An Analysis of Interoperability and Cost Factors for Regional Digital Backbone Networks

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ABSTRACT

In major metropolitan areas the need exists to consolidate headends and to provide a wide variety of video, data and telephony services across the CATV network. Digital Backbone Networks which connect a number of primary transport hubs together are the primary means of establishing these metropolitan networks. Other means are broadband linear (AM) supertrunks.

Questions arise as to the degree of interoperability of these networks with the standard telephony network; the need to transport BTSC compatible video, baseband and RF scrambled video, satellite delivered MPEG-2; management of local commercial insertion, preservation of revenue generating data within the video vertical blanking interval, the need to carry telephony and data traffic, and the amount of ancillary processing equipment required at each primary hub.

This paper analyzes the need for SONET compatibility in the metropolitan network, and provides an economic and technical analysis of signal quality at the subscriber, processing equipment at the various primary headends and effects on the design and cost of the AM hybrid fiber/coax networks which are fed by the digital backbone network, based upon the technologies used.

A network design is presented which allows cost effective implementation of digital video and telephony services today, plus a graceful migration path which provides a means of network expansion for accommodating higher levels of telephony and data traffic for the future.

METROPOLITAN AREA NETWORK ATTRIBUTES

A typical metropolitan area network consists of one or two master headends (also called television operating centers, TVOC's) which are connected with primary hubs (also called remote headends). The area covered by the network may be that of a large city, or a wide region. The largest known system of this type currently is installed by Continental Cable, and covers their properties in the three states consisting of Massachusetts, New Hampshire and Maine. Whether metropolitan or regional in its area of coverage, the term metropolitan area network is used to reference these networks in this paper.

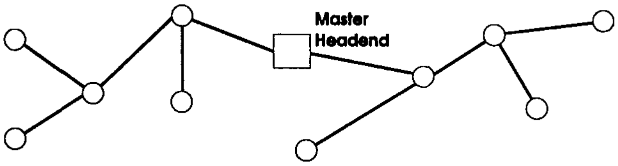

Figure 1 Metropolitan Area Network

Signals between the hubs and subscribers are not usually considered part of the metropolitan area network, but rather the distribution network. In some large CATV networks, secondary hubs are also employed. However, secondary hubs are usually considered as part of the distribution network versus the metropolitan area backbone network.

Metropolitan area networks can be designed in bus, ring and star topologies. However, some topologies are less conducive for providing high reliability and delivery of advanced services than others. This will be addressed later in this paper.

METROPOLITAN AREA NETWORK VS. PUBLIC SWITCHED NETWORK

The characteristics which define the metropolitan area network differ significantly from the characteristics of the public switched network. In the metropolitan network:

1. There is only one carrier (or a very small number of carriers) who owns and manages the network;

2. Communications in the network is highly asymmetrical;

3. For most traffic within the network, there are highly defined points of origin. Even in the case of video on demand (VOD) services, the number of origination points is small compared to the number of subscribers. Most communications enters the network via gateways (e.g. satellite receiver, digital server, etc.). Symmetrical traffic tends to leave the network via gateways;

4. Traffic types within the network are highly predictable in terms of types and numbers of each type of channel. For example, if a channel is being used to transport a service such as CNN at 5:35 PM, it is highly unlikely that this same channel will be transporting a combination of voice and data services at 5:36 PM.

SONET IN THE METROPOLITAN AREA NETWORK

To understand if SONET provides a value within the metropolitan network it is helpful to review the intended benefits of SONET, and very importantly, to whom those direct benefits are intended. SONET was designed for the ubiquitous network in which the number of channels, their size and content are not predictable. SONET is very valuable in this environment. In theory, it allows information to be transported from one carrier to another across multiple carrier boundaries without regard to content, and via universal interfaces. Note that SONET provides no direct benefits to end users. The direct benefits of SONET are to communications carriers operating in a multi-carrier environment. As exemplified above, this is not the environment of the metropolitan network.

SONET does not come without cost. For a metropolitan area network with a typical mix of cable entertainment channels, near video on demand, video on demand channels and telephony, a SONET digital backbone will cost two to three times that of an uncompressed high speed digital fiber backbone which is not fully SONET compatible. For the average metropolitan network, this amounts to millions of dollars.

One can argue that the benefits to SONET include indirect savings. But these suggested savings if any, are not comparable to the cost penalties imposed today by SONET. The video distribution network is not an unpredictable, multiple carrier environment, even when there are multiple service offerings. In the competitive world of video distribution, each dollar of capital equipment cost trickles down into the cost of providing the subscriber with specific services. This is the same reason that hybrid fiber/coax systems as opposed to traditional telephony architectures, are being designed and implemented for so many enhanced services networks.

The cost penalties of SONET for the metropolitan area network arise in four basic areas:

1. Additional cost of ancillary video signal processing equipment required at primary hubs due to the inability of compressed video codecs to support the video signal format requirements of the network;

2. Opportunity cost in terms of lost revenue, due to the inability to carry certain types of information which are additional sources of revenue to the operator;

3. Additional cost to the broadband linear

hybrid fiber/coax network for signal transport from the digital hubs to the serving areas, in order to achieve the targeted performance level at the subscriber drop;

4. Cost per Gb/s for the transport system itself including space and power requirements.

1. Additional Ancillary Equipment

The need for additional ancillary equipment arises out of the inability of the SONET based transport system to accommodate video signals in a format which is necessary or optimal for signal quality. One such straightforward example is an RF scrambled video channel. If a codec which employs compression is used to transport video, it cannot accommodate such a scrambled signal. Therefore, each signal to be scrambled must be sent from the master headend to the hubs in baseband format. At each hub site a separate signal scrambler is required for each channel to be scrambled. The greater the number of hubs in the network, the larger the cost penalty is for duplicate scramblers at each location. Additionally, since many channels like HBO employ three audio channels (left, right, and second language), the cost of the codec itself may be more expensive. In fact some codecs only support two channels of audio per video. Therefore, an auxiliary audio transport system may be required to accommodate the additional audio requirements of these channels.

A more subtle example but with wider ranging effects is the handling of BTSC subcarrier audio. North American video transmission standards allow for audio to be transmitted as a subcarrier to video at 4.5 MHz. Therefore, if the audio is BTSC encoded, stereo audio and SAP audio can be accommodated within the 4.5 MHz subcarrier. This can be encoded along with video as a composite signal by a majority of compression based codecs. However, this creates two significant disadvantages with regards to signal quality:

The first disadvantage is within the codec itself, and is very straightforward. Any digital encoder has a finite dynamic range. For optimum video signal to noise (SNR) performance, the video signal amplitude must be adjusted such that at maximum amplitude, it occupies the entire encoding range. If the audio subcarrier is included with the video, part of the encoding resolution must be used for the audio subcarrier.

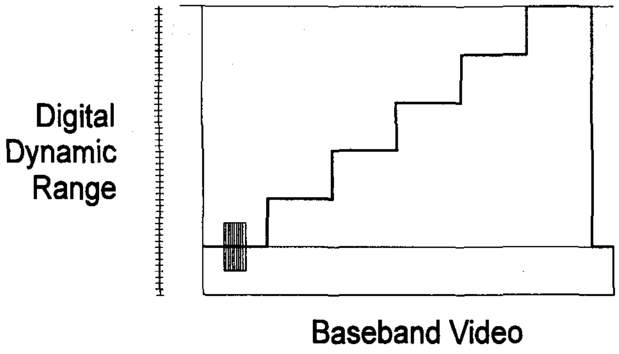

Figure 2 Baseband Video Encoding

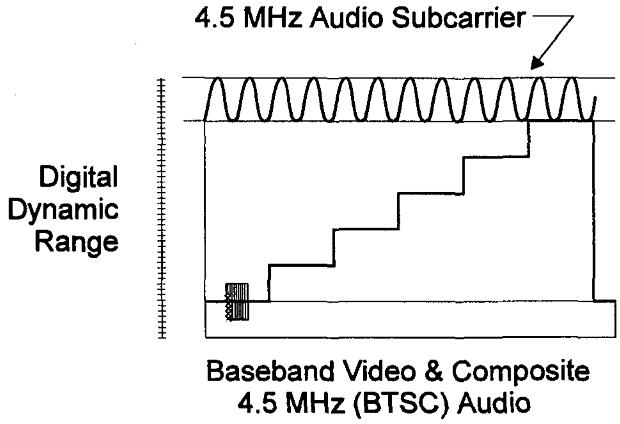

Figure 3 Composite Video Encoding
Note lower dynamic range available for video signal

Since part of the codec's dynamic range has been taken by the audio subcarrier, the absolute video SNR is less for a composite encoded signal than it will be if the audio subcarrier is encoded separately of video. A 2 dB SNR penalty is possible. This is not inconsequential. The video performance at the subscriber drop is proportional to the SNR contribution of the metropolitan network as well as the hybrid fiber/coax distribution system. This is explained in the next section of this paper. An additional problem is that encoding the two signals together produces a classic 920 KHz beat due to interaction between the 3.58 MHz color subcarrier and the 4.5 MHz audio subcarrier. This phenomenon is well known to video engineers and therefore needs no further explanation.

The second disadvantage of composite video encoding has nothing to do with the digital transport system itself, but rather with the VSB/AM modulator which follows. If a composite signal is fed to a VSB/AM modulator, it must first separate the signal into the discrete baseband video and the separate audio subcarrier so that AM modulation and sideband filtering can be performed on the video only. The highest video frequency is 4.2 MHz. If the filter required to perform this separation has too sharp a cutoff, then its group delay performance will be poor and characteristics such as video differential gain and chrominance to luminance will suffer. If the filter is made softer as is the case in normal practice, then the upper video frequencies will be cut off.

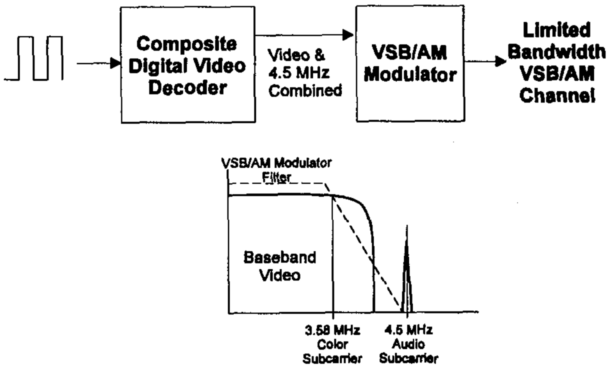

Figure 4 4.5 MHz Cutoff Filter Problems

Since video resolution is directly related to video bandwidth, the effect of this filter is to reduce video resolution and picture clarity. In today's systems, the subscribers who typically pay the largest monthly cable bills also have large screen televisions. Therefore, they will be the subscribers most deleteriously affected by the loss of resolution that results. If the digital transport system cannot carry 4.5 MHz audio as a separate discrete digitized carrier, then audio must be sent as baseband, and BTSC encoders replicated at each and every hub site. This results in significant added cost and operational penalties to the network operator.

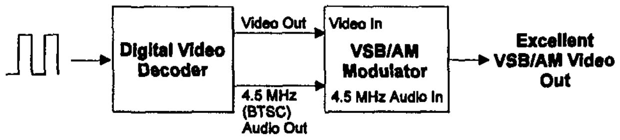

Figure 5 Proper Handling of 4.5 MHz Audio

2. Lost Revenue Opportunities

In the compression process, certain information is stripped out of the signal which is unnecessary to the video content. This information can be regenerated at the decode side of the system. One such area in the video waveform is the video blanking interval, referred to as the VBI or VITS area. However, in many CATV systems, the VITS area is used to carry revenue generating information services which are not related to the video itself. Examples of VITS data include: FNN stock updates, XPRESS computer service, etc. Since the location of these services may vary from video channel to channel, it is not straightforward to simply preserve a few selected VBI lines.

In contrast to the compression based codecs used in SONET systems, uncompressed video encoders do not modify or delete VITS information. Therefore, these sources of additional revenue are preserved.

Advanced Digital Video Services Distribution

The first uses of digital video channels which are n-QAM and n-VSB modulated will be for near video on demand applications. Initially the cost of the modulators to produce the n-M and n-VSB carriers will be quite high. Operationally, it will be desirable to digitally modulate once at the master headend and distribute channels to the hubs. An uncompressed digital system can do this. For example, the DV6000 by American Lightwave Systems, Inc. has already undergone tests with the Zenith 16 VSB encoding stream to demonstrate compatibility. Such a capability has not been developed for SONET based systems to date.

3. SNR Performance versus Distribution Network Cost

The true signal quality delivered to the subscriber is a combination of the addition of all noise contributions in the network from the master headend to the subscriber. Carrier to noise only characterizes the quality of the video carrier from the point of modulation, which in many cases will be the primary hub. Ultimately, it is SNR that is the determinant of picture quality on the subscriber's TV set. If the CNR of a distribution network is converted to an equivalent SNR contribution, then a total logarithmic addition of SNR contributions is possible. For a VSB/AM path, its SNR contribution is slightly lower than CNR. For the following illustration, VSB/AM SNR is approximated as equal to CNR for simplification. The conclusions from the following analysis are not affected by this simplification.

Distribution systems being designed for the future have total CNR contributions in the range of 47 dB to 49 dB. It is typical for CATV distribution system designers to assume that the metropolitan network feeding the primary hubs is transparent, and therefore is not accounted for in computing end of line SNR performance. But what performance level constitutes transparency?

To establish this requires examination of the addition of the noise contribution from the metropolitan backbone fiber system from the master headend to the hub and the noise contribution of the distribution system from the hub to the subscriber. If we assume the distribution system to be state of the art 49 dB CNR, then its SNR is approximately 49 dB. A graph can be generated which shows the effect of metropolitan network SNR performance on the resulting performance at the subscriber drop. In the figure which follows metropolitan backbone SNR is shown on the X axis, and the resulting SNR performance at the subscriber drop which is the summation of the two portion of the networks together, assuming a constant 49 dB for the distribution network.

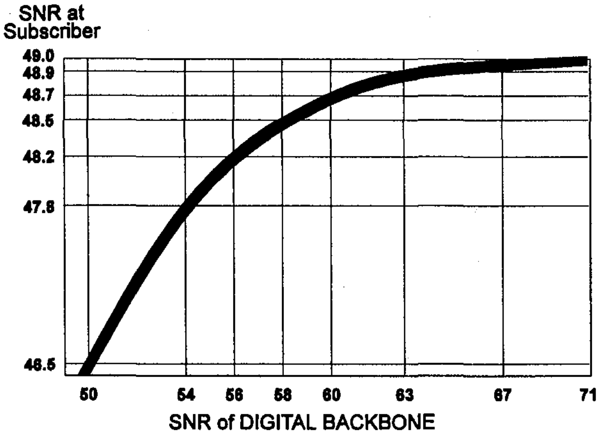

Figure 6 Subscriber SNR as a Function of Metropolitan System SNR (Distribution CNR held constant at 49 dB)

The conclusion is quite evident. At SNR levels above 59 dB SNR, the metropolitan network has a negligible effect (less than a .3 dB) on subscriber signal quality. However, when the contribution of the metropolitan network is 56 dB, almost a full 1 dB is lost at the subscriber. At 54 dB this degradation jumps to 1.2 dB, i.e. performance at the subscriber degrades to 47.8 dB. If the target at the subscriber is 49 dB, how can this be achieved with a metropolitan network whose performance is only 54 - 56 dB? (This is the CNR performance level of an unrepeatered AM supertrunk used for a star based metropolitan network versus a high performance uncompressed digital network with multiple repeaters.)

The only way this is possible is for the distribution network to be upgraded above 49 dB in CNR performance. In practice, this means either a shorter cascade or fewer optical nodes served by a single optical transmitter. Since the former is much more expensive at a performance level of 49 dB, I shall concentrate on the latter. Let's assume that the 49 dB CNR was achieved by taking a 50 dB CNR optical link in combination with a 56 dB CNR amplifier cascade. (This design assumes an average of 4 nodes served from one transmitter in a metropolitan area.) From the illustration above, the distribution system performance must be raised from 49 dB to 50.5 dB. If this is done via improvement of the AM fiber link versus shortening of the amplifier cascade, then the AM fiber link performance must go from 50 dB to 54 dB. Therefore, instead of serving four nodes per transmitter, only two nodes can be served per transmitter at this higher required performance level. Double the number of AM transmitters are required in the distribution network to achieve the original target of 49 dB at the subscriber!

The closer that the SNR of the metropolitan network is to the SNR of the distribution network, the more deleterious the effect on end subscriber picture quality. Or alternatively, the more expensive the subscriber distribution network has to be in order to achieve a desired performance level at the subscriber. As the above example shows, the expense of this can be very significant.

Given that the true SNR of compressed digital codecs used in CATV SONET links may have performance in the very low 50's dB as measured by digital SNR techniques such as ANSI proposed standard T1Q1.5/91-205R2, the cost penalty to the distribution network which follows a SONET system is very high when compared to an uncompressed digital system with SNR of 59 dB which places no cost penalty on the distribution network whatsoever.

4. System Space, Power

In addition to the higher cost of the SONET equipment itself, the cost of a SONET system for metropolitan network will be higher in terms of both space and power than a modular uncompressed digital system. A high performance uncompressed digital transmission system can fit 2.4 Gb/sec. of transmission equipment including individual channel drop/add/pass functionality, redundant optics and power supplies, plus 16 channels of encoding equipment, all into 19 inches of vertical rack space, consuming 170 watts of power.

In comparison, a SONET OC-48 system (2.48 Gb/s) will take a complete 19" rack without adding in the video codecs. Power consumption is more than double. When ancillary equipment requirements are added, the space penalty may be as high as three to one.

Cost Model

A cost model can be created to show a typical network and the cost differences between an uncompressed system and SONET based system. The ALS DV6000 was used as the uncompressed system. The model used for this paper is conservative and consists of the following:

One Master Headend
Serving Six Primary Hubs

60 Channels Basic CATV Service:
- 25 CH w/Stereo Audio (need BTSC)
- 5 CH Monaural w/2nd Language (need BTSC)
- 25 CH Monaural only
- 5 CH w/Local Commercial Insertion at Hubs (audio sent baseband)

10 Premium Channels - Scrambled, all Stereo, half with SAP
5 PPV Channel - Scrambled, all Stereo and SAP
6 DS3 Telephony Channels - Alternate Access Business
6 DS1 Channels - Service Center Consolidation

The costs of ancillary equipment were chosen to be in the middle range. The results of this analysis showed the following:

TOTAL NETWORK COST COMPARISON

	SONET SYSTEM A	DV6000 SYSTEM
MASTER HEADEND	$350,000	$300,000
6 HUBS	2,500,000	1,400,000
TOTALS:	$2,850,000	$1,700,000
ADDITIONAL AM TX'S TO ACHIEVE 48.7 dB SNR	800,000	0
TRUE COST FOR EQUIVALENT PERFORMANCE AT SUBSCRIBER	$3,646,963	$1,797,875
LOST REVENUES FROM INABILITY TO DELIVER SPECIAL SERVICES	???	0

Figure 7 Cost Summary

In summary, the cost of system and ancillary hardware for the SONET system was approximately 1.7 times the cost of the uncompressed digital solution. When the penalty for restoring 49 dB performance at the subscriber is added, the difference in costs between the systems increases to 2.15 times.

REDUNDANCY ISSUES

Today, both SONET and at least one high end uncompressed digital system offer fiber hot standby switching and other forms of redundancy. However, redundancy in video systems is based on the ability to protect and restore an individual channel. Therefore, the metropolitan system must provide protection at the hub sites so that if an individual decoder fails *or if the VSB/AM modulator which follows the decoder fail*s, that active spares can be remotely switched to restore the received channel to service on the proper channel number without any manual intervention or replacement of any equipment. This is possible today in uncompressed digital systems which are modular in design and provide single channel video encoder and decoder modules, channel drop/add/pass capability exists, and interfaces have been developed so that VSB//AM modulators may also be controlled via custom software.

In contrast, SONET based systems have primarily used packaging in which multiple decoders are in the same physical box. (This is also true of some earlier vintage uncompressed digital systems.) Therefore, if one module fails, more than one channel may be lost. With this form of equipment packaging it is not possible to use 1 X N channel protection to restore service. A hard outage normally occurs, and therefore a truck roll is necessary in systems which are configured with multiple channels per module.

TELEPHONY AND DATA TRANSPORT

The metropolitan area network must provide the ability to transport telephony and data channels in addition to video channels. Today virtually 100% of these channels will range from DS0 (64 kbs) to DS3 (45 Mbs). It is obvious that higher level rates are easily accommodated by the SONET transport system. New generation uncompressed digital systems also provide DS0 - DS3 capability, and provide added flexibility for interconnecting PBX's with individual DS1 channels which avoid the use of costly M13 multiplexors. This is highly desirable for consolidating customer service centers, for example. The concept of the uncompressed digital system is to provide an economic means of providing the ability to add telephony and data capability to the network gradually, without the penalty of a second network. If telephony traffic grows to a high level (nine or more DS3 channels between sites), then at that time perhaps it makes sense to add a SONET OC-12 system to handle this specialized traffic. However, alternatively, it appears not to make sense to create a very costly SONET OC-48 network for video in order to accommodate an initial telephony and data traffic which might encompass only a limited number of DS3's. Since state of the art uncompressed digital systems provide interfaces to standard telco network monitoring systems, a single operations support system (OSS) can manage the entire network.

VIDEO TRANSPORT IN THE PUBLIC NETWORK

If the network is not SONET based, how can information make its way to and from the video distribution network? Clearly, the ability to extract information and to insert information onto the public SONET based network is imperative. Therefore, advanced video distribution networks based upon high speed uncompressed digital transmission are designed with a SONET gateway at the master headend, typically with an STS-3c interface. Channels originating in the video distribution network therefore can access the SONET network. Likewise, channels which originate in other networks can enter the video distribution network. In this way, the cost of SONET is only imposed upon those services which derive direct benefit from SONET.

NETWORK CONTROL AND STATUS MONITORING

The need exists to monitor and control all traffic into and out of the metropolitan network. For telephony and data traffic, strict monitoring of incoming and outgoing bit error rates is imperative in order to characterize system performance, provide back up switching and conduct fault isolation. Support of standards such as TCP/IP and TL1 are critical to provide universal interfaces to an OSS. Both SONET and state of the art uncompressed digital systems provide this capability. However, in the metropolitan network, information about the content of channels is also very critical. When channels must be dropped, added or inserted, it is key to be able to determine what video service is riding on each channel, and to check automatically and prevent human errors such as inadvertent replacement of one video service with another at a channel insertion site. State of the art uncompressed digital systems provide this capability.

METROPOLITAN NETWORK ARCHITECTURES

There are three major architectures which are in use for metropolitan area networks today. These consist of the Star, Bus and Ring topologies. Of these, the star is the most limiting, when considerations of high reliability and fiber miles are concerned over any metropolitan or regional area which covers significant distances.

Star Network

In the star network, virtually all signals emanate from the master headend which is the center of the star. If the distance from the center of the star to each hub is within the reach of an AM supertrunk system, then the cost of signal conversion from digital to VSB/AM signals can be avoided. This results in considerable cost savings for the forward path.

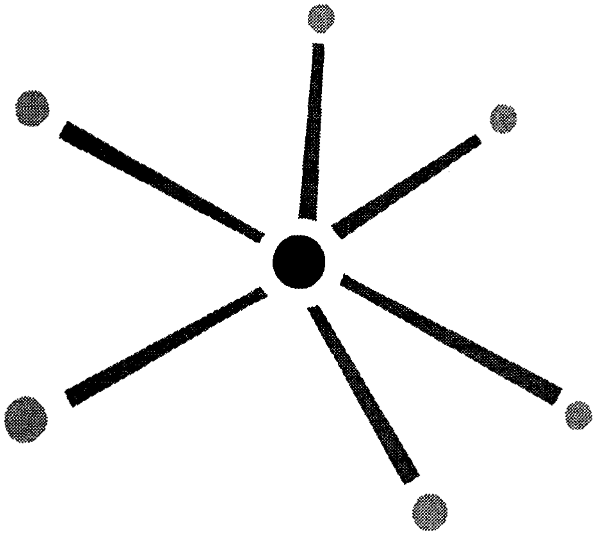

Figure 8 Star Architecture

The disadvantages of the star network are based on reliability and flexibility. Reliability of the network is proportional to the total number of fiber cable kilometers and the ability to provide automatic redundancy. As the average distance from the center of the star to the hubs gets larger and the number of hubs served by the star increases, the amount of fiber necessary to create the network grows exponentially. If a cable cut occurs, there is no simple way to provide redundancy from the master headend, and if redundancy is provided, there is a high likelihood for the necessity of repeaters with associated degradation of signal quality. Therefore, a hard loss of service will occur. Based on standard probabilities, the greater the amount of fiber, the greater the likelihood for a fiber cable cut.

Therefore, implementation of a star network calls for serious consideration of totally underground cable construction, since two-way redundant paths will be very expensive and very possibly require the use of repeaters. If the network is established using AM supertrunking instead of a digital transmission system, the use of a repeater will deleteriously affect subscriber performance, or cause the distribution system to go up significantly in cost as illustrated previously.

Bus Network

The bus network is highly flexible, especially for long distance networks in which signals can enter and exit the network at multiple hubs or gateways. Traffic can be both symmetrical and asymmetrical. Redundancy for most services can be established by providing two master headend locations, each which feeds all hub locations. In the event of a fiber cut, switch over to the alternate path can be made locally at each hub in a few milliseconds. However, some types of telephone and data communications may be more difficult to back up. This architecture is only practical with a digital system.

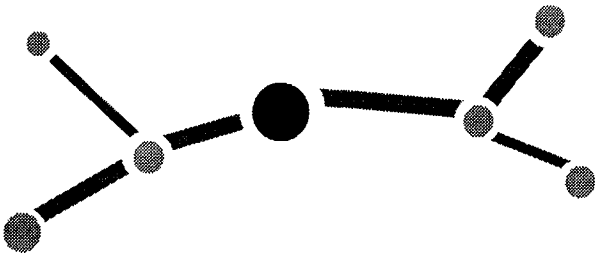

Figure 9 Bus Architecture

Ring Network

Ring networks can be designed with a number of variations. The ring may be open, closed, or closed with redundant counter rotating signals. If AM supertrunking is used, only two remote sites are possible with redundancy. If uncompressed or compressed digital systems are used, signals may be sent to many sites, dropped and added, and fully backed up with no loss of signal quality (except of course for degradations in the compressed digital system associated with the codecs themselves, as noted previously).

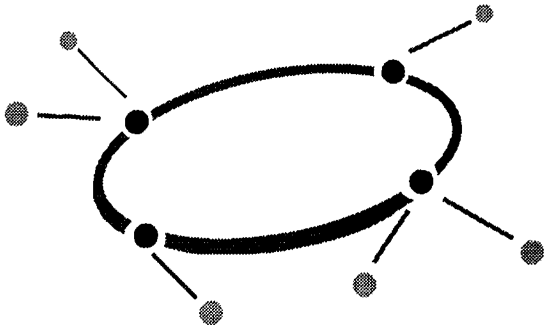

Figure 10 Ring Architecture

Star vs. Bus vs. Ring

Larger networks will preclude the use of star technology. Bus and ring topologies are both attractive for larger networks. The choice will be based both on network geography and mix of services provided.

CONCLUSIONS

It is imperative that the metropolitan network must be highly efficient and economical. This means that there is no room for added cost without direct quantifiable economic benefit. Therefore, it is not viable to extend SONET into the metropolitan network today and for the foreseeable future. If SONET did not impose such a cost and performance penalty on the network it could be argued that there is some benefit in providing compatibility deeper into the network. Someday, the cost differential may decrease between uncompressed digital backbones and SONET digital backbones. If this happens then there is a reason to implement SONET, because it will no longer impact the cost of providing subscriber services. Gateways to SONET are viable currently. However, elimination of the great cost differential between uncompressed digital transport and SONET for the video distribution system is not in sight today.

AM supertrunks are not viable for metropolitan networks due to the large distances, number of locations, channel drop/insert flexibility, and redundancy issues associated with these networks. As networks provide more demand based services, these will be more difficult to supply in a supertrunk based architecture. Supertrunks should be associated with distribution based networks.