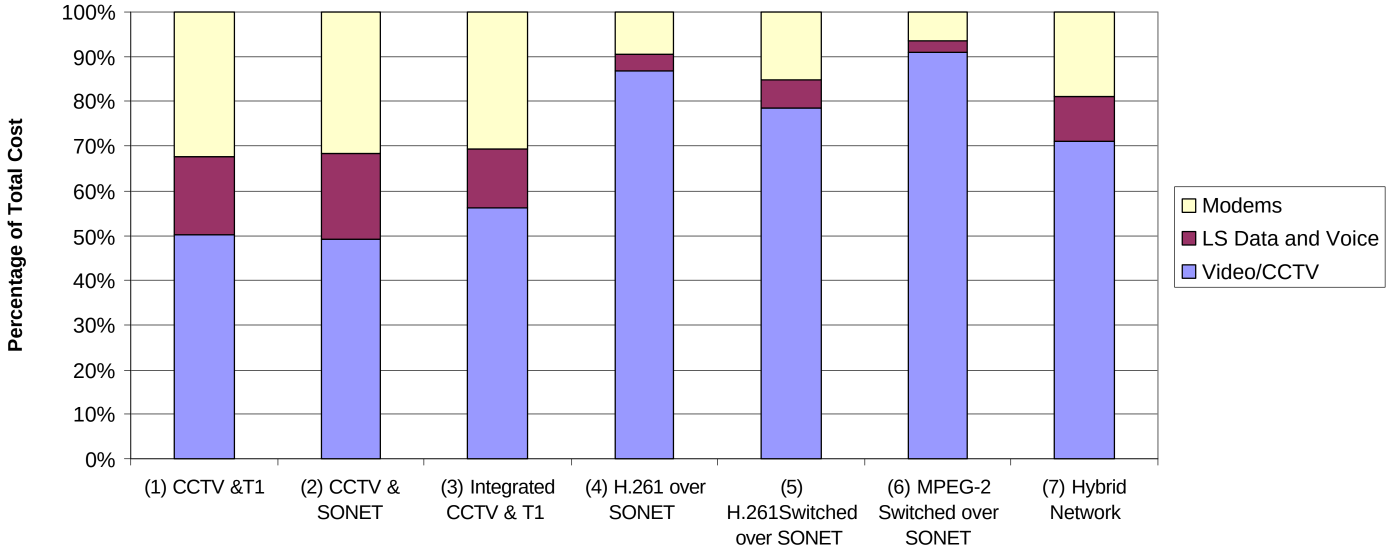


Figure 7: Network Services Cost Ratio



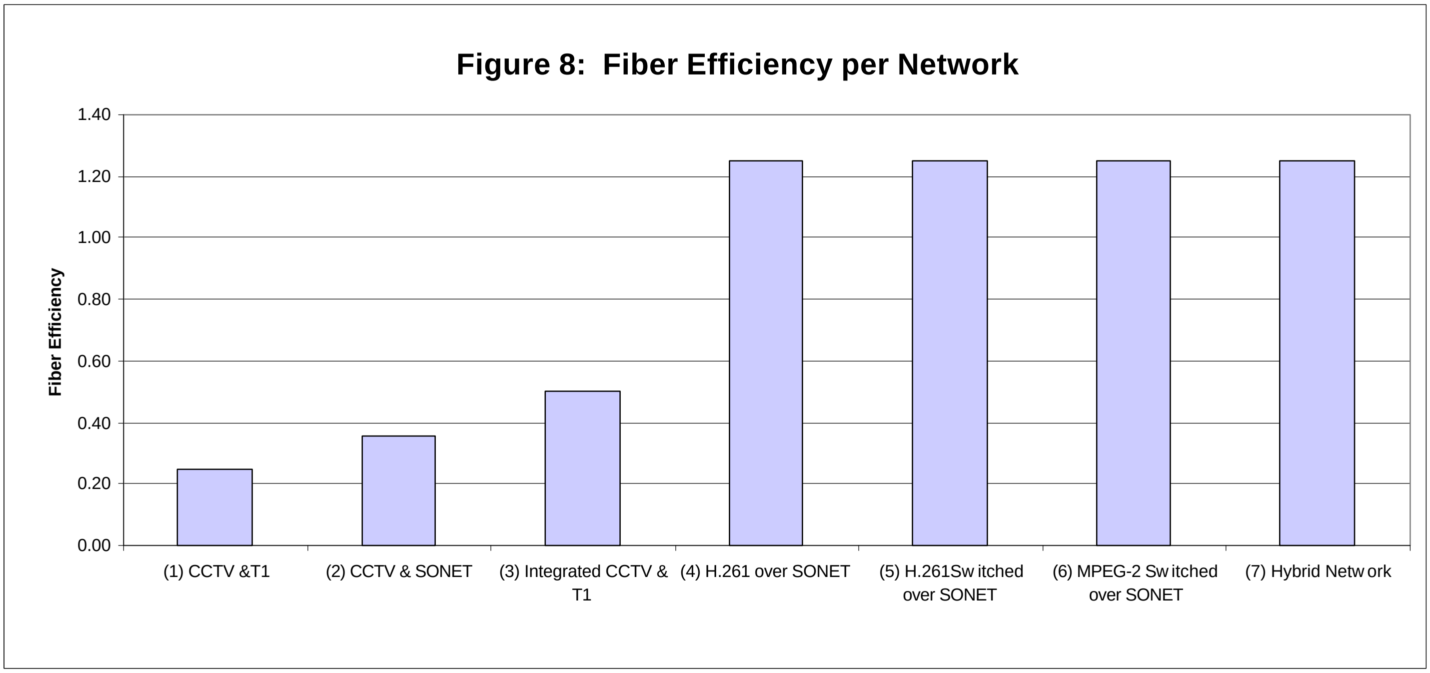


Figure 8: Fiber Efficiency per Network
Fiber Efficiency
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
(1) CCTV &T1
(2) CCTV & SONET
(3) Integrated CCTV & T1
(4) H.261 over SONET
(5) H.261Sw itched over SONET
(6) MPEG-2 Sw itched over SONET
(7) Hybrid Netw ork

CONCLUSION

Every fiber optic ITS communications network will have its own unique set of requirements. As such, the specific criteria to be addressed by the network design must be well understood before determining the most appropriate network design.

The five network design architectures discussed each offer their own respective strengths and weaknesses, with the hybrid network approach (CCTV video multiplexers wavelength division multiplexed with SONET equipment) ostensibly representing the highest value-added solution. The final design choice made by network design consultants and transportation agencies should be based on the network design option that best addresses the criteria established for the particular project in question. Following the network design assessment framework outlined in this paper will assist in achieving this goal.