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Alexander G. Fraser (M'76–SM'77) received the B.Sc. degree in aeronautical engineering from Bristol University, Bristol, England, and the Ph.D. degree in computing from Cambridge University, Cambridge, England.

He wrote the file system for the Atlas 2 computer at Cambridge University. Since joining Bell Laboratories in 1969 his personal research interests have been in architecture of data communications networks and circuit design aids. He is currently Director of the Computing Science Research Center, Bell Laboratories, Murray Hill, NJ, which covers basic research in most aspects of computer science.

Dr. Fraser is a member of the Association for Computing Machinery.

Cable-Based Metro Area Networks

TERRENCE P. McGARTY, MEMBER, IEEE, AND GERALD J. CLANCY, JR.

***Abstract*—This paper examines the system design considerations of metropolitan area networks utilizing cable television networks for the delivery of a variety of services to residential customers. Specifically, this paper focuses on the technology, marketplace, and regulatory aspects of this new and expanding market.**

I. Introduction

LOCAL cable systems, called CATV (community antenna television), are expanding at a dramatic rate into many large metropolitan areas. These systems are, in many cases, capable of carrying two-way communications to the residential subscriber. Over the past six years many cable companies have proposed two-way interactive systems such as Warner Cable's QUBE and Cox's INDAX [6]. These systems represent the forefront of a residential based metropolitan area network (MAN) that could provide the catalyst for dramatic growth in new communications services.

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The authors are with Warner Communications Inc., New York, NY 10022.

The first cable system was started in 1949 and for almost 30 years was considered no more than a simple communication path for consumer entertainment products. The technology of the cable world was dominated by TV transmission, with no insight into the capabilities of digital data transmission. As a result, CATV has only recently been recognized as a true communications medium capable of multiple applications. The first breakthrough was in 1977 with the introduction of Warner's QUBE in Columbus, OH. This two-way data communications system now serves almost half a million homes. It may be viewed as the largest urban residential time sharing system in the world.

The pressure to expand the data carrying capabilities is not coming from within the cable community, but from the banking and merchandising world which views interactive cable systems as a new electronic marketing and distribu-

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tion channel. These interests are trying to provide new and advanced services such as home banking and home shopping. These new markets are placing drastically different technical demands on the cable system.

The new technical demands focus on such areas as

- *Multiple Access:* How best to use the two-way capacity to allow simultaneous use by 2000–8000 subscribers per cable segment.
- *Interconnect:* How to let the subscribers communicate with other networks, databases, and computers in a highly interactive fashion.
- *Home Terminals:* How to choose the most effective terminals that balance local intelligence, data storage, and data communications capability.
- *Mixed Media:* How best to combine cable and telephone into hybrid networks.

This paper addresses these issues. It recognizes that cable in the CATV context is more than just an extended local area network. It is a new communications medium that must exist in an environment pressured by marketing demands, cost limitations, technical options, and regulatory concerns. It is still a technical area that has many more issues than answers. The technical challenge is to balance all of these interests and produce the best compromise.

II. Definitions

One is always hesitant to define concepts for which there seem to be as many versions as there are proponents of products embodying some form of the concept, but a useful discussion of the subject requires some bounding. There exists today a very wide variety of network offerings; most fall into one or more of the following categories.

Wide Area Network: These networks may be characterized by their use of local and long distance telecommunications facilities (telephone, microwave, and satellite) for the purposes of internodal communication. Their size may be local, regional, or national in scope. Transmission rates typically range for 300–19 200 bits/s, and occasionally as high as 56 000 bits/s. Interface costs are typically measured in terms of one or a few hundred dollars per device. The number of interconnects may range from tens of stations to several thousand.

Metropolitan Area Networks (MAN's): These networks are generally restricted to a metropolitan area, often just a city alone. Most of the activity in this area has been focused on the use of community antenna television (CATV) systems, but few would deny that the local telephone systems also offer a viable alternative for the delivery of many services. Other MAN offerings include cable/telco hybrids. The most common offerings today utilize fixed or frequency-agile modems to transmit data on a point-to-point basis at data rates common to wide area networks, while a few offer higher speed multiaccess channels. A base of perhaps several hundred thousand must be served. For cable systems, this may mean as many as 10 000 subscribers per distribution cable.

Local Area Networks (LAN's): There is, unfortunately, no one definition of a LAN. Heated debates have raged for years over whether they are limited to five, ten, or twenty miles; whether they are baseband or broad band; whether the local PBX counts.

Many of these arguments have been politically or economically motivated. The truth is, all of the above could be local area networks. Some techniques work well at short distances, while others provide better service over longer distances; some are inexpensive, while others not; some offer high bandwidth, others low-speed channels. Different needs require different solutions. Nonetheless, excepting the PBX, one can characterize local networks as predominately single multiaccess bus- or ring-oriented cables whose end-to-end length may approach 20 km, but which are typically within 5 km. The LAN may be intradepartmental, intrabuilding, or intracampus, but rarely exceeds this topological scope. Other key distinguishing aspects are the lack of a network-level protocol since switching is not required between stations and the peer nature of the connected stations.

Generally, most of the access techniques utilized for LAN's (e.g., CSMA, CSMA/CD, token, various ring alternatives, etc.) are inappropriate for application in MAN's due to their sensitivity to the length of the network. This is particularly true of CSMA/CD due to its sensitivity to propagation delay, but even token access suffers degradation in response time in city-wide networks since it is impractical to wire cities in a physical ring topology. This has led to the use of standard and adaptive point-to-multipoint polling protocols for lower cost solutions and to consideration of reservation time-division multiplexing where cost is not the overriding factor. The latter seeks to mitigate the effect of propagation delay by reserving time slots in advance of their need.

Due to their geographic spread, virtually all MAN's are wired in a distributed star topology. This is true of telephone distribution systems, which wire from central offices (CO's) to branch exchanges and from there to neighborhood distribution centers. Residences and businesses are then connected from these distribution centers.

Cable systems follow this analog: headends distribute signals to hubbing points, which may further distribute them to subhubs, and then to distribution cable off which home or business drops are made. Economics and signal quality constraints dictate this topology. A signal may be reamplified about 25 times before the quality of the video signals degrade below acceptable viewing standards. Elaborate "strand mapping" is done within the metro area in order to minimize the amount of cable required to deliver service to residences and businesses.

III. Cable Network Characteristics

CATV systems are comprised of two types of cables, subscriber and institutional. The latter type has been introduced only within the past several years. The subscriber cable is used to support the distribution of televised entertainment using 6 MHz spaced video channels. In some systems (see Table I) there is a two-way portion activated which allows the subscriber to respond to inquiries.

The institutional cable, on the other hand, is a cable

TABLE I
GROWTH OF TWO-WAY CABLE SYSTEMS

CABLE TV GROWTH: 1982 - 1990
(Yearend)

	1982	1985	1990
TV Households (HHs 000s)	83,700	86,700	94,700
Homes Passed by Cable	49,500	61,500	75,200
% TV HH	59%	71%	79%
Homes Passed by Active Two-Way Cable	197	3,769 (± 10%)	14,104 (± 30%)
% Total Homes Passed . .	1%	6% (± 10%)	19% (± 30%)
Total Cable (HH 000s) . .	28,205	36,900	48,100
% Total Homes Passed . .	57%	60%	64%
Pay-Per-View HHs . . .	1,900	7,800	32,227
% Total Homes Passed . .	4% 5	13%	43%
% Cable HHs.	7%	21%	64%

Source: The Yankee Group.

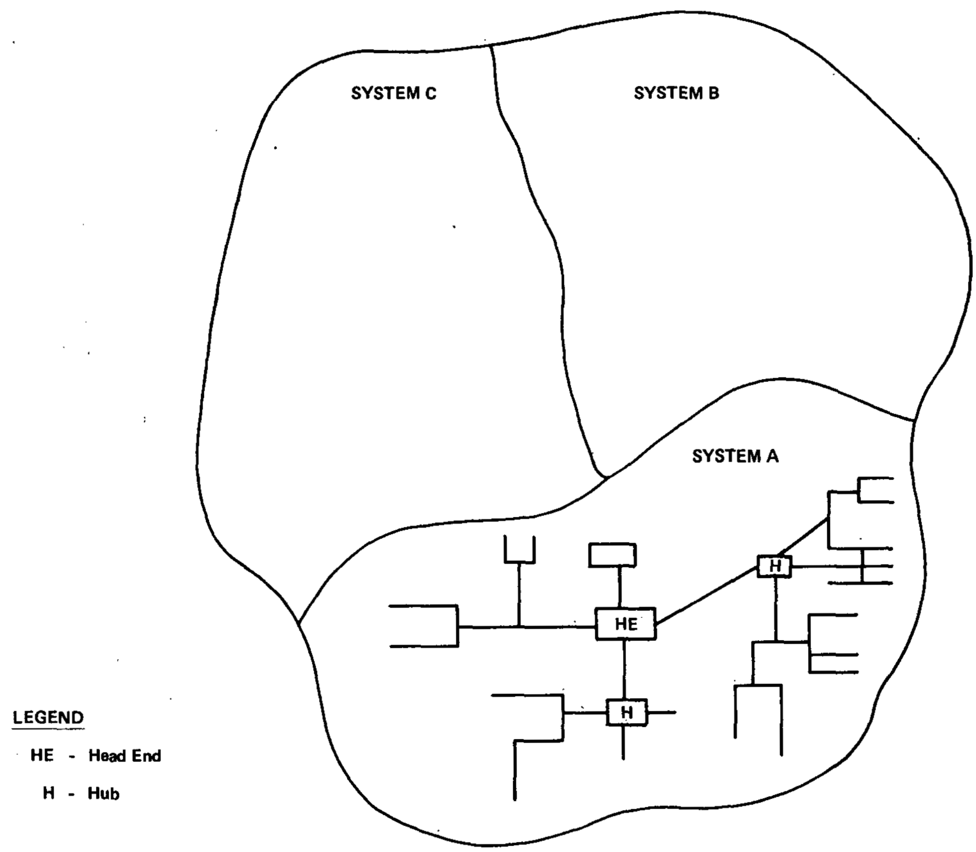

Fig. 1. Cable plant topology.

fully dedicated to nonsubscriber uses such as local municipal institution use and commercial data communications. The actual utilization of the institutional cable is still in its infancy and developing slowly. Such multiple system operators (MSO's) as Manhattan Cable in New York, NY, and Warner Amex in Pittsburgh, PA, currently offer data circuits.

The typical cable plant topology is shown in Fig. 1 [7]. Shown is a large metropolitan area with three separate systems covering separate regions. Within a single region, the cable plant of a single company is comprised of a headend location and a plant that provides service to subscribers. The typical architecture shows the headend connected to hubs using a supertrunk cable. From these hubs, distribution trunks span out to cover separate subscriber areas. The distribution trunks can only service up to 10 000 subscribers due to signal distortion limitations of the cable resulting from subscriber feeder taps. A typical hub may have three or more distribution trunks and thus can serve 30 000 or more subscribers. In a system with 300 000 subscribers this means that there are about 10 hubs with associated distribution networks. A very large metropolitan area may require as many as 30 or 40 hubs over three or four separate systems to service all subscribers.

This hierarchical architecture is becoming more prevalent in larger systems. In smaller systems, there is usually no supertrunk and only one or two distribution trunks. In general, the different regions are not interconnected. Thus, each region is isolated as far as communications is concerned. This architecture describes the subscriber loop. The institutional cable typically shadows the subscriber cable, and in some cases follows routes that are either dictated by the franchise rules or by commercial interest.

The cable system typically has usable bandwidth between 300 and 450 MHz [11]. There have been several developments which extend this to 500–600 MHz/cable. As the cable bandwidth increases the number of amplifiers per mile also increases. Most systems today are organized into a subsplit spectral division. The lower band (5–50 MHz) is channelized into 6 MHz bands and is used to transmit from the subscriber to the headend. A guard band of 1–10 MHz is used between the forward (downstream) and reverse (upstream) channels, depending on the filters. The top band is also channelized in 6 MHz spacings and is used to transmit to the home. The institutional cable is usually midsplit with equal bandwidth in each direction.

The distance from the headend to the hub is usually 5–10 mi, and distribution trunks from hub to home are also 5–10 mi in length [14]. Thus, the typical large metropolitan systems may cover an area of radius 20 mi, which is quite substantial as compared to a LAN area.

The key factors in a subscriber cable network are its architecture, bandwidth, spectral division, and length. For the most part, the data network designer must accept these as given.

With these system architectures, two-way communication with the subscriber is generally made via a CPU connected to the headend. The modulation schemes proposed are typically binary PSK and FSK. The cable environment provides a very high E_b/N_0 (energy per bit to noise spectral density ratio) so that the bit error rate (BER) is quite low (10^{-9} or less).

There are generally two types of multiple-access schemes that have been used, polling and CSMA/CD. The following subsections describe how both function in a cable environment and demonstrate the effect of the cable architecture constraints on multiple-access design and performance.

IV. Access Schemes

Four alternate access schemes for the delivery of services to homes are presented and later compared. These are

- CSMA/CD using two-way cable,
- polling using two-way cable,
- hybrid cable/telco technique, and
- telco only.

In some cases different data transmission rates are utilized to demonstrate their effect on throughput.

A. Models

The model for the cable-only approaches is shown in Fig. 2. This model is also valid for the cable portion of the cable/telco hybrid. The model for the hybrid cable/telco approach is shown in Fig. 3. It uses the local area data transport scheme (LADT) to be discussed. The cable system consists of a headend, at which the service computer is located, and 10 hubs. Each hub supports up to 30 000 subscribers. Each hub also supports three distribution cables, of which up to 10 000 homes per cable are connected. Overall, the system can support 300 000 subscribers.

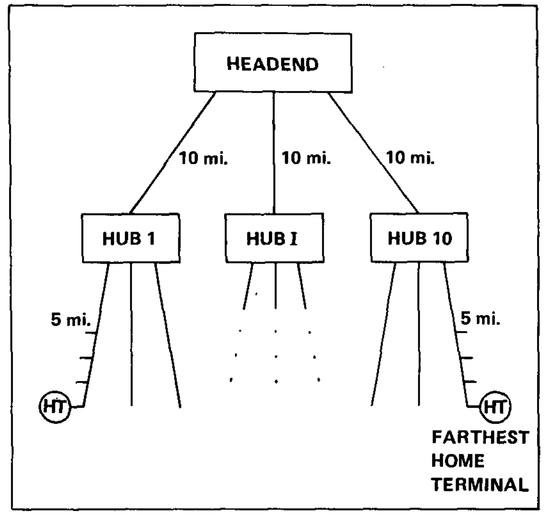

Fig. 2. Cable system model.

The distance between the headend and each hub is 10 mi on the average, and each distribution cable averages 5 mi in length. For the purposes of calculating propagation delays for the alternatives, a measured value of 7.1 μs/mi is used. This incorporates the necessary signal amplification delays.

Fig. 4 shows the LADT portion of the hybrid system in further detail. Homes are connected by two media. Upstream traffic is transmitted on the telco link, with downstream traffic transmitted via the cable system. The model proposes utilization of the emerging local area data transport (LADT) service (Fig. 4), currently tariffed by Southern Bell on a trial basis [9]. Upstream traffic from 1200 bit/s links connected to the homes is concentrated at the central office and forwarded to the headend computer over 56 kbit/s links.

B. Polling

The polling approach was developed in the 1975–1977 period by Warner Cable in conjunction with Pioneer of America. It uses a hierarchical network structure and bridger gate controllers, which limit the number of homes which are capable of upstream transmission. In this way noise ingress is substantially limited.

The original scheme polled each home once every 20 s to determine if there was a subscriber response. This has been termed the entertainment poll group (EPG). In the earlier designs, all subscribers were in the entertainment poll group.

To provide for increased levels of service to such applications, a concept called adaptive polling has been introduced. For the original services offered, the 20 s cycle was adequate. To introduce other services, different polling rates and groups are required. The polling table is a table

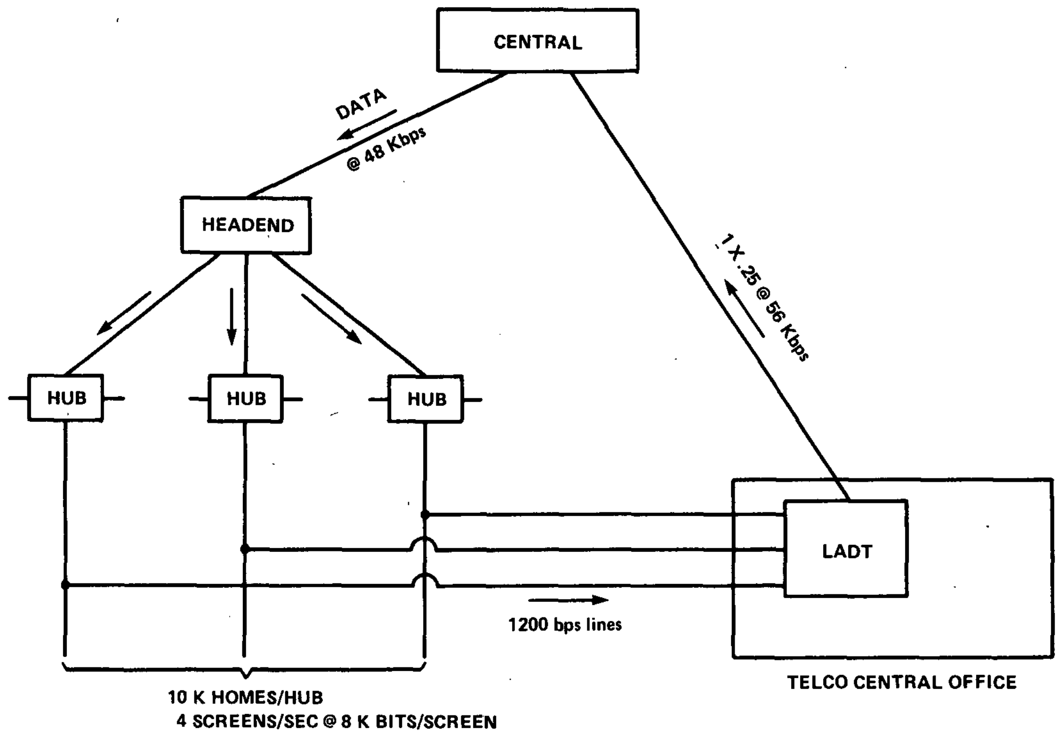

Fig. 3. Hybrid/telco option.

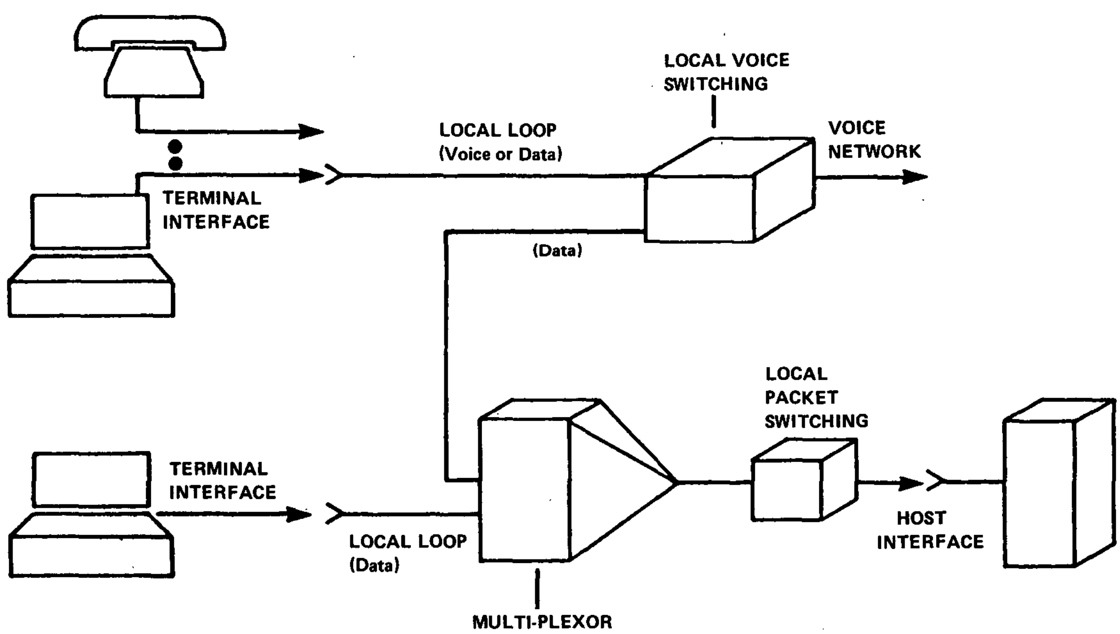

Fig. 4. LADT architecture.

that tells the computer when to poll each home. Normally it polls each home only once per cycle. With the introduction of new services three new polling groups are added.

1) Transaction Services Poll Group: for terminals authorized but not in active use; one poll per terminal every 5 s;

2) Videotex Poll Group: for terminals actively viewing videotex screens (transmitted on a separate data channel) of full motion video; one poll per terminal every 1/2 s;

3) Rapid Poll Group: for terminals actively using transaction services requiring very fast headend response; one poll per terminal every one-tenth of a second.

These are summarized in Table II. Fig. 5 depicts the adaptive polling table with the entries from the four groups. The list is divided into 200 segments. Each segment contains the complete rapid poll group (RPG), 20 percent of the videotex poll group (VPG), 2 percent of the transaction services poll group (TSG), and 0.5 percent of the balance, or entertainment poll group. Each segment must execute within the one-tenth s constraint, while the entire composite poll cycle must be completed every 20 s.

In implementation, the composite poll cycle may take many forms. For example, four physical polling lists could exist, representing the groupings of subscribers. Four timer intervals could be set successively during the execution of a poll segment to interrupt the processor so that it can move

TABLE II
ADAPTIVE POLLING GROUPS

POLL GROUPS

Name	Characteristics	Use
ENTERTAINMENT (EPG)	EVERY 20 SEC. ALL SUBSCRIBERS (SUBS)	ENTERTAINMENT SUBSCRIBER RESPONSE
TRANSACTION (TSG)	EVERY 5 SEC. TRANSACTION SUBS ONLY	TO TEST IF A TRANSACTION SUBSCRIBER IS ACTIVE
VIDEOTEX (VPG)	EVERY 0.5 SEC. ACTIVE TRANSACTION ONLY	TO TEST IF THERE IS A RESPONSE TO A VIDEOTEX SCREEN
RAPID (RPG)	EVERY 0.1 SEC. HYPERACTIVE USERS ONLY	TO BE USED FOR RAPID RESPONSE APPLICATIONS

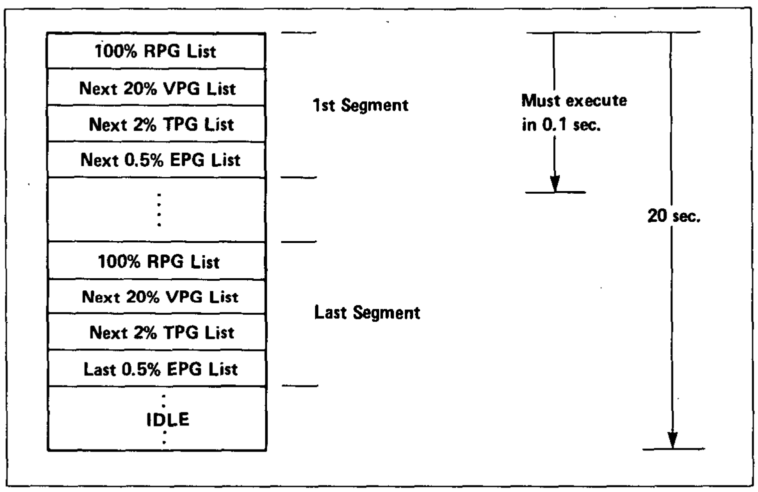

Fig. 5. Adaptive polling table showing 0.1 s segment polls with full 20 s cycle.

to the next physical polling list. Alternately, counters can be set which, when decremented to zero, cause the processor to move to the next poll list.

There is a wide variation in the relative sizes of the four polling groups. The transaction services poll group might only be 20 percent of the size of the entertainment poll group. Similarly, the videotex poll group might be half of that, and the rapid poll group might well be less than 1 percent of the size of the entertainment poll group. The total number of entries in all poll lists remains relatively constant, changing only as subscribers are added to or deleted from the service. The size of each poll group, however, changes constantly as subscribers move from one group to another.

What is of interest is to determine the maximum number of terminals which can be supported by the access technique. Extrapolating from [19], the maximum mean message throughput rate can be approximated as

$$\frac{1}{T_{\text{message}} + T_{\text{overhead}}}$$

where T_{message} is the time required to transmit a poll packet and T_{overhead} is the time required to poll the next station. Since the reverse channel is utilized for the response, only one-way propagation need be considered.

It is of interest to examine the QUBE design. Here a poll packet is 40 bits in length and a data transmission rate of 256 bits/s is used. Referring to the model, the average one-way propagation is 12.5 mi. Thus,

$$\text{max throughput} = \frac{1}{\dfrac{40 \text{ bits/pkt}}{256 \text{ kbits/s}} + (88.75 \times 10^{-6}) \text{ s}}$$
$$= 4086 \text{ pkt/s}.$$

This defines the maximum terminal capacity per channel. A larger population can be supported if the polls are stacked several at a time so that several homes are polled in the same sequence, thus reducing the effect of propagation delay.

As noted, the polling design has a capacity. This is the number of packets that can be fitted into a polling cycle. The capacity is the number of users that can be supported in a given time. This will depend upon

- the total number of users,

TABLE III
MAXIMUM THROUGHPUT OF POLLING AT VARIOUS RATES ON TWO-WAY CABLE

Data Trans. Rate (Kb/s)	$T_{message}$ (msec.)	T_{slot} (bits)	T_{slot} (msec.)	Maximum Throughput (pkts./sec.)
64	2.0	5.7	.0888	479
128	1.0	11.4	.0888	919
256	0.5	22.7	.0888	1,701
2,000	0.064	177.5	.0888	6,579

TABLE IV
POLLING CHANNELS REQUIRED AND THEIR EFFICIENCY AT OFFERED LOAD OF 51 450 PACKETS/S

Data Trans. Rate (Kb/s)	Maximum Efficiency	Minimum Channels Required
64	53.9%	108
128	51.7%	56
256	47.8%	31
2,000	23.7%	8

- the percent that are instantaneously active in a transaction mode, and
- the percent that are instantaneously active in a videotex or rapid poll mode.

As an example, we consider the case of a system of 300 000 users 3 percent of whom are instantaneously active, with 75 percent of those active in videotex and 25 percent in rapid poll. Two percent of all users are in the transaction groups, with the balance in entertainment. The poll list then consists of

6000 in transactions
6750 in videotex
2250 in rapid poll
285 000 in entertainment.

Each segment of the poll list, which must execute in one-tenth of a second, consists of

100 percent RPG = 2250
20 percent VPG = 1350
2 percent TPG = 120
0.5 percent EPG = 1425
5145

Ten segments must be executed each second. Thus, 51 450 terminals must be polled per second. Since each channel could possibly handle 4086 polls/s, a minimum of 13 channels is required. Polling each of the 30 distribution points independently would result in 42 percent loading of each channel.

This analysis of the QUBE polling approach indicates that it is a viable technology that can support a wide variety of interactive applications. Historically it was developed before CSMA/CD and was based upon proven computer time sharing multiple-access schemes. It avoids collision phenomenon, yet has the delay due to average trip and multiple polls. As shown, the QUBE system tries to maximize efficiency and in turn capacity by several unique techniques.

We now take a uniform set of assumptions which will be used as the basis for the later comparison of the access schemes. Assume a poll or request packet size of 128 bits and the following transmission rates: 64, 128, 256, and 2000 kbits/s. The same system loading parameters as for the previous example are used.

A poll packet is assumed to be an HDLC-like frame, consisting of 56 control bits (2 flags, 2 byte address, control byte, and 2 byte frame check sequence) and 72 data bits.

Again, $T_{message}$, the packet size divided by the data transmission rate, will vary with the latter. T_{slot} remains 88.75×10^{-6}, as before.

Table III summarizes the maximum throughput for the polling scheme at the various data transmission rates on two-way cable. The number of bits in T_{slot} is calculated by dividing the slot time by the bit time. As shown earlier, it is required that 51 450 terminals be polled every second. Table IV summarizes the number of channels required to accomplish this for the various data rates.

Table IV also identifies the efficiency of the datalinks with this access procedure, calculated as

$$\text{EFF} = \frac{\text{bits/pkt} \times \text{max pkts/s}}{\text{data transmission rate}}$$

C. CSMA/CD

Carrier sensed multiple access with collision detection (CSMA/CD) is a more recent entry as a multiple-access protocol. Unlike the previous technique, which must continually poll every active and inactive terminal, CSMA/CD operates on an exception basis. That is, when a home terminal changes state (e.g., goes active or inactive, receives a user input, etc.), the terminal attempts to transmit the information to the computer at the headend. Since a multiaccess channel is used it may be busy. Even if apparently free a collision may still occur due to signal propagation effects. When a collision is detected by the transmitting station, which is listening to its own transmission, the transmission is aborted and replaced with a jamming signal for a defined duration to ensure that all stations hear the collision. The station then executes the backoff algorithm and retries.

CSMA/CD was originally conceived for LAN's where the distance on an end-to-end basis was 1–2 km (about 1 mi), not the 20–40 mi end-to-end of a cable network. Thus, it is important to see what the impact of this cable extension has on the performance. From [19] we determine the maximum throughput of CSMA/CD as

$$\frac{1}{T_{\text{message}} + (2e-1)T_{\text{slot}}}.$$

T_{message} is a function of the packet size divided by the data transmission rate. Referencing Section 3.1.1 in [20], a poll packet consists of 208 control bits (7 bytes preamble, 1 start-of-frame delimiter, 12 bytes addressing, 2 bytes length, and 4 bytes FCS) and a sufficient number of data plus pad bits to make T_{message} a minimum of one slot time. T_{slot} must be calculated from the cable system parameters. Using the draft IEEE 802 Baseband CSMA/CD Standard [20, Section 9] as a guide and extrapolating for broad band, we use the following scenario for estimation of the minimum frame length.

1) A home terminal at the end of a distribution cable transmits a packet to the headend computer on the upstream frequency. This will take 15×7.1 or 106.5 μs.

2) The headend translates the message (estimate 4 μs) to the downstream frequency. Just before receipt of the last bit at the headend (the destination), a collision occurs. The headend generates 48 bits of jamming signal.

3) The RF signal propagates to the original transmitter where the collision is detected upon receipt of the last bit. This takes another 106.5 μs.

It is assumed to take 3 μs for the receiver to digest the message and another 4 μs to analyze it. According to the general principles of CSMA/CD, the message from the home terminal "must be long enough such that it is still sending when the collision occurred" [20, Section 9].

Since we are using RF signaling rather than baseband, it is assumed that no *repeaters* are required. However, an interframe gap of 9.6 μs is assumed.

T_{slot} now can be estimated as the sum of these times [20], 233.6 μs, plus the time for 48 jam bits. How many minimum packet bits are involved will therefore depend upon the transmission rate. We assume 300 000 users divided functionally as in the poll groups discussion. Further,

- 5 percent of those terminals in the entertainment mode will generate a status message each s,
- each of those terminals in the transaction and videotex modes will generate a message to the headend once every 15 s on the average, and
- each terminal in the rapid mode will generate a message to the headend once every second on the average.

Inactive terminals are ignored, as they will generate a "going active" message when required. Later, for comparison of CSMA/CD under lighter loads, the entertainment group will be eliminated from the load.

The offered load in the system with both groups included is then approximately 17 350 packets/s. Table V defines the minimum packet sizes, or T_{slot}, for data transmission rates of 64, 128, 256, and 2000 kbits/s; T_{message}; and the calculated maximum throughput in packets/s on the average.

In actual practice, it would not be possible to provide this throughput with CSMA/CD. A review of previous work in this area [1], [2], [22] indicates that only a portion of this throughput is usable due to the nonlinear nature of CSMA/CD with respect to delay versus the propagation delay—data transmission rate product and channel loading. The relatively long propagation delays, small packet size, and heavy loading of the channels substantially reduces channel efficiency, particularly at the high data rates. Rough estimates have been made of the usable throughput by data rate (shown in Table VI) in order to provide estimates of the channels which might typically be required.

Table VI identifies the efficiency of the access method at the various data rates. Efficiency is stated both as a maximum, ignoring delay implications, and as bounded by maximum delay requirements (usable throughput). The number of channels required is determined as

$$\frac{\text{arrival rate of packets}}{\text{maximum packet rate/channel}}.$$

Let us now assume that it is unnecessary for the terminals in the entertainment group to send status messages to the headend every 20 s; rather, let us assume that state changes occur in these terminals at a rate of 0.5 percent/s (e.g., subs watching pay-per-view programs) resulting in 1425 packets/s arriving at the headend, together with the 3100 videotex, transaction, and rapid poll group packets. This represents an offered load of 4525 packets/s at the headend computer.

The number of channels required is given in Table VII.

D. Hybrid Telco

Two-way cable, noted earlier, is operational in only a small fraction of the U.S. There is, therefore, a growing attempt at using two-way hybrid cable and telephone systems [4], [9], [15], [16]. The cable is used to transmit data to the home, and the telephone is used to transmit data to the headend. The major problems that mitigate against using the telephone are

- the cost of a phone circuit, on a measured use basis, is high: 6¢–12¢/min,
- the data call has a longer holding time than a voice call and can dramatically increase the load on the central office switch, and
- the data call ties up the home phone for incoming calls.

The Bell System has proposed, developed, and tariffed a new service called local area data transport (LADT) that gets around these major objections (Fig. 6). There are two versions: version 1 is 1200 bits/s with alternate voice and data, and the second is 4800 or 9600 bits/s with data over voice. Both versions use a synchronous interface to the home and provide an X.25 data circuit at 56 kbits/s to the cable headend.

This LADT service is planned for use in a nonhybrid configuration in the fall of 1983 in the Knight-Ridder test in Florida. The key difference in the 1200 bits/s link is that it provides the service at 1.6¢/min, a drastic reduction over previous tariff rates.

TABLE V
MAXIMUM THROUGHPUT OF CSMA/CD AT VARIOUS RATES

Data Trans. Rate (Kb/s)	$T_{message}$ (msec.)	T_{slot}		Maximum Throughput (pkts./sec.)
		(bits)	(msec.)	
64	4.38	63	0.98	115
128	2.19	78	0.61	204
256	1.09	108	0.42	339
2,000	0.26	516	0.26	708

TABLE VI
CSMA/CD CHANNELS REQUIRED AND THEIR EFFICIENCY AT OFFERED LOAD OF 17 350 PACKETS/S

Data Rate (Kb/s)	Efficiency		Channels Required	
	Maximum %	Useable Throughput	Minimum	Given Useable Throughput
64	12.9	75	151	202
128	11.5	70	85	122
256	9.5	60	52	86
2,000	2.5	30	25	82

TABLE VII
CSMA/CD CHANNELS REQUIRED AT OFFERED LOAD OF 4525 PACKETS/S

Data Rate (Kb/s)	Channels Required	
	Minimum	Given Useable Throughput
64	40	53
128	23	32
256	14	23
2,000	7	22

Hybrid schemes are destined to become more popular over the next decade. Most importantly they provide a way to interconnect many cable systems in a consistant format. In addition, the Bell Operating Companies could get into the business of actually interconnecting the various MSO cable headends. At this time, several companies such as Gill Cable, Central (Videopath), and 3M are proposing video-only interconnects. If the BOC's recognize the data as well as video opportunities, then interconnection has a tremendous market potential.

Like CSMA/CD, the hybrid alternative operates on an exception basis, i.e., transmissions are only forwarded to the headend when a change in state at the home terminal occurs. A major difference, however, is that each home has its own private link to the headend (via the LADT central office facilities). Thus, link efficiency is of little concern. It is required, though, that the headend computer have sufficient capacity to support the links from the central office.

E. Telco Only

In the telco-only configuration, each home is linked to the central facility, as in the hybrid case. The major difference is that all data are sent downstream over the same link. Line contention is not the problem with this alternative, rather delay is. A typical videotex screen using the North American presentation layer protocol (NAPLP) may require the transmission of 1000 bytes of data. This will take approximately 7 s at 1200 bits/s, leaving little margin for other processing or transmission delays. Of course, higher data rates could be used but at prohibitive cost for the home device.

Delay for all alternatives will be considered in the next section.

F. Comparisons

Due to different assumptions, not all four access approaches can be directly compared. However, several observations can be made.

The main advantage of polling is that it is a straightforward and simple technique, proven by years of experience. It is also deterministic, not given to the random vagaries of CSMA/CD. Its main disadvantage is that all stations must be polled during some defined poll cycle whether active or not, whether or not useful data are ready to be returned. This is a particular burden when relatively few stations in the total population typically respond. The main advantages of CSMA/CD are the reverse: only stations that have something to say need transmit, and no central control of the channel is required. Its main disadvantages are its sensitivity to propagation delay and loading.

Table VIII summarizes the throughput and efficiency of the polling and CSMA/CD access techniques. Our analysis indicates the following:

- As one might expect, CSMA/CD substantially reduces the number of channels required in the light load case (4525 packets/s) at the lower data transmission rates as compared to polling all terminals. However, in the heavier load case (17 350 packets/s) it is outperformed by the polling alternative.
- CSMA/CD makes very inefficient use of bandwidth due to the large slot time required at these distances and the fact that only short messages need be transmitted in this application. The channel efficiency of CSMA/CD never exceeds 12.9 percent and ranges as low as 2.5 percent for the data rates compared. Polling efficiency, on the other hand, ranges from 53.9 percent to 23.7 percent.
- The increases in throughput with respect to increases in the data transmission rate are very nonlinear in CSMA/CD. A 31 times increase in the data rate only

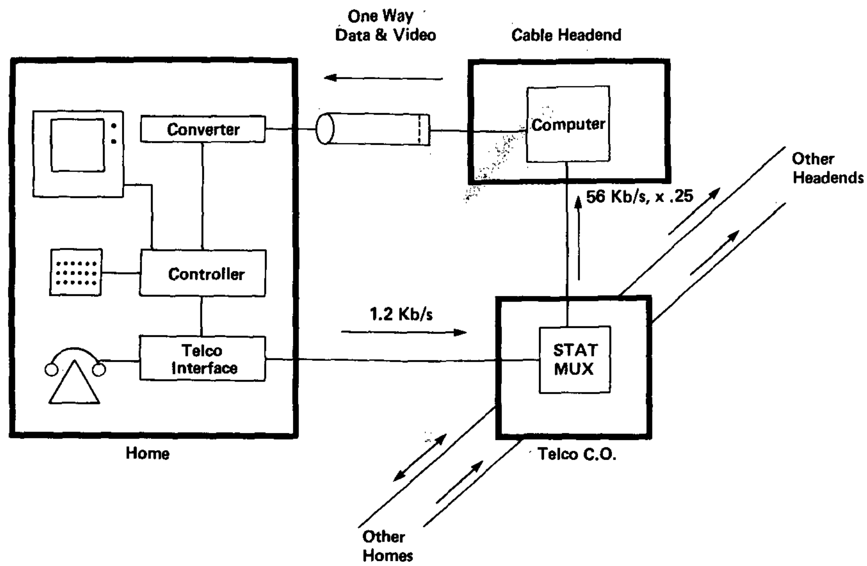

Fig. 6. LADT/cable hybrid for information provision.

TABLE VIII
SUMMARY OF THROUGHPUT AND EFFICIENCY FOR POLLING AND CSMA/CD

Data Trans. Rate (Kb/s)	Throughput (Pkts/Sec.)			Efficiency (%)	
	Polling	CSMA/CD		Polling	CSMA/CD
		Max.	Useable		
64	479	115	86	53.9	12.9
128	919	204	143	51.7	11.5
256	1,701	339	203	47.8	9.5
2,000	6,579	708	212	23.7	2.5

increases throughput 2.5 times. In contrast to this, the same increase in the data rate brings a 13.7 times increase in polling throughput.

- Considering usable throughput, it would appear that exceeding a data transmission rate of 256 kbits/s is not warranted with CSMA/CD in a system with these parameters.

The hybrid has substantial advantages.

- Since each home has its own link upstream, data can be forwarded on an exception basis, as in CSMA/CD, eliminating the need for polling.
- The upstream phone interface is cheaper than the upstream cable interface.
- The hybrid may be used with one-way cable systems, which will predominate for many years to come.
- The short upstream messages can be readily accommodated by the low-speed telco links, while the relatively large downstream messages (e.g., videotex screens) can be delivered very quickly via high-speed cable channels.

The telco-only alternative shares the first two advantages, but not the last, as downstream transmission of screens over the telco link is time consuming.

G. Delay

The importance of delay can be seen from an examination of Tables IX, X, and XI. Table IX provides examples of data loading parameters. Table X identifies the timing budget for generating a request from a home terminal to the headend computer and receiving the response. It is assumed that the data required are local to the headend

TABLE IX
DATA LOADING

	From Home	To Home
TOTAL USERS	100K	100K
ANNUAL USAGE PER USER (HRS.)	90	90
ANNUAL HOURS (HRS.)	5840	5840
PERCENT ACTIVE	1.5	1.5
PEAK TO AVERAGE	2.0	2.0
PEAK USERS	3000	3000
RESPONSES/SECOND	1/15	1/15
BITS/RESPONSE	100	8000
TOTAL DATA RATE	20 Kbps	1600 Kbps
RATE/ACTIVE USER	6.67 bps	533.3 bps

TABLE X
LOCAL VIDEOTEX TIMING BUDGET

Function	Average	99.9%
REQUEST RECEIVED BY FEP	0.10	0.20
REQUEST PROCESSED BY FEP	0.10	0.25
REQUEST PROCESSED BY CPU	0.5	1.5
DATA RETREIVED FROM DISK	0.15	0.30
DATA PROCESSED BY FEP	0.10	0.25
DATA RECEIVED BY TERMINAL	0.25	0.75
HT LOADING/PROCESSING	0.10	0.15
TOTAL	1.30 SEC.	3.40 SEC.

TABLE XI
GATEWAY VIDEOTEX TIMING BUDGET

Function	Average	99.9%
REQUEST RECEIVED FEP . . .	0.10	0.2
REQUEST PROCESSED BY FEP	0.10	0.25
REQUEST PROCESSED BY CPU	0.5	1.5
GATEWAY PROCESSED BY BEP	0.1	0.3
TRANSMITTED TO REMOTE	0.10	0.25
REQUEST PROCESSED BY FEP	0.1	0.25
REMOTE PROCESSED BY CPU	1.0	2.0
RETURNED PROCESSED BY FEP	0.1	0.25
TRANSMIT TO CENTRAL . . .	0.3	0.75
PROCESSED BY BEP	0.10	0.3
PASSED TO FEP BY CPS	0.10	0.2
FEP PROCESSED	0.10	0.2
DATA TRANSMITTED	0.35	0.75
HT LOAD PROCESS	0.1	0.2
TOTAL	3.15 SEC.	7.40 SEC.

computer. Using a relatively high data transmission rate on the cable for downstream transmission, the screen can be delivered typically within about 1.3 s and within 3.4 s 99.9 percent of the time. Note, however, the effect a gateway request for information retrieval (Table XI) has on the timing budget: average response has increased to 3.15 s, while the 99.9 percent case has increased to 7.4 s.

It turns out that any of the schemes described earlier except the telco-only alternative can provide this level of response. The CSMA/CD loading per channel can be constrained to provide the appropriate level of response *on the average* (but at the expense of additional channels, as we have seen). The use of the telco-only alternative could have a disastrous effect on response time, increasing the average gateway case to over 10 s. This is not considered an acceptable delay from the consumer's point of view.

V. Residential Characteristics

The residential or consumer area is one in which the metropolitan area network (MAN) concept will play a large role. To understand what technological choices are most effective one must understand the market characteristics of this segment. A typical business plan is developed by asking three questions in order of importance.

- How can the business make a profit?
- How can the product be sold?
- How can the product or service be delivered?

The first question addresses the viability of the business area as a profit making entity. It considers revenue in return for benefits, expenses in return for service, and capital in return for delivery. The second question relates to who wants to try what and why. The third question relates to the technology: how to embody the concept in some technical form. All too often there is a technology in search of a market; an answer to question three driving question one. This seldom works, especially in the consumer area where revenue comes from individuals dispensing with discretionary income.

Thus understanding of the residential market requires first an understanding of the basic market issues such as services and needs, revenues and costs, and business roles and missions. From these flow the basic system requirements, and finally alternative configurations or architectures to satisfy those requirements. This section addresses each of these three major areas.

A. Market Requirements

The U.S. is comprised of approximately 85 million households with 235 million people. Approximately 60 percent of these households are passed by cable with more than 30 percent subscribing. There is a growing market for more complex interactive home services (IHS) directed towards this market. This market is broken down into the following categories [5], [8], [18], [19].

- *Transaction:* Services which allow the consumer to purchase items or change items in such databases as home banking. Transaction services by their nature are interactive and they allow the consumer to make changes to remote data fields. Typical services are shopping, banking and financial, travel reservations, and event ticketing.
- *Information:* These services allow the consumer access to read-only databases. Typical are classified advertising, local services directory (yellow pages), database information, and education.
- *Entertainment:* These allow the consumer to receive, on demand, entertainment services such as interactive games downloaded to a video game machine and pay-per-view television.

There are other interactive services such as home security and medical alert that also fit in IHS.

The typical household spends between \$2000 and \$8000 per year on these services. This represents a \$200–\$800 billion a year market. If only 1 percent of this market can use an IHS electronic marketing channel this represents a \$2–\$8 billion a year business. It is this driving factor that makes the application of MAN's to IHS so attractive.

In terms of market size, in the top 40 SMSA (standard metropolitan statistical areas), there is an average of 500 000 homes, and of those, 20 percent will be the target for services of these types. That means close to 4 million households with an average of 100 000 households in each area.

There are two general scenarios that describe how this IHS industry will function. Understanding these is key to understanding the technological implications. They are

1) *S/IP/SO:* This model has the basic supplier (S) of goods and services interfacing with an agent called an information provider (IP). The IP is who the consumer deals with. The term originates in the videotex context of providing information only. The IP's attach themselves to a system operator (SO) who provides both the consumer and the IP with a communications network to the home. In this case the consumers use their own home terminals to access an SO network and in turn an IP. The consumer, in a session, is in communication with the IP. This design is dominated by large amounts of gateway communications. Roughly 5 percent of the time the consumer is dealing with the SO, and 95 percent of the time the consumer is gatewayed to an IP. In addition, each IP has its own database [7].

In this scenario the consumer also purchases a home

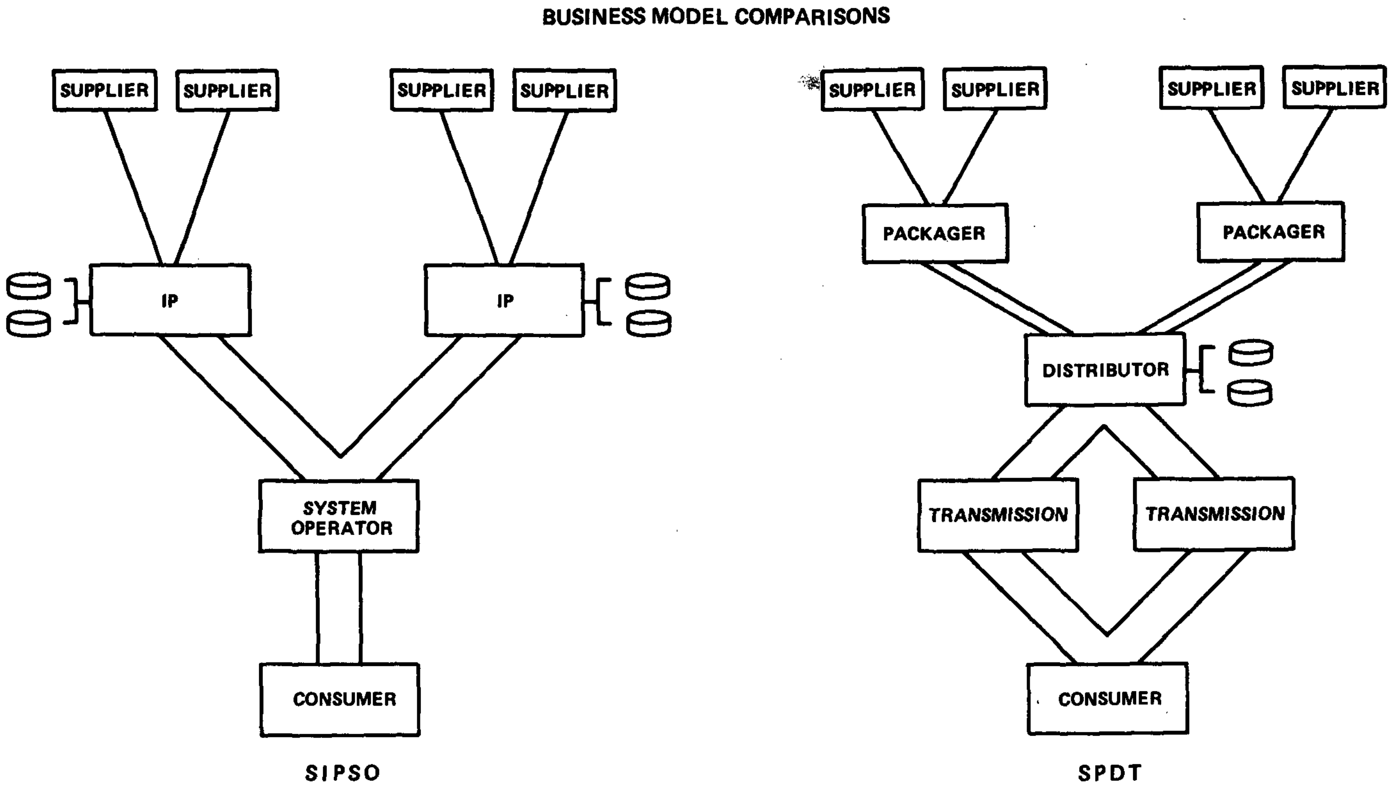

Fig. 7. Business models.

TABLE XII
COMPARISON OF BUSINESS MODELS

Model	Gateway Traffic	Consumer Agent	Transmission Agent	Home Terminal	Consumer Presentation	Business Driver
SIPSO	95% OFFNET 5% ONNET	IP - NEW FORMAT FOR EACH	IP - SINGLE MEDIUM	VARIES FOR IP	TEXT AND GRAPHICS	INFORMATION
SPDT	5% OFFNET 95% ONNET	DISTRIBUTOR SINGLE DATA FORMAT	DISTRIBUTOR MIXED MEDIA OF CABLE AND TELCO	SINGLE TERMINAL	TEXT AND GRAPHICS	TRANSACTION INFORMATION ENTERTAINMENT

terminal. Their costs vary from $300 to $600, which is also what Knight-Ridder is charging the consumer for the ATT terminal in Florida.

2) *S/P/D/T:* This model introduces a more transaction-based approach to providing the business services. As before the supplier (S) desires to communicate with the consumer. There are other agents in this model.

- *Packager (P):* This is a national or regional electronic agent existing on an industry by industry basis, that facilitates suppliers' entry to the business.
- *Distributor (D):* This entity is local to an SMSA and provides local data storage at a single point. The consumer communicates with the distributor locally 95 percent of the time. Only 5 percent of the time does the distributor have to through a gateway. The distributor also does marketing, sales and customer services.
- *Transmission (T):* This may be cable or telco. Since both are available and can be coordinated by the distributor, the consumer can be provided readily with text and high resolution graphics in addition to CATV services.
- *Terminal Provider:* The home terminal may be provided by the consumer or by some other agent.

In the SPDT model the distributor provides a single terminal, has a resident database of text, and gateways to packagers only for small amounts of data.

The SIPSO model is highly distributed with the SO only in control of communications. The SPDT model is hierarchical with the distributor in local control and the packager in national control. Fig. 7 depicts these two models and Table XII provides a comparison of their characteristics.

B. System Loads and Requirements

Previously it was assumed that there will be up to 100 000 users for systems with many different applications. There are then two key questions with respect to load. First is the issue of usage. How often are users on the system and when do peaks occur. Second, for each session on the system, what are the data requirements?

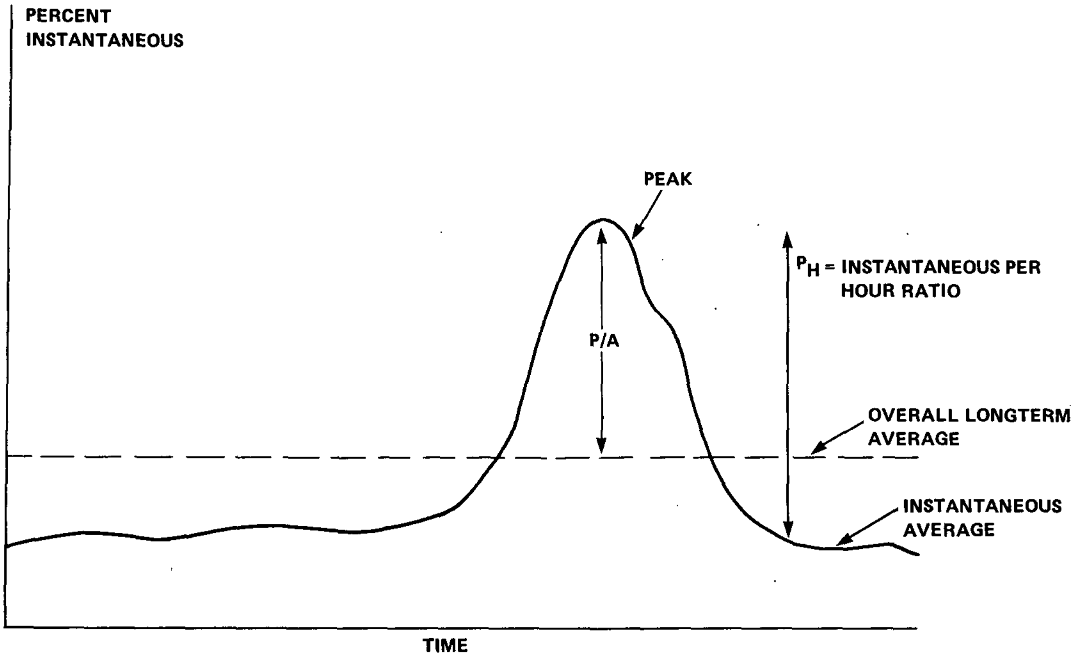

Fig. 8. Traffic peaking.

Let us begin with a typical user's session. The session is broken into subsessions (banking, shopping, etc.). A simple segment is composed of a request sent to the central facility and a screen transmitted to and received by the home terminal. The user requests are known as upstream data traffic packets and the returned screens are known as downstream data packets. There is a one-to-one correspondence between the data packets and subsessions.

Let us now consider a simple example of system loading (see [10] for some explanatory data).

- Assume that there are 100 000 users.
- Assume that each user is on the system 90 h/yr.
- Assume 16 h/day of use for a total of 5840 h/yr.
- Then the overall long term fraction active at one time is 90/5840 or about 1.54 percent, representing 1540 users. Clearly as the hours of usage increase, this percentage increases proportionately.

This overall average or long term average (LTA) percent is clearly not the design factor. The system must be designed for peak loads. Fig. 8 depicts the percent instantaneous as a function of time. The peak is the key design number. The peak-to-average ratio (PA) is defined as the ratio of the instantaneous peak to LTA. The instantaneous average (IA) is the base of the traffic curve. PA can be shown to equal

$$PA = \frac{P_H}{(1-\bar{N}_H)(1-\bar{N}_D)+\bar{N}_D(1-\bar{N}_H)P_D+\bar{N}_D\bar{N}_H P_H}$$

where P_H, P_D are the peak hours and day to IA ratios, and $\bar{N}_D$, $\bar{N}_H$ are the fraction of days/h that the peak is in.

Now when multiple applications are used there is a further smoothing due to noncoincidental peaks as shown in Fig. 9. Table XIII shows some of the sample loading numbers of the typical applications. This analysis results in a PA ratio averaged over all applications of about 2. Thus, in the previous example the number of peak instantaneous subscribers is 3000 or 13 percent.

We can now consider the data traffic loads. The analysis is as follows.

- In a typical system of 100 000 subscribers there is more than one hub or distribution point. Assume 10. Thus there are 10 000 subs/distribution point.
- With 3 percent instantaneously active this yields 300 subs/hub.
- The data response per subscriber are on average one per 15 s. Thus, there are 20 responses/s at peak per hub.
- The upstream data are 100 bits/request on the average so that this yields a peak rate of 2000 bits/s upstream.
- The downstream data are 8000 bits/request so that the rate is 160 000 bits/s downstream.

This methodology indicates how to evaluate data rates and the implications of loading. The major observations made here are

- The upstream traffic is very low.
- The peak depends on the total yearly usage and instantaneous peak. Unfortunately no adequate database yet exists on these numbers.
- Downstream is readily handled by VBI, single cable data streams, or telephone lines.

C. System Architectures and Cost Implications

The system architecture for the consumer networks is comprised of several elements: terminal, local network design, headend design, and interconnect [13].

For the home terminal, one of the key factors is cost. This cost should not exceed $300 per home. In the Warner system, the terminal by Pioneer is in the $150–200 range and provides modulation, multiple access, two microprocessors, ROM, RAM, keyboard, and RF tuning and discrambling. These capabilities are essential. Assuming a 30 month payback, this implies $10/month/subscriber for terminal payback on a $300 terminal.

The plant architecture has been discussed in detail. Installed plan costs in capital range from $10 000 to

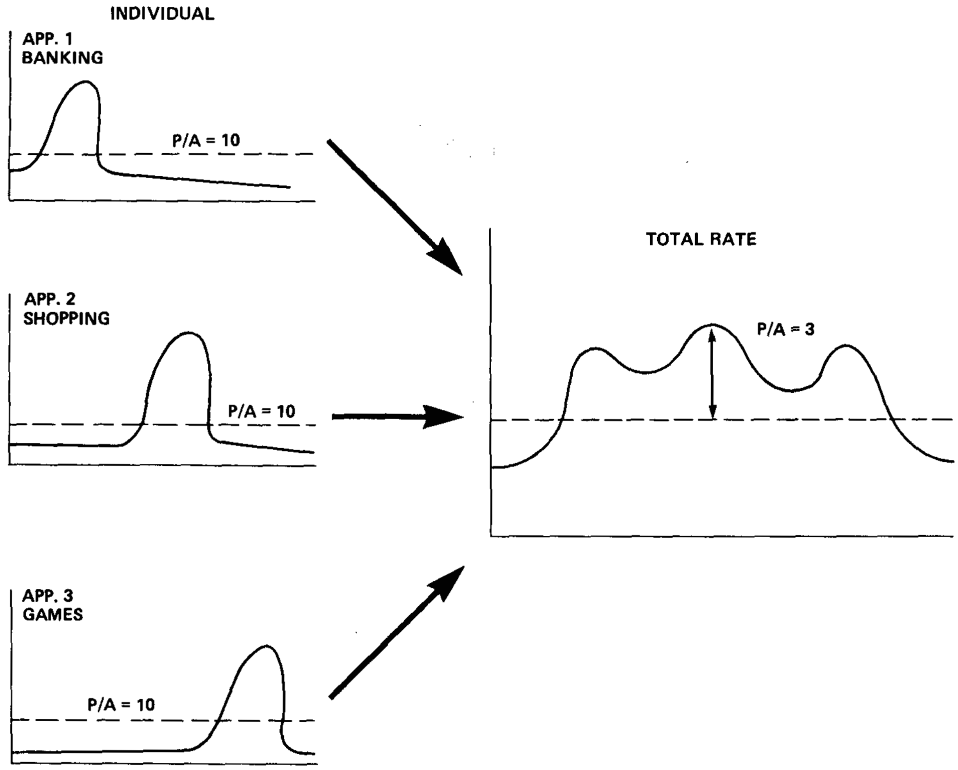

Fig. 9. Noncoincidental traffic peaks.

TABLE XIII
DATA USAGE AND LOADING

Application	% Who Use	No. of Sub-sessions Per Yr./Subscribers	Length of Sub-session (min)	Peak Day	No. of Peak Hrs./Peak Day	Peak to Avg. Ratio.
BANKING	80	104	5.0	Mon, Thurs	4	4
CLASSIFIED	60	50	5.0	Thurs	6	4
INFO/EDUCATION. . .	50	100	15.0	Tues, Thurs	6	4
GAMES	40	250	6.0	Mon, Fri	6	4
MAIL	40	90	5.0	--	-	-
MERCHANDISE SHOP.	75	104	10.0	Mon, Thurs, Fri	6	4
TICKETING	60	30	6.0	Mon - Thurs	6	4
TRAVEL	70	10	12.0	Sun	8	4

\$50 000/mi and the number of households ranges from 20 to 150/mi. This is a range of \$66 per home passed to \$2500 per home passed. The spread of this range is a dominant factor in cable design and profitability. The average is \$150–\$300/home. Thus payback on terminal and plant is in the \$10–\$20/month range. This does not include operating expenses. The MSO designs the plant to be a best compromise between matching franchise requirements and minimizing capital per home.

The interconnect issue is the most important. The need to interconnect MSO headends has already been made. The present direction in interconnect ranges for Centel's regulated Videopath, Gill's advertising oriented approach, 3M's attempts in several markets such as New York City, and the more recent approaches taken by the BOC's. Fig. 10 depicts three possible configurations. The fully interconnected approach seems to be the best approach for an MSO coalition. The ring network could best be supported by a fiber optics network provided by an MSO coalition or the BOC. The central interconnect approach provides either transport or enhancement such as protocol conversion. The former is a BOC possibility, the latter is for an independent entity.

VI. Regulatory Environment

Telecommunications has always stood on a three legged platform: the market, technology, and the regulatory environment. The three major regulatory bodies involved in MAN's are the FCC, the state Public Utility Commissions (PUC), and its local franchising authority (FA). The BOC's are governed under tariffs by both the FCC and PUC. Now with deregulation, pursuant to the 1982 consent decree, the BOC's will handle only local transmission,

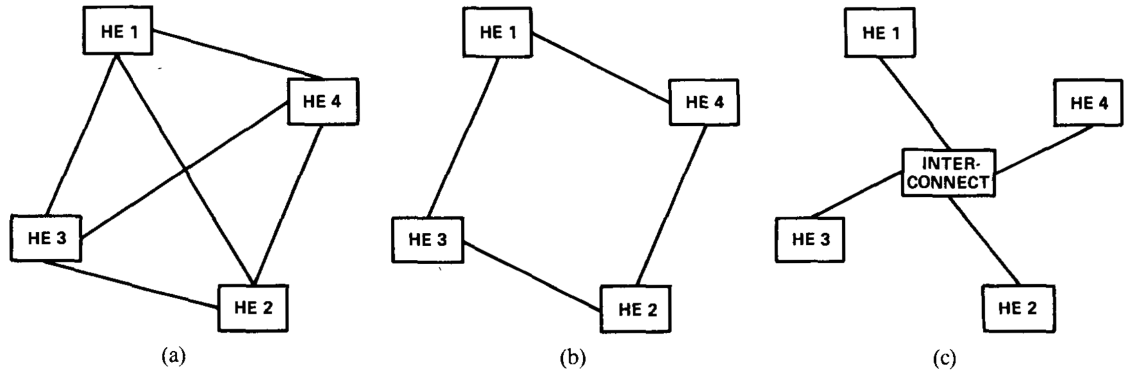

Fig. 10. Interconnection topologies for multiple MSO's. (a) Fully interconnected. (b) Ring network. (c) Central interconnect.

including switching, and ATT will do all long distance transmission along with the other specialized common carriers (SCC) such as MCI, SBS, Telenet, etc. The FCC has ruled that it has no jurisdiction to control the cable transmission. These are usually controlled by the FA's. The BOC's typically file with the PUC's on a state-by-state basis and the PUC's have traditionally not required the cable companies to file tariffs since cable has not been considered a common carrier. This environment is now changing [12].

A. Computer Inquiry II

Computer Inquiry II defined two types of service: basic transmission and enhanced. Enhanced is a service that provides a value added to the transmission. In its narrowest sense it would mean some complicated data processing. In its broadest sense it would include protocol conversion (asynchronous to synchronous). Enhanced services are not regulated and the BOC's are prohibited from providing them except in a separate organization.

Clearly this approach is very narrow in some cases and could severely limit a cost effective hybrid telco/cable MAN capability. If the BOC's cannot translate asynch to synchronous, then this could dramatically drive up the cost of consumer terminals. This broadest interpretation may very well be challenged in the near future.

B. Common Carrier

Is cable a common carrier and should it be regulated? The FCC has traditionally had a hands-off policy to cable due to its entertainment-only nature. But the FCC can have jurisdiction via the Communications Act of 1934, under the common carrier clause. That act defines common carrier as "any person engaged as a common carrier for hire, in interstate or foreign communications by wire or radio..." When does cable become a common carrier? It must satisfy three requirements: it must be interstate, be for hire, and be offered to the public. Clearly, cable satisfied the last two but not the first, or does it? Does not HBO, in using a satellite, cross state lines? Yes, but it is not the distributor, only the supplier who crosses the state lines. But as we look at new technologies, it is conceivable that some may entail services that are clearly interstate, such as electronic mail. Does this make it a common carrier and subject to such regulation?

To answer this it is necessary to review three recent decisions. As indicated, in Computer Inquiry II, the Commission introduced the concept of basic and enhanced services. Basic is basic transmission, qua transmission. Enhanced is anything else! Enhanced services *are not* subject to regulation. Thus, over the cable, the question arises, what constitutes basic and enhanced? The second ruling is the NARUC I (National Association of Regulatory Utility Commissioners) in 1976 which stated that you were a common carrier if you held yourself out to the public indiscriminately. In NARUC II it was ruled that cable could be treated as a common carrier in just a portion of its service.

The question then is where does all of this legislation leave cable? Recently Mr. H. Geller has tried to introduce legislation to regulate up to 25 percent of cable systems as common carriers. He is quoted as saying, "It is terribly important that the cable owner *not be allowed* to control all of the 100 or so channels on his system." In light of this regulatory posture, the demands to control cable are in what could best be called a quagmire, and what services are actually anticipated must be considered.

We can now address the issue of what technology is available and what new services it will support. There are two key technologies that will revolutionize the cable as a new distribution medium. The first is the home computer. Not meant is the personal computer such as an Apple or IBM *personal* computer which costs $2500 or more and requires hours to assemble and a great deal of patience and interest, but a preprogrammed *home* computer which costs $325–$350, has a single wall socket plug and can, with the right software, "talk" to you when you turn on the switch. It is a "friendly" terminal and makes you comfortable. The second technology is high density optical memory. This technology does not go in the home but at a more central site. It is used to allow you, at home, to access infinite sources of data and video information via your *home* computer. It is these two elements that take full advantage of the interaction, a capability of cable—a capability to provide two-way interaction, a capability to provide video, something your telephone lines can never do. Once this synergism is recognized, a plethora of new services become meaningful and attainable.

In combination with these new technologies, cable provides a new mode of distribution to the home, and elsewhere, of a variety of new, *enhanced* services. Typical services are home shopping and home banking, two very important transaction services. Information services such as travel, real estate guides, educational training, databases, and entertainment services such as games.

C. PUC's

In early 1983 the Nebraska PUC filed a cease and desist order against Cox Cable in Omaha, NE, based on its operations of both its consumer enhanced services returns and its commercial network called Comline. This was done at the instigation of the local BOC. At the same time Pacific Northwest Bell (PNB) informed the Portland, Oregon, cable operator of its intent to do the same in that city's institutional network. Cox has filed before the FCC for relief and at this time it is still pending. At issue is whether cable is a common carrier as is the Telco, and if so, then are the consumer and commercial services basic or enhanced.

These issues will play a dramatic role in the evolution of MAN's.

VII. Conclusions

We have argued in this paper that there are many technical challenges in the CATV areas as applied to MAN's. The issues of multiple access are not readily settled and are even more complex than those that abound in the LAN area, as was demonstrated by the IEEE 802 Committee. The key driving forces are the yet to be understood consumer market and the rapidly changing regulatory environment.

This paper has tried to argue that the consumer market requirements will play a dominant factor in how MAN's evolve on the residential side. Such issues as peak loading, data rates and formats, interconnect, and gateways will play a significant role in MAN growth. The issue of centralized versus distributed control plays not only a technical role but is key to how this new industry will evolve.

The regulatory environment is also critical. Will the PUC's regulate cable as a common carrier? If it does, will that regulation stifle growth, as it has in many markets, or will it protect cable from the problems of local franchise control boards? How is the public interest best served? What is the potential of a hybrid telco/cable system? Cable can easily distribute full motion video on demand. Telco can provide a reliable two-way data path in low data rates. How can these best be combined?

These and many more issues will evolve over the next decade in the residential MAN network.

Acknowledgment

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Terrence P. McGarty (S'64–M'66) received the Ph.D. degree in electrical engineering and computer science from the Massachusetts Institute of Technology, Cambridge, MA.

He is President of Warner Electronic Home Services, a Division of Warner Communications Inc. (WCI), New York, NY. In that position he is responsible for the development of new business areas for the consumer residential market that use interactive computer and communications technology. Prior to joining WCI, he was Vice President of Advanced Services, Warner-Amex Cable (a joint venture of WCI and American Express), where he had responsibility for commercial and consumer cable services. He has 20 years experience in the telecommunications field with senior management positions at Comsat and Continental Telephone. He started his career with New York Telephone and Bell Laboratories. He is the author of over 50 papers and two books in the area of computers and communications.

Gerald J. Clancy, Jr. received the B.S. degree in mathematics from Monmouth College, West Long Branch, NJ.

He is Vice President of Engineering in the Warner Electronic Home Services Division, Warner Communications Inc. (WCI), New York, NY. In that position he is responsible for the hardware and software development associated with bringing interactive business services to the home. Prior to joining WCI, he was Director of Systems and Technology, Warner-Amex Cable. He previously held positions in sales, software development, systems engineering, network planning, and business and strategic planning with Honeywell and IBM over a 20 year period.

Mr. Clancy led the IEEE 802 Local Network Standards Committee's efforts in the development of the media access methods (token and CSMA/CD) and logical link control. He currently serves on the Executive Committee of that effort.