Fiber Optic Supertrunking: A Comparison of Parameters and Topologies Using Analog and or Digital Techniques

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Abstract: Fiber optic supertrunking has a well established place in larger CATV networks. Supertrunks have to be transparent to the signal quality and they have to have no impact on the system reliability of the total network. 60 dB video SNR has to be achieved and down times of less than one hour per year are desirable. AM on fiber cannot achieve these goals (yet). FM and digital with a 20 dB higher loss budget than AM and better inherent reliability are well suited for high transmission quality as well as for redundant supertrunk topologies, achieving excellent system availability numbers.

Introduction:

Supertrunks need to be transparent to the signals that are normally fed from a satellite dish through the CATV network into a set top converter and/or the TV set. The achievable quality of a satellite link has to be determined first. Then the degradation caused by the coaxial network and by the set top converter and/or TV set needs to be estimated. Then parameters of a transparent supertrunk can be found. Down time of a supertrunk can be estimated as a function of the topology of the supertrunk.

1. Noise accumulation in various sections of a CATV network:

1.1. The set top converter

Assuming that the set top converter has a noise figure of approximately 15 dB and that the signal level at the outlet is 7 dBmV the set top limitation for signal to noise is approximately:

Video SNR = 174 - 66 - 15 + (7-49) = 51 dB

This is approximately the limit of perceptibility of noise in an average TV picture.

1.2. Trunk and distribution

In a CATV system that uses fiber optic supertrunks the target picture quality after trunking and distribution is normally high, the video SNR planned to be 48 to 50 dB at the outlet. Together with the set top converter the video SNR limitation is then 46.2 to 47.5 dB.

1.3. Supertrunk

Supertrunks are designed to produce a video SNR of 60..65 dB. Together with trunk, distribution, and set top converter the video SNR limitation is now 46.0 to 47.3 dB with a 60 dB supertrunk and 46.1 to 47.4 dB with a 65 dB supertrunk. Obviously supertrunks that are better than 60 dB in video SNR do not improve total system performance significantly.

1.4. Satellite link

Using the numbers from [1], let us compare three dishes, each of them with three different LNB noise temperatures:

Dish size:	4.5m	7m	10m
Noise temp.			
90K	50.3	54.7	58.7 (dB)
80K	50.7	55.1	59.1 (dB)
35K	51.7	57.6	61.5 (dB)

Combining these satellite video SNR's with the SNR of the cascade supertrunk, trunk, distribution, and set top converter (46 to 47.4 dB) the following SNR ranges are found:

Video SNR of total system:

4.5m dish with 90K LNB:	44.6 to 45.6dB
4.5m dish with 35K LNB:	45.0 to 46.0dB
7.0m dish with 80K LNB:	45.5 to 46.7dB
7.0m dish with 35K LNB:	45.7 to 47.0dB
10 m dish with 35K LNB:	45.9 to 47.2dB

1.5. Conclusions on system noise performance:

A 4.5m dish with a noisy LNB is not adequate for the use in a high quality CATV system. A 7m dish with a very low noise LNB is probably the best compromise between cost and signal degradation. Higher signal levels into the set top converter or a lower noise figure for the set top converter would improve the picture quality.

Assuming that the set top converter can handle full channel loading at 10 dBmV (without a noise figure change because of AGC and no set top CTB) then the following numbers could be achieved:

Set top converter	54.0 dB
Trunk/distribution	50.0 dB
Supertrunk	62.0 dB
Satellite receiver	57.6 dB
System Total	48.0 dB

The picture quality for a 48 dB video SNR is approximately 3dB worse then the limit of perceptibility of noise. The quality number in accordance with CCIR Report 959 and CCIR Rec. 500-2 is 4.75, 5 being a perfect picture without any impairment.

2. Performance parameters of different modulation schemes used in fiber optic supertrunks:

2.1. AM techniques

Amplitude modulation does not offer the possibility of a trade off between CNR and occupied bandwidth like FM or digital. AM is about 30 dB more susceptible to noise than FM. It requires therefore the use of very advanced techniques in lasers and fiber optics in order to achieve CNR's that are typically 10 dB worse than what can be achieved with FM or digital. Nevertheless the absence of modulation conversion equipment makes AM on fiber attractive. The basic AM system calculations as they are known today are:

2.1.1. Noise in AM systems

Two years ago, DFB lasers that were designed for digital applications typically achieved RIN numbers of -150 dB/Hz. Today's DFB lasers, that are designed for AM applications, are reported to have RIN's of -155 to -160 dB/Hz. Nevertheless the production yield of lasers with RIN's better than -155dB/Hz is only 5% [2]!

The TV channel CNR produced by the laser RIN is:

$$CNR_{(\text{laser RIN})} = -RIN + 20\log(m) - 3 - 10\log(4.2\text{MHz})$$

$$= -RIN + 20\log(m) - 69$$

The receiver noise consists of shot noise (or quantum noise) of the detection process and of the noise in the following RF amplifiers. A convenient way to describe this is:

$$CNR_{(\text{receiver})} = 152 + 20\log(m) + P_{opt}(\text{dBm}) - 10\log(4.2\text{ MHz}) - N_a$$

$$= 86 + 20\log(m) + P_{opt} - N_a$$

N_a is the differential between total receiver noise and shot noise. This differential is a quality number for various receiver designs. One of the best receivers, Ortel's 2605A, is 1dB at 0dBm, 1.5dB at -5dBm, 4dB at -10dBm, and 10 dB at -15 dBm.

Another noise source is the fiber itself. McGrath [3] reports that laser phase noise can be converted to intensity noise by reflections in the fiber link. Assuming a 4 GHz bandwidth of the laser (chirping because of modulation) and a fiber reflectivity of 29 dB one can calculate an equivalent fiber RIN of -152 dB/Hz. The fiber limitation to CNR is therefore:

$$CNR(fiber)= 20\log(m)+152-3-66= 20\log(m)+83$$

Assuming a laser RIN of -155 dB/Hz (which is optimistic) the following link performances for -3 dBm, -6 dBm, and -10 dBm optical received power can be estimated:

Estimated AM link performance:

	Number of channels: 10	20	40
Modulation index m:	0.12	0.075	0.06
Laser noise:	67.6	63.5	61.6 (dB)
Fiber noise:	64.6	60.5	58.6 (dB)
Total noise laser & fiber:	62.8	58.7	56.8 (dB)
Receiver noise at -3dBm:	63.6	59.5	57.6 (dB)
Total noise at -3dBm:	60.2	56.1	54.2 (dB)
Receiver noise at -6dBm:	59.6	55.5	53.6 (dB)
Total noise at -6dBm:	57.9	53.8	51.1 (dB)
Receiver noise at -10dBm:	53.6	49.5	47.6 (dB)
Total noise at -10dBm:	53.1	49.0	47.1 (dB)

Obviously only a 10 channel loading is useful for supertrunking. Even then the received optical power should not be less than -3 dBm. Using a 4mW laser a loss budget of up to 9 dB can be achieved.

2.1.2. Usefulness of AM supertrunks

Above numbers indicate that AM fiber optic systems produce substantially lower SNR's than FM or digital. AM is therefore more useful in applications in the trunk and/or feeder section of a CATV network, where it can outperform coaxial techniques. In AM supertrunks channel numbers of ten or less have to be used and optical receive powers of -3 dB are minimum, limiting its usefulness considerably.

2.2. Frequency modulation

FM has been used successfully for many years. Using a deviation of 8 MHz sync tip to peak white the FM improvement over AM is 30 dB. Received CNR's of 30 dB (in 4.2MHz bandwidth) still produce a 60 dB video SNR. It is useful to use APD's in the optical receiver to achieve very good loss budgets with receivers of reasonable complexity. A Germanium APD receiver needs about 5µW (-23dBm) of optical received power to produce 60 dB video SNR with 16 channels. Supertrunks using FM therefore outperform ones using AM by about 20 dB of optical loss.

2.3. Digital techniques

So far video compression techniques have rarely been used for digital supertrunks and are therefore not considered here. Early systems used 7 bit resolution, achieving video qualities far below the ones achievable by using FM. Today's designs use 8 or 9 bits. The quantization noise is:

$$SNR = 6n + 1.8 \quad (dB)$$

n is the number of bits. This is an rms number and needs correction, when applied to video. Assuming no overhead and a range of conversion of the video signal with -40 IRE corresponding with 00..0 and +100 IRE with 11..1 then 9 dB can be added because video SNR is referenced to a peak to peak number (black to white). 3 dB has to be subtracted because video SNR uses 100 IRE as the signal reference and not 140. Video SNR is:

$$SNR_{(video)}= 6n+7.8 \quad (dB)$$

and weighted video SNR is:

$$SNR_{(video,weighted)}= 6n+7.8+7.4 \quad (dB)$$

(assuming flat quantization noise). Several mechanisms can produce noise that increases with video frequency. Therefore the above equation is too optimistic by 1 to 3 dB.

The theoretical numbers are:

Resolution:	7	8	9	10 (Bits)
Video SNR:	57.2	63.2	69.2	75.2 (dB)
Practical Video SNR:	55	61	67	73 (dB)

8 bit is a sufficient resolution for supertrunks. Going to 9 bits increases cost more than proportionally and improves the system video SNR after the set top converter by only 0.19 dB.

2.3.1. TDM systems

Time division multiplex (TDM) is attractive because of relatively inexpensive high speed digital multiplexing and demultiplexing IC's [4]. A system with 8 bits resolution and approximately 2 bits overhead for BTSC stereo transmission and synchronization needs at least a data rate of 107 Mb/s. A 16 channel system runs at a 1.8 Gb/s data rate.

2.3.2. Digital modulation of RF carriers

A well established way of transmitting digital data over phone lines, satellite links etc. is using digitally modulated carriers. Typical modulation formats are FSK, PSK, ASK etc. [5]. A lot of work has been done to find modulation formats that make an efficient use of the available spectrum as well as of the power capability of the transmitters. In satellite down links it is of great importance not to waste power by using up to 10 dB of backoff [6]. Modulation schemes that produce non constant envelopes require backoff because operating a transmitter near compression restores sidebands that have been filtered. QPSK modulation is well known for this phenomena. A multi channel fiber link is very different in that respect. Bandwidth of up to approximately 2 GHz is readily available. The only device operating close to compression is the laser, which is periodically driven into clipping. The nonlinear distortions are well known CSO, CTB etc. They can be considered additional noise and limit system performance well before the unwanted sidebands of the individual channels are restored. QPSK is therefore a very good candidate for digital carrier systems on fiber because of its simplicity. It has a bandwidth efficiency of 2bits/Hz, so that a 107 MB/s channel occupies approximately 54 MHz. A 16 channel system can therefore be realized with 900 MHz of RF bandwidth, slightly higher than FM.

2.3.3. Comparison TDM/QPSK

TDM-NRZ and QPSK have theoretically the same bandwidth efficiency. In practice TDM needs slightly more bandwidth than QPSK. A TDM system requires a very flat amplitude and group delay response of the transmission path, down to very low frequencies. A 3 dB roll off over the 1 MHz to 1.2 GHz transmission path can cause nearly a 30% reduction of the eye opening. That means in practice that the bit error rates are higher than calculated from the received CNR. A 3 dB amplitude error is what FM system FO links typically achieve when they are well maintained. The 3 dB roll off does not affect FM or QPSK link performance at all.

Another very important difference is reliability (or better availability) of the supertrunk. A TDM link that has a problem means that all channels are down whereas in an FM or QPSK link only the channel which has a problem is affected.

QPSK links are basically analog links in the RF section. It is therefore very easy to add other analog channels like FM stereo, satellite IF signals etc.

Although, TDM signals can be repeated nearly endlessly, we have not found the need for more than 2 to 3 repeats even in advanced redundancy schemes. Multichannel QPSK signals can easily be repeated by that number.

A 12 channel QPSK link can be realized using approximately 700 MHz of RF bandwidth. It can easily be expanded to a 24 channel link by optically combining 12 channels that modulate one laser up to 750 MHz and 12 more channels modulating a second laser from 900 tp 1700 MHz. TDM would have to multiplex in the time domain, a task that is difficult above 2Gb/s.

Figure 1. shows how a 24 channel QPSK system can be configured.

An other important difference is the ease of maintenance of a QPSK system. A standard spectrum analyzer is enough to locate problem channels. No Gbit test equipment is needed as would be the case for TDM.

2.3.4. Comparison AM/FM/QPSK

The following table shows the most important differences when 4mW transmit power is used (FM and QPSK after conversion to AM channels):

	AM	FM	QPSK	QPSK
Number of channels:	10	16	12	24
Video SNR:	60	60	60	60 (dB)
Loss budget:	9	29	30	26 (dB)
RF bandwidth:	0.06	0.7	0.7	1.4 (GHz)
CTB:	65	70	70	70 (dB)
CSO:	70	70	70	70 (dB)
Maintenance:	high	med.	low	low

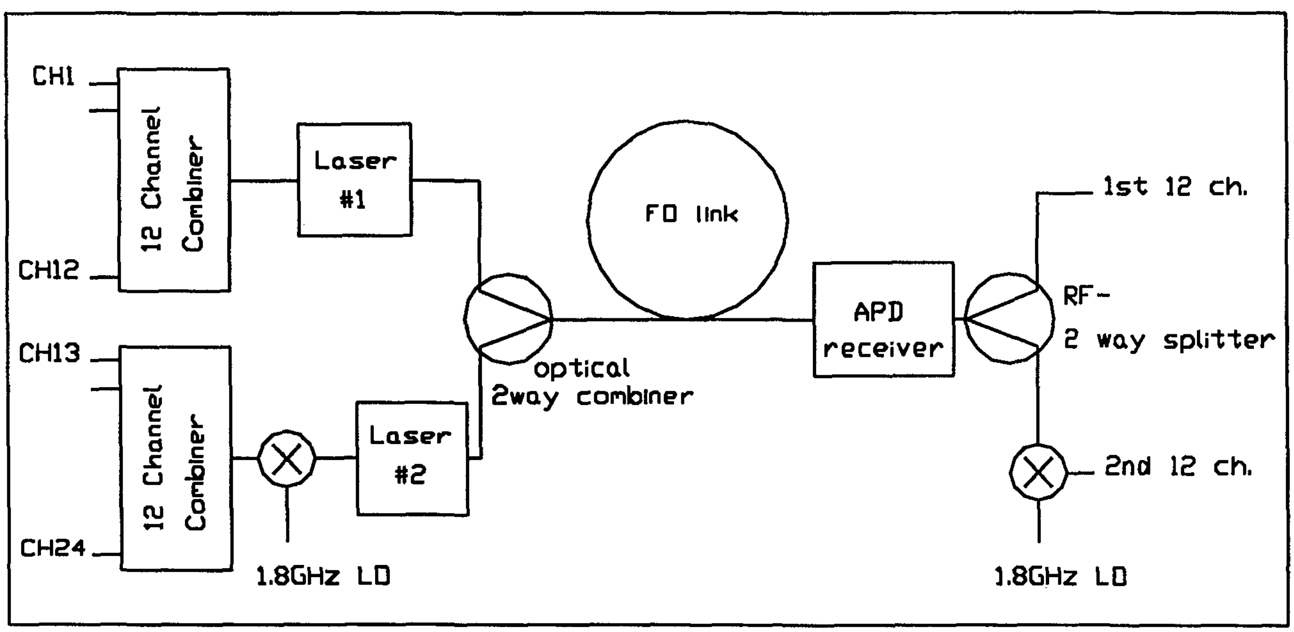

Figure 1.
A 24 channel QPSK system

Fiber optic systems have like other systems a certain hidden cost in maintenance. Fiber optic systems in general have bigger variations in CNR, CTB, and CSO than coaxial links. Especially short systems like AM systems depend heavily on the dynamic performance of the laser. CNR, CTB, and CSO can vary substantially with reflections, temperature changes in the optical isolators, etc. Ironically AM systems need to be planned therefore with more margin than FM or digital systems. Maintenance cost is a function of that margin. With no margin at all a system has to be maintained on a daily basis. 3 dB margin in optical power brings maintenance cost into a reasonable range. 6 dB makes maintenance cost negligible. The real numbers are difficult to obtain. Figure 2. shows approximately how maintenance cost of AM, FM, and digital compare.

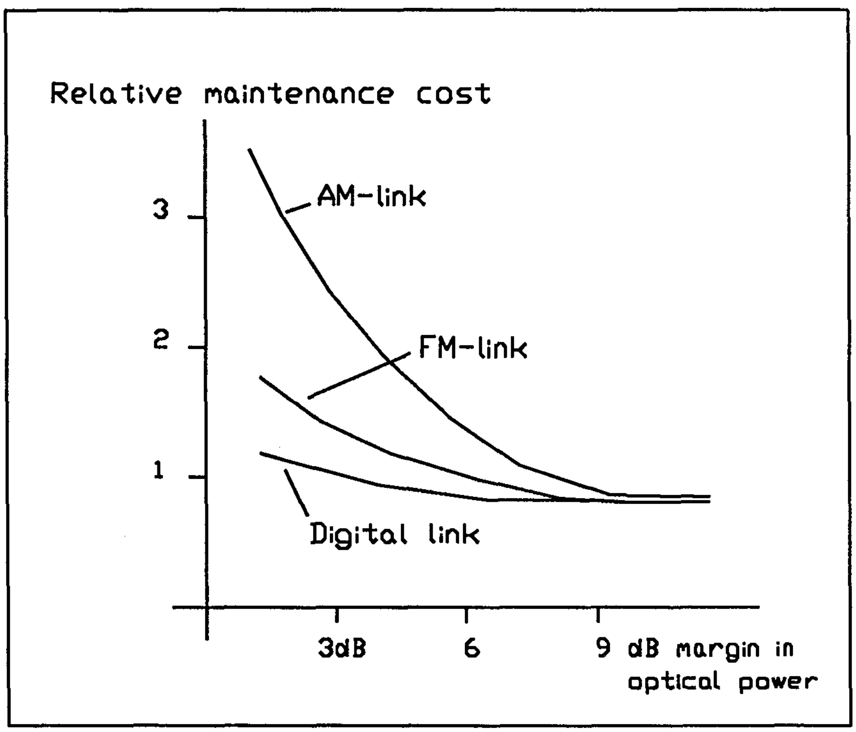

Figure 2.
Maintenance cost of AM, FM, and digital as a function of optical power margin

3. Supertrunk concepts using digital

The biggest advantage of digital supertrunks in comparison to AM supertrunks is their nearly 20 dB higher loss budget as well as their lower maintenance. The down time of a critical supertrunk system can be made to be nearly zero, when each hub is reached by two fibers that do not have common paths (fiber breaks normally cut all fibers in one cable). Figure 3. shows such a system.

Eight Supertrunks deliver the signals from the Headend to eight Hub Sites (A,B,C,D,E,F,G and H). The signals reach Hub Site A through one main fiber. If there is a fiber break in the main path, Hub Site A switches to a redundant fiber coming from Hub Site B.

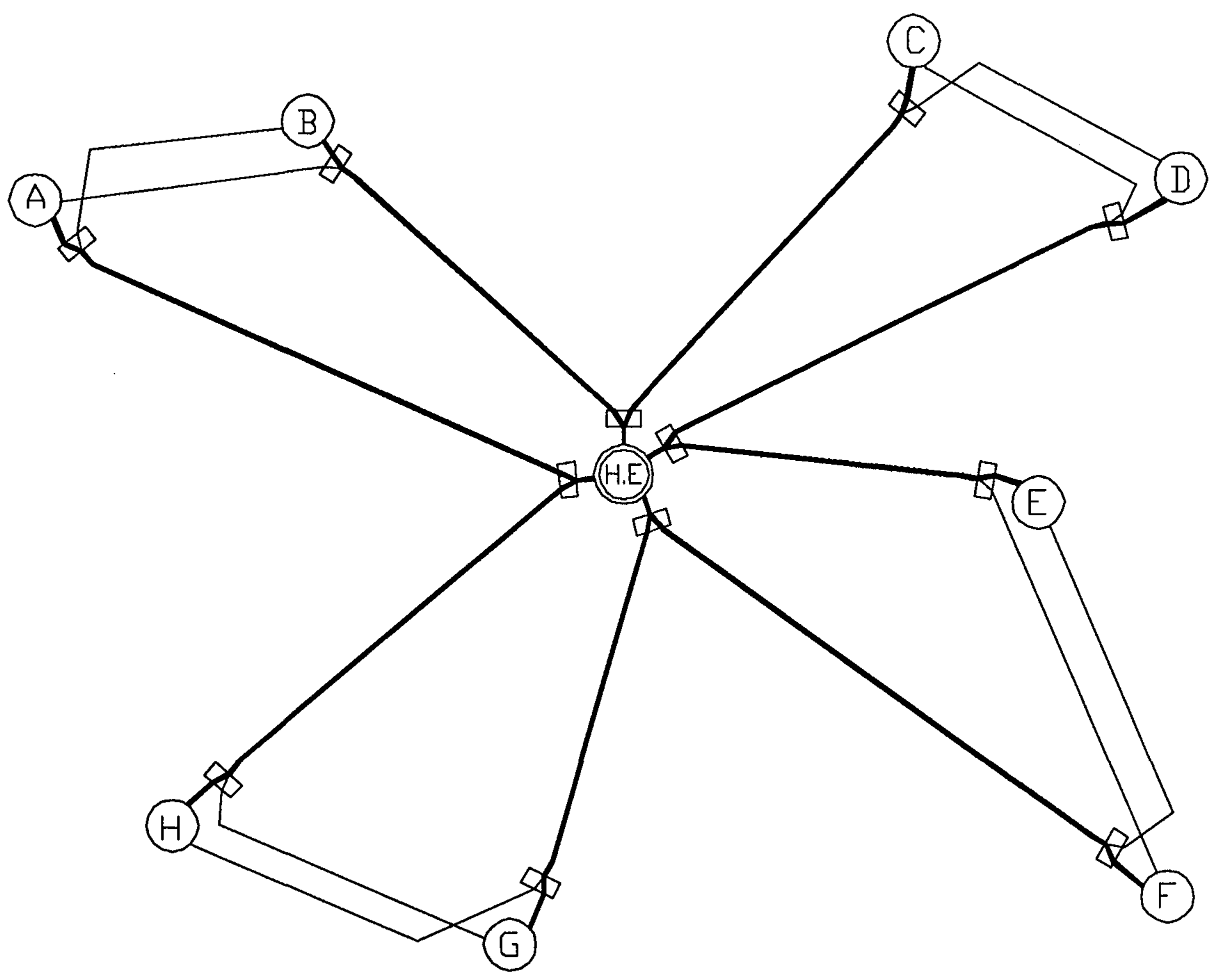

Figure 3.
A redundant supertrunk using independent redundancy paths

Supertrunk availability can be defined as:

$A= 1\text{-down time/total time}$

With three days down per year that availability would be 0.992. If a redundant supertrunk is used the new availability number is:

$Ar=1-(1-A)^2$

or in the above example 0.99993 or an average down time of only 36 min/year. By going to a redundant (and independent) path the reliability of the system has therefore been improved dramatically.

The price to pay is additional fiber installation as well as higher optical loss budgets. Digital (as well as FM) can perform with the higher loss budget, AM cannot. But AM has a reliability advantage because no modulation conversion equipment is needed.

4. BTSC stereo

In digital links video and audio is normally encoded in a base band format. Special schemes have been developed for the transmission of BTSC stereo so that the hubs do not need BTSC stereo encoders. The cheapest way is to add a 4.5 MHz subcarrier to the video before digitization. This method has some drawbacks:

A. The resolution that is available for video is reduced.

B. Video overshoots cause 920 kHz beats as well as audio buzz when the A/D converter is overdriven.

In FM we used discrete audio carriers very successfully. There was no interaction between audio and video whatsoever. We did the same with digital. The BTSC stereo signal produces an independent bitstream that is digitally multiplexed to the one produced by video.

5. What about scrambling

One of the biggest advantages an AM supertrunk has is that there is no need to treat scrambled signals separately. We have developed (and applied for a patent) a scheme that takes Baseband or RF scrambled signals down to a video baseband signal that can be transmitted by FM or digital. In the case of RF scrambling timing information on the sound IF carrier has to be transmitted as well. Our BTSC transmission scheme does this. All scrambling methods can be transmitted, keeping in mind that what we really transmit is the in phase component of the VSB envelope, or the information that the TV receiver really needs. Even a phase modulated signal (Zenith PM) can be handled. It will produce positive and negative envelopes, therefore reducing the SNR by 6 dB.

Digital transmission of these signals is very advantageous when dynamic video inversion is used, where DC stability is critical.

Conclusions:

The achievable picture quality in a carefully designed CATV system can be very high. The limiting elements are set top converter (and/or TV set) and to some degree the satellite dish and receiver. Supertrunks should be designed to achieve 60 dB video SNR or better. AM on fiber can do that with 10 channels when the 5% best lasers are selected and when no margin is needed. FM and digital can achieve that number, digital achieves 60 dB consistently, FM can achieve even better numbers in shorter supertrunks. AM has a limited loss budget that is approximately 20 dB less than what can be achieved using FM or digital. Supertrunks are critical for the reliability of a CATV network. Redundant schemes can easily be implemented using FM or digital but not with AM. The scrambling advantage of AM is irrelevant, FM and especially digital can transmit scrambled signals as well.

References:

[1] Communication with Ken Cannon, Scientific Atlanta

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[6] K. Sreenath et al: QAM and QPRS digital broadband cable systems, International journal of digital and analog cabled systems. Vol.2, pp. 139-148, 1989