adjusting user setup screens to match the dimensions and levels currently defined in the system. If the MPAA defines another level (as they did when NC-17 was introduced), the system can accommodate it seamlessly.

Rating regions

It may be in North America that Canada and Mexico will not elect to use the same standards for program ratings we use in the United States. SI provides a means to define several independent rating systems, where each system is identified by its "region" and given its own name. The Rating System Table provides the mapping between the rating region code and its textual name.

Decoders can be assigned to a rating region either through an installation or user-preference option, or by a private message individually addressed to the Decoder. If the Decoder offers the user a choice of rating system, it labels those choices using the names in the RST.

Each rated program must carry with it, either within the Program Map Table or an message in that same PID, rating data for each supported region.

Currency System Table

Currency regions are to IPPV what rating regions are to parental ratings. SI carries a Currency System Table that assigns a textual name to each currency region supported in the system. Currency regions are handled in the Decoder much like rating regions, in that each Decoder is assigned (by the user or system operator) to one region.

Decoders in the US would be placed into the US currency region, and IPPV programs will indicate cost in terms of US dollars. If a currency region is established for Mexico, IPPV programs for Decoders in the Mexican currency region can be labeled with costs in units of pesos.

Map Name Table

In some instances, it can be helpful if the system provides to the Decoder a textual name for Virtual Channel Tables in use. This feature is expected to be most useful for over the air broadcast use of VCTs, but may prove to be useful in cable systems as well.

CONCLUSION

This paper has shown how ATSC A/56, *System Information for Digital Television* applies to cable, how it is used to define the environment in which digital cable Decoders navigate among available analog and digital services, and how it facilitates and supports the use of some of the new features made available by digital transport.

APPENDIX F

CATV Return Path Characterization for Reliable Communications

Operators with CATV systems are interested in offering telecommunications services, so there is a tremendous need for equipment to support bidirectional communications over HFC. Providing reliable solutions for bidirectional HFC communications will require a thorough understanding of the channel characteristics in the return direction.

Charles A. Eldering, Nageen Himayat, and Floyd M. Gardner

The Community Access Television (CATV) industry was established by providing low-cost distribution of broadcast video signals to subscribers. The Hybrid Fiber-Coax (HFC) architecture, in which a fiber is used to transport subcarrier multiplexed signals to a group of 500 to 2000 subscribers, has become standard in the CATV industry and provides up to 750 MHz of bandwidth to the subscriber in the forward (broadcast) direction. Because the architecture does not contain switching elements in the distribution plant, and only requires optical-to-electrical and electrical-to-optical conversion, amplification, and power splitting, the plant cost is relatively low. Typical HFC costs are on the order of US$300 per home passed (500 home node, 70 percent aerial plant, including installation) not including settop costs. The HFC architecture is now also being considered as a bidirectional broadband communications infrastructure, with the 5 to 40 MHz portion of the spectrum available in the distribution plant for transmission from the subscribers to the headend/central office. The incremental cost for adding telecommunications services over HFC is expected to be below $300 for volume deployments, even when the penetration rate for the services is relatively low (10 to 20 percent). Because the cost for adding telecommunications services over HFC is relatively low, and because operators with CATV systems are interested in offering telecommunications services, there is a tremendous need for equipment to support bidirectional communications over HFC. Providing reliable solutions for bidirectional HFC communications will require a thorough understanding of the channel characteristics in the return direction.

The HFC plant is a tree and branch network emanating from a headend or central office, and terminating at the subscriber residences. This architecture is shown in Fig. 1. In the forward direction transmission from the central office/head end is via a single mode fiber, with the source being a highly linear optical modulator operating at a wavelength in the 1310 or 1550 nm range. Both distributed feedback (DFB) lasers and external modulators are used as sources. The node performs the function of optical to electrical conversion and signal amplification for transmission on the coaxial portion of the network. Active elements provide amplification along the coaxial path, and passive taps are used to provide a portion of the signal power to the subscriber via the drop cable. Additional splitting may take place in the residence. In the return direction, signals sent from the subscriber reach the first active, are amplified and transmitted to the node where they are combined with signals from the other coaxial branches, and are modulated onto a laser which transmits the signals to an optical receiver at the central office/headend. In new installations the usable downstream bandwidth extends from 50 to 750 MHz and the return bandwidth is from 5 to 40 MHz.

Return Path Characteristics

The HFC network provides a cost-effective means of delivering bandwidth in the downstream and providing subscribers with approximately 700 MHz of useable bandwidth for both analog and digital signals. Because the network is a tree and branch architecture, the transmission path from the subscribers to the headend is shared and, as discussed previously, provides 35 MHz of spectrum in the 5 to 40 MHz portion of the spectrum. This spectrum is shared among subscribers with the net effect that the signal received at the headend is the sum of the subscriber signals. The return path is generally engineered to provide unity gain from the first return active as seen coming from the subscriber to the headend receiver, thus signals generated at the subscriber location encounter varying degrees of attenuation from the subscriber to the first active, and are received at the headend at the same signal level which appears at the first return active.

The tree and branch architecture results in a phenomena commonly called noise funneling, which is the summation of the unwanted noise and ingress from both the subscribers and the cable plant

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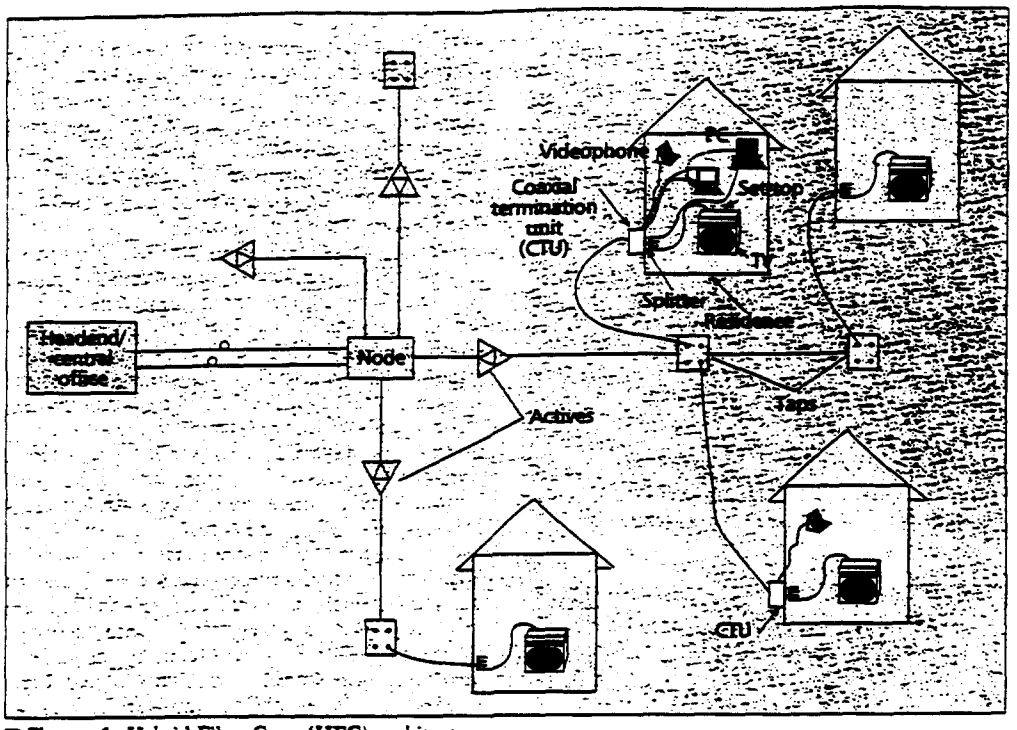
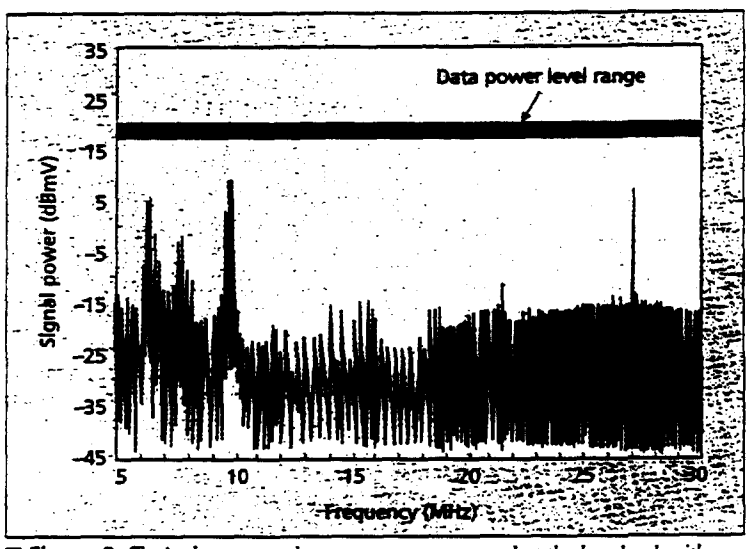


■ **Figure 1.** *Hybrid Fiber-Coax (HFC) architecture.*

in the return transmission system. The following examples illustrate the effect of noise funneling and are based on the assumptions that sources of unwanted signals are located at the subscriber locations and that their amplitudes are varied to produce a specified level at the input to the return amplifiers. For unwanted signals which are uncorrelated noise (e.g., Gaussian noise) the signals sum noncoherently: if the signal levels from each subscriber as measured at the input to the first return active (amplifier) were equal, then the noise funneling factor would be equal to $10\log n$ where n is the number of subscribers. If the signals are correlated and are exactly in phase, the noise funneling factor would be equal to $20\log n$. As an example of the effect of noise funneling, a 500 home node would exhibit a noise funneling factor of 27 dB for uncorrelated noise sources, and a factor of 54 dB for correlated in-phase sources.

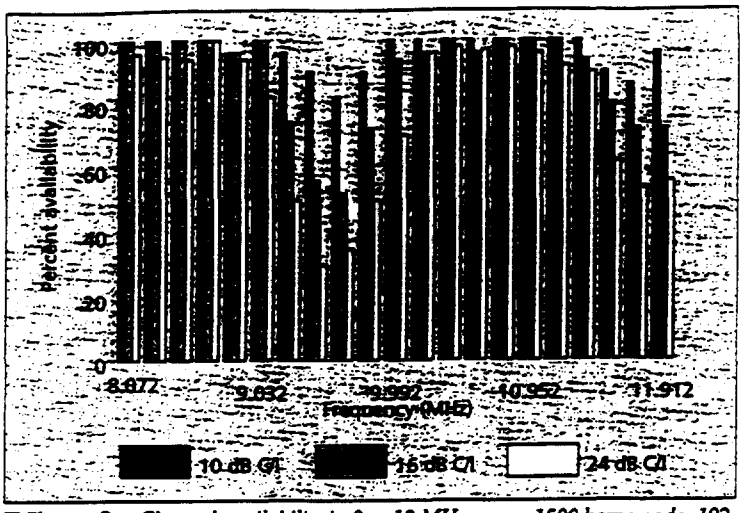
The fact that noise funneling occurs was confirmed by observing the return path spectrum at various headends (the measurement setup is described in Appendix A), which typically contain a number of narrowband interferers that are clearly identified as AM shortwave stations. Measurements of the signals on the coaxial cable at an individual subscriber location (with all of the coaxial cables in the home funneled into the home splitter) indicated the same types of AM signals, but at a lower level than what was observed at the headend. Accounting for a typical loss between the subscriber and the first return active of 18 dB, and a noise funneling factor of 32 to 45 dB (assuming a 1500 home node and some degree of coherency between subscriber signals) the expected value at the headend would be 14 to 27 dB higher than the signals observed at the subscriber location. This was in fact the case, with a typical AM signal at the home location being in the range of −25 to −35 dBmV, and the signals at the headend



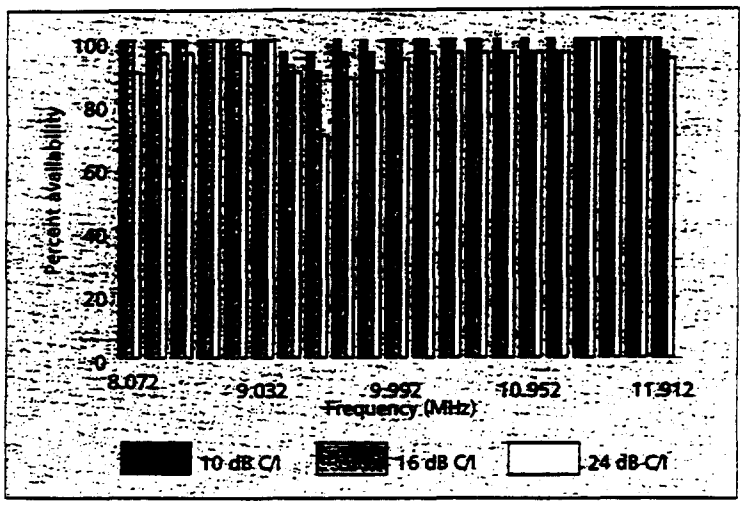
■ **Figure 2.** *Typical return path spectrum as measured at the headend, with data power level range indicated.*

being in the range of −21 to 2 dBmV for a return path with unity gain. Figure 2 illustrates a typical return path spectrum as measured at the headend in the absence of active data carriers. The expected data power level is 25 dBmV and is indicated on the figure. In this system there was an additional 10 dB gain in the return path, thus, the observed noise signals in the range of −13 to +13 dBmV are close to the range of expected values. The narrowband interferers are clearly identified in Fig. 2, and it was possible to demodulate them and identify particular AM shortwave transmissions at the headend, as well as at the subscriber locations.

The types of ingress which appear on the cable return path can be classified into three broad categories:



■ **Figure 3a.** *Channel availability in 8 to 12 MHz range, 1500 home node, 192 kHz wide channels.*



■ **Figure 3b.** *Channel availability in 8 to 12 Mhz range, 500 home node, 192 kHz wide channels.*

- Narrowband shortwave signals propagated through the atmosphere and coupled to the return path at the subscriber location or in the distribution plant.
- Impulse noise.
- Common mode distortion, originating from nonlinearities in the plant (e.g., oxidized connectors).
- Location specific interference (intentional or unintentional) generated by a device at a subscriber location.

Narrowband interference is most easily understood by considering the characteristics of propagation of HF signals. Signals in the 5 to 30 MHz region of the spectrum can be propagated around the world with the success of propagation depending on the amount of skip which occurs in the upper layers of the atmosphere. In addition to the diurnal variations in propagation, there is also a strong dependence on the 10.7-year solar sunspot cycle. Increases in solar sunspot activity are highly correlated with increases in the maximum useable frequency, due to increased ionization in the upper layers of the atmosphere. A low in sunspot activity will occur during the period 1994-97, and the peak is expected to occur sometime in 1998-2007. This will potentially result in increased propagation of HF signals in the upper part of the 5 to 30 MHz spectrum, and if the ingress is coupled in from subscriber locations, may result in decreased availability of channels. Methods of decoupling the cable return path from the coaxial network in subscriber location in order to reduce ingress will be discussed in a following section.

Impulse noise is present on the cable return and may occur via the coupling of impulse events generating strong electromagnetic fields at particular subscriber locations, which couple to a particular coaxial drop or feeder cable, or from impulse events generating fields propagated though the atmosphere that couple to the plant at numerous subscriber locations. Impulse noise is generated by man-made sources such as electrical motors, engine ignitions, and power switching, and although these sources generally produce events in the 60 Hz to 2 MHz portion of the spectrum, the harmonics of these events contribute to impulse noise at higher frequencies. Computers and digital equipment are sources of impulse noise in the 5 to 40 MHz portion of the spectrum. Naturally occurring sources of impulse noise include lightning, atmospherics, galactic noise, and electrostatic discharge. These naturally occurring impulse events cause disturbances which typically extend from 2 kHz to 100 MHz. CCIR studies on man-made radio noise have shown that there is a strong $1/f$ dependence on the noise observed (both impulse and background noise) in the atmosphere as well as a dependence on the location, with industrial and urban locations showing higher levels of noise than rural locations [1]. Considering that much of the man-made noise is impulsive in nature, there is bound to be a strong man-made component of impulse noise on the return path. The consequence of impulse noise is that even if narrowband interference is not present, impulse events may limit the bit error ratio performance of HFC systems unless Forward Error Correction (FEC) is employed. Present data indicate that FEC can be employed to correct for the majority of errors caused by impulse noise, thus impulse noise is not seen to be a limiting factor for HFC communications. In addition to the use of FEC, filtering techniques to reduce the cumulative ingress will also aid in reducing impulse noise.

Common mode distortion, caused by nonlinearities in the plant (typically oxidized connectors and fittings) can be observed in many cable returns as discrete noise peaks in the return spectrum spaced by 6 MHz. In properly designed and maintained plants this phenomena can be controlled.

Location-specific interference may be intentional or unintentional and results in sources at a subscriber site which couple high levels of interference in the 5 to 40 MHz region into the cable return system. Examples of these types of interferers include amateur radio operators with equipment connected to the cable return, or homes in which the coaxial cable wiring is close to a piece of equipment which transmits high power levels in the 5 to 40 MHz range. These types of interferers need to be dealt with by search and disconnect algorithms which locate the source of the interference and disconnect that subscriber or a small portion of the network from the return system. A description of methods to perform this are beyond the scope of this article, but it suffices to say that if discon-

nect points are available at the subscriber locations (e.g., telecommunications unit on the side of the home) and for small (e.g., 16 to 32) numbers of subscribers, it will be possible to locate and disconnect location specific sources of interference. It should be noted that although interference cancellation algorithms may be successfully employed to cancel a limited number of relatively stationary narrowband interferers, these algorithms cannot be expected to protect the network against maliciously generated interference.

Spectral Availability

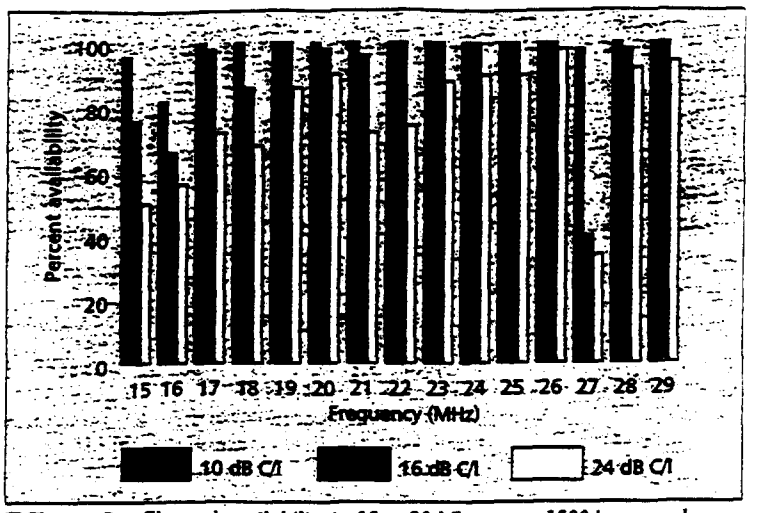
In order to determine the effect of narrowband interferers on channel availability, measurements were made on cable return systems and involved taking automated spectral captures of return path ingress every one to five minutes over an extended period of time (48 to 72 hours). The data were then postprocessed to determine what percentage of time channels of a particular bandwidth would have been unavailable, given that a particular modulation format (e.g., QPSK or 16QAM) was utilized.

In order to transmit QPSK and achieve a BER $\leq 10^{-10}$ in the presence of Gaussian noise and interference, the required C/(N + I) must be at least 15.8 dB. However, if the C/N is higher than 15.8 dB, narrowband interferers can be tolerated and the BER maintained. As an example of this, if the C/N is maintained at 21 dB, a single narrowband interferer as high as 10 dB below the equivalent unmodulated carrier (resulting in a C/I of 10 dB) can be tolerated [2].

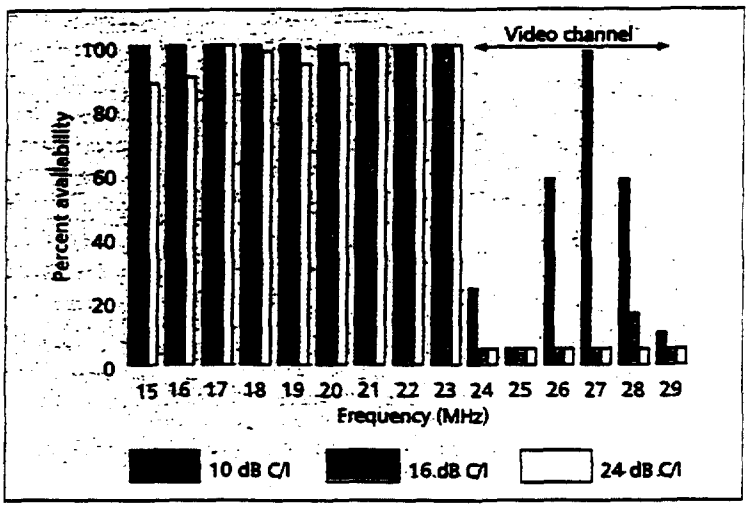
Figures 3a and 3d illustrate channel availability (in the 5 to 15 MHz band for 192 kHz wide channels, and in the 15-30 MHz band for 1 MHz wide channels) and illustrate the effect of reducing node size. It should be noted that the 1500 home node represented in Figs. 3a and 3c was a different node than that represented in Figs. 3b and 3d, however, both nodes are representative of suburban cable plants. It is clear that a reduction in node size reduces the noise funneling effect. In addition, channel size has an important effect on the efficiency of usage of the return spectrum. Availability of the overall spectrum when wider channels are used can be significantly lower than with narrow channels, as each wide channel which becomes unusable due to a the presence of one or a few narrowband interferers will cause a substantial decrease in the payload carrying capacity of the return spectrum. The regions of lower availability in the 5 to 15 MHz range were clearly identified as regions where AM commercial shortwave signals were predominant. It should also be noted that in Fig. 3d the low availability in the 24 to 30 MHz region was due to the presence of a 6 MHz video carrier being transmitted from a subscriber location (in this case the Town Hall) to the headend for subsequent retransmission to all of the subscribers in that serving area.

Return Path Filtering

Filtering of the return path is a possible means of reducing return path interference. The principal of filtering is illustrated in Fig. 4 and consists of blocking a portion of the spectrum from in-home devices (e.g., set-tops) and thus



■ **Figure 3c.** *Channel availability in 15 to 30 Mhz range, 1500 home node, 1 MHz wide channels.*



■ **Figure 3d.** *Channel availability in 15 to 30 Mhz range, 500 home node, 1 MHz wide channels. Note that the presence of a video channel in the 24 to 30 MHz region resulted in a low degree of availability.*

eliminating cumulative ingress coming from inside the residence. In the proposed scheme, the 5 to 15 MHz band is accessible from inside the home, but a low pass filter prevents any signals in the 15 to 40 MHz region originating inside the subscriber residence from entering the return path. A modem providing telecommunications services (e.g., POTs, videotelephony, and high speed data) utilizes the 15 to 40 MHz portion of the spectrum, and is located after (coming from the subscriber) the blocking filter. In this way the amount of ingress in the return path in a particular frequency range can be significantly reduced. Although still under study, the present data suggests that the majority of the ingress originates from inside the subscriber residence.

Modulation and Multiple Access Techniques

There are a number of modulation formats and multiple access techniques which can be used to transmit data on the cable return path.

Multiple access technique	Method of allocating subscriber bandwidth
TDMA	Assignment of additional time slots
CDMA	Increase subscriber data rate with appropriate increase in subscriber power
FDMA	Increase in number of assigned channels

■ **Table 1.** *Bandwidth allocation methods for multiple access techniques.*

In the following sections a comparison of three basic multiple access techniques is given and a number of phenomena which can affect their performance are discussed.

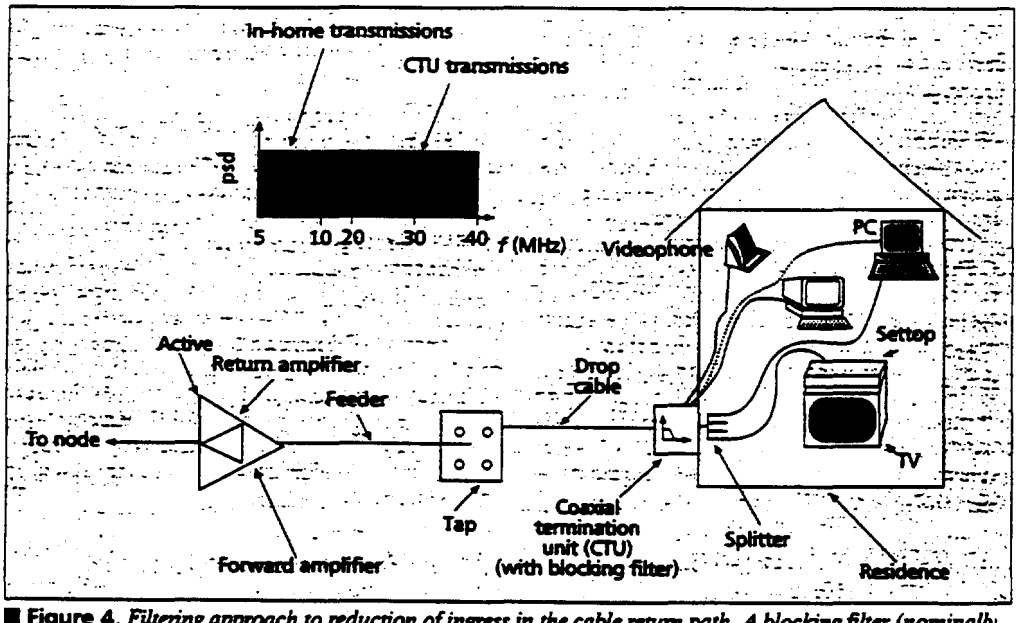
A well-engineered cable plant has nearly flat amplitude response and nearly linear phase response over its entire useful passband. Little intersymbol interference (ISI) is induced in the cable portion of the plant. Subscribers' premises are less easily controlled and unterminated cables, bridged taps, and other noncomformities generate echoes on the subscriber-generated signal, but the echoes generated can be dealt with at the receiver via equalization techniques. The ratio of upstream signal power to internal Gaussian noise is in the neighborhood of 28 dB. Such a high SNR permits use of high-order, bandwidth-efficient constellations (e.g., 64QAM) with low probability of transmission error, in the absence of other disturbances. Because the plant is well controlled in terms of amplitude and phase response and has a controlled SNR which can be quite high, one would expect the capacity of the return system to be quite high from a theoretical standpoint. Indeed, with 25 MHz of bandwidth and 28 dB signal-to-noise ratio with respect to Gaussian noise, the Shannon capacity of upstream transmission is 233 Mb/s, equivalent to 3634 DS-0 channels of 64 Kb/s each.

From a practical standpoint, a bandwidth of 25 MHz can support a maximum symbol rate of 25×10^6 PAM/QAM symbols per second. At b = 1 b/symbol, a bit-rate of 25 Mb/s is possible, or 390 DS-0 channels. For $b = 4$ (e.g., 16QAM), 1560 DS-0 channels are predicted, while 2340 channels are predicted for $b = 6$ (64 QAM). Although these are upper theoretical bounds, not realizable in practice, they do show that substantial capacity is potentially available in the upstream cable. Because the return path has inherent difficulties due to noise funneling, and the multiple access protocol will have overhead, it is important to understand the capacities which might be obtained using particular modulation formats and multiple access techniques.

Three different methods of multiple access in widespread use are:

- Time Division Multiple Access (TDMA).
- Frequency Division Multiple Access (FDMA).
- Code Division Multiple Access (CDMA).

Each can be subdivided into subcategories: For TDMA, one could have a single data stream on the cable, with up to 25×10^6 serial time slots per second. More likely is a combined TDMA/FDMA scheme, with perhaps 1×10^6 time slots per second on each of up to 25 carriers. Either way, a subscriber is assigned particular time slots on a particular carrier. For FDMA, each signal might have a single carrier, or might have multiple tones (multicarrier modulation [3]). A subscriber then is assigned particular frequency slots. For CDMA, each subscriber is assigned a particular spreading sequence, or a particular delay shift of a spreading sequence common to all subscribers. Table 1 summarizes the bandwidth allocation methods for each of the multiple access techniques. Each method for multiple access has its own distinct vulnerability to the disturbances present in a CATV return system, as discussed in the following sections.



■ **Figure 4.** *Filtering approach to reduction of ingress in the cable return path. A blocking filter (nominally 15 to 40 MHz) is deployed between the in-home splitter and a side of the home transmission unit called the Coaxial Transmission Unit (CTU). Signals from in-home devices (e.g., set-tops) can be transmitted directly in the 5 to 15 MHz region, while signals in the 15 to 40 MHz region are added in the CTU.*

Power Backoff

Signal transmission is peak-power limited to P_m Watts. Exceeding that power level causes unacceptable distortion. In single-carrier TDMA, in which only one signal is on the line at any one instant, the average power of transmission can be P_m. In all other multiple-access methods (including combined TDMA/FDMA), multiple simultaneous signals share the line; the peak power of their sum must be constrained. In practice, the average power of the sum will be constrained to be P_m/γ, where γ is a crest factor, whose value is determine empirically such that the peak power of the sum of signals rarely exceeds P_m. Typical values of γ range from 5 to 15 (7 to 12 dB). Thus, all other methods take a 7 to 12 dB power penalty with respect to fast, single-carrier TDMA. The 28 dB signal-to-noise ratio previously mentioned already includes a crest-factor allowance.

Multiple Access Interference (MAI)

Both TDMA and FDMA can be arranged so that adjacent slot (time slot or frequency slot) signals contribute negligible interference to the desired signal. By contrast, the massively dominant limitation on CDMA capacity is the multiple access interface (MAI) from other CDMA signals sharing the same channel. Research is underway to develop CDMA receivers with improved MAI, but the attainable performance remains to be determined [4].

Echoes

TDMA, and in particular single-carrier high data rate TDMA, is vulnerable to the ISI caused by echoes. Required equalization is unique to each individual upstream signal, thus equalizers would have to be fast and complicated. Narrowband FDMA should be virtually immune to echoes. No significant ISI is expected. At worst, provisions are needed for comparatively slow amplitude and phase adjustments for each carrier or each tone. Simple CDMA tends to reject echoes sufficiently time-displaced from the direct signal, while more sophisticated CDMA employing diversity reception combines those echoes with the direct signal for improved performance.

Multiple access technique	Effect of interferer
TDMA	Channel cannot be [illegible] certain level
CDMA	After despreading interference appears as white noise, capacity of system decreases accordingly.
FDMA	Deletion of corrupted frequency [illegible] system decreases accordingly.

■ **Table 2.** *Effect of a narrowband interferer on a given multiple access technique.*

Narrowband Interferers

TDMA is exceedingly vulnerable to narrowband interferers; small numbers of sufficiently strong interferers can wipe out an entire TDMA stream. Combined TDMA/FDMA is less vulnerable because fewer interferers are likely to appear in a narrower bandwidth. If the cable channel can be monitored, and if FDMA frequencies can be assigned on the basis of the interference environment, then interfered channels can be avoided. With intelligent assignments, FDMA capacity is nearly unaffected by moderate numbers of narrowband interferers. Analysis suggests that maximum transmission capacity is retained if individual FDMA bandwidths are made comparable to the bandwidths of typical interferers (about 6 kHz for shortwave signals). This property favors multitone transmission of each subscriber's signal. A CDMA receiver spreads the spectrum of an interferer, to make it a wideband disturbance. Each individual interferer is suppressed by the processing gain of the spread-spectrum system, but the wide bandwidth admits many more interferers than would a narrowband system. Therefore, no net improvement is gained by spectrum spreading if the interferers are uniformly distributed (on average) across the spectrum. A summary of the effect of narrowband interferers on each of the basic multiple access techniques is given in Table 2.

Multiple access technique	Parameters	Modulation type*	Number of 64 kb/s data channels supported
TDMA	$\alpha = 0.5$ No preamble or guard time $\gamma = 1$	16QAM	1040
CDMA: perfect synchronization	$\alpha = 0.5$ $\rho = 260$ Perfect synchronization $\gamma = 10$	16QAM	1040
CDMA: asynchronous	$\alpha = 0.5$ $\rho = 260$ No synchronization $\gamma = 10$	BPSK	15 to 60
FDMA	$\alpha = 0.5$ $\gamma = 10$	16QAM	1040

α = excess bandwidth factor; ρ = spreading factor; γ = crest factor
* Higher order constellations could be used for TDMA and FDMA, achieving greater capacity

■ **Table 3.** *DS0 capacities in an ingress-free 5 to 30 MHz cable return path (BER < 10^{-9}).*

Ingress in the cable return path is primarily due to broadcast signals that accumulate due to the noise-funneling effect of the cable return.

Impulse noise

All CDMA users are equally afflicted by the interference that is present, because spectrum spreading also spreads the affliction, rather than allowing it to be concentrated on those unlucky few users whose frequencies coincide with interferers. TDMA readily counteracts impulse disturbances with error-correction coding. FDMA spreads the energy of an impulse among all frequency slots, in such manner that it takes a stronger impulse to cause an error than in the equivalent TDMA signal. In that sense, FDMA is more resistant to impulses than TDMA. But if the impulse is strong enough to cause an error, then it is likely to affect all FDMA channels at once, and cause a large number of errors. Moreover, repetitive errors due to periodic impulse trains (e.g., from power-line corona) are much more damaging in FDMA because of the high ratio of impulse events to transmitted symbols; coding is much less effective than for TDMA. CDMA is presumed to respond to impulses much like FDMA of the same symbol rate.

Comparison of Capacities

A simple comparison of the capacity of a 25 MHz ingress-free return path serves to illustrate the fundamental differences between the multiple access techniques. A summary of such a comparison is given in Table 3 and includes the assumptions made in calculating the capacities. From this comparison it can be seen that in theory TDMA, FDMA, and CDMA would inherently have the same capacity. Achievement of this capacity for CDMA would require perfect synchronization, down to a fraction of a symbol. If there is no degree of synchronization in the CDMA system, the capacity drops to less than 10 percent of the capacity when perfectly synchronized due to multiple access interference [5]. In the case of unsynchronized CDMA, the modulation type does not affect the capacity, due to the fact that a higher order modulation format would support a higher data rate, but would also require a higher SNR after the correlator. It should be noted that CDMA may be preferable over TDMA and FDMA in cellular radio systems, however, this is due in part to cell-reuse and multiple path interference issues which do not exist on the fixed cable return system.

Conclusions

In this article we have examined the basic characteristics of hybrid-fiber coax (HFC) return systems to evaluate their ability to support bidirectional communications. The ability to support bidirectional communications on cable plants will allow deployment of two-way video applications as well as telecommunications services over the HFC plant.

The results of our studies indicate that ingress in the cable return path is primarily due to broadcast signals which accumulate due to the noise-funneling effect of the cable return. Although this ingress can manifest itself in strong narrowband interferers which will prevent the use of large bandwidth channels, a reduction of node size to nodes on the order of 500 homes or lower will reduce the amount of interference. Filtering, in which a portion of the spectrum is blocked from the subscriber residence may also result in a significant reduction of ingress. Other phenomena on the return path can be dealt with by means of sound communication system design, including Forward Error Correction to deal with impulse noise, and adaptive equalizers to deal with reflections in high data rate designs.

TDMA, FDMA, and CDMA can all be utilized on the cable return path, but the capacities which result when less than perfectly synchronized CDMA is utilized are substantially lower than for TDMA and FDMA. A single carrier TDMA approach will be highly susceptible to narrowband interferers, and is unlikely to be successful. For these reasons a TDMA/FDMA or pure FDMA approach with narrow channels is likely to be the most robust multiple access technique for the cable return path.

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Biographies

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