Internet *vs.* Circuit Switched Telephony: Cost and QoS of Large Scale Integrated Services Networks

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Abstract

Telephony is an Internet application that has the potential to radically alter the telecommunications environment. This application may affect traditional regulatory structures, subsidy structures, business models, *etc.* Today, users can transmit telephone-like voice traffic over the Internet at zero incremental price, unlike circuit switched telephony, which has a per-minute incremental price. These economics make Itel a compelling application for international users in particular. In our earlier paper [16], we showed that this was not due to a regulatory artifact, but to fundamentally lower cost for voice only networks with equivalent quality. In this paper, we consider the cost and quality issues of integrated services networks, as these are the networks that are evolving.

To compare these networks, we build a "green fields" network for an area and a population equivalent to the US state of Rhode Island ($\approx$ 1M people in 3140 km^2) using each technologies. We employed "normal" engineering standards for voice quality service and then compared the costs. To realize the comparable packet switched voice service with circuit switched, we dimension the Itel network to have a service quality generally similar to conventional telephony. The network simulation models are developed to support the appropriate dimensioning of the networks. In this initial computation, we assume that the local loop costs are identical for both technologies, and that the services provided are identical.

In our earlier paper, we found that the switching and transmission costs for Itel are approximately 50% lower than the costs for circuit switching. We further find that this cost difference is largely due to the reduced interoffice transmission capacity required by Itel. This is consistent with the findings in [14] and what many potential ITSPs (Internet Telephony Service Providers)[1] claim [1]. We find that the incremental cost of integrated services under Itel is near zero for a integrated service load that is 75% for voice, while it is much higher for the circuit switched networks. This has profound implications for the business models of telecommunications carriers.

1 Introduction

One of the most challenging developments in telecommunications for providers and regulators in recent years has been the emergence of Internet Telephony (Itel)[2]. In the U.S., Internet Service Providers (ISPs) are exempt from the access charge system that is used to support local service. Internationally, ISPs are often outside of the traditional regulatory structures because they are Value Added Networks (VANs), which have historically been less regulated than providers of public switched service. Furthermore, the international accounting and settlements process is substantially challenged in the face of Itel, because the benefits of

[1] For example Concentric Network Corp.

[2] We would like to thank the people at Cisco Systems, Inc., Hyperion Telecommunications, Inc. and NPT Systems, Inc. for their time and willingness to help.

arbitrage are substantial. Even if including Itel under the normal regulatory framework was a social goal, it is far from clear how [6].

One of the questions that has arisen is whether the per call price difference between Itel and the public switched telephone network occurs because Itel fundamentally more cost effective than the traditional public switched telephone network, or it is due to a regulatory artifact[3]. If it is the former, it implies a pending revolution in the design, organization, and operation of the public network infrastructure. If it is the latter, Itel will be a marginal phenomenon in the long run, requiring little if any attention from public regulators[4].

Our initial approach to addressing this question was to construct voice-only networks using "traditional" circuit switched technology and current generation internet systems [16] making many simplifying assumptions. In this paper, we extend this analysis by considering the cost of integrated services networks. We continue using simplifying assumptions. As before, this estimate is intended to be a rough estimate subject to refinement as the assumptions are relaxed.

2 Technological Overview

The purpose of this section is to outline the key distinctions between these two technologies. More definitive discussions can be found elsewhere.

2.1 Assumptions and Simplifications

As this is a first order analysis, there are some simplifying assumptions that we wish to make. These include:

1. *The focus will be on the costs of switching, signaling and trunking.* Thus, we will assume that similar access and transmission technologies will be used. An actual Itel-based network might well consider alternatives to the current local loop technology. In terms of transmission, this assumption is not unreasonable, as the higher speed aggregate transmission links probably would use the same technology.
2. *We will assume current technologies.* We considered compressed voice and silence suppression technologies for the Itel access networks and fast IP router switches for Itel switching functions.
3. *We will assume equal levels of demand for both technologies.*
4. *We will assume that the services are perfect substitutes for each other.* That is, we will assume that the user will not be able to tell the difference between Itel and traditional telephone service from the point of view of major functions. Today, many consumers report poorer service quality with Itel as well as limitations surrounding the PC [5]. This assumption implies that the traffic load will be identical for both networks because users will perceive no significant difference.
5. *We will assume that neither service is subject to line charges for regulatory purposes.*
6. *We assume this network is only connected to similar networks.* As a result, we make no allowance for gateway or interconnection facilities.
7. *We assume that the cost of transmission is constant over the life of the study.*

2.2 The Public Switched Telephone Network

The public switched telephone network has evolved into its present form over its 100 year history. The network was initially optimized to handle low bandwidth (4kHz) channels using manual technology (no mean feat, as illustrated by Mueller [11]). As technology evolved, so did the way in which switching was performed. The digitization of the network allowed for high speed data services. Advances in packet switching technology allowed for the transformation of the signaling network to support a wide array of enhancements to basic service. Despite these advances, the circuit switched telephone network can be characterized by the following:

[3] This sentiment has recently been expressed by Jack Grubman, a well known telecom analyst with Salomon Smith Barney (in [14]).

[4] Investments by carriers such as Qwest Communications suggests that the cost may be lower.

1. It is capable of handling many dedicated low bandwidth channels (64kbps or 4kHz). Adaptive Differential PCM (ADPCM) was developed to transmit "toll quality" voice over 32kbps, but this technology has not been widely installed.

2. It is independent of content - once the channel has been allocated, it remains allocated whether it is used or not. That bandwidth cannot be used by others during idle periods.

3. Network attachments (*i.e.*, telephones) are cheap because their functionality is specialized and limited.

Numerous other characteristics also exist; the above list attempts to capture those of relevance to this study.

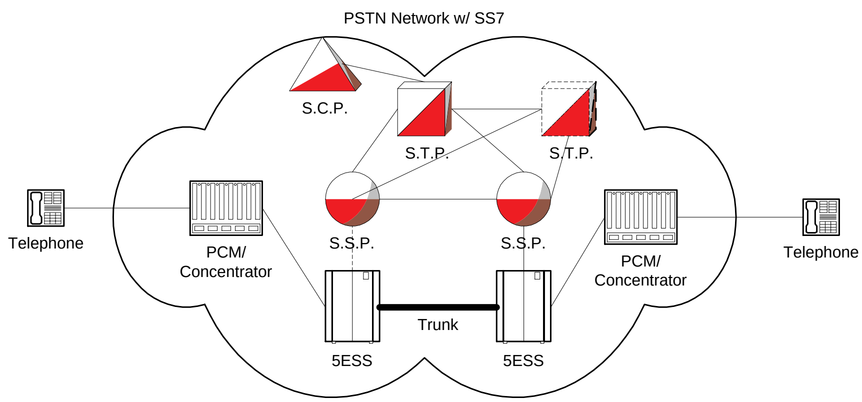

Figure 1: Circuit Switched Architecture

2.3 Internet Telephony

Internet telephony has grown as a specialized application of the Internet. A dominant characteristic of TCP/IP, as with most packet networks, is that most resources are shared (as opposed to dedicated). Thus, the bandwidth of a transmission channel is dynamically allocated to those who are using it at the moment. If their use disappears for a time, no system resources are dedicated to that user. The system was not designed to support services that require guaranteed timely packet arrivals. In summary, the essential characteristics of TCP/IP networks are:

1. It is capable of handling many application types, and allocating bandwidth dynamically between them on demand. This makes the development of integrated services particularly easy.

2. It cannot easily make performance guarantees, especially arrival time guarantees. This leads to quality of service degradation if the network is used for voice traffic. Note that this can be substantially mitigated if the network is engineered to low utilization, which increases cost.

2.4 Architecture of Internet Telephony

In this subsection, we discuss the different feature components of Itel from the circuit switched network. Followings are the key components of Itel architecture.

Loop Interface Since we assumed only that the copper wires in the loop were constant, we configured the Itel approach with xDSL. As a result, the Itel configuration includes DSLAMs, which raises the capital cost of Itel significantly. We also assume that the users have an Itel "appliance"[5] that performs the G.729A compression and packetization using RTP/UDP/IP.

[5]See, for example, http://www.selsius.com: Selsius phone 12S Series' price is ranging from $200 to $400 currently.

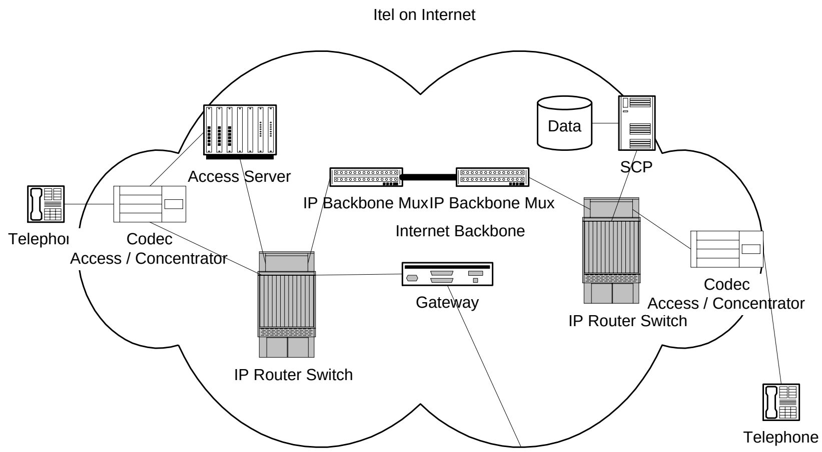

Figure 2: Internet Telephony Architecture

IP router switches IP router switches have a much higher performance than traditional IP routers, with faster packet processing and forwarding capabilities. Current generation IP switches provide packet processing rates in excess of a million of packets per second and have internal switching busses above one Gbps speed. In our simulation, we mainly assumed Cisco equipment (see [9] for more discussion).

Backbone OC-3 Trunk carrying IP IP over SONET technology is being implemented in many of IP backbone router switches. Another approach is to carry IP over ATM over SONET. When IP traffic is dominant (as would be the case for Itel carriers), direct IP over SONET is a more efficient solution [10]. Figure 6 shows the protocol stack of Itel central switching office example. In our model, typical OC-3 SONET trunks among COs provide enough capacity utilizing a utilization of less than 40% for most of the trunks.

Backbone Itel Gateway supporting SS7 In the case of Hybrid packet and circuit switched network would require the gateway solution to provide the signaling interface and routing. Numbering-to-IP conversion function may be implemented in this gateway.

2.5 RTP/UDP/IP Protocol Stack in Itel

The dominant standard for transmitting real time data in packet switched networks is ITU standard H.323 which uses RTP/UDP/IP encapsulation. RTP (Real-Time Transport Protocol) supports end-to-end delivery services of applications transmitting real-time data over IP networks[6]. While it does not guarantee timely delivery or quality of service, RTP provides the sequence number and time stamp information needed to assemble a real time data stream from packets. It typically runs over UDP to utilize its multiplexing and checksum services and specifies the payload type to support multiple data and compression types[7].

2.6 Packet Length of Itel

The length of the IP packets used in Itel is currently the subject of some debate, although 20 bytes seems to be emerging as the standard. The length is varyies with the choice of the codec and implementation scheme for aggregating the voice frames into IP packets. These choices affect on the delay quality of the Itel calls. For example, a higher compression rate may improve trunking efficiency, but it requires the higher effective look ahead delay than the lower compression rates. Smaller packet length may have lower delay

[6]RTP is defined in in RFC 1889 [3] and its use for audio and video is discussed in RFC 1890 [12].

[7]G.723 , G.729, and G.729A are the popular compression types for the codecs in Voice Over IP (VIOP). The VOIP standard committee proposed a subset of H.323 for audio over IP. Many Internet Telephony vendors developed the products based on this standard.

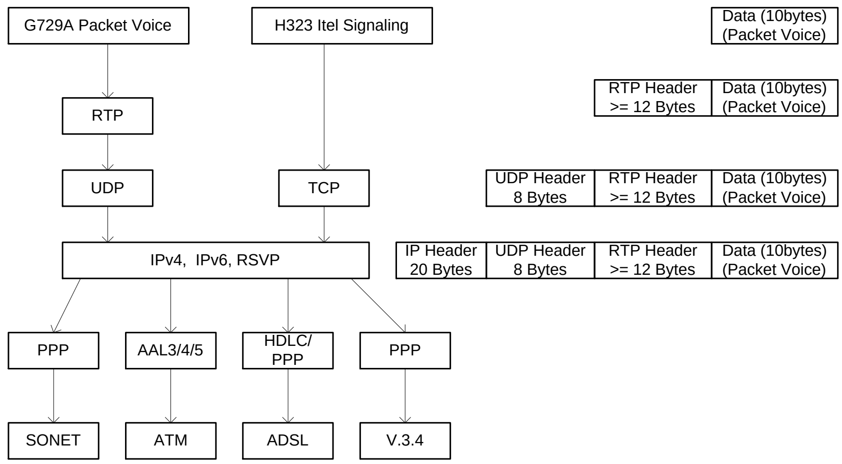

Figure 3: RTP protocol stack (10 byte packetization)

characteristics for short hops due to the lower encoding, decoding and dejitter buffer delay, but this approach requires higher processing power on the IP router due to the increased packet rate relative to larger packets for a given level of offered traffic. In addition higher voice packet aggregation into one IP packet will decrease the overhead ratio VOIP packet which will provides efficient utilization of the interoffice trunks. Figure 3 shows the case of IP encapsulation of one 10 byte G.729a coded voice packet; by adding one more 10 byte voice frame, the overhead to payload ratio would decrease to 4:1 from 2:1. Although most of our model assumes 10 byte packets, we studied the impact of larger packets in our simulation model and present the results in Section 4.

2.7 Delay Components in Itel

Unlike the circuit switched network, the upper-bound delay and its variation, called jitter, are significant factors for Itel call quality. To achieve toll-quality service for internet telephony, the upper bound (percentile) of the all Itel packet should be under certain threshold of end-to-end delay. For PSTN-like quality, the ITU recommends an end-to-end delay of under 150 milliseconds. Since delay is stochastic in Itel, we interepret this to be the 95th percentile delay. In addition, delay variation should be short enough to enable the dejitter buffer of the receiving Itel phone to equalize the delay and disaggregate the Itel packet. The jitter requirement may vary depending on the selection of the CODEC and Itel packet encapsulation option.

There are many factors that contribute to delay and delay jitter; the routing method and queueing discipline are important among them. Our findings suggest that the traffic aggregation of integrated service traffic on the access router is another important engineering consideration that affects these variables. All the deterministic delay components such as access link transmission, voice packet look ahead, coder, packetization, trunk serialization, propagation, dejitter buffer queueing, and decoding delays are dependent on the choice of access technology, CODEC, IP encapsulation option, and trunking. The variable delay components such as router processor buffer queueing, processing, and forwarding delay on switching bus can be scaled based on the offered Itel traffic load, other aggregated IP application traffic characteristics, and the choice of IP router switches.

Most of the deterministic delay components are determined on an end-to-end basis since the propagation and trunking serializations are relatively small compare to the access link transmission time and codeing-decoding delay in most of the cases. The variable delay components are more sensitive to the hop count of the delay and the delay measures incrementes as the number of passing hop of Itel packet increases. Even though the per hop based variable delay would be clearly smaller than deterministic delay using the advanced high performance IP router switches, the variable delay becomes significant on an absolute basis if we consider that the average IP packet traverses an average of 15 hops on today's Internet. In addition, this variable delay contributes significantly to jitter.

To be conservative, we use worst-case assumptions in our analysis. The following equation summarizes the delay components:

$$\begin{aligned} T_{ITEL} &= 2 * D_{access} + N * D_{packetization} + H * D_{trunk} + H * V_{packet} \\ D_{packetization} &= D_{lookahead} + D_{coding} + D_{decoding} + D_{dejitter(PerPacket)} \\ V_{packet} &= V_{processing} + V_{forwarding(PerHopUpperBound)} \end{aligned}$$

where D_{access} is the transmission delay of a access line on each end, D_{trunk} is the average trunk serialization delay (per hop), N is the IP encapsulation option (1-3) based on the CODEC, and H is the average number of hops. The "D" terms are deterministic delays and the "V" terms are variable delays.

For example, if a G.729 CODEC is selected and one VOIP frame is encapsulated into one IP packet (forming 50 byte Itel packets), the look ahead delay, coder delay and dejitter buffer delays are 3-5 msec, 10 msec, and 30 msec, respectively. If two VOIP frames are encapusulated, the delays will be 5 msec, 20 msec, and 50 msec, respectively. The access transmission delay will be approximately 1 msec and 10 msec for each end for 640 kbps ADSL connection and 64 kbps DS0 connections, respectively. The dejitter buffers are typically designed to tolerate up to the double sum of coder and lookahead delay. Our delay analysis of simulation is done based on the above delay component consideration which will be discussed in the sections 3.3 and 4.

2.8 QoS Technologies for Itel

The public internet is still 'best-effort' based, so quality of service (QoS) cannot be guaranteed since the networks. As real time applications, such as Itel, are introduced to the public Internet, QoS issues become more critical because of its real time requirements. Typically, Itel quality is concerned with the delay and delay jitter of the voice messages; for the "toll quality" calls, the end-to-end delay should be less than 300 msec and the tolerable delay variation of less than 30 msec. To control quality in Itel, properly designed IP switches, required QoS signaling protocol support, Classification of Services, and appropriate dimensioning and traffic engineering of the network are required. Generally, the strategies available for achieving this involve overengineering the networks, using IP over ATM, using QoS signalling (such as RTCP or RSVP), or class of service differentiation.

Most of the analysis in this paper is based on a strategy of overengineering. Future research will focus on the other approaches.

3 Model Description

In this section, we describe the parameters of the simulation model. The network parameters for the circuit switched case and the Itel case are presented in their respective sections along with the summary results from the simulation.

3.1 The Service Area

To estimate the cost for each system, we constructed a "green field" system of each type for the same service area (a population of 1 million people uniformly distributed over an area of 3140 square kilometers – equivalent to the U.S. State of Rhode Island). To simplify the calculation, we make the following assumptions:

- An average population density of 2.2 person per household
- Square service area (56km per side)
- No geographical barriers
- Households uniformly distributed over the service area (constant population density)
- Homogeneity of users

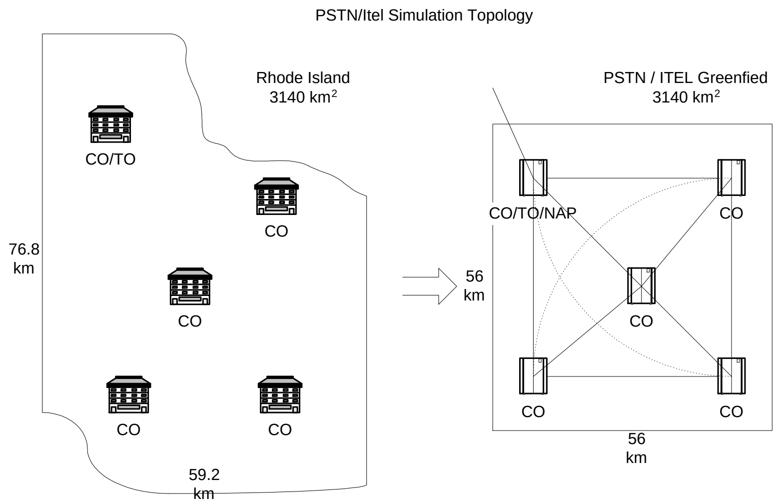

Figure 4: Simulation Topology

- Consistency of a user's behavior between systems (*i.e.*, we assume away price and demand issues)

We assumed the local loop with with 19 gauge copper twisted pairs which can be extended up to 30 k-ft[8]. Since we will assume all the loop conditions and requirement will be same, we will assume the situation with 19 gauge wire. We will assume five local switching location because a 5ESS-2000 can support up to 100,000 line and the loop runs are within the capabilities of 19 AWG wire. If we assume one line per household, then each local switching location (CO or ITSP-CO) is terminating its assigned 454545 local loop lines. We assume all the originated traffic be distributed as 10% for outgoing from its service region and the rest for five local switching points evenly. The incoming traffic from the other service region is assume to be same with the amount of outgoing through one Tandem or NAP.

3.2 Circuit Switched Model

In addition to the general assumptions described above, we have made following additional assumptions that pertain specifically to the circuit switched network (the assumptions are summarized in Table 1):

1. A 5ESS-2000 switch supports 100,000 lines at 3.6 CCS/line (0.1 Erlang) in the busy hour. Therefore, each switch is receiving 9090.9 Erlangs of traffic from its assigned local service loops.

2. We assumed the most of the blocking occurs not in the switches but at the trunk side among the switches at one percent blocking probability.

3. Since we have only five switches within the given service region, we assumed each switch will have a direct trunk from and to each others.

4. The signaling network (SS7 Signaling System 7) is configured in a way that each local switch equipped SSP (Service Switching Points) connects to two STPs (Signal Transfer Points) and additional two STPs are forming a quadrupled mesh STP networks to access a SCP and outside signaling network STPs. Each signaling link (between SSP and STP) is engineered to have 0.4 utilization, so that if a failure occurred, the expected utilization would be 0.8 per link.[2]

5. The data rate per signaling link is 64 kbps. Each call generates average 3.5 signaling messages from an originating party and 3.5 signaling messages from the terminating party. Average signal length is 15 octet per message which comprise 1.875 msec duration.

[8]The local loop standard specification is 22 gauge wire extending up to 5.5 *km* (1.8 k-feet) without load coil in the US. We realize that nobody uses 19 gauge wire in practice, but since this research was not focussed on the local loop, making this assumption allowed us to ignore the impact of different loop carrier systems by using only “home runs”.

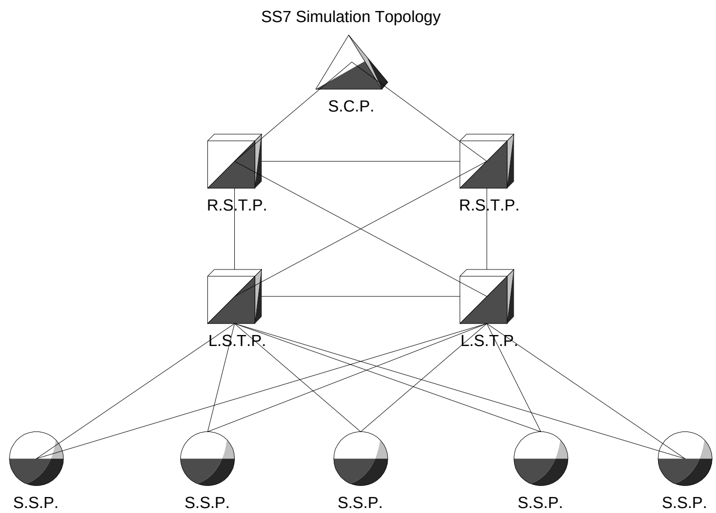

Figure 5: SS7 Network Simulation Topology

Circuit Switched and SS7 Network Parameters	**Values**
Ckt. Switched Parameters	
Data Rate per Channel	$64Kbps$
Local Loop	19 gauge twisted pair
Circuit Switch	5ESS-2000
Fraction of outgoing call	0.1
Originated Traffic per line	0.1 Erlangs
No. of loop lines per CO	90909
Inter Arrival Time for CO	0.0264 sec
Inter Arrival Time for Toll Office	0.0176 sec
Average Call Duration	240 sec
SS7 Parameters	
No. of SSP	5
No. of LSTP	2
No. of RSTP	2
No. of SCP	1
Engineering Utilization	0.4
Unit of SS7 link group	8 DS0s
Average signaling messages per call	7
Average signaling message size	15 octets

Table 1: Assumptions for Circuit Switched Model

Based on the above assumptions we dimensioned circuit switched network as follows:

1. The capacity of the trunks between any two normal COs and between a CO and Tandem will be bi-directional 210,816 Kbps (for each direction) and 326,400 Kbps respectively. With this configuration, COMNET III simulated 1 percent call blocking.
2. The capacity of the signaling links between a SSP and a Local STP; between two local STPs; between a Local STP and Remote STP and between two Remote STPs are bi-directional 326 Kbps (326 Kbps for each direction), 1,630 Kbps, 111 Kbps and 222 Kbps respectively.

The summary of circuit switched network simulation output is in Table 2. The simulated trunk capacity (211 Mbps) between each CO and Toll Office requires two OC-3 and one OC-1 SONET leased trunks[9]. The trunk capacity (327 Mbps) between each CO requires one OC-3 and one OC-1 SONET Trunks[10]. The OC-1s shown in the table are the separate trunks between each CO which cannot be aggregated to OC-3s.

Circuit Switch and SS7 Network requirement	**Values**
Circuit Switched Network	
Four Trunks between each CO and a Toll	4 X (2 OC-3 and 1 OC-1)
Six Trunks between each CO	6 X (1 OC-3 and 1 OC-1)
Blocking Probability	0.01
Call Attempted per Hour	750299
Call Carried per Hour	742454
SS7 Network	
SS7 Links between SSP and LSTP	80 DS0
SS7 Links between LSTPs	32 DS0
SS7 Links between LSTP and RSTP	8 DS0
SS7 Links between RSTPs	8 DS0

Table 2: Summary of Simulation Output for Circuit Switched Network

3.3 Itel Model

Itel simulation model assumed in our analysis is based on RTP/UDP/IP standardized on ITU H.323. In this protocol, sequence numbers and time stamps are used to reassemble the real time voice traffic, although this provides no quality guarantee. TCP/IP is used to control the call (like SS7 in the circuit switched model). The simulated Itel model would provide the comparable functionality of network with circuit switched model, however it will not provide comparable quality and reliability of voice calls under circuit switching.

Figure 6 represents the Itel architecture model in our simulation. The simulation is concentrated on the IP router switching and trunking. IP Access Server and Edge Concentrator in the figure represent DLSAMs (Digital Subscriber Line Access Multiplexer) which do not have much effect on delay in the simulation.

The assumptions made for Itel simulation model are specified below and in Table 3.

- All voice traffic would be compressed from 64 Kbps PCM voice to 8 Kbps compressed data using G.729A codec.
- Silence suppression will be enabled in each codec, with 60% of a session being silent in one way.
- On the suppressed codec output, RTP, UDP and IP overhead will make actual average throughput around 14 Kbps.
- Each voice is packetized to a 10 byte voice packet every 10 msec and buffered to make the 20 byte payload from compression codec and encapsulated in the 40 byte RTP/UDP/IP header.

[9]Total 4 pairs of this type are required in the simulated service area networks.

[10]Total 6 pairs of this type trunks are required in the simulated service area networks.

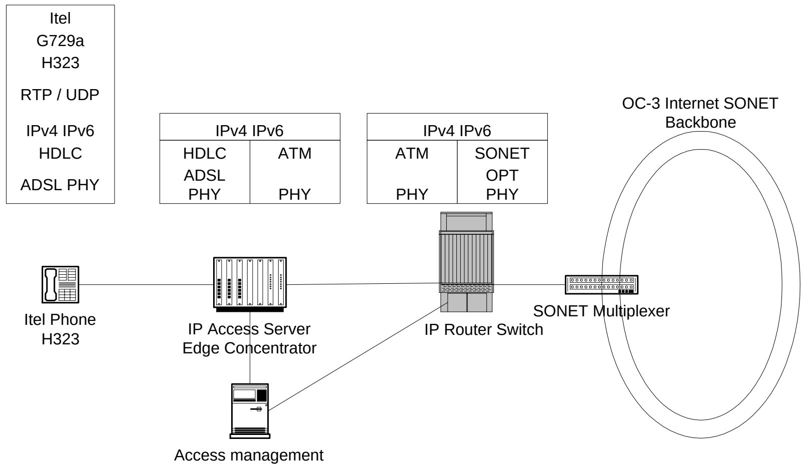

Figure 6: Internet Telephony Central Switching Office Protocol Stack

- For the packet voice, the burst packet voice is modeled with average 350 msec exponentially distributed active state and 650 msec exponentially distributed silence state [11].
- The Itel call is modeled as a connectionless UDP/IP session with exponentially distributed session length of 240 sec.

Itel Network Parameters	**Values**
Compressed Peak Data Rate per Channel	8 Kbps (G.729A)
Local Loop	19 gauge twisted pair, ADSL
Packet Switch	IP Switch (>10 Gbps and 1 MPPS)
Fraction of outgoing call	0.1
Originated Traffic per line	0.1 Erlangs
No. of loop lines per CO	90909
Packet Voice Size	10 bytes (10 msec)
Packet Payload Size	20 bytes
Protocol Overhead	40 bytes (RTP/UDP/IP)
Packet Voice Burst Distribution	burst 350 msec, silence 650 msec
Packet Delay Constraint	less than 250 msec
RTP Session (Itel Call) Setup Delay Constraint	less than 1 sec

Table 3: Assumptions for Itel Simulation Model

In the simulation, we found the average and 95th percentile delays for packets through the network. This delay was modelled using the delay budgets in Table 5. We assumed that this would provide a connection equality that was approximately equivalent to circuit switched voice[12] (Table 4 shows the ITU recommendations). The source was initially modelled using an "on-off" speaker model. We found that, when aggregated, these could be modelled reasonably well by an exponential distribution, so that is what we used to reduce the running time of the simulation.

Unlike a conventional ISP that terminates the user line through a CSU or a DSU on LAN, the Itel user access line for the carrier solution is terminated through a DSL Access Multiplexer (DSLAM), which is

[11] See Figure 7.

[12] Total delay is a function of operating system and sound device delay in the end devices as well as network delay. Informal measurements suggest that these delays can be very high in WinTel PCs using standard sound cards.

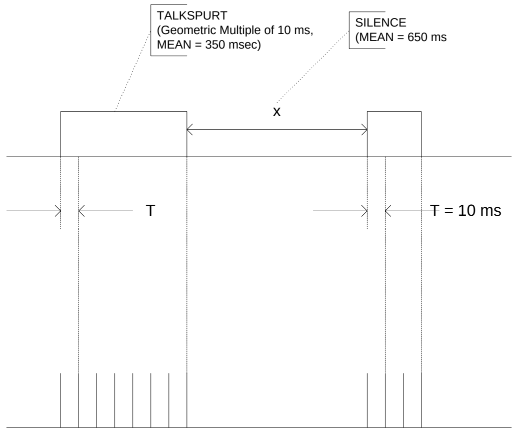

Figure 7: Packetized Voice Distribution

One Way Delay	Description
0-150	Acceptable for most user applications.
150-400	Acceptable provided that administrations are aware of the transmission time impact on the transmission quality of user applications.
400-	Unacceptable for general network planning purposes; however it is recognized that in some exceptional cases this limits will be exceeded.

Table 4: ITU Delay Recommendations

Itel Network requirement	Values
Itel Network	
Trunk among COs	OC-3 Sonet Ring (= 10 OC-3)
Local interface of each IP Switch	12 DS-3 ATM
Major Network Components	Itel Access Server Concentrator IP Switch Sonet Mux
Itel Delay Budget	
Average Switch Utilization	0.62
Average Variable Packet Delay	3.41 msec
95 Percentile Variable Packet Delay	18.44 msec
Acess,Lookahead, Encoding, Decoding and Dejitter G729A	77 msec
Average End-to-End Packet Delay	80.41 msec
95 Percentile End-to-End Packet Delay	95.44 msec
Average Delay Jitter	8.45 msec

Table 5: Summary of Simulation Output for Itel

connected to the IP switches via internal OC3 or T3 circuits. Figure 6 shows the operational architecture of VoIP Itel Co/ISP model. The simulation results show that 12 DS3 interfaces is required for the local interface with the concentrator from IP switches and OC-3 line can support all trunk connection between any COs with more than 50% spare capacity. With OC-1, the trunks are so fully utilized that it increases the packet delay critically in the simulation. Therefore one SONET OC-3 Ring would provide enough capacity for the assumed Itel trunk traffic among the ISP/COs. In this simulation model, SS7 call setup function is simulated as session setup using TCP/IP. Therefore, no additional capacity dimensioning is required for each links. The output of simulation for Itel is summarized in Table 5.

3.4 Integrated Service Network Model

We include an integrated services requirement in this paper that was not included in our earlier work [16]. For the circuit switched model, the access link technology is changed to ADSL, so a DSL Concentrator, Multiplexers, DSL POTS splitters and routers for integrated services must be added into the network as shown in the Figure 8[13]. For the Itel network model, we simulate the added integrated service traffic load without any incremental hardware cost and measure the delay and delay jitter of Itel traffic as the load of integrated service traffic increases. We then find the network upgrade point, which we define to be where the quality of Itel become unaccepatble. Using the recent traffic data measured by [4], [15], and [8] on the Internet backbone OC-3 trunks, we modeled the intergated service traffic for the different level of user demand relatively to the Itel call demand.

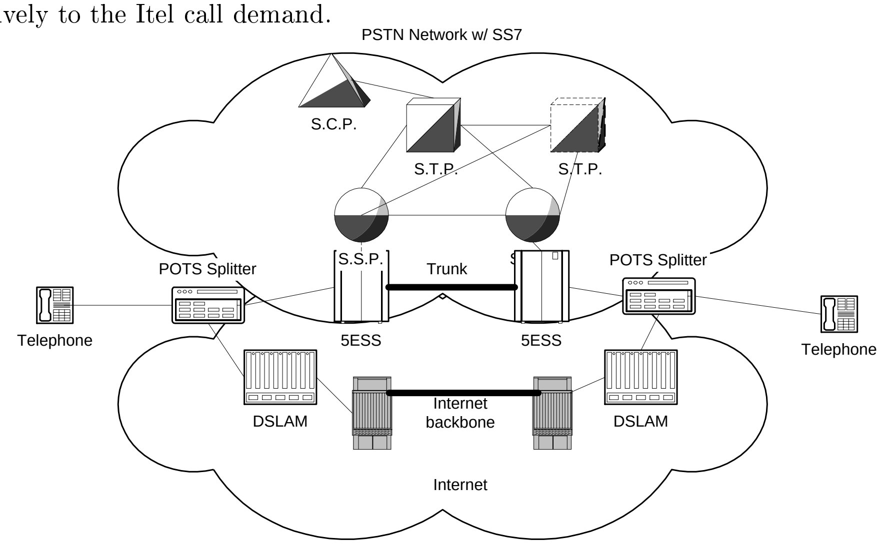

Figure 8: Integrated Service Network Architecture for PSTN

We modeled the high load traffic applications of internet such as HTTP, FTP and other traffic of TCP and DNS and RTP for UDP protocols. The integrated traffic model parameters are summarized in Table 6. Since the traffic is aggregated from many sources, we assumed an exponential inter-arrival time of traffic flows of each application. We further assumed that all the ISP servers are uniformly distributed over the whole network so that we do not have to account for traffic asymmetries of some services.

As a second experiment, we configure Itel traffic with a higher priority. We then observe the effect on utilization and delay, and delay jitter in comparison to non-priority traffic. The delay sensitivity observation of the different load of integrated traffic is presented in the next section.

[13]Providing integrated services via the circuit switched network via modems results in a qualitatively different service with respect to Itel, as customers are forced into an either-or situation unless second POTS lines are added. While we did not perform this analysis, it would require almost doubling of the capital costs of a voice only network, as the additional lines must be supported by switches. Only the incremental trunking-related costs might be lower.

Integrated Traffic Parameters	Values
TCP	
Percentage of Packets	85
Percentage of Bytes	95
Percentage of Flow	75
UDP	
Percentage of Packets	15
Percentage of Bytes	5
Percentage of Flow	25
HTTP/TCP: From Server to Client	
Percentage of Packets	38
Percentage of Bytes	70
Percentage of Flow	35
Average Packet Length	791 bytes
Major Packet Length	1500, 40, 552
Packets per Flow	14-18 packets
Average Flow Duration	10-15 seconds
Average Size per Flow	11 KBytes
HTTP/TCP: From Client to Server	
Percentage of Packets	38
Percentage of Bytes	8
Percentage of Flow	35
Average Packet Length	83 bytes
Major Packet Length	40
Packets per Flow	14-16 packets
Average Flow Duration	10-15 seconds
Average Size per Flow	1 KBytes
FTP and Other TCP	
Percentage of Packets	9
Percentage of Bytes	17
Percentage of Flow	5
Average Packet Length	600 bytes
Major Packet Length	40, 1500
DNS/UDP	
Percentage of Packets	5
Percentage of Bytes	2
Percentage of Flow	15
Average Packet Length	165 bytes
Major Packet Length	40
Packets per Flow	2-3 packets
Average Flow Duration	15 seconds
Average Size per Flow	500 Bytes
RTP/UDP	
Percentage of Packets	10
Percentage of Bytes	3
Percentage of Flow	10
Average Packet Length	401 bytes
Major Packet Length	40, 1500
Packets per Flow	50 packets
Average Flow Duration	20-30 seconds
Average Size per Flow	21 KBytes

Table 6: Summary of Integrated Traffic Parameters

4 Call Quality Sensitivity Analysis of Itel ind ISN

In this section, we present the Itel call quality for the various types of Itel and ISN network configurations. For the internet telephony network, first we monitored the delay for various router processing speeds to determine the router requirement for the comparable capacity of 5ESS PSTN switches. We observe that a router processing speed between 1 MPPS and 2 MPPS provides acceptable delay characteristics for a 100,000 line of Itel Central Offices, depending on the packetization of the IP voice packets. For 20 and 30 bytes packetization, 1 MPPS IP switch router can be used and for 10 bytes packetization, 2 MPPS IP switch router is required. We considered the 2 MPPS IP switches be the more conservative choice, so we used this IP switch configuration for the rest of our analysis. Figure 9 shows the difference of variable delay components of Itel voice packet for 1MPPS and 2MPPS IP switch routers. For 1 MPPS, the average variable delay was 3.41 msec and the delay jitter was 8.45 msec[14]. For 2 MPPS, the average delay was 0.28 msec and the delay jitter was 0.65 msec. Average IP router processor utilization of each option were 62% and 32% repectively.

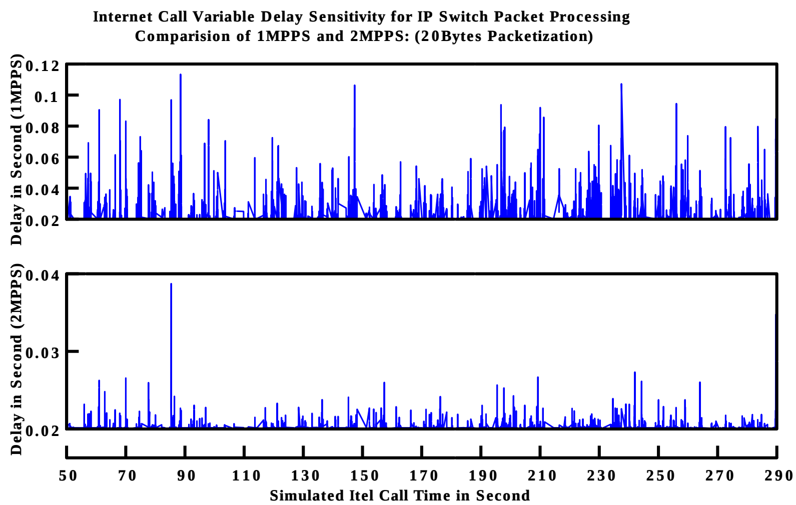

Figure 9: Itel Variable Delay for 1MPPS and 2MPPS Packet Processing: 20Bytes Packetization

Figure 10 compares the end-to-end delay for different packetization choices. The end-to-end delay for 20 bytes packetization (Top) and 10 bytes packetization (Bottom) shows the average delay of 77.27 msec and 47.64 msec. Even though the average delay of 10 bytes voice packet is low, the delay jitter for this shorter packet is 3.28 msec which is five times higher than longer packet due to the increased processing load on the switches. The 95 percentile delays of each packetization are 78.02 msec and 54.12 msec respectively.

The Figure 11 shows the end-to-end average and 95th percentile delay trend for the various incremental traffic load from non-voice services. The incremental non-voice traffic is modeled as a percentage of voice load (which is static). The unit of incremental integrated data traffic load is in percent of the total bytes of aggregated integrated data traffic relative to the given internet telephony voice traffic load in bytes. As shown in Figure 11, up to 50% of non-voice load can be added onto the network without new investments for the 20 bytes packetization configuration. At 75% relative incremental load, the average delay is still acceptable, however the 95 percentile delay and delay jitter become unacceptable. For a 10 byte packetization, the delay characteristics becomes unacceptable just after the 10% incremental integrated traffic load point. This result is due to processor loading and not trunking delays. To gain additional traffic carrying capacity, only the IP switch processors would have to be upgraded or expanded.

Figure 12 shows how the priority option for Itel traffic improves the delay jitter charcteristics and the utilization of the network. We only set the priority higher for those Itel calls that were monitored and observed the Itel traffic as a whole, so we could observe the improvement to delay and delay jitter due to

[14]The delay scale in the figure includes the addtional 20msec fixed packetization delay component to show the 20 bytes packetization option

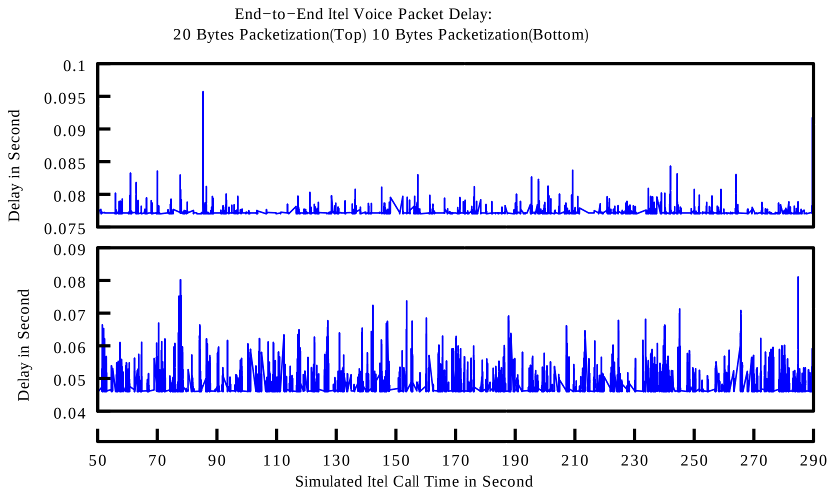

Figure 10: Itel Voice Packet End-to-End Delay for Different Packetization: 2MPPS IP Switch

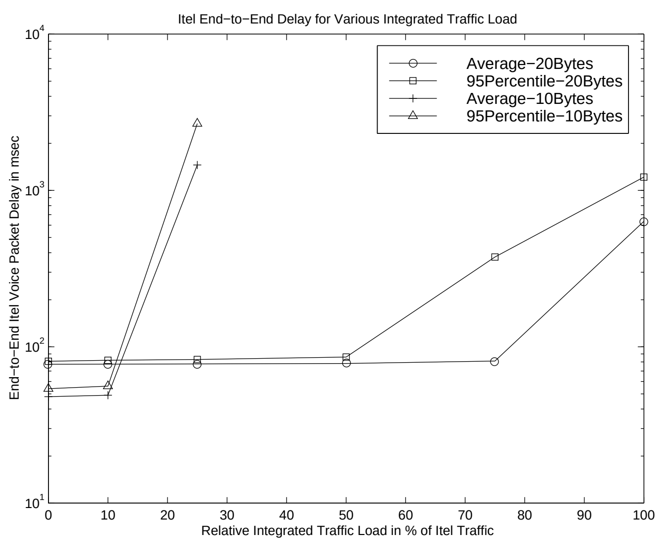

Figure 11: Itel End-to-End Delay for Various Integrated Traffic Load

priority. In a 10 byte per packet pure Itel network (0% incremental integrated traffic load), priority does not help; after the 10% incremental load point, the average delay increases regardless of priority, because the the processors is already highly utilized with priority. For 20 byte packetization, the improvement of delay jitter at the 75% incremental load is substantial, so the priority option enables the network to utilize at least 25 percentage points of additional non-voice traffic.

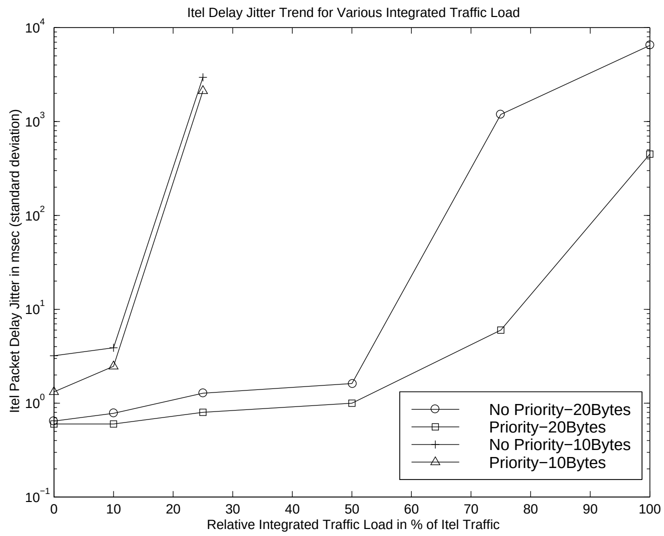

Figure 12: Itel Delay Jitter Trend for Various Traffic Load

Clearly, carriers would prefer the 20 byte packetization over a 10 byte packetization, since their costs are lower. However, since the Internet is application blind, they have no control over what users choose. In fact, examining Figures 11 and 12, end users have an incentive to choose 10 bytes, as their average delay would 50 msec as opposed to 80 msec. A 10 byte packet would require a larger dejitter buffer (hence correspondingly higher cost) due to the higher jitter and would experience a dejitter delay of 6msec as opposed to 1.8msec for the 20 byte case. In the end, a 10byte user would experience 56 msec of average delay as opposed to 81 msec for a 20 byte packet, or approximately 25 msec (30%) lower delay. It is unclear whether that delay would be sufficient to motivate users to use 10 byte packets; given the added costs, Itel network providers would certainly have the incentive to keep delays that they can control as low as possible so as to obviate the observable impact of this delay differential.

5 Estimated System Costs

With designs in hand, we consulted with vendors to review the "reasonableness" of the design and to estimate the cost of the switches/routers. The cost estimates we used were based on the information from the HAI cost model [7, p. 58] (for the circuit switched case) and Cisco (for the Itel network). The cost of the transmission links is based on leased line costs from AT&T.

The cost shown here is only focused on the differences of switching costs and trade-off trunking costs between circuit switching and packet technologies. We focused on the facility differences in the Central Offices. We add the costs of line cards and the main distribution frames (MDFs) separately because that may be considered part of the local loop in some analyses.

The cost difference of the switching technology is composed of two parts; initial investment costs and yearly recurring costs. Most of the switching equipment in a CO will be considered the initial capital investment costs and transmission links (OC-3, *etc.*) will be considered the recurring costs. The life of telephone Central Office equipment can be assumed in several ways. According to IRS documents, the product life of telephone switching equipment (Class 48.12) is 18 years[15]. Given the pace of technological change, we are doubtful that such long depreciation schedules will be sustainable in the future. Using the

[15]From IRS Publication 534, Depreciation

cost data, we have conducted sensitivity analysis of the monthly subscriber line costs in terms of the product life varying 3 years to 20 years and MARR (Minimum Attractive Rate of Return)[16] ranging from 5% to 50%.

5.1 Circuit Switched Costs

The simlation results indicate that a total of 14 OC-3's and 12 OC-1's would be needed, resulting in a $1.454 million monthly cost of trunking. The bulk price with discount rate of 50% of the cost yields $727 thousand per month. A 5ESS switching system costs around $2.94 million dollars (switching only)[17] [13]. Figure 13 is sensitivity analysis of monthly per line costs[18]. Our results show that the total local switching cost is $16.03 Million dollars (initial switching investment cost) and that the monthly cost (switching and trunking) per subscriber line is $2.3 when the 5-year product life and 5% MARR are assumed. $1.6 out of $2.3 comes from the cost of trunking per month[19]. The major cost factor of the circuit switched network is in trunking cost.

Note that Figure 13 does not include the cost of line cards, as that is arguably a local access issue, not a switching and trunking issue. Figure 14 shows the cost data with line cards included[20]. Clearly line cards are a costly element of the network that substantially increases the monthly cost of the system by a factor of 1.6 (approximately).

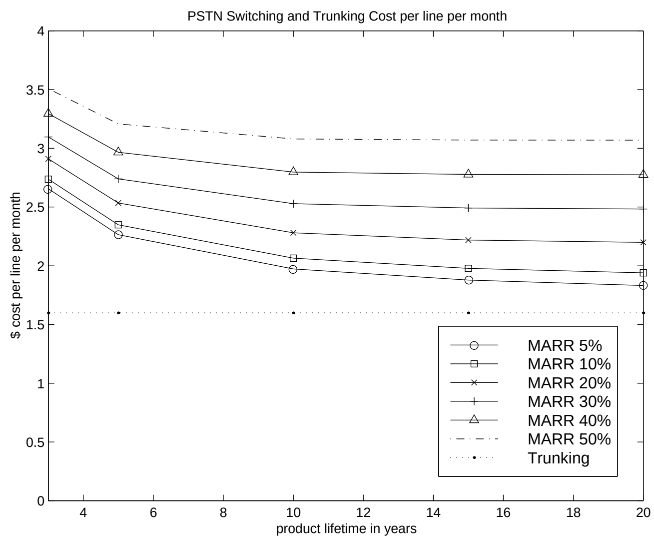

Figure 13: Switching and Trunking Cost of Circuit Switched Network per line per month

5.2 Itel Costs

For the Itel network, we used the same number of "CO's" so that the local loops between the two networks would be identical. While this might yield a sub-optimal Itel design, it was necessary so that we could ignore local loop costs in our analysis. The cost for Itel switching and trunking was the NPV of $26.6 Million, with much of the cost attributable to the DSLAM. The monthly discounted bulk rate trunking price was $286 thousand dollars, resulting in a monthly Itel subscriber line cost for switching and trunking is $1.1 when a 5-year product life and 5% MARR are assumed. As with the circuit switched network, the dominant cost component was the trunking cost, which comprises $0.63 out of the $1.1 monthly Itel subscriber line cost

[16] MARR is frequently used in the engineering economic analysis to represent the investers' expected Rate of Return. Investors use MARR, instead of Interest Rate, when they convert the NPV of initial capital investment to the average recurring cost with their return over a given life time of the capital assests. MARR may vary depending on the rate of change and riskiness of the industry investors are involved or interested in.

[17] The switching cost $2.7 per Kbps for 5ESS is used.

[18] This is bottom line cost because we counted a 5ESS switch in all the CO locations and required leased trunks only.

[19] The figures shown here are the cost figures for the circuit switched network, which dose not include the access and signaling equipment. We will see this cost is still high enough to top the Itel cost analyzed in the section 5.2.

[20] As before, the cost data were taken from the HAI cost model.

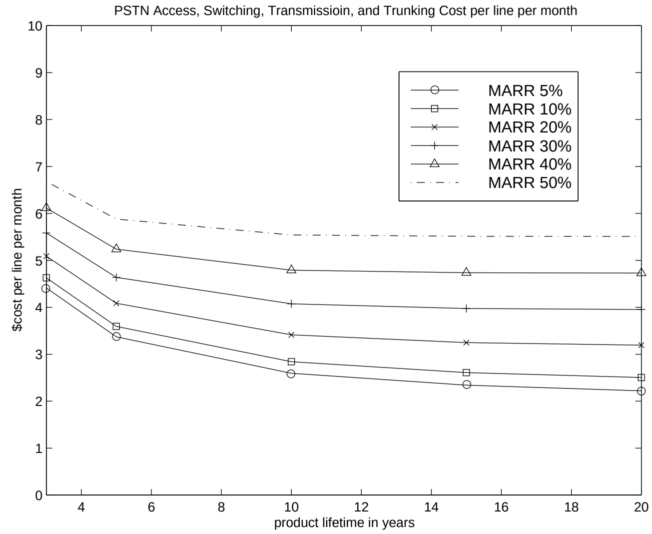

Figure 14: Total Circuit Switched Network Cost per line per month

for switching and trunking. Figure 15 shows the cost per line per month for varying product lifetime and MARR.

As before, Figure 15 does not include DSL line cards in the CO. If we compute the cost of a complete CO (with line cards), the cost structure changes as illustrated in Figure 16. The cost increases by a factor of approximately 3.0, reflecting the relatively high cost of DSL line cards. Also, we added only one Sun UltraSPARC at each CO for call processing. Carrier-level call processing software is still not available, so it is difficult to size this correctly. The cost of this element may well be higher than we budgeted. Finally, that these figures do not include equipment discounts.

With no discount for Itel equipment and the discounts embedded in the HAI model, the costs of the two networks are essentially identical. But this is unlikely, as the equipment vendors would most certainly provide discounts to win a network contract of this magnitude. If Itel equipment is discounted by 50% off of list[21], Itel is cheaper by 20-30% (depending on life and MARR), as illustrated in Figure 17 at three different MARRs.

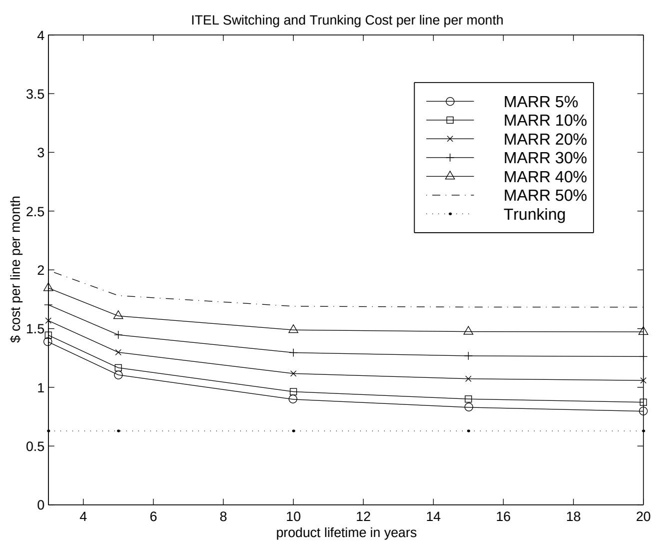

Figure 15: Switching and Trunking Cost of Itel per line per month-No Discount for Switching Equips

[21]Informal conversations with vendors indicate that 50% is a reasonable discount for a network of this size.

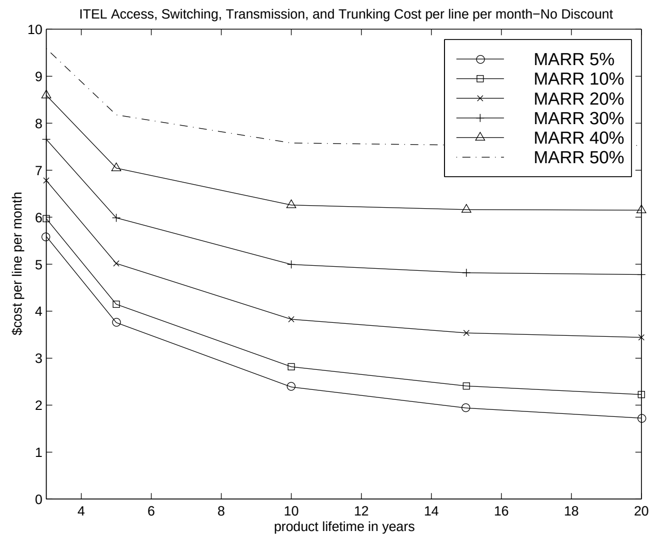

Figure 16: Total Itel Cost per line per month-No Discount

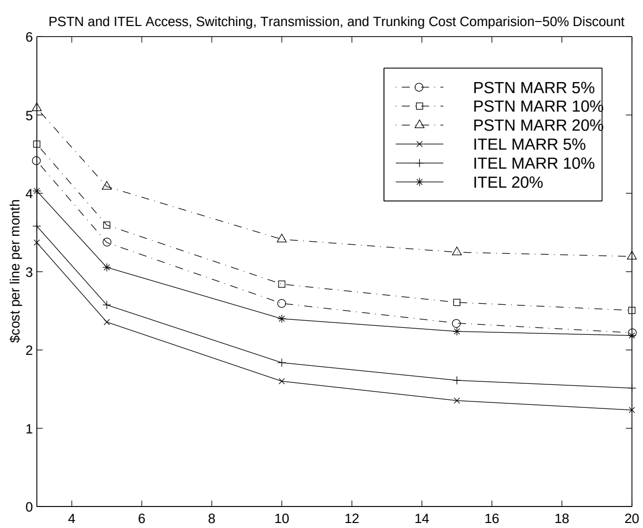

Figure 17: Total PSTN and Itel Cost Comparision-50% Discount

5.3 Incremental Cost for Integrated Service Network

One of the relevant advantages of Internet Telephony Carriers would be the lower incremental cost to provide the integrated network services to their internet telephony customers. In this section, we analyze the incremental cost incurred by PSTN network carriers for the load that can be provided to the Internet telephony users with zero incremental cost through the ITC (Internet Telephony Carrier) networks, as discussed in Section 4. With the priority option enabled and 20 byte packetization, the Itel network was shown to be able to provide more than 75% integrated incremental data traffic load with zero incremnental cost. Figure 18 shows the incremental cost for switching and trunking incurred by the circuit switched carrier to provide services for additional 75-100% integrated incremental data traffic load. For example, with a 20% MARR and 10-year product life, the incremental cost for switching and trunking per line per month incurred by circuit switched carriers will be around $0.45.

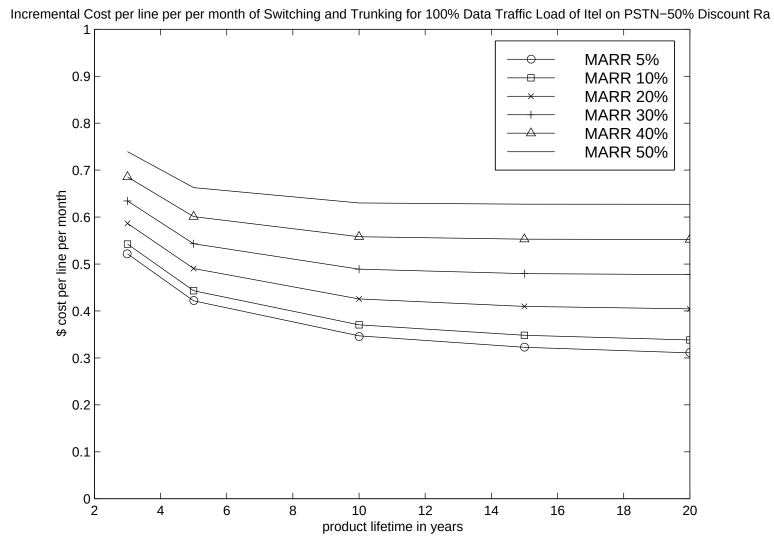

Figure 18: Incremental Cost per line per month of Switching and Trunking

When the subscriber access equipment is included (ADSL POTS splitter card and ADSL subscriber line card), the cost increases as shown in Figure 19[22]. This figure can be interpreted as the total incremental cost per line per month when the PSTN carriers are migrating to the Integrated Service Network. The Figure 20 shows the ratio of each incremental cost component to provide 100% load of integrated traffic load from PSTN carriers. The 20% MARR, 10-year product life, and 50% discount rate were applied in this figure. The discounted NPVs for access, trunking, and switching were $40.2 million, $5.91 million, and $4.1 million respectively.

6 Discussion and Conclusions

We can draw a number of conclusions from the results of this paper. First, when considering transmission and switching costs only, Itel is substantially less expensive (about 50% or $1.0 per line per month, depending on equipment life and MARR) than circuit switching. If subscriber access equipment is included, Itel is at worst equivalent in cost to circuit switching with a very costly access technology (DSL). Second, the incremental cost of integrated service is essentially zero for Itel for a substantial load of added services, whereas implementing a network to provide similar service is substantially higher for circuit switching (60% higher, again depending on life and MARR). This is illustrated in Figure 21, which shows the costs of voice, 100% ISN and 200% ISN at different lifetimes and MARRs.

This is a fairly strong result. Since the capital cost of the circuit switched network exceeds the capital cost of Itel, Itel switching is cheaper at all levels of discount. When access parts such as line cards and MDFs are

[22]Currently POTS splitter card cost ranges around $200 per quad lines and ADSL subscriber line card is around $500 per quad lines.

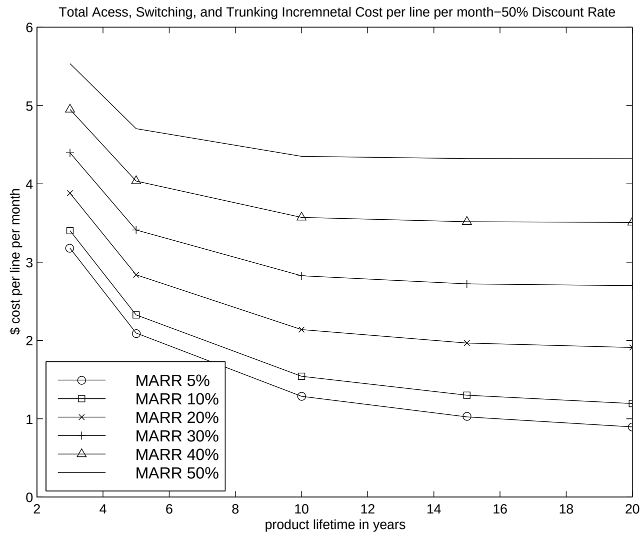

Figure 19: Total Access, Switching, and Trunking Incremental Cost per line per month from PSTN to ISN

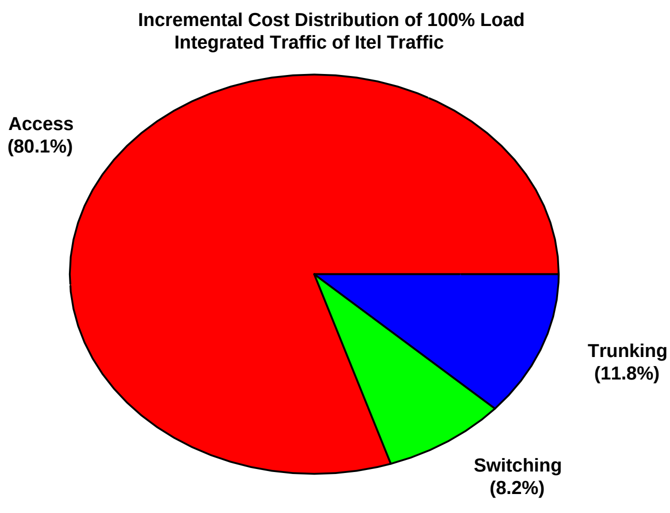

Figure 20: Incremental Cost Distribution Chart

added in, the monthly line costs of both Itel and PSTN are comparable with facility based trunking which has almost zero incremental trunking cost for additional interoffice trunking traffic. With the integrated services component, the advantages of Itel are greater. To put this in comparison, at a 20% MARR, the cost of 5 year integrated services Itel network is slightly less than the cost of a 10 year circuit switched network (at a 50% trunking discount). This allows the equipment to be upgraded twice as often in the Itel case as compared to the circuit switched case without increasing the cost.

With respect to the first result, the dominant cost factor is the cost of interoffice transmission; the compression and silence suppression enabled the use of 29% less transmission capacity in Itel[23]. Note that it would be more difficult to include compression technology in circuit switched networks for a number of reasons because the network would have to be able to differentiate applications, since the compression algorithms are designed for voice and not for modems, fax machines, *etc.* Even if application detection were feasible, it might run afoul of privacy regulations.

Still, these results do need to be put into perspective. In particular, the following issues are important in terms of the overall impact of the results of this study:

1. Generally speaking, the transmission and switching costs of an IXC are around 22% of their total cost structure [14]. One of the largest unknown costs for Itel are the OA&M costs and billing costs[24]. These systems are highly developed for circuit switched networks and are of major importance to carriers.

2. We did not consider operations cost differences between the two technologies, or their relative reliability, security *etc.* There is no reason to believe that these would be constant across the technologies.

3. We did not account for terminal devices. POTS telephones are inexpensive compared with Itel devices, and that could influence consumer choices in the voice only case. In the ISN case, more capable terminals would be needed by both network types.

4. Relaxing many of the simplifying assumptions could have an impact on the overall costs, although we believe them to be second-order impacts.

5. Many AIN services have yet to be ported onto Itel networks. It is uncertain as to the cost of supporting these services.

6. The use of better QoS technologies has the potential for affecting the cost for Itel.

From a regulatory perspective, this paper suggests that the issues raised by Itel will not go away, and that regulators will have to continue to confront them. It also suggests an imminent technology conversion for telephone companies as they continue to seek lower costs of delivering their services.

A significant part of the impact on telephone companies is that Itel networks can add a level of integrated services at zero incremental cost (and presumably not at zero price!) while circuit switched carriers require a significant investment in order to offer competing services. This means that the profitability of carriers will be enhanced in Itel based carriers (as compared to circuit switched carriers). It may well be that this potential growth in profitability is what is ultimately compelling for telcos and their shareholders.

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[24] Based on informal conversations with a representative from Hyperion Communications.

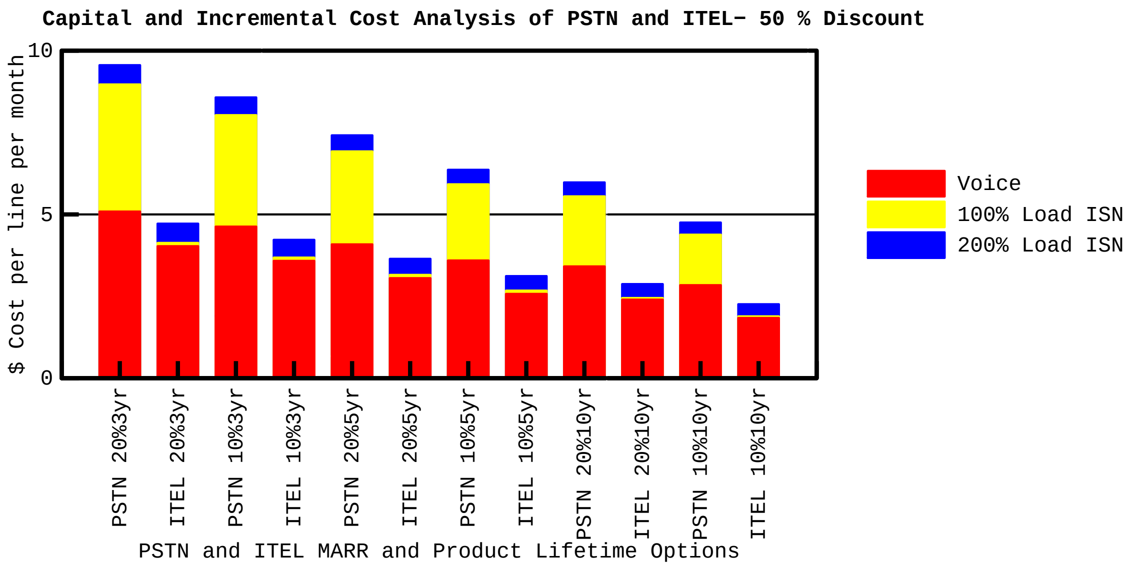

Figure 21: Capital and Incremental Cost Comparison of PSTN and Itel-50% Discount

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