Engineering Requirements for Hybrid Fiber - Coax Telephony Systems

Charles Eldering[†]
Marc Kauffman[†]
David Grubb[†]
Steve Warwick[‡]
George Hawley[‡]

[†]General Instrument Corporation
GI Communications Division
2200 Byberry Rd.
Hatboro, PA 19040

[‡]DSC Communications
1310-C Redwood Way
P.O. Box 750699
Petaluma, CA 94975-0699

Abstract

Deployment of telephony services over the hybrid fiber-coax plant requires an understanding of the key system design parameters including bit error ratio, round trip delay, available bandwidth, system capacity, and system reliability. This article examines these parameters and discusses ways in which the cable operator will be able to provide telephony and advanced services over the hybrid fiber-coax plant.

Introduction

The rapid convergence of the cable and telephony industries poses the challenge to develop systems that can support traditional voice and data services, traditional broadcast services, and provide a migration path for advanced two-way video and multimedia services. The motivation for designing an integrated system over hybrid fiber-coax is to produce a single system which provides all of these services at a lower cost than separate systems that provide the same services.

Development of equipment to provide these services requires hybrid fiber-coax plant of suitable quality with node sizes of 500 - 2000 homes, as well as recognition of the key system design parameters such as bit error ratio and round trip delay which will need to be considered when deploying systems that support telephony services over the fiber-coax plant.

In this article we discuss a number of engineering requirements for hybrid fiber-coax systems, including the applicability of Bellcore Fiber In The Loop (FITL) requirements, requirements for the distribution system, channel capacity and bandwidth allocation, encryption requirements, round trip delay requirements, and system reliability. Finally we show how telephony services will eventually be integrated with advanced video and data services on the fiber-coax network.

Figure 1 illustrates an architecture for initial telephony services deployment, in which Coaxial Network Units (CNUs) are served off of the feeder part of the network by power passing taps and drop cables, and which provide telephony services to customers via twisted pair drops. The CNUs support 18-64 customers, and are similar in functionality to the Optical Network Units (ONUs) used in FITL applications. If the CNUs are supported by a Host Digital Terminal (HDT) as shown in Figure 1, fibers can be run to high density areas or businesses which have a service demand which will support a dedicated fiber.

Figure 2 illustrates a more advanced architecture in which Coaxial Termination Units (CTUs) are deployed at the side of the subscriber residence and provide basic telephony and advanced telecommunications (N-ISDN, videotelephony, and data) services. In this architecture, the Integrated Services Host Digital Terminal (ISHDT) has added functionality which provides media access control and data packet routing as well as accessing the public switched telephony network. The ISHDT is obtained by augmenting present HDT equipment with additional equipment to provide this functionality: replacement of the HDT is not necessary.

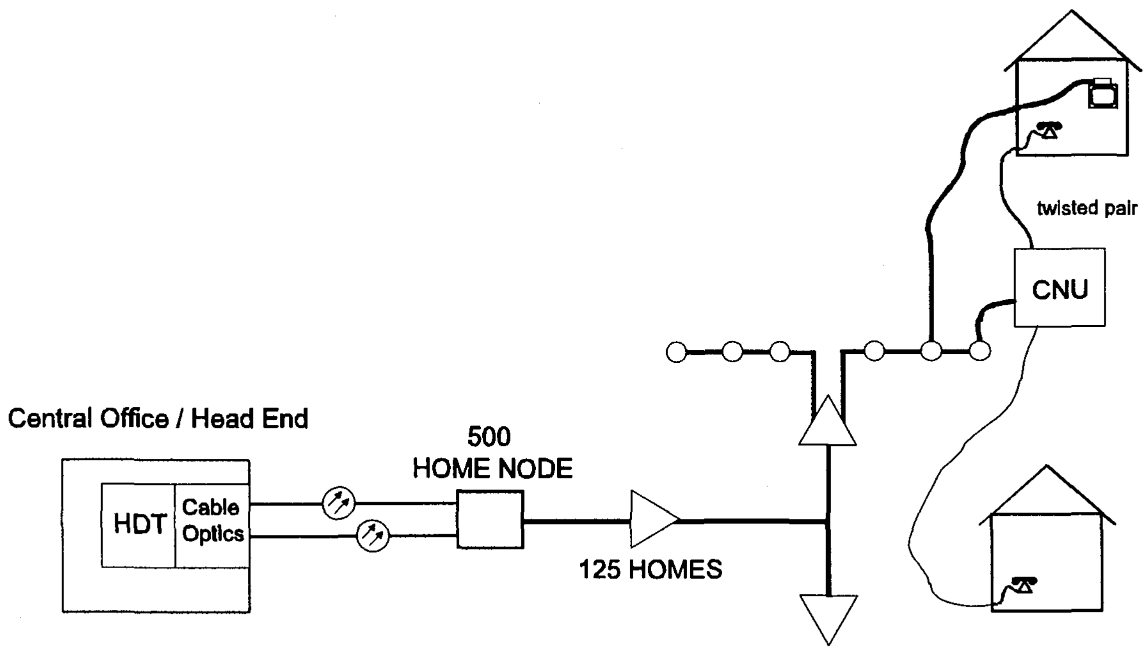

Figure 1. Initial telephony deployment, in which Cable Network Units (CNUs) are supported by the distribution network and the Host Digital Terminal (HDT) which is deployed at the head-end or central office. The CNUs provide service to 18-64 customers via twisted pair drops.

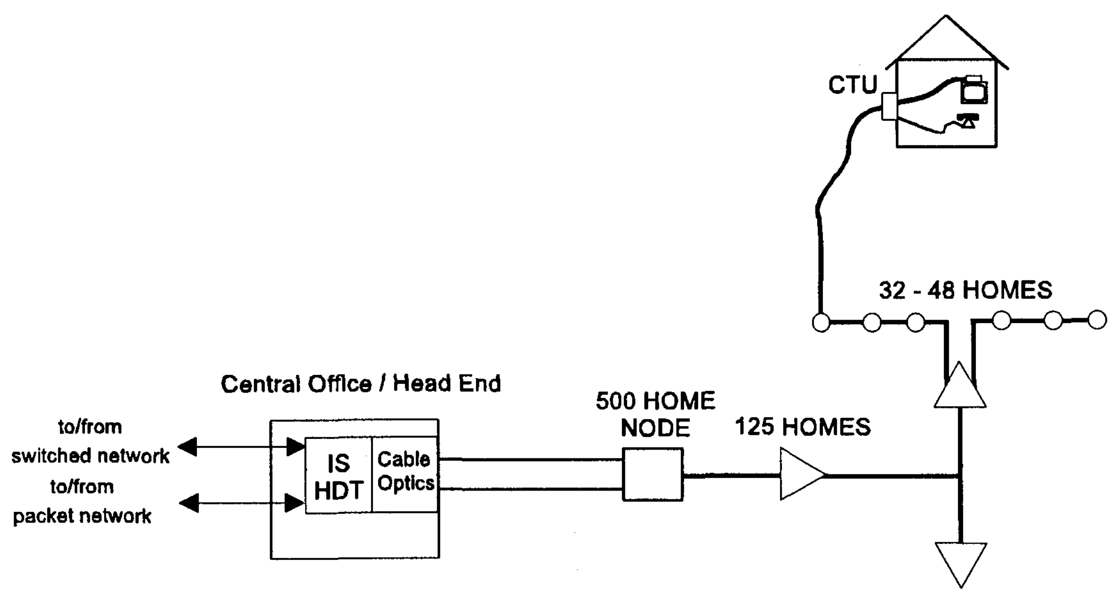

Figure 2. Advanced telephony deployment, in which Coaxial Termination Units (CTUs) are deployed at the residence, and are supported by the Integrated Services Host Digital Terminal (ISHDT) deployed at the head end or central office.

Applicability of Bellcore Fiber In The Loop requirements to hybrid fiber-coax systems

Telecommunications services provided over the cable network must ultimately be competitive with FITL services on a cost and performance basis, and must be compatible with FITL platforms. Although there may be exceptions for certain business scenarios, the long term requirement will be to develop cable telephony systems which meet the service objectives of Bellcore[1] TR-NWT-000909:

Service availability of 99.99%, corresponding to a downtime of 53 min/yr/line, excluding the local switch and the customer premises equipment,

Round trip delay not exceeding 2.1 ms, (for universal FITL systems)

BER performance for a DS1 signal transported through a cable telecommunications system of less than $1x10^{-9}$, excluding all Burst Errored Seconds in the measurement period,

Errored Seconds[2] not exceeding 0.14% for a DS1 signal transported through the cable telecommunications system. This is equivalent to no more than 10 Errored Seconds during a two-hour, one-way (loopback) test,

An average frequency of Burst Errored Seconds[3] for a DS1 signal transported through a cable telecommunications system of no more than 4 per day.

Although there are a number of other performance requirements related to transmission, as well as the switch and subscriber interfaces, the parameters listed above will be the most challenging for cable operators to meet. The ability to meet these requirements in the long term will assure that cable telecommunication services are performance competitive with FITL services.

The Bellcore switch interface requirements will be directly applicable to fiber-coax systems, as it will be necessary to support both older TR-008 and TR-057 interfaces, as well as the TR-303 interface, which will become the standard interface in the US. When fully supported by switch manufacturers, the TR-303 switch interface will allow a number of Operations,. Administration and Maintenance (OA&M) functions to be performed by the switch, as well as significantly lowering the costs of providing N-ISDN services.

Distribution plant requirements

For broadcast video services, the distribution plant has shown a continual evolution from a large number of subscribers (20,000 and greater) per head end transmission point over a purely coaxial system, to fiber-coax systems with four 500 - 2000 home nodes served from a single optical transmitter, followed by a coaxial transmission system in which the number of actives is highly reduced or in some cases even eliminated. This trend will facilitate the deployment of 2-way telecommunications services including data, but additional effort will be required to make the distribution plant reliable and secure in order to meet the reliability and service objectives presently met by FITL systems.

Figure 3 shows a Broadband Telecommunications Architecture (BTA) which uses a single optical transmitter for four 500 home nodes, and a dedicated optical transmitter for each return path. The fiber to coaxial transition is at the mini-bridger, which connects to additional mini-bridgers and serves subscribers via feeders and taps to drop cables.

Because the fiber-coax network is a point-to-multipoint system, the use of the return path for telecommunications services will require additional network security to prevent intentional or non intentional interference from rendering the network inoperative. A network security device, as shown in Figure 3, can perform this function by removing one or more subscribers from the network once it is determined that the source of interference originates from that part of the network. One approach to network security will be to develop the ability disconnect a small number (e.g. 4-12) subscribers from the network if the source of interference is located in any part of the distribution network. If necessary, it will also be possible to use addressable taps to individually disconnect a subscriber at the tap. It should be noted that the CTU will also contain a network security device for removing the subscriber from service if that subscriber is identified as an interferer, thus the distribution network security device is additional protection which allows disconnection of that part of the network from the CTU on back in which the interference originates. Techniques for detection of interferers and methods of locating them are presently being developed.

Bandwidth on the return path, and more importantly, usable bandwidth on the return path, is an important issue for deployment of telephony services on the fiber-coax system. Present systems typically have the 5 -30 MHz region available for return path transmission, and systems are now being upgraded for a 5-40 MHz return path. Settops presently operating in the 8-12 MHz region may require additional bandwidth for multimedia services and extension of the settop return path frequencies to the 8-15 MHz region is foreseen. The functions of status monitoring systems operating in the 5-8 MHz range are likely to increase, and this much bandwidth may be necessary for these systems in the future. As will be discussed, the frequency allocation on the return path will be important, as will reduction of the amount of ingress in the system. The achievable signal to noise ratio on the return path is adequate for modulation formats of 64QAM, but interference is likely to limit the modulation format to Quadrature Phase Shift Keying (QPSK) or 16 state Quadrature Amplitude Modulation (16QAM). However, it appears possible to make a portion of the return path spectrum reliable for telecommunications services. If we consider allocation of 25 MHz in the 15-40 MHz range to telecommunications services, there will be sufficient bandwidth for telephony services, but addition of advanced services such as videotelephony, data, and wireless services will undoubtedly require increased return path bandwidth. This can be accomplished by the use of frequency upconversion in the branches of the return path, as shown in Figure 4. In this scenario, all but one of the return path branches are upconverted, and the return path laser is modulated above 40 MHz. Since there is a potentially large bandwidth available from the return path transmitter at the fiber to the headend, (e.g. 750 MHz if a high bandwidth laser is used on the return link) upconversion provides the possibility of greatly increasing the return path bandwidth from the subscriber by translating the 5-40 MHz return spectrum to a region above 40 MHz. A possible frequency allocation utilizing upconversion will be discussed in a later section. The use of a high-split return (900 MHz - 1 GHz) is also possible, but the large transition region required for low cost diplex filters and high gain return path amplifiers make it a generally less desirable approach. However, if ingress and interference problems in the 5-40 MHz region cannot be overcome, the high-split return will become a suitable alternative to upconversion for increased bandwidth.

Powering is a critical issue for both FITL and fiber-coax systems. With the deployment of digital loop carriers, telcos were able to save money by running a fiber to a serving area and deploying the subscriber line card remotely from the central office, instead of running a large bundle of twisted pairs from subscriber line cards in the central office to the subscriber. However, this has complicated the powering scenario in the sense that the remote deployment of line cards will require back up power (e.g. batteries and connection to a remote powering source for generator backup) which was previously located at the central office. The deployment of smaller remote terminals, whether in FITL or fiber-coax scenarios, requires re-engineering of the power distribution network. A detailed discussion of all of the powering alternatives is beyond the scope of this paper, but it is clear that careful analysis of the cost and reliability tradeoffs will be necessary to determine the optimum location of battery backup and remote powering access for generator backup in the fiber-coax network. It is clear however, that in the case of CTU deployment (Figure 2) it will be necessary to power the CTU from the network to insure service during power outage. While power can be distributed from the node through the feeder network, it is not clear that supplying power to the CTU directly via the coaxial drop is optimum. An alternative to powering through the coaxial drop is the use of twisted pair from the tap for powering only. A comparison of the advantages of each of these powering schemes is given in Table I. From this table it can be seen that the advantage of coaxial drop powering is that the simple coaxial connection is compatible with present systems. The principal disadvantages are that the diplexing functions which enable power to be combined and later separated from the RF signal add RF signal loss and require additional diplexing filters, and the center conductor of the coaxial drop cable may exhibit higher I^2R losses than a twisted pair drop. For the twisted pair drop from the tap, the diplexing problem is avoided, but there is additional cost and complexity in terms of connectors and additional cable. Both solutions are technically feasible.

In summary, powering will be a major system consideration for fiber-coax telephony, and while it is likely that an AC, current limited scheme can be used to power the CTU, the tradeoffs between coaxial powering or a twisted pair power drop from the tap need to be carefully examined. For the CNU, coaxial powering will be possible, with minimal impact on the presently used powering schemes. For CTU powering, the presently used distribution network can be modified to support powering, but optimization of the powering scheme will be necessary to reduce cost and maximize reliability.

Table I
Comparison of advantages and disadvantages for coaxial vs. twisted pair drop powering

Coaxial drop powering	Twisted pair drop powering
Advantages:	Advantages:
Installer friendly: does not require separate connection at tap or at subscriber unit	Eliminates power/RF diplexing points at tap and at subscriber unit
Backward compatible with existing drop cables, if cables are in good condition	Low power loss
Disadvantages:	Disadvantages:
Added RF signal loss at tap and CTU	Additional cost in cable and connectors
Potentially high I^2R losses for power distribution	Not backwards compatible with existing cable plants

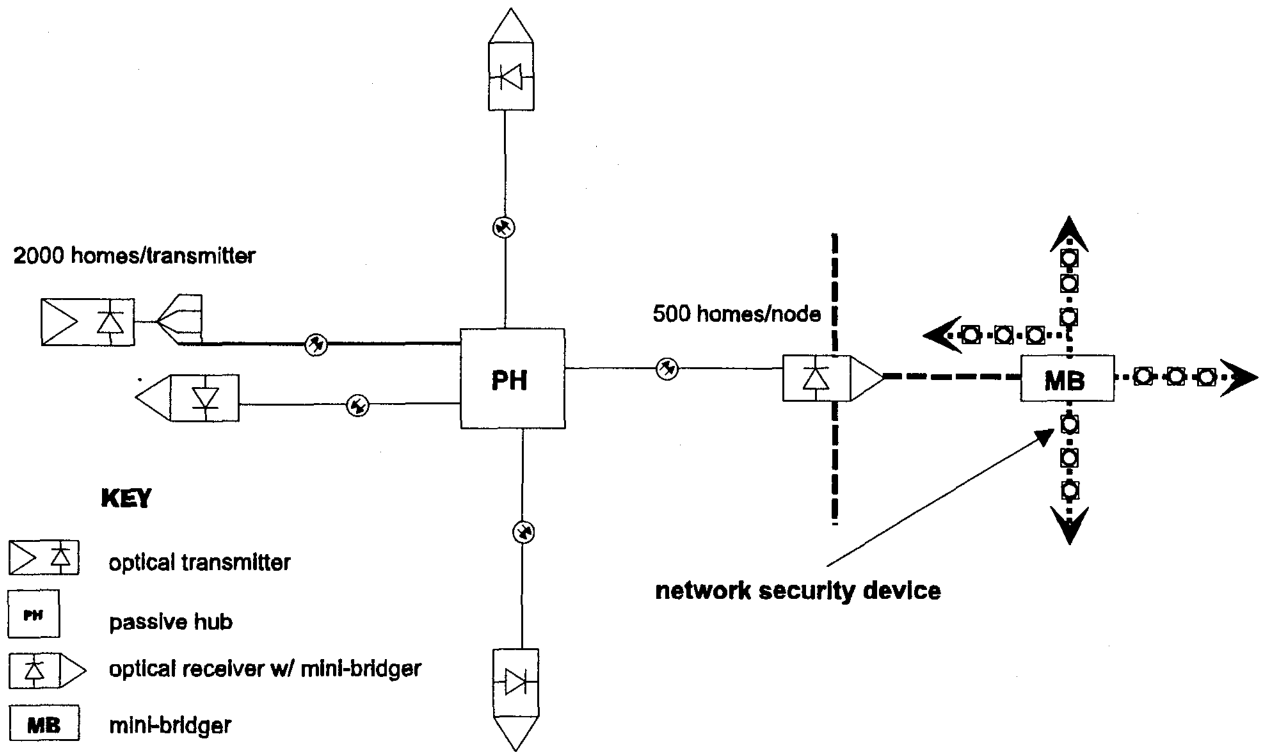

Figure 3. Broadband Telecommunications Architecture (BTA) using 500 home nodes and 2000 homes per optical transmitter.

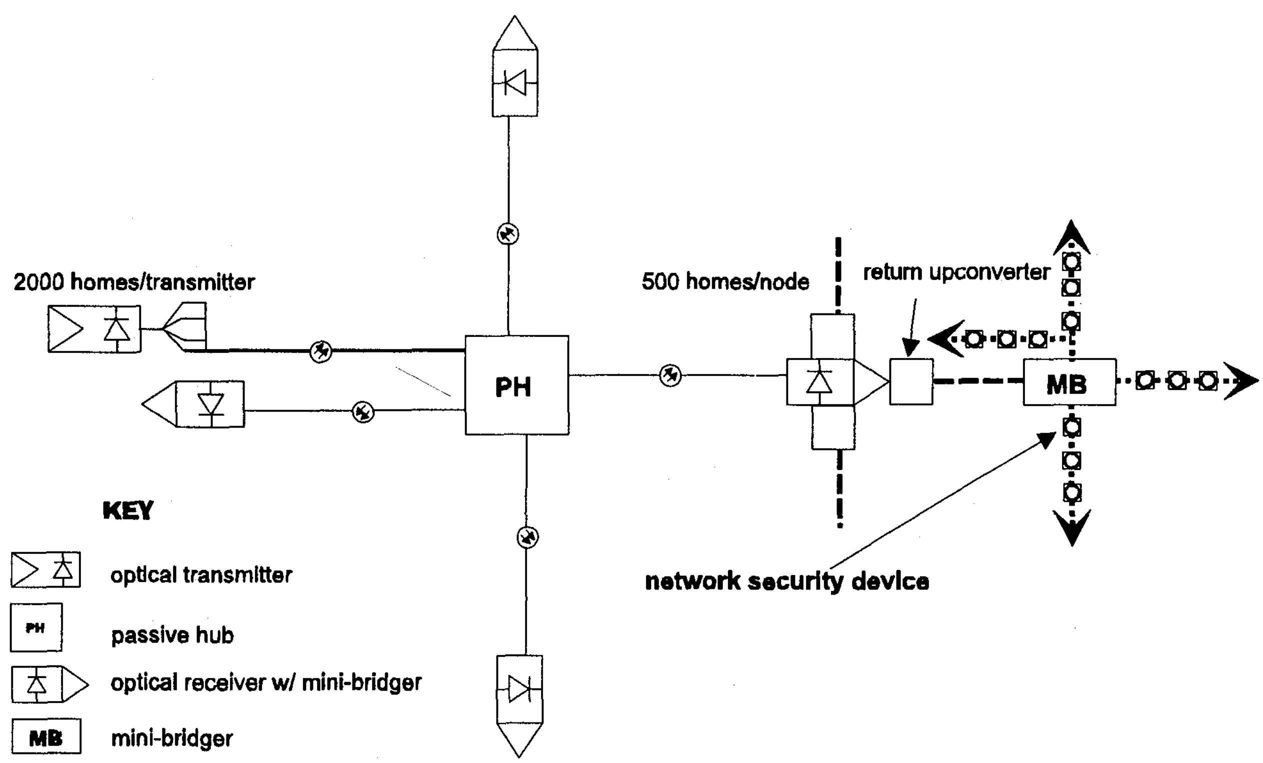

Figure 4. Broadband Telecommunications Architecture (BTA) using 500 home nodes and 2000 homes per optical transmitter, with frequency upconversion at the node for increased return path bandwidth.

Capacity and bandwidth allocation

While it is envisioned that modulation formats such as QPSK will initially be used on the return path, the ability to control ingress will eventually allow the use of a higher spectral density format such as 16QAM. In addition, the use of upconversion will allow tremendous expansion of the return path bandwidth and will provide sufficient bandwidth for a number of services in addition to telephony. For CNU service, QPSK modulation using frequency division multiplexing will be used to establish logical point-to-point connections between the HDT and CNUs in both the downstream and upstream. For the deployment of CTUs, downstream channels are expected to be transported in 27 Mb/s channels which fit in a 6 MHz bandwidth and which are transmitted using a 64QAM format. Table II shows both the upstream and downstream channel requirements and approximate system capacity for both QPSK and 16QAM modulation formats, assuming the use of 64QAM on the downstream. The channel capacity, while expressed in 64 kb/s (DS0) circuit switched connections, does not imply that the entire capacity of the system is dedicated to the switched telephony network. It is likely that in the future a substantial portion of the system capacity would be dedicated to packet based services which multiplex bandwidth on a statistical basis, and do not have circuit based DS0 or n x DS0 connections.

A proposed allocation of frequencies on 5-30 or 5-40 MHz return paths is shown in Figure 5. This allocation would allow status monitoring and settop services to coexist with telecommunications services. The downstream and upstream frequency allocations for this scenario are shown in Figure 6. Figure 7 illustrates a possible frequency allocation which would be used if upconversion at the node is used to expand the return path bandwidth. Figure 8 shows the downstream and upstream frequency allocations for this scenario.

Table II
Upstream and downstream channel requirements and capacity

upstream modulation technique	return path bandwidth	maximum number of 1.2 MHz upstream channels	number of 64 QAM (6 MHz) downstream channels required to support upstream requirements*	approximate number of DS0s supported per 500 home noae
QPSK	25 MHz (15-40 MHz)	20	8 (2)	480
QPSK	100 MHz (15-40 MHz with upconversion)	80	28 (8)	2106
16 QAM	25 MHz (15-40 MHz)	20	12 (3)	864
16 QAM	100 MHz (15-40 MHz with upconversion)	80	48 (12)	3744

* numbers shown here assume 2000 homes per optical transmitter, and 500 homes per transmitter (in parentheses)

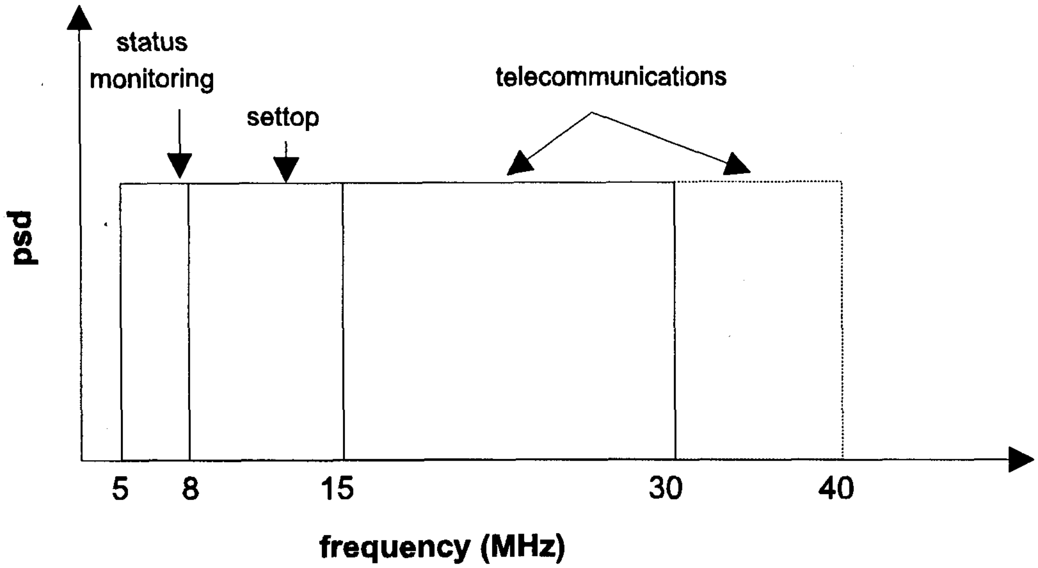

Figure 5. Proposed initial frequency allocations for upstream services on 5-30 and 5-40 MHz return paths.

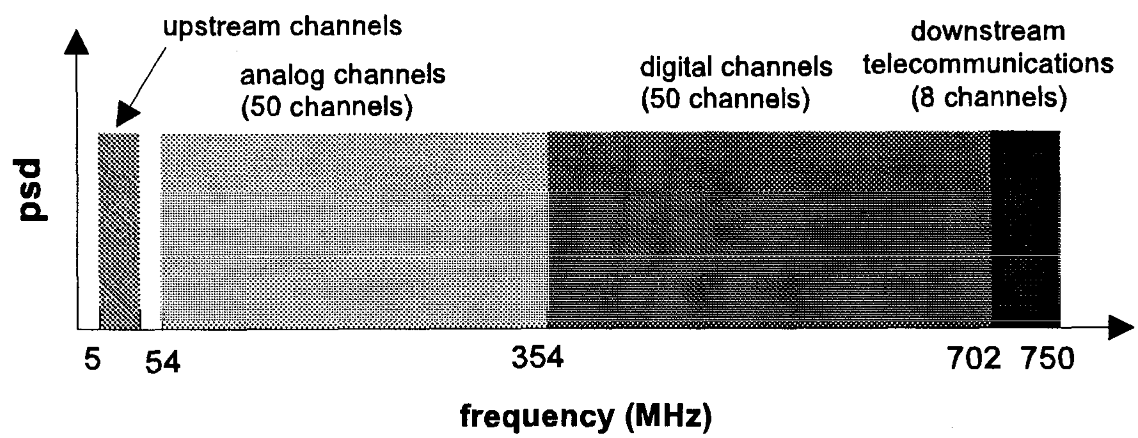

Figure 6. Downstream and upstream frequency allocations based on the use of a Broadband Telecommunications Architecture (BTA) using 500 home nodes, 2000 homes per optical transmitter, and QPSK transmission on the return path.

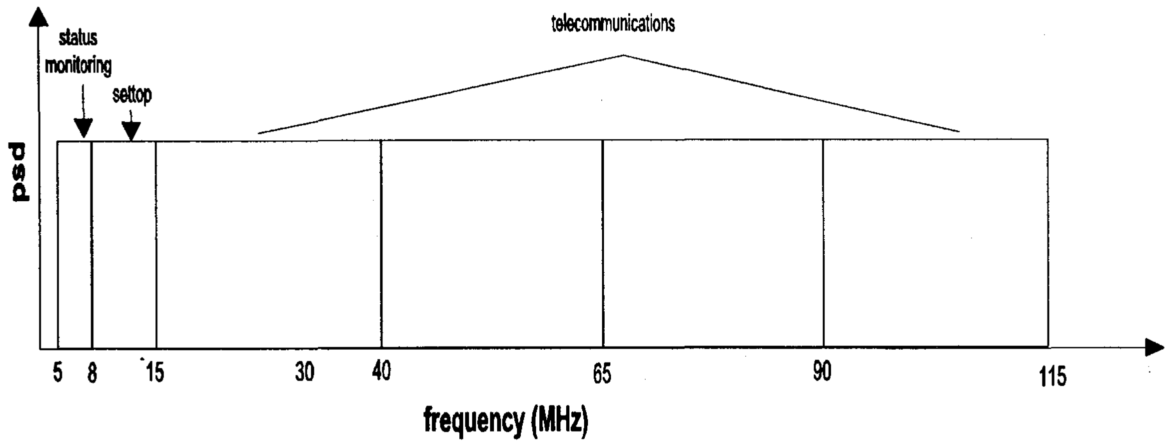

Figure 7. Proposed initial frequency allocations for upstream services using frequency upconversion at the node.

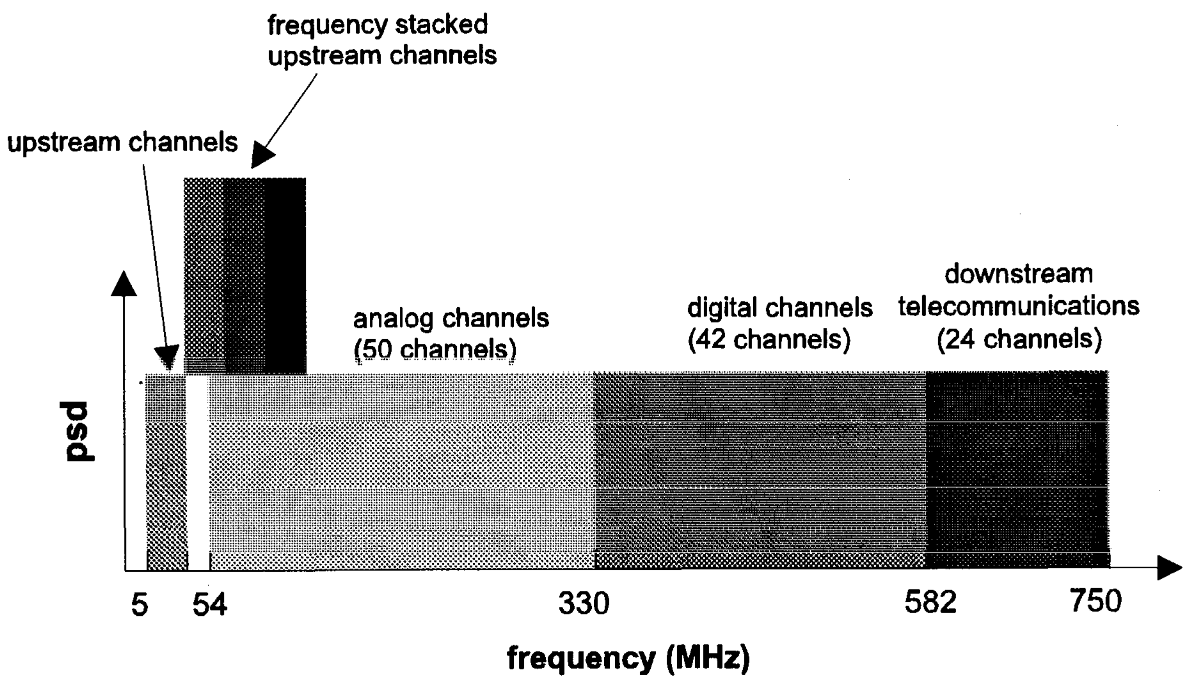

Figure 8. Downstream and upstream frequency allocations based on the use of a Broadband Telecommunications Architecture (BTA) using 500 home nodes, 2000 homes per optical transmitter, and QPSK transmission on the return path.

Encryption requirements

Unlike the current point-to-point topology of the residential telephony plant, the fiber-coax topology is point-to-multipoint. This will result in a potentially significant cost savings, but will require additional security measures to ensure privacy and resistance to unauthorized access. Encryption is currently used in video distribution products to prevent unauthorized reception of programs, but even if the code is broken the service to other customers is not affected since unauthorized reception does not affect the value of the service to the other customers. For telecommunications services this is not the case since even the perception that calls made over the facility are not secure devalues the service. In addition, system security is much more important for telecommunications services since users are billed on a direct usage basis. These reasons make the use of encryption for telecommunications services a must.

Encryption can be best supported on the network through the use of a key hierarchy, which includes both physical and algorithmic security. Such systems use multiple levels of key protected by distinct mechanisms and varied periodically to provide an extremely high level of security. Presently used broadcast video encryption methods can be modified to make encryption of telecommunications services possible.

The use of data encryption for telecommunications services has become a political and regulatory controversy due to the fact that government agencies may require access for authorized tapping. However, services such as call forwarding will make accessing the subscriber after the switch and signal transfer point practically useless, and it would appear that the only reasonable point for tapping will be at the switch. This would allow the use of high security encryption techniques on the access part of the network (either fiber or fiber-coax).

Round trip delay requirements

One of the basic performance parameters of voice communications systems is the round trip delay, due to the fact that excessively long delays can result in a degradation of service due to perceivable echo. In general, one-way delays of greater than 25 ms will cause any existing echoes of the speakers own voice (speaker echo path) to be annoyingly perceived by the speaker. Excessively long delays (e.g. 500 ms) can result in difficulties due to pure speech delay, even when echo cancellors are used to remove talker echo.[4] Because of these reasons, it is necessary to limit the total transmission delay, including the contribution of the delay in the access part of the network (switch to subscriber). CCITT recommendations[5,6] only provide recommendations for the one-way delay between speaker and listener, but the delay contributed by the fiber-coax part of the network must be included in this calculation. Bellcore recommendations[1] include a limit on the round trip delay from subscriber to subscriber which has a limit of 2.1 ms for a universal FITL system, and 1.5 ms for and integrated FITL system. In systems which do not meet this specification, active echo cancellation must be incorporated.

The 2.1/1.5 ms specification includes both the physical delay of the facility and the processing delay for the digitally encoded signals. In general, the physical delay is a lesser contributor in the loop plant. The primary contributors to processing delay include:

frame buffering of digital streams

upstream TDMA frame formation

symbol-to-binary conversion (modem processing delay)

error detection and correction

As is to be expected, manufacturers will need to develop means to perform these functions in a manner which meet the delay specifications, or incorporate echo cancellation.

System reliability

The deployment of fiber optic components in the local loop has raised the concern that system reliability will decrease with respect to the mature but bandwidth limited twisted pair solution. Because of this, Bellcore has paid particular attention to local loop reliability for FITL and have established downtime objectives for FITL systems.[1,7] Similarly, hybrid fiber-coax systems which support telephony will need to support downtime objectives, although it is probable that there will be different initial and long term objectives to allow for upgrading of the distribution plant and the development of methods to reduce ingress which may initially limit the availability of the return path. Table III shows the initial and long term downtime objectives for hybrid fiber-coax systems. These calculations include a MTTR of 2 hours for the central office/headend equipment, 4 hours for the distribution equipment and 6 hours for the CNU/CTU.

These calculations illustrate that the active distribution elements and ingress in the return path may initially make the unavailability of hybrid fiber-coax systems greater than the 53 min/yr FITL objective. However, the observed reliability of some distribution elements is much higher than the predicted reliability, and it is likely that the impact of actives in the distribution plant on overall system reliability will be minimal, due to the fact that the active elements contain mature and highly reliable technology. The forward and return path lasers are the exception to this, and laser reliability will be an issue which can be addressed by redundancy as well as increased component reliability. Methods of reducing ingress and the resulting interference in the return path are actively being studied to maximize the availability of the return path channel. It should also be noted that the long term goal for downtime of the CNU/CTU is lower than that for ONUs (26 min/yr) which should be achievable since there are no optical components in the CNU/CTU.[7]

Table III
Initial and long-term downtime objectives for hybrid fiber-coax telephony systems

Network Segment/Element	initial downtime (min/yr)	long term downtime (min/yr)
Digital Cross-Connect & Transmission Facility		
- hardware	2	2
- media	6	6
HDT	10	10
CableOptics	10	2
Distribution Components		
-receiver and mini-bridger	8	5
- mini-bridger	6	1
- line extenders (3)	18	2
- return path optics	12	5
CNU/CTU	26	10
Return path ingress	60	1
Unassigned	9	9
Total	167	53

Integration of telephony and advanced video/data/wireless services

While telephony coupled with analog and broadcast video services are expected to provide services in a cost effective manner, advanced services such as video on demand, data and wireless services are expected to generate additional revenue, if they can be deployed on the network at a reasonable incremental cost. Figure 9 illustrates the integration of these services, and illustrate the use of a network switch for routing of packet based video and data services, and Figure 10 shows a possible frequency allocation. The bandwidth allocated to each of the services will be dynamically allocated, to ensure best use of the entire spectrum. Integration will provide a cost effective means of not only providing, but provisioning, and administrating these services.[8]

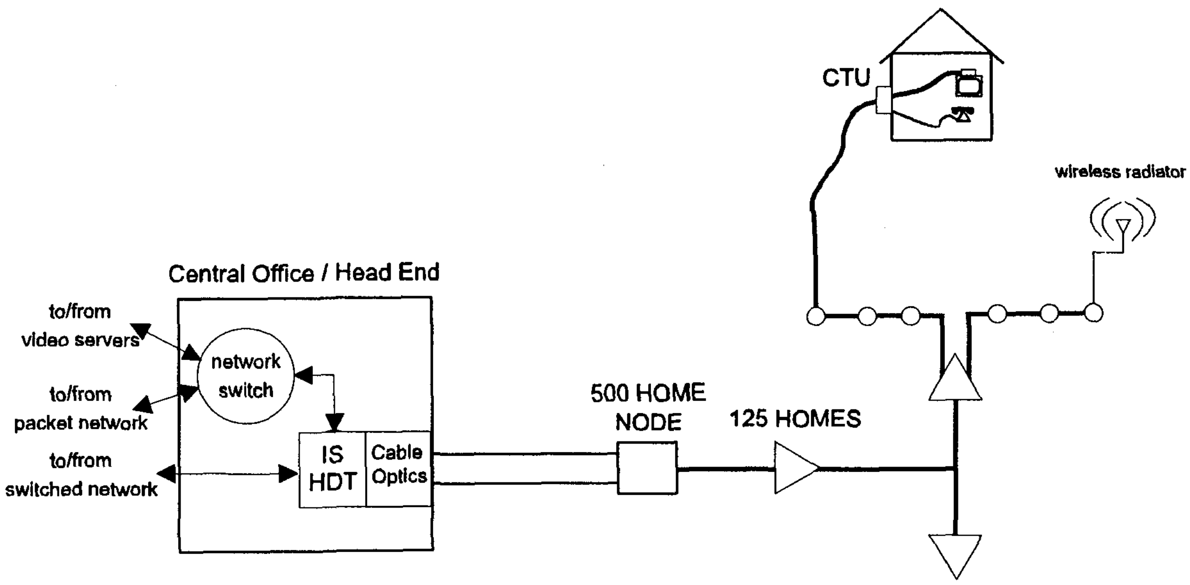

Figure 9. Integration of telephony, advanced video, wireless, and data services.

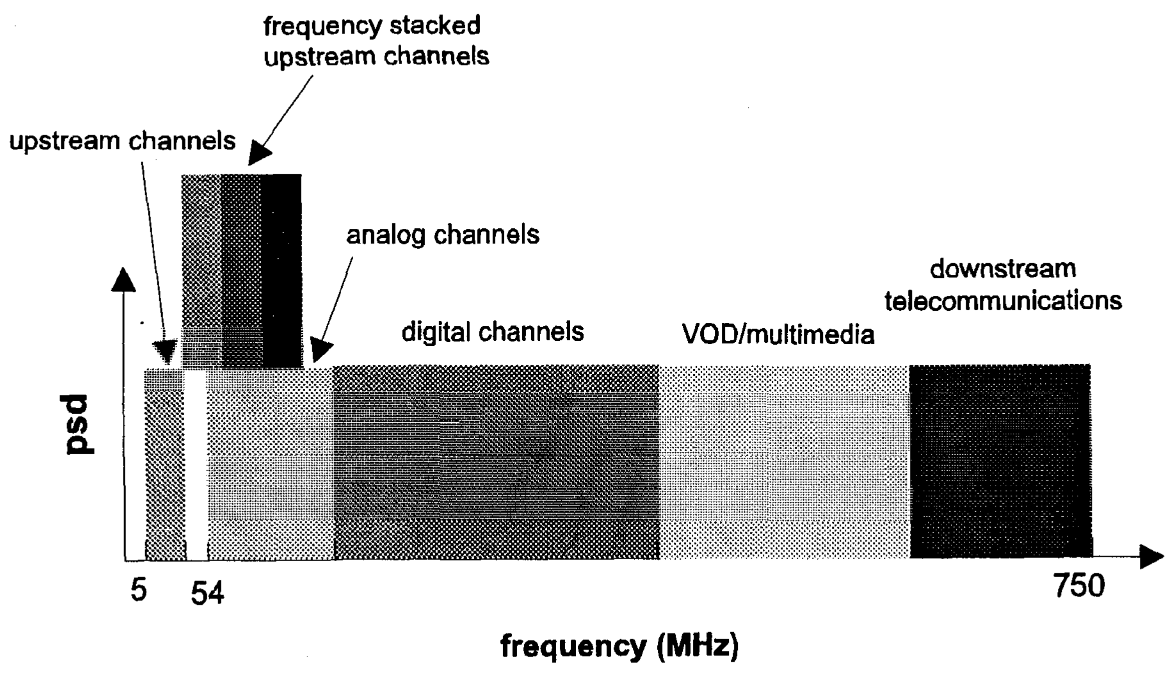

Figure 10. Frequency allocations for a fully integrated video and telecommunications system.

Conclusions

In this article we have discussed the primary engineering requirements for deployment of telephony over hybrid fiber-coax systems. Meeting these requirements and making the hybrid fiber-coax environment compatible and performance competitive with Fiber In The Loop will insure successful deployment of telephony services over hybrid fiber-coax. Particular concern will have to be paid to bit error ratio, round trip delay, and system reliability in order to match FITL service objectives. The ability to meet these objectives, coupled with the advanced video, data and wireless services which can be deployed over the broadband plant will insure the success of hybrid fiber-coax as the local loop transport means for all communications services.

Acknowledgments

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References

[1]TR-NWT-000909, *Generic Requirements and Objectives for Fiber In The Loop Systems*, Issue 1 (Bellcore, December 1991).

[2] An Errored Second is defined by Bellcore as a second in which at least one bit error was received, stated as a percentage over some time interval.

[3] A Burst Errored Second is defined by Bellcore as any Errored Second containing at least 100 errors.

[4] N. Kitawaki, K. Itoh, "Pure delay effects on speech quality in telecommunications," *IEEE J. on Selected Areas in Communications*, vol. 9, no. 4, pp. 586-593, May 1991.

[5] CCITT Recommendation G.131, "Stability and Echo," Fascicle III.1, pp. 143-155 (1988).

[6] CCITT Recommendation G.114, "Mean One-Way Propagation Time," Fascicle III.1, pp. 84-94 (1988).

[7] B. Unger, J. Spencer, "Fiber in the loop reliability: the impact for fiber optic components," *Optical Engineering*, vol. 30, no. 6, pp. 815-820 (June 1991).

[8] R. Safadi, "An optimal approach to a full service broadband communications network," *Proceedings of the 1994 NCTA Convention & Exposition*, (New Orleans, May 1-5, 1994).