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Reliability and Cost Evaluation of Third-Generation Wireless Access Network Topologies: A Case Study

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***Abstract*—The "explosive growth in bursty traffic" changes the network dynamics and requires a good evaluation of various classes of service when designing an access network. From a topological standpoint, the multiservice networks in this paper are heterogeneous systems which integrate both a core and some wireless access networks into an infrastructure similar to third-generation wireless networks. Such networks require reliable and cost-effective solutions to the problem of selecting access technologies for satisfying performance and quality of service requirements related to the services and applications envisioned.**

This paper analyzes the reliability aspects of some access network topologies to insure a certain level of quality of service at the lowest cost for the end users. It considers a mass market equivalent to 1.6 million subscribers, the objective being to determine the cost the users are ready to pay to benefit from services and applications provided by these multiservice networks. For these purposes, the relative behavior of 3 access-network topologies are studied: the tree with parallel backup links, the ring, and the partially meshed topologies.

In ring topology, simulation results show that a great connectivity in the access network is not justified in terms of reliability requirements; the partially meshed topology, even if it has redundant links which affect its cost, outperforms the tree with parallel backup links; and the ring topology is more reliable in terms of disconnected sessions than the tree topology. By considering both reliability and cost, a tree with parallel backup links appears the best topology for the access network and its cost is acceptable for the end user. This study can be extended by: 1) establishing the cost as a function of the quality of service; 2) optimizing the partially meshed topology for more reliable networks; and 3) defining a (shaping) policy to deal with a variety of traffic schemes.

***Index Terms*—Access network, cost evaluation, multi-service network, quality of service, third-generation wireless network, topological design.**

ACRONYMS AND ABBREVIATIONS[1]

ADSL	asymmetric digital subscriber line
AR	access router
ATM	asynchronous transfer mode
ATU-C	ADSL transmission unit, C
ATU-R	ADSL transmission unit, R
BS	base station
DSL	digital subscriber line
Gbps	gigabit per second
HDSL	high-data-rate DSL
IDSL	ISDN DSL
IP	internet protocol
ISDN	integrated service digital network
Kbps	kilobit per second
LAN	local area network
MAN	metropolitan area network
Mbps	megabit per second
Mux	multiplexer
μsec	microsecond
MTBF	mean time between failures
MTTF	mean time to failure
MTTR	mean time to repair
OC-1	optical carrier level #1 (51.84 Mbps)
OC-2	optical carrier level #2 (103.68 Mbps)
OC-3	optical carrier level #3 (155.52 Mbps)
OC-12	optical carrier level #12 (622.08 Mbps)
POP	point-of-presence (location of an access point to the Internet)
QoS	quality of service
RF	radio frequency
RP	route processor
s-	implies: statistical(ly)
TS	transceiver set
VC	virtual circuit
VoD	video-on-demand
VDSL	very-high-data-rate DSL
WAN	wide area network
WLAN	wireless LAN
$	US dollar
k$	10^3 US dollars.

NOTATION

C_{end}	end equipment cost
C_{TS}	transceiver cost
M_{TS}	transceiver capacity (number of users)
C_{mux}	Mux cost
U	maximum number of users per Mux
C_{AR}	AR cost
M_{AR}	maximum number of users served by an AR, and by the link from the AR to the POP

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[1]The singular and plural of an acronym/abbreviation are always spelled the same.

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C_I	AR-to-AR or AR-to-POP interface cost
p_0	number of Mux (or direct OC-1 links) on 1 AR
A	amortization period (in years)
n	number of nodes
p	number of normal OC-3 links
k_T	number of redundant/backup links
f	link failure probability
V, V'	system failure probability
Cost	total initial cost per user
$\text{Init}_{\text{month}}$	initial monthly cost per user
$\text{Total}_{\text{month}}$	total monthly cost.

I. Introduction

A TELECOMMUNICATION network is a set of equipment linked to each other through communication links. These equipment and communication links permit the exchange of messages among geographically scattered users. For the network to be functional, its components (nodes and links) must be fit for service. Unfortunately, this is not always the case, because network components are not always reliable [2], [4], [5], [8], [9], [15].

In recent years, a variety of mobile computers equipped with wireless communication devices have become popular. During this time, the revolution in networking starting with broadband technologies makes possible a wide variety of services and applications, such as file transfer, video-conferencing, electronic mail, graphical user interfaces, and remote file systems. The concept of multi-service cellular network is then used to denote the integrated infrastructure dedicated to support these applications and services. Multi-service networks refer to networks carrying multimedia, voice, data, and video traffic [3], [6], [7], [16]. Their architecture integrates broadband and wireless mobile networks such that they are suitable for multimedia and mobile applications with bursty traffic [1], [6].

Typically, a wireless mobile network consists of two distinct sets of entities: mobile hosts and fixed hosts. Some of the fixed hosts, called BS, are augmented with a wireless interface to communicate with mobile hosts. Each BS covers a wireless cell gathering one or more mobile units of a given area.

From a topological standpoint, the multi-service networks in this paper are heterogeneous systems which integrate both a core network and some access networks into an infrastructure similar to third-generation wireless networks. Such networks require reliable and cost-effective solutions to the problem of selecting access technologies for satisfying QoS and performance requirements related to the services and applications envisioned.

This paper analyzes the reliability aspects of some access-network topologies in order to insure a certain level of QoS and reliability at the lowest cost for the end users. It considers a mass market equivalent to 1.6 million subscribers, and the analysis envisioned is essentially related to third-generation networks, the objective being to determine the cost the users are ready to pay to benefit from such networks.

Section II defines some basic concepts and states the background. Section III deals with some topological considerations and reliability issues. Section IV analyzes cost-effectiveness issues and simulation results.

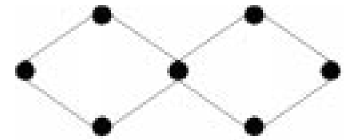

Fig. 1. Example of a 2-link-connected graph.

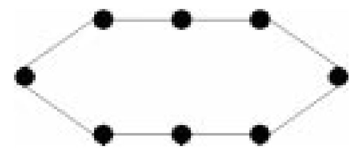

Fig. 2. Example of a 2-node-connected graph.

II. Basic Concepts and Background

Nomenclature:

- link: an arc that carries information in a computer network (in this paper, link is a synonym for arc and edge).
- link capacity: maximum data-rate carried by a link.
- link flow: effective data-rate carried by a link.
- traffic: rate of exchanging packets.
- K-link-connected: a graph is K-link-connected if and only if each pair of nodes is connected by at least K link-disjoint paths; e.g., the graph of Fig. 1 is 2-link-connected.
- K-node-connected: a graph is K-node-connected (K-connected) if and only if each pair of nodes is connected by at least K node-disjoint paths; e.g., the graph of Fig. 2 is 2-node-connected while the graph of Fig. 1 is not.
- link-connectivity: the largest value of K for which a network is K-link-connected.
- node-connectivity: the largest value of K for which a network is K-node-connected.
- MTTF: the mean time that a system operates before the first failure.
- LAN: network connecting several local nodes and making possible high-speed data transfer through short distances.
- MAN: network with more or less reduced data throughput which connects several nodes located at the same city.
- WAN: (backbone or core) network used to connect several cities located at about 10 kilometers between each other.

Generally, 3 types of networks are distinguished: LAN, MAN, and WAN. In the third-generation networks considered, the core network is a WAN or a MAN, whereas the access networks are LAN or WLAN which essentially consist of AR, hubs, and Mux. To each AR, one can add an interface which allows each router to communicate with another one. Another kind of interface which can also be added to the AR is a small RF interface to edge users; it handles approximately 300 users who can each have a 2 Mbps peak rate.

The topology of a network describes its physical characteristics, i.e., the way in which its nodes are linked to each other, and the capacity of each of its links [2], [12], [14]. An access network can have a star, tree, ring, or mesh topology [11].

- In a star topology, all nodes are linked to a common central node: the star center. All communications placed in this type of network must go through this node.
- In a tree topology, the network has a hierarchical directory structure. The principal node of this topology through which all applications pass, is the tree root. In such a structure, the common link takes the form of a cable (with several branches) to which one or several stations are attached.
- In a ring topology, all the nodes are interconnected to form a closed ring, which, in its turn, takes a point-to-point form.
- A (partially)-meshed topology is formed by several links such that each node pair of the network is linked by more than 1 path. When each node-pair of a network is linked by a direct arc, the topology is totally meshed or fully meshed.

The main components of a network are nodes and links. The nodes can be terminals, servers, computers, multiplexers, hubs, switches, bridges, routers, etc. The most relevant attributes of a network are: cost, capacity, availability, and reliability [11], [13].

- Node-cost includes purchasing and maintenance, and the cost of related software.
- Node-capacity refers to the speed of its processor, the size of both programs and available memories.
- Availability refers to the probability that a network is usable during a period of time, given redundancies, breakdown detection, repair procedures, and reconfiguration mechanisms [9], [11]. Availability can be expressed by: MTBF/(MTBF $+$ MTTR).
- Reliability of a computer network can be defined as the probability that at least 1 path exists between each pair of nodes in this network [5]. It depends on the availability or reliability of their components. Thus it is necessary to evaluate the overall network reliability by taking into account, in the topological design phase, the possibility of link or node failures [1], [4], [5], [8]–[10]. For these purposes, many network reliability measures have been proposed [4], [5], [9], [12]. The most popular among these is the concept of K-connectivity which integrates both link-connectivity and node-connectivity. For a strong topological design, node-connectivity appears to be more relevant than link-connectivity for measuring network reliability as well as for providing a certain level of network survivability and fault-tolerance. Network availability and reliability are among the key factors which determine QoS.

In the simplest sense, QoS means providing consistent, predefined “data delivery service” in order to satisfy customer-application requirements, *viz*, the ability of a network element (e.g., an application, host, or router) to have some level of assurance that its traffic and service requirements can be satisfied. This requires the cooperation of all network layers from top-to-bottom, as well as every network element from end to end.

On the other hand, with the Internet phenomenon in the past few years, the number of business and residential subscribers getting on the Internet has increased exponentially. As a result, there is an increasing demand for interactive broadband services, such as high-speed Internet access and video-conferencing [16]. Furthermore, noninteractive services such as VoD become important and might be delivered by the same solution [7], [16]. Since the 1980s, various forms of high-speed modem technologies enabling high-speed services through copper lines have been developed as partial solution of the access problem. Among them are Cable Modem and ADSL [17].

Cable modem is a device that allows high-speed access to the Internet or other data networks via a television cable. It typically has two connections: one for a coaxial cable and another for a computer. The cable modem is fast, but its speed is variable. Depending on the direction (input/output), whether the data are sent from the network to the subscriber (downstream) or from the subscriber to the network (upstream), certain types of modems can reach speeds of 10 Mbps.

ADSL is one of a variety of DSL systems built upon the existing twisted-pair telephone line. The four DSL systems are: ADSL, HDSL, VDSL, and IDSL. The ADSL link is provided by a pair of modems: the ATU-C at the local exchange (central office) and the ATU-R at the subscriber’s premises (remote site). ADSL modems can pump several Mbps downstream into a subscriber line, subject to the local loop length. When ADSL was developed, the broadband service for the mass residential market was thought to be VoD. ADSL is now considered as a good vehicle for Internet access and telecommuting applications.

III. Topological Considerations and Reliability Issues

The problem to solve can be formulated as determining the access-network topology which minimizes the total cost of the links for a given cost structure, link-failure probabilities, AR capacity and locations, subject to a reliability constraint, e.g., 0.001% failure probability for voice traffic.

Define a POP as the location of an access point to the Internet. The reliability analysis is based on the following considerations and assumptions:

1) The topology for the access network consists of edge routers (AXI 540), hubs, and BS—interconnected as in Fig. 3.
2) The topology is between a tree and a totally meshed topology with n nodes and $n \cdot (n-1)/2$ links.
3) The whole access path, from the edge router to the edge BS, is incorporated into a single AR. The RF technology used can manage links with a capacity up to OC-3.
4) The links from the AR to a POP, or to another AR, use two interfaces which cost \$50 000 each.
5) An “AXI 540 edge router cost” $\approx$ \$100 000.
6) The link MTBF is $\approx$ 19 yr $=$ 166 440 h; the MTTR $\approx$ 2 h.
7) Trying to improve the reliability occurs only from the AR to the POP. Reliability from the users to the Mux is sufficient.
8) The MTBF and MTTR are derived from the technical specifications of the AXI 540 edge router.

A. Reliability Analysis

The AXI 540 router MTBF statistics have been calculated in accordance with Bellcore standards, at a 40° C

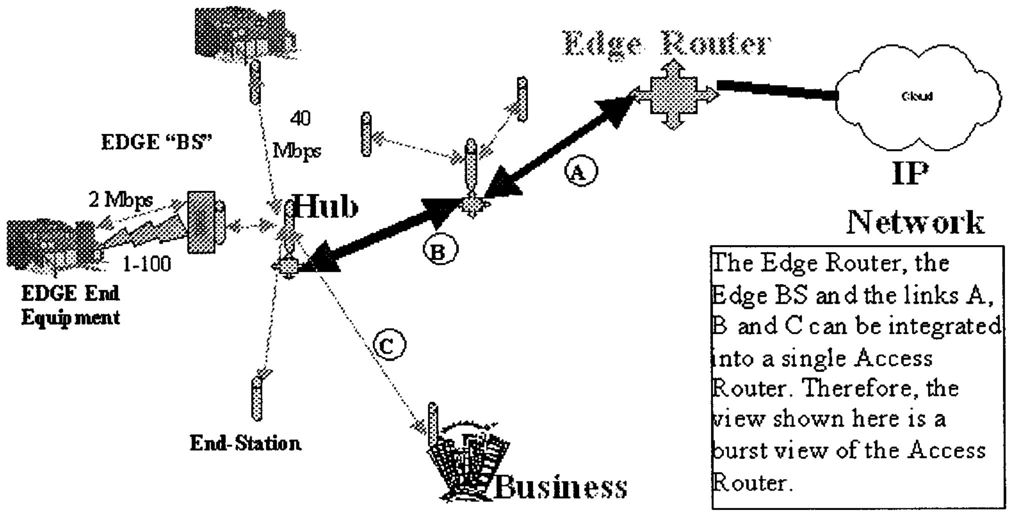

Fig. 3. Existing topology of the access network.

(Room 25° + 15° C over-temperature in cabinet) component ambient temperature.[2] Table I shows the MTTFs; MTTF = MTBF, if the "repair time" < MTTF.'

The AXI 540 router modules are all hot swappable and can be replaced on the fly with spare units, thus minimizing the MTTR. A minimally trained field technician is expected to replace any AXI 540 router modules within 10 min. However, MTTR = 2 h in this paper, because it is the most common value in the industry, including travelling time to the site. Since the common hardware is all 1 : 1 redundant (for each active component, there is one standby backup) and hot-swappable, replacement of any failed common component (e.g., RP, switch fabric, power supplies, fan trays) does not result in any system downtime.

From a software perspective, two types of software component failure can be considered:

- a soft failure resulting in an automatic restart of the failed process,
- a hard failure requiring reboot or replacement of the processor.

For a soft failure, resolution is virtually instantaneous, with resumption of process execution occurring within 1 to 2 s. Hard failure is minimized via the AXI 540 router hot-standby resiliency features that allow an optional RP to take over in the event of a failure. Recovery time from hard failure is configuration-dependent, e.g., based on the type of protocols used, or numbers of peers. Also, the software is in a "warm-boot" state: upon a failure, it is necessary to restart only the process daemons rather than rebooting the entire operating system.

If the failure distributions are s-independent and exponentially distributed with mean working time equal to the MTTF, the MTTF for the entire AXI 540 system can be approximated as in Table II. The hardware failure probability of the AR is very low (less than the maximum failure probability allowed for voice). This probability accounts for the redundancy. Without redundancy, the availability is somewhat less than its specification.

[2]As required by Bellcore TR-332, *Reliability Prediction Procedure for Electronic Equipment.*

TABLE I
MTBF FOR THE BASIC COMPONENTS OF AXI 540

Component	MTTF
Switch Fabric	30.8 years = 269,808 hours
Backplane	113.4 years = 993,384 hours
LED Board	695.8 years = 6,095,208 hours
Route Processor	389.4 years = 3,411,144 hours

TABLE II
AXI 540 AVAILABILITY

	MTTF (hours)	Unavailability (MTTR/MTTF)	Availability
Switch Fabric	269808	$7.41268 \cdot 10^{-6}$	0.999992587
Backplane	993384	$2.01332 \cdot 10^{-6}$	0.999997987
LED Board	6095208	$3.28127 \cdot 10^{-7}$	0.999999672
Route Processor	3411144	$5.86314 \cdot 10^{-7}$	0.999999414
Total*		$1.03404 \cdot 10^{-5}$	0.99998966
Total**		$1.0692387 \cdot 10^{-10}$	0.999999999

* product of availabilities ** with 1:1 redundant components

Now, evaluate the failure probability of the links.

In a star topology, the failure of 1 link isolates a whole portion of the access network. The probability f that $M_{\rm AR}$ users will be isolated from the net is the probability of failure of the AR-to-POP link. Therefore, the AR-to-POP link failure probability should be as small as feasible.

With the tree topology in Fig. 3, $f = 2/166440 = 1.201 \cdot 10^{-6}$ (the numbers come from hypothesis 6 of Section III). This is more than the maximum voice failure probability (0.001%), and with an important number of users on this link, chances are that some users notice from time to time the failure of the system. Thus, try to improve the reliability at the link level by increasing the link-connectivity while maintaining a reasonable cost.

Given that the star topology is clearly not reliable enough, evaluate alternate topologies including a tree with parallel backup links as shown in Fig. 4. Three cases are considered:

1) no overload tolerance,
2) very rare overload tolerance,
3) other similar configurations.

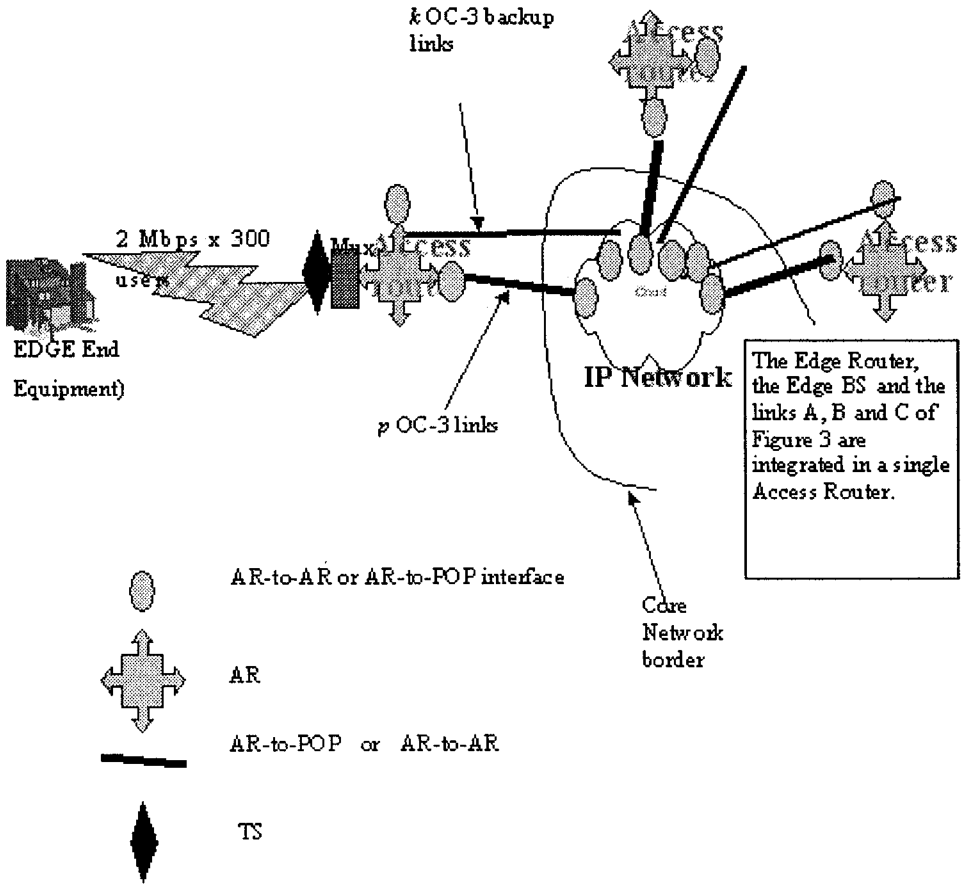

Fig. 4. Tree topology with parallel backup links.

Case 1—No Overload Tolerance: From each AR to POP there are at least 2 link-independent routes: one with normal links and one with backup links. The redundancy of the links is $k : p$ (k backup links for p active ones);

$p \equiv$ number of direct OC-3 links
$k \equiv$ number of backup links
$f \equiv$ failure probability of an OC-3 link.

For k additional links, $2k$ additional interfaces are needed. The system has an abnormal operation if at least $k+1$ links fail. The probability that the system will be overloaded is:

$$V = \sum_{i=k+1}^{p+k} C_{p+k}^{i} \cdot f^{i} \cdot (1-f)^{p+k-i} = 1 - \sum_{i=0}^{k} C_{p+k}^{i} \cdot f^{i} \cdot (1-f)^{p+k-i}, \quad C_n^i \equiv \frac{n!}{i! \cdot (n-1)!}. \tag{1}$$

Table III shows some values of V as a function of k and p.

For comparison, the required failure probability for voice is 10^{-5}. Therefore, 1 redundant link is sufficient.

Case 2—Very Rare Overload Tolerance: If some occasional overload is tolerated and $2k$ additional interfaces per AR are added, then the network supports the failure of $k+1$ links with an overload of $1/(p-1)$ per remaining links (since the k redundant links are not usually used). Then the abnormal operation occurs in case of failure of $k+2$ links; for example one can decide that the network could also support the failure of $k+2$ links with an overload of $2/(p-2)$ and then carry out the same calculations for $k+2$ links. The failure probability of $k+2$ links is:

$$V' = \sum_{i=k+2}^{p+k} C_{p+k}^{i} \cdot f^{i} \cdot (1-f)^{p+k-i} = 1 - \sum_{i=0}^{k} C_{p+k}^{i} \cdot f^{i} \cdot (1-f)^{p+k-i}, \quad C_n^i \equiv \frac{n!}{i! \cdot (n-1)!}. \tag{2}$$

If k links fail, the network still has a normal operation with no overload: the $V' < V$ in case 1.

TABLE III
VALUES OF V AS A FUNCTION OF k AND p

k	p	V
1	3	$8.66 \cdot 10^{-10}$
1	8	$5.2 \cdot 10^{-9}$
1	16	$1.97 \cdot 10^{-8}$
1	30	$6.71 \cdot 10^{-8}$

$k \equiv$ number of redundant links
$p \equiv$ number of normal links

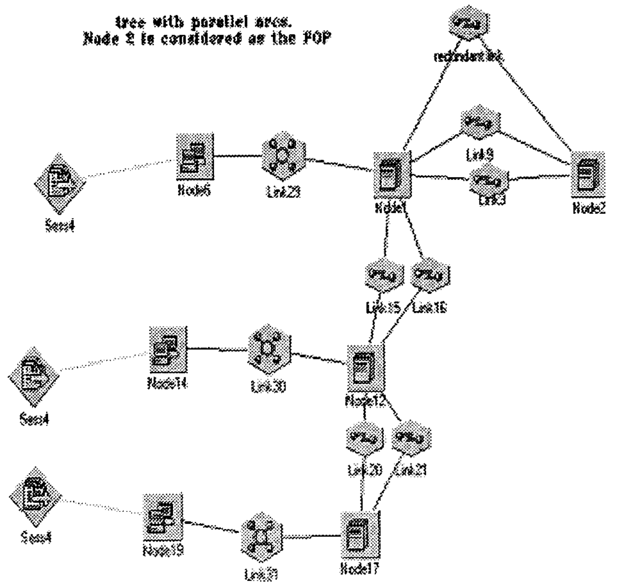

Fig. 5. Tree with parallel backup links topology. A node is either a computer group representing users, or a processing node representing a router. Sess designates a session source generating traffic. Link is a connecting point-to-point or multipoint link between nodes.

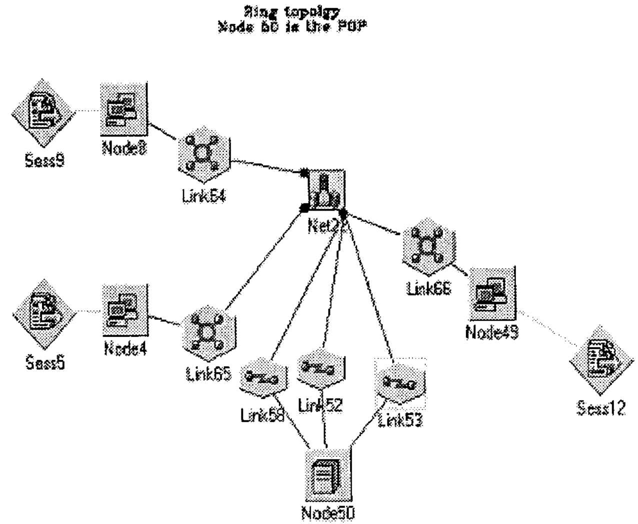

Fig. 6. Ring topology. A node is either a computer group representing users, or a processing node representing a router. Sess designates a session source generating traffic. Link is a connecting point-to-point or multipoint link between nodes. Net22 is a subnetwork whose internal topology is shown in Fig.7.

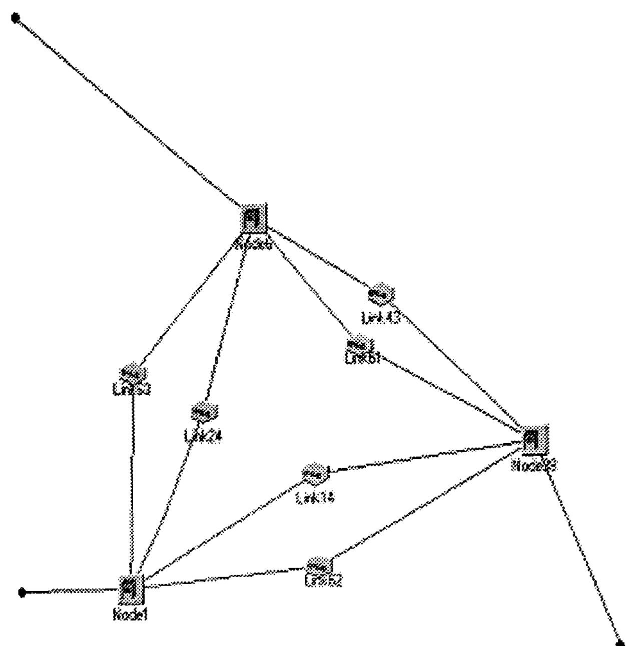

Fig. 7. Access subnet (Net22) for the ring topology. A node is either a computer group representing users, or a processing node representing a router. Link is a connecting point-to-point or multipoint link between nodes

In Fig. 4, for the sake of simplicity, let each AR be directly connected to a POP. But, the AR already exist in the access tree. Thus, some AR can access the POP via another AR (the root AR). However, remember that the root AR has a limited capacity and the RF technology limits the use to at most OC-3 links. In this case, the nonroot AR can simply be considered as Mux. Their load is not the maximum load. Estimate that the reliability of their links to the root AR is sufficient for the number of users they serve. Consequently, only the root AR to POP link has a redundant link.

Case 3—Other Similar Configurations: Carrying out the same analysis for the ring and partially meshed topologies is more complex. Therefore, the relative behavior of the different topologies using simulation are studied. By considering the simulation results, the performance of the “best” topology can be calculated.

B. Simulation Results

Using the CACI Comnet III® simulation tool [18], three access network topologies were simulated:

- the tree with parallel backup links,
- the ring,
- the partially meshed topologies (Figs. 5–9).

In this context, an exponential traffic is used which represents a link channel utilization of approximately 15%. The exponential traffic is used for simplicity; and as research is concerned only with the reliability of various kinds of topology, the reliability is assumed not to depend on the nature of the traffic. Three AR were used with the same incoming traffic. However, depending on the topology, the traffic through each AR will change.

In this analysis, we try to keep a very low failure-probability for the links. However, the real probability numbers could not be used because they are too low for the simulation. For simulation purposes, the probabilities were adjusted: the link failure-time is distributed exponentially with mean 2 min, and the repair time is distributed exponentially with mean 0.01 min. The link-failure probability is then approximately 0.005. Doing so, we hope that this will not impact the results, because we are interested only in the relative behavior of each topology. Consequently, if with these figures, one topology is better than another, there should be no reason that the compared performance will change with the real figures.

Each normal link is represented by two s-independent sub-links or channels. This is motivated because the capacity of the RF links is at most OC-3. Therefore, many s-independent OC-3 links are likely to be used to route the flow if it is more than

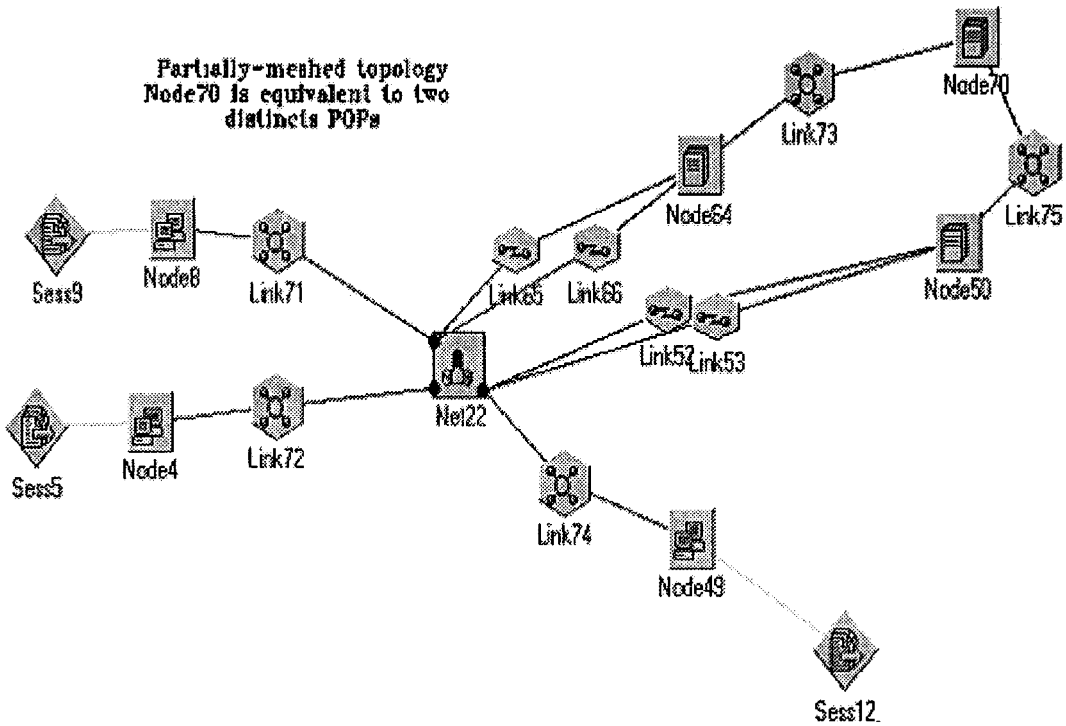

Fig. 8. Partially meshed topology. A node is either a computer group representing users, or a processing node representing a router. Sess designates a session source generating traffic. Link is a connecting point-to-point or multipoint link between nodes. Net22 is a subnetwork whose internal topology is shown in Fig.9.

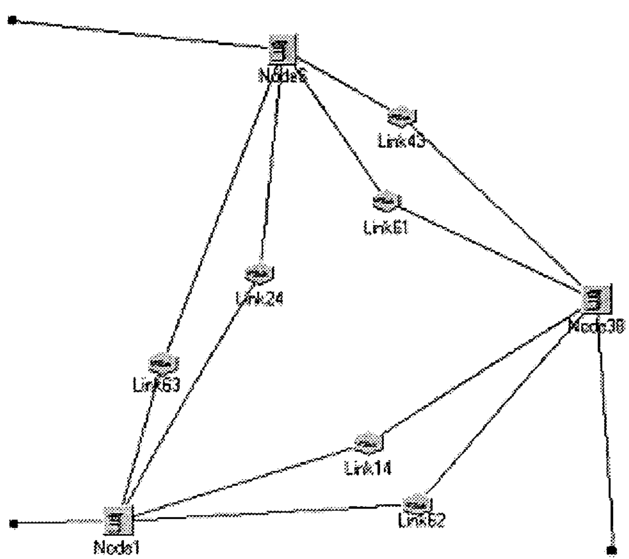

Fig. 9. Access subnet (Net22) for the partially meshed topology. A node is a processing node representing a router. Link is a connecting point-to-point between nodes.

the OC-3 capacity. As backup link, a single-channel link or an OC-3 is used. This is the case for the tree and ring topologies. Table IV summarizes the total number of OC-3 channels for each topology.

More generally, Table V gives the total number of links per topology.

Because the probabilities are very low, it is not guaranteed that the simulation reaches a steady-state phase, nor that the generated probabilities are stable. Consequently, the simulation was

TABLE IV
TOTAL NUMBER OF OC-3 CHANNELS PER TOPOLOGY

Topology	Tree	Ring	Partially-meshed
Number of channels	7	9	10

TABLE V
NUMBER OF LINKS PER TOPOLOGY

Topology	Tree	Ring	Partially-meshed
Number of links	$n \cdot p + k_T$	$(n+1) \cdot p + k_T$	$(n+2) \cdot p + k_T$

$n \equiv$ number of nodes (AR),

$p \equiv$ total number of normal sub-links needed,

k_T total number of redundant links added in a given topology

done for four increasing durations (6000, 10 000, 18 000, 25 000 s) with the hope of reaching a steady-state probability. But this was not the case for all the topologies. To have a better perception, the mean of the four simulations was calculated. Table VI shows the results for the blocking probability.

Generally, the simulation gives more blocking probability for the ring topology than for the tree topology. The blocking refers to the number of session setup attempts which failed due to link-failure. In the ring topology, the conclusion is that there is no use to have a great connectivity in the access network and a weak connection from the access net to the POP. However, even if it has redundant links which affect its cost, the partially meshed topology outperforms the tree with parallel backup links. Importantly, the partially meshed topology uses more links than the tree with parallel backup links (about $2p_T$ more links). Table VII compares disconnection probability for

TABLE VI
BLOCKING PROBABILITIES

Duration (seconds)	Tree	Ring	Partially-meshed
6000	$2.37 \cdot 10^{-4}$	$8.52 \cdot 10^{-4}$	$4.31 \cdot 10^{-5}$
10000	$2.78 \cdot 10^{-4}$	$5.69 \cdot 10^{-4}$	$4.53 \cdot 10^{-5}$
18000	$2.52 \cdot 10^{-4}$	$3.74 \cdot 10^{-4}$	$7.55 \cdot 10^{-5}$
25000	$2.74 \cdot 10^{-4}$	$3.15 \cdot 10^{-4}$	$1.65 \cdot 10^{-4}$
Mean	$2.60 \cdot 10^{-4}$	$5.28 \cdot 10^{-4}$	$8.23 \cdot 10^{-5}$

TABLE VII
DISCONNECTION PROBABILITIES

Duration (seconds)	Tree	Ring	Partially-meshed
6000	$1.13 \cdot 10^{-3}$	$9.925 \cdot 10^{-4}$	$5.72 \cdot 10^{-4}$
10000	$1.26 \cdot 10^{-3}$	$9.830 \cdot 10^{-4}$	$5.56 \cdot 10^{-4}$
18000	$1.22 \cdot 10^{-3}$	$9.240 \cdot 10^{-4}$	$5.82 \cdot 10^{-4}$
25000	$1.25 \cdot 10^{-3}$	$9.180 \cdot 10^{-4}$	$6.15 \cdot 10^{-4}$
Mean	$1.21 \cdot 10^{-3}$	$9.420 \cdot 10^{-4}$	$5.81 \cdot 10^{-4}$

TABLE VIII
GLOBAL PROBABILITIES

Tree	Ring	Partially-meshed
$2.61 \cdot 10^{-4}$	$5.28 \cdot 10^{-4}$	$8.24 \cdot 10^{-5}$

TABLE IX
GENERAL AXI 540 INFORMATION

CHASSIS
· AXI 540
· 15 Slots
· (20 Gbps)
SCALE
· Forwarding: > 20 Mbps
· Latency: < 29 msec
PORT DENSITY
· 120 Fast Ethernet Ports
· 15 Gigabit Ethernet Ports
· 60 OC-3 Ports
· 30 OC-12 Ports
· 60 DS3 Ports
· > 120,000 ATM VCs
· > 7,500 FT1/T1 terminations

TABLE X
DATA SET RELATED TO THE AXI 540

Item	Amount
C_{end}	\$200
C_{TS}	\$10,000
M_{TS}	100 users
C_{mux}	\$10,000
U	300 users
C_{AR}	\$100,000
C_I	\$50,000

each topology; the ring topology is more reliable in terms of disconnected sessions than the tree topology.

To have a global view, let the network try only once to reroute the disconnected sessions; Table VIII illustrates the results. The global probabilities are approximately equal to the blocking probabilities (see Table VI). The tree topology gives better results than the ring topology, while being more economical. The two topologies of interest are then the tree topology with parallel backup links and the partially meshed topology. Nevertheless, the tree with parallel backup links could achieve the reliability goal with fewer links than the partially meshed topology. This is mainly due to the good reliability of the AR and links.

IV. COST-EFFECTIVENESS ISSUES AND RESULTS

The user cost consists roughly of two parts:

1) A fixed cost for the basic equipment such as the phone-terminal located at the user's house and for the activation of the service.
2) The monthly usage of the equipment.

To determine the monthly-cost per user, the following assumptions, a)–d), are used.

a) The equipment cost is established as:
   - The AR-to-AR or AR-to-POP interface costs \$50 000.
   - The AR costs \$100 000.
   - The 40 Mbps to 2 Mbps Mux costs is ≈\$10 000.
   - The Transceiver set costs \$10 000.
   - The end equipment cost in the user house ≈\$200.

b) The connection from the AR to the POP is a link whose capacity is at least 40 Mbps. A standard link value like OC1, OC2, …, can be used. Each TS can handle no more than 100 users. If the Mux serves more than 100 users, additional TS are used. The maximum number of transceivers on a Mux is determined by the number of users with 2 Mbps peak rate, one can multiplex on a 40 Mbps link.

c) The maximum number of 40 Mbps Mux and AR-to-AR interfaces is determined by the capacity of the AR-to-AR (or AR-to-POP) link and the capacity of the AR (AXI 540). The AXI 540 has a theoretical throughput of 20 Gbps.

d) The initial cost depends on the topology chosen from the topologies of interest: tree with parallel backup links, ring, and partially meshed topologies.

A. Tree With Parallel Backup Links Topology

The network topology is approximately as in Fig. 10. First, determine the number of Mux and AR-to-AR interfaces on the AR. The standard value closest to 40 Mbps is OC-1, which has a 51.84 Mbps throughput. Therefore, use OC-1 links instead of 40 Mbps links. Table IX gives the characteristics of the AXI-540 edge router.

Of the 60 OC-3 ports in Table IX, 30 are used for redundancy. If only 25 OC-3 ports are used (which corresponds to about 4 Gbps and represents approximately 1/5 of AXI 540 throughput) and spare 5 OC-3 ports for future expansion or other needs like overload in case of failure of another AR. The AR-to-POP links should at least be able to handle the ingress flow generated by

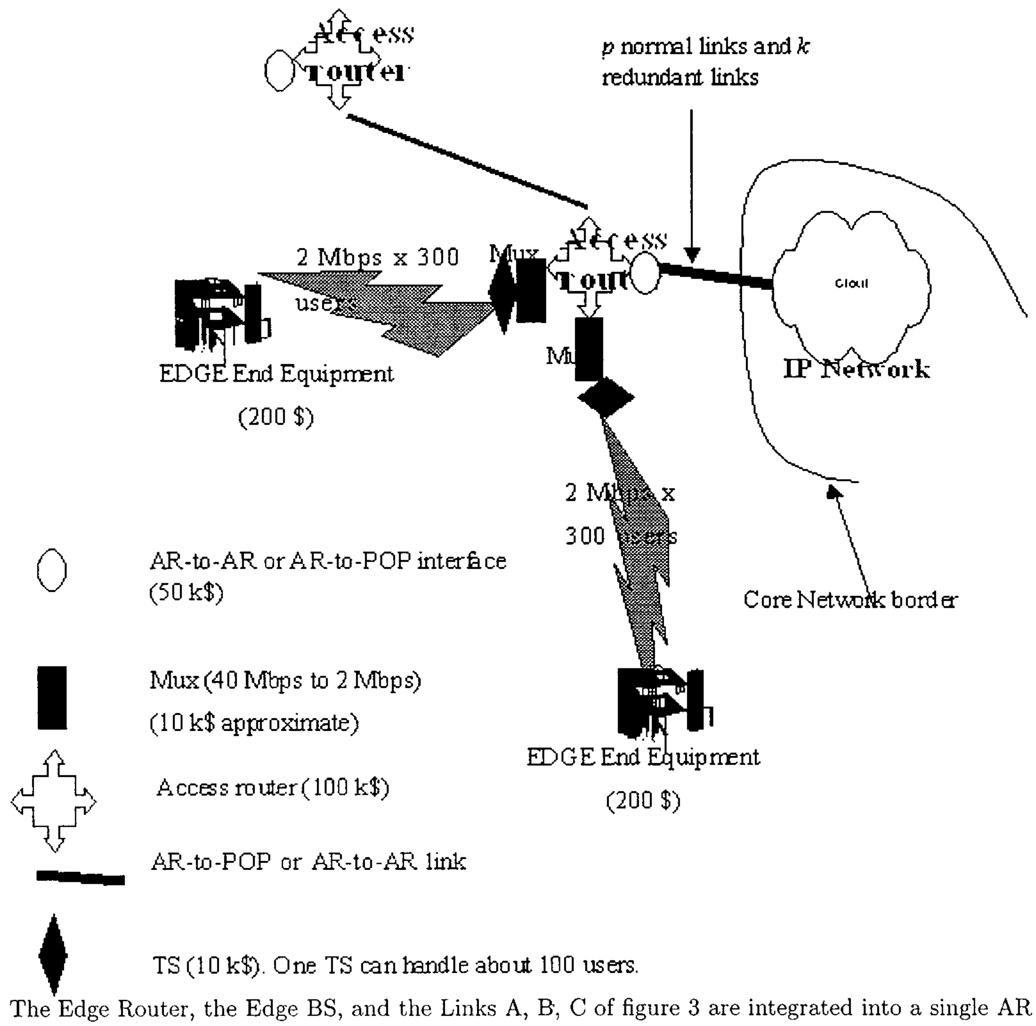

Fig. 10. Tree with parallel backup-links access network topology.

the Mux. Let $p_0 \equiv$ the number of Mux on 1 AR (p_0 is also the total number of OC-1 direct links), use only 25 OC-3 ports, and consider that the egress flow is equal to the ingress throughput, then

$p_0 = p_1 = p_2$;
$p_1 =$ number of Mux (or OC-1) links;
$p_2 =$ throughput of the active output ports;
The total flow handled by the AR is
$p_1 + p_2 = 25 \cdot 3$.
This gives $p = p_1 = p_2 = 37$. Then one can put 37 Mux on one AR, and this gives the minimum capacity of the AR-to-AR link which is OC-37.
This gives $p_2 = 37$. Then one can put 37 Mux on one AR, and this gives the minimum capacity of the AR-to-AR link which is OC-37.

In practice, use 13 OC-3 links for the AR-to-POP links, plus 1 redundant OC-3 link; the total is $2 \cdot (13 + 1) = 28$ interfaces per root AR. The AXI 540 is a big router (only 1/5 of its capacity is used). The AR which are not root (that is, directly connected to a POP) handle less traffic than the root. Consequently, one should use smaller routers inside the access tree and leave the AXI 540 for the access tree root node.

The initial cost per user is

$$\text{Cost} = C_{\text{end}} + \frac{C_{\text{TS}}}{M_{\text{TS}}} + \frac{C_{\max}}{U} + \frac{C_{\text{AR}} + 28C_I}{p_0 \cdot U}. \quad (3)$$

The initial monthly cost, using (3), is:

$$\text{Init}_{\text{month}} = \frac{\text{Cost}}{12A}. \quad (4)$$

With an amortization period of 3 years and the data-set in Table X, the initial cost per user is \$469. This includes the user equipment cost (\$200) and the infrastructure cost (\$269). At the other end, let $U = 100$ users instead of 300. With the data set of Table X, the initial-cost per user is now \$806 (\$200 for the user equipment and \$606 for the infrastructure). Table XI summarizes the initial-cost issues.

Consider 300 users, the initial cost is about \$7.5. This is almost the same as the monthly supplement billed by cable and ADSL North American providers to users who were not previously their customers. Usually, this supplement should reflect the additional charge to connect the noncable-TV customers to the network. However, for ADSL, this supplement is more like an incentive for the user to become a long-distance customer.

TABLE XI
INITIAL COST ISSUES FOR THE TREE WITH PARALLEL-LINKS TOPOLOGY

Total initial cost per user is from (3).
Monthly initial cost per user is from (4).

Maximum number of users per Mux*	Total initial cost per user	User equipment	Amortization period (year)	$\text{Init}_{\text{month}}$ (excluding equipment)	$\text{Init}_{\text{month}}$ (including equipment)
100	$806	$200	3	$16.9	$22
300	$469	$200	3	$7.5	$13
500	$402	$200	3	$5.7	$11

* The other parameters are as in table 9.

TABLE XII
COST SUMMARY FOR THE RING TOPOLOGY

Total initial cost per user is from (5).

Maximum number of users per Mux*	Total initial cost per user	User equipment	Amortization period (year)	$\text{Init}_{\text{month}}$ (excluding equipment)	$\text{Init}_{\text{month}}$ (including equipment)
100	$2554	$200	3	$66	$71
300	$1051	$200	3	$24	$29
500	$751	$200	3	$15	$21

* The other parameters are as in table 9.

TABLE XIII
COST SUMMARY FOR THE PARTIALLY MESHED TOPOLOGY

Total initial cost per user is from (6).

Maximum number of users per Mux*	Total initial cost per user	User equipment	Amortization period (year)	$\text{Init}_{\text{month}}$ (excluding equipment)	$\text{Init}_{\text{month}}$ (including equipment)
100	$3554	$200	3	$99	$93
300	$1385	$200	3	$38	$33
500	$951	$200	3	$26	$21

* The other parameters are as in table 9.

Therefore, the initial cost for the adopted topology is very acceptable for the end user compared to the rates applied by wireline access providers.

B. Ring Topology and Partially Meshed Topology

As shown in Table V, the number of links per AR in a ring topology with n nodes (AR) is

$(n+1)\cdot p + k_T$;
$p \equiv$ number of normal sublinks;
$k_T \equiv$ number of redundant links.

Use the same $p = 13$, and the same $k_T = 1$, as for the tree with parallel backup links topology. For a tree with parallel backup-links topology, let $n = 1$. Table XII gives some cost figures of the maximum number of users per Mux. In all the schemes, the ring topology is more expensive than the tree topology because it uses more links; furthermore, it does not achieve the required reliability.

The cost for the ring topology is

$$\text{Cost} = C_{\text{end}} + \frac{C_{\text{TS}}}{M_{\text{TS}}} + \frac{C_{\max}}{U} + \frac{C_{\text{AR}} + 2(2\cdot p + 1)\cdot C_I}{p_0 \cdot U}. \quad (5)$$

For partially meshed topology, the analysis is similar to the ring-topology case. Use the same values for p, k_T, n. The cost figures are in Table XIII. The partially meshed topology achieves the required reliability but is more expensive. It would be recommended in case more stringent reliability constraints are needed. As a result, the tree with parallel backup links topology remains the "best" topology for the access networks because it achieves the required reliability and QoS, with the least cost.

The cost for the partially meshed topology is

$$\text{Cost} = C_{\text{end}} + \frac{C_{\text{TS}}}{M_{\text{TS}}} + \frac{C_{\max}}{U} + \frac{C_{\text{AR}} + 2(3\cdot p + 1)\cdot C_I}{p_0 + \cdot U}. \quad (6)$$

C. Monthly Cost Determination

The objective is to determine a unique monthly-cost per user. The wireline-access companies bill a fixed amount to the user with no relation to the QoS (i.e., all the users have the same QoS). The monthly utilization cost is made up of the monthly initial cost (from the tree with parallel links topology) and a monthly cost paid by the end user to use the network (in the case where the price is scaled in function of the QoS, this second part would be variable). Because the third-generation technology is new, and has not yet been implemented, consider a wireline access user who was not a previous customer of the provider as a benchmark. For cable modem, a nonprevious user is charged ≈$7 monthly plus an initial fee of ≈$50 (a total initial monthly payment of $12 if the amortization period is 1 year). When considering cable modem users with a monthly subscription and with a annual subscription, the monthly utilization fee is ≈$9. Consequently, the utilization cost represents 75% of the initial cost.

TABLE XIV

Total monthly cost per user is from (8).

U *	Amortization period (year)	Monthly cost per end user
100	3	\$42.25
300	3	\$18.75
500	3	\$14.25

* The other parameters are as in table 9.

Deduce by the 70–30% rule (the cost due to the routing in the access network generally represents 70% of the end-to-end routing cost) the total utilization cost (cost for both access network and core network utilization). The total monthly cost for the tree with parallel backup links topology is:

$$\text{Total}_{\text{month}} = \frac{1.75(\text{Cost} - C_{\text{end}})}{0.7 \cdot (12A)}. \tag{7}$$

For the cases previously considered, Table XIV gives the total monthly cost per user. Considering 300 users, the costs obtained are very similar to those of the existing wireline accesses. However, the third-generation technology seems to be more competitive because it will likely have 500 users (instead of the conservative figure of 300). Another important point is that monthly costs do not include the end equipment cost (about \$200). This cost can be totally paid at the connection by the end user or spread over a certain period, depending on the service-provider policy.

The appropriate equation is:

$$\text{Total}_{\text{month}} = \frac{1.75}{12 \cdot 0.7A} \cdot \left(\frac{C_{\text{TS}}}{M_{\text{TS}}} + \frac{C_{\max}}{U} + \frac{C_{\text{AR}} + 28C_I}{p_0 \cdot U} \right). \tag{8}$$

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