INTEGRATED AML/FIBER BACKBONE SYSTEMS

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ABSTRACT

A fiber optic backbone system fed by AML is a cable system architecture that provides both performance and cost advantages. Although both AML and a fiber backbone have been separately proposed as means of improving the overall cable system carrier-to-noise ratio, the attributes of AML and AM-fiber are in this case complimentary rather than competitive. By combining the two technologies, one can overcome the drawbacks of each. Line-of-sight and zoning restrictions sometimes limit the location of AML receive sites. Shot and thermal noise sharply limit the carrier-to-noise ratios achievable with multiple-carrier AM fiber on long paths. When the latest AML technology is used to reduce the average length of the fiber backbone, the overall system C/N can be improved. At the same time, the savings in the cost of the glass can more than offset the cost of the microwave. This paper reviews AM fiber and recent AML system performance. Examples of integrated AML/fiber backbone architecture are analyzed for both cost and performance. It is shown that an overall C/N in large cable systems of 50 dB or better at the last subscriber terminal can be obtained with today's technology.

INTRODUCTION

The fiber backbone system concept was described in a series of papers presented at the 1988 NCTA convention.[1-3] The performance goals of this system were stated to be a 10-dB optical loss budget, 42 channels, and 55 dB C/N with 65 dB C/CTB and C/CSO. By cutting the trunk amplifier cascade length to two to four amplifiers, the fiber backbone concept should provide the advantages of improved reliability, quality, and maintainability for the overall cable system. Back in 1976, similar advantages were found to apply when AML microwave was used to cut trunk cascades to a maximum of ten amplifiers.[4] However, it is not always feasible to use microwaves for these purposes. A clear line of sight with adequate path clearance is required. Zoning restrictions may ban the installation of receive sites, particularly in residential neighborhoods. In addition, if the trunk cascade is to be cut to two to four amplifiers, the number of receive sites in major cable systems would imply a broadcast type of transmit antenna. With existing power limitations, the microwave system would be restricted to very short range even if such a broadcast antenna pattern were permissible under CARS band rules. Currently, the largest point-to-point AML system utilizes only 32 receive sites.

On the other hand, it must also be acknowledged that today's AM fiber systems still fall short of the above-stipulated performance goals, particularly at larger distances. Moreover, with a large number of fiber hubs, and multiple glass fibers to each hub, the overall cost of glass is not an insignificant item. For these reasons, it us useful to consider a system architecture using AML microwave to sharply reduce the length of the fiber runs. Each microwave receive site, aside from taking the place of one fiber hub, then becomes the source for feeding a dozen or more fiber backbone hubs. With modern AML equipment, it is possible to achieve high-quality performance at distances in excess of 20 miles. This reach should not be confused with 32 kilometers of fiber. Whereas microwave is "as the crow flies" distance, fiber must follow routings dictated by local conditions. Even when there are no natural barriers, such as river crossings, involved, a reasonable expectation might be that the required fiber distance exceeds the microwave distance by 30 percent. Thus, the equivalent reach is 41 km of fiber. To this, one can add up to 10 km of AM fiber backbone for a total equivalent reach of over 50 km.

AM FIBER SYSTEM PARAMETERS

The general characteristics of the C/N performance of an AM fiber system have been clearly described.[5] The three contributions to overall C/N are

$$C/N_{SOURCE} = \frac{m^2/2}{RIN \cdot B} \tag{1}$$

$$C/N_{QUANTUM} = \frac{m^2 R P_R/2}{2qB} = \frac{m^2 \eta P_R/2}{2h\nu B} \tag{2}$$

$$C/N_{RECEIVER} = \frac{m^2 R^2 P_R^2 R_{eq}/2}{4kTB \cdot F} = \frac{m^2 R^2 P_R^2/2}{< i_N >^2 B} \tag{3}$$

where m is here taken as the modulation index for each individual TV channel, which is often assumed to relate to a total modulation index $M = m\sqrt{N}$, with N being the number of channels. RIN stands for "relative intensity noise" and normally describes the intensity noise of the laser. However, multiple reflections on the fiber system, aside from possibly directly degrading laser RIN, can also give rise to additional RIN through conversion of phase noise to intensity noise.[6] A typical linewidth for a DFB laser is 50 MHz. With this linewidth, a better than 40 dB return loss must be required of all fiber system components to keep the additional RIN at channel 2 (54 MHz) under -160 dBc/Hz. This is important when, with the use of optical isolators, the laser RIN is maintained at -152 dBc/Hz or better.

In equation (2), η is the quantum efficiency, a measure of the probability that an incoming photon of energy, $h\nu$ (h = Planck's constant and ν = optical frequency) will generate a hole-electron pair that is collected across the junction of a p-i-n photodetector. Although quantum noise is identified with receiver shot noise, it is based on a fundamental limit intrinsic to the electromagnetic field, wherein the background noise radiation at optical frequencies is approximated by $h\nu B$, rather than kTB as in microwave satellite receive terminals. A factor of two arises because direct detection is less sensitive than heterodyne detection. Since η is already quite high (a 1.3 μ detector responsivity, R of 0.7 amps/watt implies a 67 percent quantum efficiency) the only available means of significantly increasing the C/N when quantum noise is dominant is to raise either m or the average optical received power, P_R. Note that with electron charge, $q = 1.6 \times 10^{-19}$, P_R is in watts. With the NCTA definition of C/N, $B = 4 \times 10^6$.

A great deal of effort has been expended within the last decade in optimizing optical receiver sensitivity. This continuing effort[7] has focused on transimpedance amplifier designs suitable for high speed data communications. Standard receivers of this type can respond out to 550 MHz with an equivalent transimpedance, R_{eq}, of 2 kΩ and beyond 330 MHz with R_{eq} = 5 kΩ. Unfortunately, at the high P_R required by equation (2), standard receiver designs suitable for data communications are not sufficiently linear for 40-channel CATV applications. In particular, second-order distortion limits the transimpedance to on the order of 500 ohms for high-level input. Equivalently, one can ascribe an equivalent input noise current density, i_N, whose square is proportional to a noise factor, F, divided by R_{eq}. In either case, noise can be expected to increase somewhat with frequency so that the worst case $C/N_{RECEIVER}$ occurs at the high frequency channels.

Table I summarizes the assumed contributions to C/N for a hypothetical 42-channel link. It is obvious that all three contributions to system C/N must be improved to meet the original fiber backbone requirements. A 3 dB increase in laser power output would result in a 6 dB improvement of $C/N_{RECEIVER}$ but the receiver distortion limit must be raised with higher P_R. Raising transmitter output by 3 dB also increases $C/N_{QUANTUM}$ by 3 dB. At this point, C/N_{SOURCE} would become the dominant term and RIN would have to improve.

The only factor that enters into all three terms is the modulation index, m. Improved laser linearity would be required but "crash point" saturation limit cannot be very far removed since even with 4-percent per channel modulation, the 42-channel instantaneous current can, however briefly, drive the laser to below its threshold current. It has been pointed out[8] that phase fiddling in HRC systems could be useful in this regard.

The optical loss is normally assumed to be 0.5 dB/km at 1.3 μ. This includes an allowance for splice loss, but connector losses at transmitter and receiver ends and residual link margin are not included. The CATV operator will have to decide whether the planned fiber link distance can be based directly on the optical loss required for given C/N or whether 1 or 2 dB should first be subtracted before applying the 2 km/dB formula. Figure 1 plots the Table I C/N versus distance assuming a 1 dB loss holdback for connectors.

RECENT AML DEVELOPMENTS

Figure 2 summarizes the relative output capability of AML transmitters. The point to be made is not only the wide range in output capability but also the wide diversity of choice. The day when AML transmitters were available in only two varieties is long since gone.

Two transmitters are of particular recent significance. The SSTX-145 is a solid-state high-power channelized transmitter[9] that is almost comparable in power with traditional

TABLE I
ASSUMED FIBER OPTIC LINK PARAMETERS

Optical Loss (dB)	C/N_{SOURCE}	$C/N_{QUANTUM}$	$C/N^*_{RECEIVER}$	C/N_{LINK}
2	55.0	60.6	68.0	53.8
4	55.0	58.6	64.0	53.1
6	55.0	56.6	60.0	52.0
8	55.0	54.6	56.0	50.4
10	55.0	52.6	52.0	48.2

m = 4% (N = 42)
RIN = –152 dBc/Hz
P_{LASER} = 2 mW (into fiber after isolator)

R = 0.7 A/W
$i_N = 5\ pA/\sqrt{Hz}$

*Distortion, particularly at higher input levels, may be excessive.

high-power AML but uses half the floor space and one fifth of the primary power. At the recent Western Cable Show, this transmitter was teamed with a new Compact Outdoor Receiver[10] for a live demonstration of a simulated eight-output 40-channel 32-km microwave link with 60 dB S/N. The AML demonstration equipment is depicted in Figure 3. By measuring baseband characteristics including differential gain and phase, it was shown that the signal was indeed of a high quality. The S/N was largely determined by the higher than normal receiver microwave AGC threshold setting. This level setting trades off C/N against C/CTB and C/CSO. At the normal factory setting of -46 dBm for the COR-299 6-dB noise-figure receiver, C/N is 56 dB, C/CTB is 75 dB, and C/CSO is 70 dB for 40-channel loading.

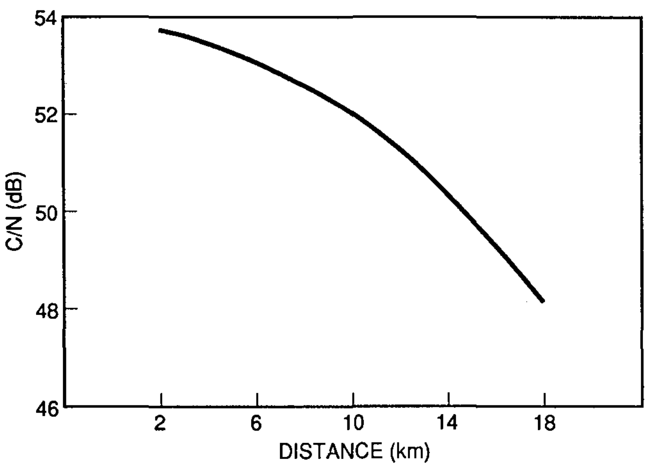

Figure 1 Calculated AM fiber-optic link C/N versus distance.

Figure 4 shows another recent AML development, the block upconverting IBBT-116 transmitter.[11] Table II summarizes its performance capabilities. This transmitter with a two-tone 3-IM intercept point of +57 dBm has 8 dB greater output capability than any previous CARS-band block-conversion type of transmitter. It is capable of full 80-channel loading, but when loaded with only 42 channels, its output is +9 dBm with 60 dB C/N, 65 dB C/CTB, and 65 dB C/CSO. Including a four-way split to 16-km microwave paths, the received signal level would be -42 dBm.

It is clear from the above that for supertrunk applications, AML microwave performance far outpaces what AM fiber systems can deliver. Moreover, for the two examples given, overall system costs for AML microwave will be far less than for the corresponding fiber system (disregarding for now the performance differences). Cost will of course vary greatly depending upon site availability, type of fiber construction,

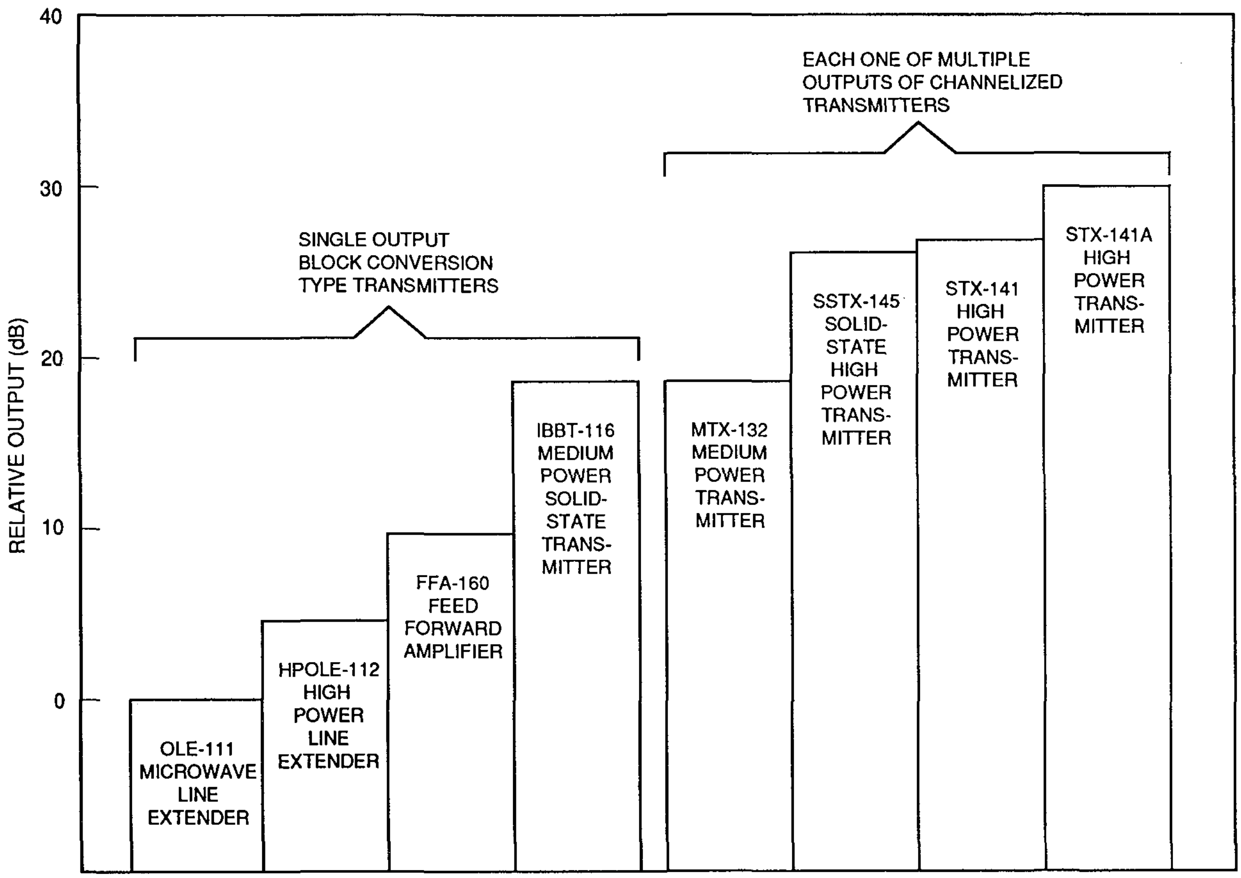

Figure 2 Relative output capability of AML transmitters.

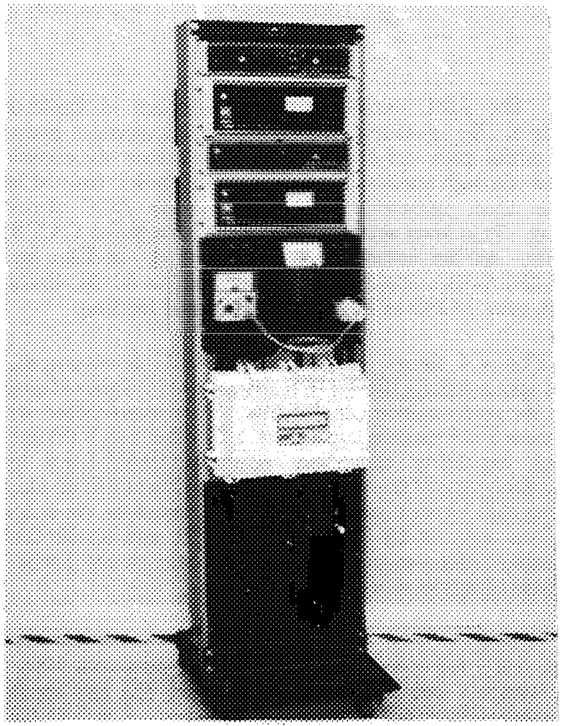

Figure 3 AML equipment used in 60-dB S/N demonstration.

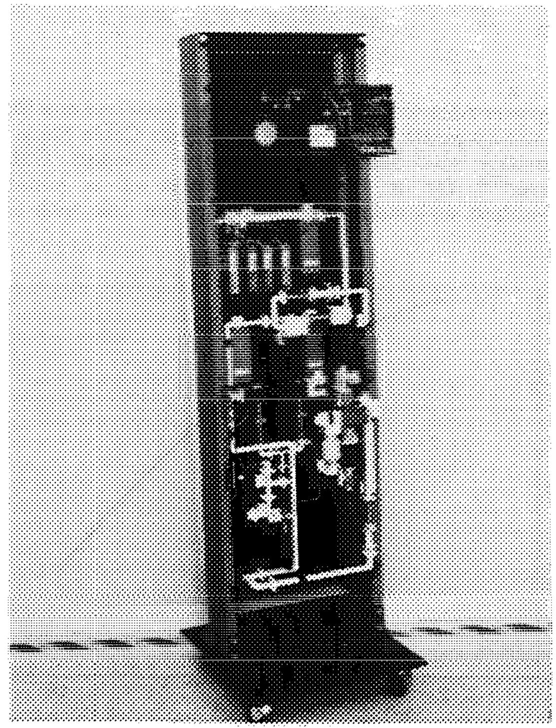

Figure 4 AML IBBT-116 transmitter.

TABLE II

IBBT POWER OUTPUT AND C/N FOR 65 dB C/CTB AND 65 dB C/CSO

No. of Channels	P_0 (dBm)	C/N (dB)
12	15	66
21	13	64
35	10	61
60	7	58
80	5	56

etc., but in general, microwave will be more economical except for applications involving multiple paths under two to three miles in length or where the total of all path lengths add up to less than ten miles. Thus, if cost and performance are the criteria, AML microwave will be preferred in most supertrunk applications. However, in the fiber backbone application, the one technology complements the other.

COMBINED AML AND FIBER BACKBONE

Consider a rather idealized fiber backbone system in which the fiber nodes are uniformly spaced on an 8 by 8 grid. Assume further that the central head-end is located at the point "X" shown in Figure 5a. If the streets run north- south and east-west, the fiber routes might exit the head-end as shown. In total, there are 63 fiber hubs with the four directions connecting respectively to 17, 16, 15, and 15 hubs. If the spacing between hubs is conceived to be unity distance, the maximum length fiber run is eight units long, and the average distance is four units.

Contrast this with the situation in Figure 5b, in which four AML receive sites, indicated by the circles, have been added. The maximum length of fiber run is now reduced to three units, and the average length is 1.85 units. The number of fiber hubs has also been reduced down to 59, because the AML receivers replace the fiber hubs at their locations. The total cable distance is likewise reduced from 63 to 59 units. The central head-end services 11 fiber sites, while each of the AML receivers connects to 12 fiber hubs. Table III summarizes the situation. The cost savings that can be realized in the fiber plant will, of course, depend critically on the actual unit distance. Typically, the "unit" will be in the range of one to two miles or even greater if the length of the trunk cascade is allowed to grow above 4.

A second critical parameter is the number of fibers that will be dedicated to each hub. An estimate of four (including spares) may not be unreasonable, but in some cases there may be even more. One reason for using multiple fibers is to reduce the channel loading on the individual fiber link. In particular, if the loading is reduced to 18 channels, a frequency plan that avoids in-band second-order distortions can be constructed. Aside from being able to increase the per-channel modulation index, m, roughly in proportion to the inverse square root of the

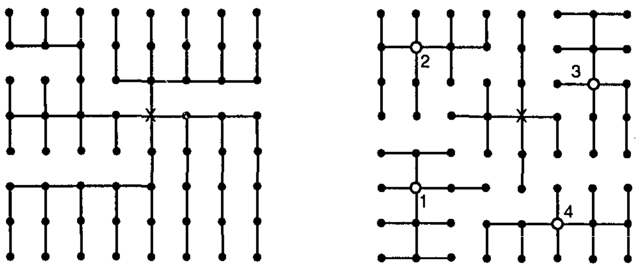

Figure 5 Idealized fiber backbone systems.

number of channels, a further increase in m may be possible if filtering is applied to remove the out-of-band second-order products at the photo receiver output prior to recombining the channels. In all, the C/N shown in Figure 1 might then be increased by about 4 dB, assuming all other DSB laser and receiver parameters were held the same. The exception would be the cross-over channels since the broadband noise would leak through and degrade C/N at the filter band edge. When the signal source is also broadband, as is the case with the AML receiver, it is probable that a guard-band channel would have, in any case, to be set aside to prevent undesired signal phasing effects due to inadequate overall filtering at the source and fiber receiver ends. In any case, multiple fiber links to each fiber hub, although increasing complexity and cost of the electronics (assuming the same quality laser and receiver) is another option which presents itself to the CATV system designer.

To make a numerical comparison between the fiber backbone systems with and without AML, it is necessary to assign a definite length to the unit distance in Table III. With 2-1/4 km, the maximum fiber run length without AML is 18 km. It is assumed that increased C/N can be traded 1:2 for C/CTB without "crashing" the fiber system. Adding 1 dB to Figure 1, one then achieves a more respectable 49.2 dB. However, for the shorter 6-3/4 km maximum fiber distance with AML, normal 65-dB CTB operation is assumed. The AML system consists of an IBBT-116 transmitter backed off to +7 dBm/channel output to improve C/CTB. This can be done, since the maximum AML path length here is only five miles long. The calculation assumes that C/CTB from a chain of dissimilar devices will add randomly, i.e., on a power-addition basis. The AML system cost includes the transmitter, four receivers, antennas, waveguide, typical installation costs, and a $30 K allowance for a transmit tower. The advantage in both cost and performance is evident even at these small distances. As the unit distance increases, the advantages of incorporating AML will tend to increase further.

It is of interest to compare this idealized system with a real CATV system layout. For this purpose, an enlarged cable system trunk route map corresponding to the fiber backbone system described in references 2 and 3 was obtained. Figure 6 shows the originally proposed 61-node fiber plant with four AML receive locations (circles) superimposed. With fiber rerouting, the receive sites service 7, 11, 12, and 14 fiber hubs, respectively, while the central point is connected to only 13 hubs. Although the fiber maximum distance was, without AML, only 9 miles (14.4 km), the ratio of average fiber route distance with and without AML worked out to be 0.50, which compares fairly well with the 0.46 ratio in Table III. The ratio of maximum fiber length correlated less well: 0.44 in the real system versus 0.37 in the idealized case.

TABLE III
COMPARISON OF IDEALIZED FIBER BACKBONE SYSTEMS

System Parameters	Without AML	With AML IBBT-116
Number of fiber hubs	63	59
Maximum fiber-run distance (unit)	8	3
Average fiber-run distance (unit)	4	1.85
Total fiber distance for one fiber/hub (unit)	252	109
Total fiber distance for four fiber/hub (unit)	1008	436
Total fiber cable distance (unit)	63	59
Max. distance from head-end to AML receive site (unit)		3.6
<u>If unit distance = 2–1/4 km</u>		
C/N of longest 42-channel fiber link (dB)	49.2	52.8
C/CTB of fiber link (dB)	63	65
Combined C/N with AML (dB)	49.2	50.3
Combined C/CTB with AML (dB)	63	63.2
Installed cable cost saving @ $6.8K/mile		$38K
Glass cost savings @ 7¢/foot and four fibers/hub		$297K
Fiber hub savings @ $20K/Tx–Rc pair		$80K
AML IBBT-116 System Cost		<$267K>
NET SAVINGS		$148K

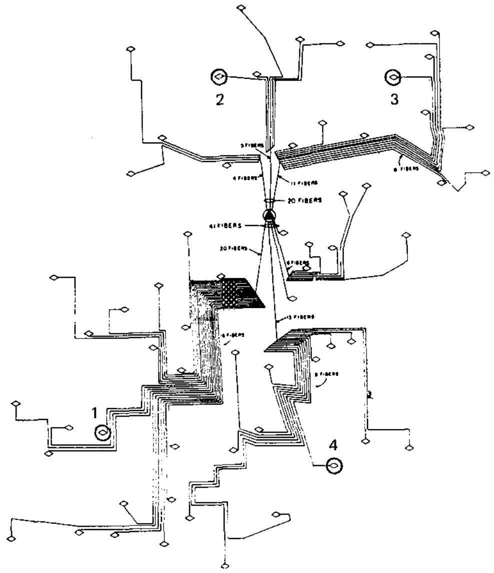

Figure 6 Fiber backbone system[2] with overlay of AML receive sites (fiber layout corresponding to Figure 5b, not shown).

Although there are many similarities between the idealized and real systems, two factors diminish the AML advantage. One is the aforementioned smaller distance. The second factor stems from the Florida location where the rainfall environment is particularly severe. Nevertheless, another possible option in this case serves to illustrate a general point. The central hub site is itself fed from an existing channelized 7.6-mile-distant AML transmitter with parallel 47 dB C/N AM fiber being used to provide a fail soft type of route redundancy to protect against rain fades. With presently unused AML transmitter outputs, additional paths could potentially be implemented to provide signals to one or more of the AML receive sites indicated in Figure 6. Although the cost of possibly upgrading the transmitter must be considered, in many cases the only real cost would be the addition of the receive path(s). In such a case, the economic advantage with AML would be overwhelming.

To achieve the goals[1] of the fiber backbone system with present-day systems, one could construct a system based upon either the AML MTX-132 transmitter or the SSTX-145 transmitter and the above-described reduced channel loading fiber plant. The channelized AML transmitters lend themselves to fiber backbone systems with many more fiber hubs than considered in Figures 5 and 6. The geographic coverage of such systems would extend over large urban and suburban areas. The principal drawback to such systems would be the complexity and cost associated with filtering and multiple laser sources to service each fiber hub.

One could, however, achieve the 50-dB distribution-system goal required by HDTV carriage[12] without reducing the per-fiber channel loading to below 40 channels. For instance, by assigning 58 dB C/N to AML, 52.3 dB to the fiber, and 56 dB to the remaining trunk and distribution, one calculates an overall 50 dB C/N. Table IV summarizes the reach of such a system in a mid-Atlantic (average) rain zone region.

TABLE IV
42-CHANNEL LARGE-AREA FIBER BACKBONE SYSTEM

	MTX-132	SSTX-145
AML transmitter output (dBm)	+9	+16
Number of outputs before splitting	8	8
Assumed antenna diameters (feet)	10	10
Assumed waveguide loss (total transmit and receive) (dB)	4	4
Maximum microwave path length (km)	21.6	30.4
AML system C/N with AGC disabled (dB)	63.3	67.3
AML system C/N (dB)	58	58
Path availability[1] for 54 dB C/N (%) (49 dB total cable distribution system C/N)	99.5	99.6
Path unavailability[1] for 35 dB C/N (hrs/yr)	1	1
Maximum fiber reach for 52.3 dB C/N (km)	9	9
Total equivalent[2] path reach (km)	37	48

[1]Combined rainfall and multipath for CCIR region D2 and 0.25 multipath factor.

[2]Microwave distance multiplied by 1.3 for equivalent fiber distance.

CONCLUSION

A system architecture in which AML drives a fiber backbone system can result in both performance and cost advantages. Generally speaking, the larger the system, the greater the advantage in utilizing AML. However, utilization of recently developed block-conversion type AML equipment can even lead to advantages in modestly sized systems. The tradeoffs are sufficiently complex and employ such a widely ranging set of parameters that each case must be analyzed on its own.

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