21

Diffusion of Network Innovation: Implications for Adoption of Internet Services

By

Marc S. Shuster

Submitted to the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degrees of

Bachelor of Science in Electrical Engineering and Computer Science and Master of Engineering in Electrical Engineering and Computer Science at the Massachusetts Institute of Technology

June 1998

Author ______________________________
Department of Electrical Engineering and Computer Science
May 8, 1998

Certified by ______________________________
Dr. Lee W. McKnight
Lecturer, Technology and Policy Program
Thesis Supervisor

Accepted by ______________________________
Arthur C. Smith
Professor of Electrical Engineering and Computer Science
Chairman, Department Committee on Graduate Theses

Diffusion of Network Innovation:
Implications for Adoption of Internet Services

by

Marc S. Shuster

Submitted to the
Department of Electrical Engineering and Computer Science

May 8, 1998

in Partial Fulfillment of the Requirements for the Degrees of
Bachelor of Science in Electrical Engineering and Computer Science
and Master of Engineering in Electrical Engineering and Computer Science

ABSTRACT

The Internet and network applications have achieved significant growth. This thesis reviews the historical development of the Internet and projects future expansion of network application usage. Observed data points for Internet hosts, World Wide Web servers, the Multicasting Backbone, USENET, and Internet telephony were fit to an s-shaped logistic curve. The results of the model predict the applications' growth rate, halfway points of growth, and saturation limits. The number of Internet hosts is expected saturate at about 39 million hosts by the early part of the next century, while the number of Web server will saturate at about 40% of responding Internet hosts.

The adoption rate of Internet Telephony was estimated by analogy to adoption patterns of more established applications. The factors necessary for successful deployment of Internet telephony were addressed in terms of network architecture and user interface. Internet telephony and multicast applications that require reserved network resources were concluded to be in very early stages of development. At the time of this writing, only a small fraction of the users who have knowledge and have tried telephony applications are willing to adopt and actively use the technology. This indicates that augmentations to Internet services are necessary to improve the usability of realtime applications, such as Internet telephony.

Thesis Supervisor: Dr. Lee W. McKnight
Lecturer, Technology and Policy Program

TABLE OF CONTENTS

1. Introduction

This thesis examines the diffusion of new technologies and considers the challenges to enabling voice communications on the net. Forecasts concerning the use of the Internet and technology, in general, are difficult to make. The Internet is fundamentally unpredictable. It functions as a decentralized network of networks, has no central point of control or planning and is continuously changing. Without any central authority, technology and the demands of users on the network's periphery drive adoption patterns. In contrast, the telephone network consists of switches that serve as central points of control. Regional telephone companies, Post, Telegraph and Telephone (PTT) organizations, and regulators act as planners.

Noam proposes that the telecommunications industry is shifting from a supply-oriented to a consumer-driven model.[42] User behavior will be the most crucial factor in technology adoption in a compatible market. The consumer's willingness to try and exploit new technologies will determine the future direction of communications networks. The design of modern networks allows user needs to be accommodated by configuring end-node equipment instead of the network itself. For example, the World Wide Web emerged as a result of the demand for easy-to-use information retrieval software and the widespread adoption of browser software by Internet users.

With end-users gaining greater control of network usage, analysis of network traffic trends is becoming an important tool. In addition to measuring the volume of network traffic, statistics are being broken down by application type and content. [52] The ratio of voice to data traffic is of interest to carriers because 'basic' voice telephony is regulated and 'enhanced' data services are unregulated, providing the opportunity for unlimited entry and innovation. [33] Eventually the distinction between voice and data will begin to blur as voice transmissions are digitized and are treated identically to data. Mutooni concludes that by the year 2007 packet based data traffic will exceed voice traffic. [37] This use of data networks for voice applications may have a significant impact on the revenue of traditional carriers. [48] However, analyses of traffic trends alone are likely to be inadequate in predicting the future use of networks and the demand of applications. The technologies themselves and the rapidly the needs of users are rapidly evolving. The most important issue is clearly defining the uses of network applications and understanding what they will become.

1.1 Communication Networks and Convergence

Traditionally, communications services have been tightly coupled to their transportation medium. [56] Radio, television, and telephone service have all been bound to a dedicated network. The Internet, however, has demonstrated that a diverse set of content and applications may be provided across heterogeneous networks. The Internet Protocol (IP) allows a spanning layer between the network substrate and applications.[22] The capabilities of the Internet can be extended without modifying the underlying structure of the network. The use of cable and telephone networks for Internet access provides further evidence of the extensibility of the Internet model.

The union of computers and communication systems has enabled this unbundling of network elements. In theory, the computation performed by one computer can be emulated by any other computer. British mathematician Alan Turing proved that any mathematical operation that could be performed on one machine could be accomplished on a single universal machine.[54] By disassembling content into atomic computable units a universal, interoperable, and ubiquitous network of interconnected devices can theoretically be obtained. This convergence of technologies implies that any service can be provided over any medium. The public telephone system can carry text as well as voice. The Internet can transmit data as well as voice. Radio waves may be used for two-way telephony or broadcast. The challenge to realizing the ideal of convergence will be interconnecting a diverse set of networks and devices and overcoming the limitations of cost and capacity.

Although convergence appears to be a modern development sparked by the incorporation of computing power with communications and the digitization of information, the concept dates back to the early days of the telephone network. Theodore Vail, president of AT&T, envisioned the Bell System in 1910 as based upon "a common policy, common purpose, and common action; comprehensive, universal, interdependent, intercommunicating like the highway system of the country."[12] Paradoxically, the creation of a truly universal network through the interconnection of foreign networks and devices increases the value of the network to its users while eroding the power of the incumbent network service provider. Interconnected networks serve as both complements and competitors.[36] Historically, AT&T fought vigorously against the interconnection of independent phone companies and the attachment of third party devices. The merger of the Internet and telephony is likely to create a similar scenario of providing new features and benefits to users and competition for established players.

1.2 IP Telephony

Within this framework of convergent technologies, the opportunity exists to provide real-time voice services on data networks such as the Internet and private Intranets. Clark identifies three general classes of Internet Protocol (IP) telephony applications (see figure 1.1). [8] Although these applications are often referred to as Internet telephony applications, they may be implemented on any Internet Protocol based network, not just the public Internet. Class 1 connects Plain Old Telephone Service (POTS) equipment, with the Internet serving only as a conduit. Class 3 utilizes computers attached to the Internet for voice communications and other advanced applications. This class does not involve any interaction with the Public Switched Telephone Network (PSTN) or equipment with the possible exception of a telephone line and modem for dialup access. Class 2 is a hybrid of classes 1 and 3. Class 2 allows communication

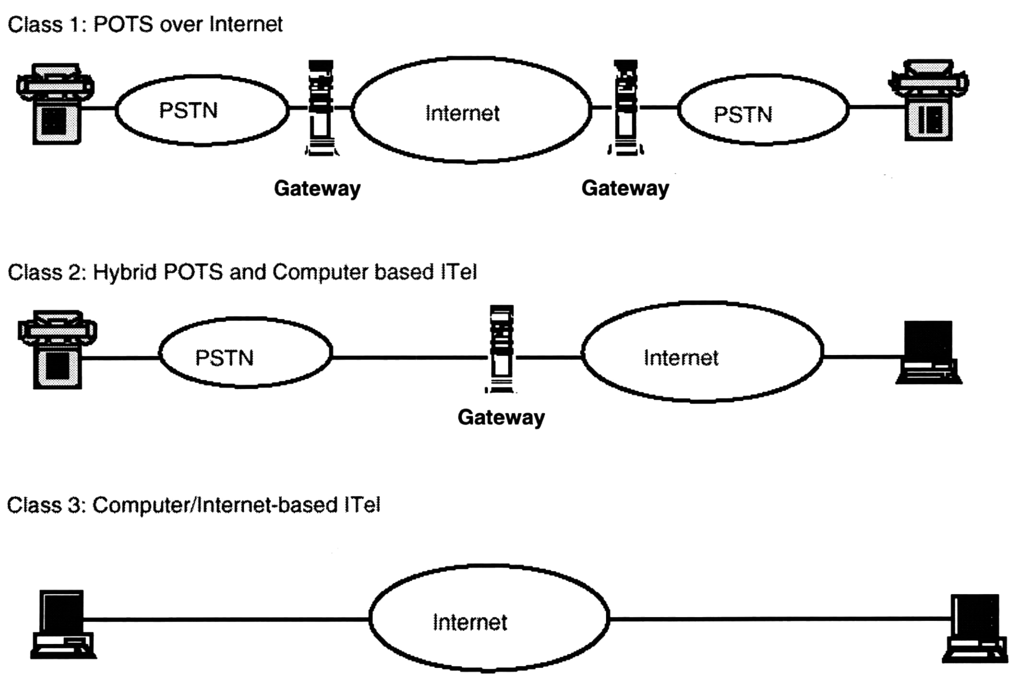

Figure 1.1: IP Telephony Applications Classes, Source: David Clark [8]

between computer based telephony systems and POTS equipment. Thus, a computer telephony application resides on one end-node and a PSTN phone resides on the other end-node. Some applications provide both class 2 and 3 capabilities.

The uses of IP telephony applications can be divided into three categories: as substitutes for traditional telephony, as enhanced telephony, and as alternative lower quality cost saving telephony. Some applications appear to the end-user as almost identical to traditional telephony and will act as substitutes. IP telephony may produce cost savings by allowing more efficient uses of transmission lines through compression, statistical sharing, and multiplexing. However, the cost savings associated with some applications are not fundamental and may disappear as regulation, industry competition and technology changes. Computer telephony integration (CTI) will permit applications

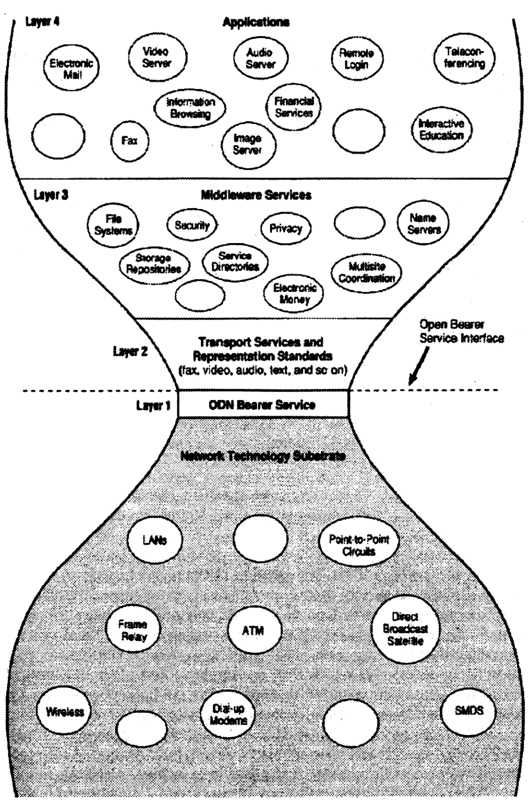

Figure 1.2: NRC Open Data Network Architecture [59]

with increased functionality such as video, improved call management, or conferencing features. [34] These added features will attract new users as cost savings begin to disappear.

1.3 Network Architecture

The independence of applications from the underlying transport is transforming the architecture of communications systems and shifting business models to focus on opportunities stemming from vertical rather than horizontal integration. In vertical integration, a single entity provides the application and a dedicated infrastructure. [22] The horizontally integrated network can be described as a four layered interoperating architecture, consisting of the bearer service, transport, middleware services, and applications, see figure 1.2. [39] At the lowest level the bearer service incorporates lines, switches and other networking components. The transport level transforms the bearer service into the proper infrastructure for higher level applications with protocols and coding formats. The combined functionality of bearer service and transport are referred to as bitways in this thesis. Middleware provides commonly used features and services to applications. At the highest level exist the applications with which the user directly interacts. The following section details the challenges to enabling these bitways and services to accommodate IP telephony applications.

1.3.1 Bitways

1.3.1.1 Local Access

The limited bandwidth of the local loop can impede the usability of applications. The local loop comprises about 90% of all telephony wiring in the US. [25] The costs for local access and distribution are significantly higher than for long-haul operations, where more users share network resources. [40] Extending fiber to the home can not be justified if sufficient demand for bandwidth does not exist and costs can not be recovered. Existing residential service offerings, such as Integrated Services Digital Network (ISDN), are complicated to configure and install and do not provide sufficient capacity and flexibility for the next generation of network applications. Newer technologies such as wireless or ADSL which utilize existing copper wiring more efficiently may help eliminate the local bandwidth bottleneck. Local loop alternatives such as cable, wireless, and satellite are being developed; however, these technologies are not fully deployed and have not yet provided an effective solution for residential access problems. Although local access is an important aspect of supporting advance network applications, a complete analysis of this issue is beyond the scope of this thesis.

1.3.1.2 Gateways

Class two and three applications require interconnection between PSTN and IP based networks. Gateways provide the capability for terminals to communicate between these networks.[44] A gateway consists of a codec software or hardware device that handles packetization, compression and decompression of calls, and line interfaces for the PSTN and LAN or PBX network.[17] Gateways can be built using a PC server with specialized telephony cards or as standalone network devices and IP telephones. [44] Organizations can install gateways on their LAN to emulate PBX systems or to provide connectivity between remote offices using leased lines. Telecommunication service companies also use gateways to provide class 2 and 3 applications to individual users.

Gateway designers encounter several problems. The first is latency, the time it takes for data to travel between two points. If the latency is above a few tenths of a second, voice conversation becomes difficult. Packet loss also affects the quality of conversations. The TCP/IP protocol causes packets to be dropped on over utilized network connections. Scalability is another issue designers must deal with. Existing gateway devices are equipped with a finite number of ports. Ports may become unavailable during peak usage periods.

1.3.2 Services

A broad range of services are required to support the commercial deployment of IP telephony applications. Security mechanisms are necessary in order to ensure the privacy of conversation, guard the safety of electronic payments, and verify user identity. Packets transmitted over the Internet can be captured by unintended recipients. However, secure transmission of information can be implemented with encryption techniques. Certification services may provide authentication for billing purposes. Improved network management tools are required track usage for billing and measuring network performance. In the following section, quality of service (QoS) and directory services are described in further detail.

1.3.2.1 Directories

Within the services layer of the network, directory functions are needed in order to locate users, groups of users, applications, services and gateways for connecting with the PSTN. User location directories provide dynamically updated information on the location of a user such as an IP address. White page directories contain information about a particular user such as name and email address. User group and conference directories provide information to facilitate multiple users interacting simultaneously. PSTN gateway directories provide services to place calls from the Internet to the telephone network, including locating telephone numbers and requesting information on gateways that can complete the call. Sears proposes that the Lightweight Directory Access Protocol (LDAP) can offer features that are necessary for IP telephony applications. [50]

1.3.2.2 Quality of Service

The single best effort quality of service afforded by the Internet creates problems for almost all applications, and yet it has been essential for expansion of the Internet as a low cost communications medium. The delay sensitive nature of telephony makes an unmanaged best effort network unreliable. To ensure the integrity of a conversation, voice traffic must be delivered reliability, with a minimum delay. Voice applications can tolerate some packet loss due to the redundancy of the human language. Data packets can tolerate longer and variable delays but no loss. [3] Real-time applications, such as telephony, typically are implemented with the User Datagram Protocol (UDP). UDP packets are not queued and jump ahead of Transmission Control Protocol (TCP) packets from other applications. TCP based applications, such as file transfer, tend to run slowly when many UDP packets are sent over the network.

The Real-time Protocol (RTP) and Reservation Setup Protocols (RSVP) were designed to alleviate some of the difficulties of implementing real-time applications on IP networks. RTP works by attaching packet timing information and a sequence number to UDP packets. This ensures that packets reach their destination on time and in the proper order, which is essential for IP telephony. RSVP allows bandwidth to be allocated along different levels of QoS. An RSVP session involve two processes: admission control and policy control. Admission control determines whether the router has sufficient resources to accommodate the requested QoS. Policy control determines whether the user has permission to make the reservation. [6] However, before applications may take advantage of these protocols, deployment problems must be addressed and pricing models must be developed to produce incentives to not overburden the network. [9]

1.3.3 Applications

Application	Architecture	QoS Requirements	Content
Telephony	Peer-to-peer	Immediate	Voice
Email, news, messaging	Client-server	Deferred	Data
Web browsing	Client-server	Delay tolerant	Data
Fax	Peer-to-peer	Delay tolerant	Data
Fax over IP	Client-server	Deferred	Data
Voice mail	Client-server	Deferred / delay tolerant	Voice
Video/audio broadcast	Multicast	Immediate	Data

Table 1.1: Comparison of network applications

Table 1.1 summarizes characteristics of various network applications. The application's architecture can be described as either peer-to-peer or client-server. Peer-to-peer applications involve two or more users interacting directly through end-node terminals or computers. In client-server applications the user interacts with a server to store information or to retrieve previously recorded information.[34] Real-time peer-to-peer voice applications, such as telephony, are sensitive to delay and require immediate QoS guarantees if the network is over-provisioned. Immediate QoS ensures that little delay occurs in transmission between peers. Delay has much less of an effect on the usability of information in a client-server environment. Electronic mail (email) requires only a deferred level of QoS. That is, application messages could be temporarily stored at intermediate points in the network without noticeably affecting the performance of the application. Thus, applications in which data can be stored and forwarded at a later time, such as fax, are amenable to networks with low immediacy QoS transport. On the other

	High Delay Tolerance	Low Delay Tolerance
High Error Tolerance	Client-Server Voice/Video Ex: Voice mail	Peer-To-Peer Voice/Video Transmission Ex: Telephony, Broadcast
Low Error Tolerance	Data Replication Ex: Backup	Data Retrieval Ex: WWW browsing

Table 1.2: Delay and Error properties of Network Applications

hand, transmission errors have a greater effect on data applications than voice or video applications. A voice message can still be understood with some amount of noise. However, a small change in a sequence of computer code will cause the information to be unusable. Client-server applications that involve user interaction such as Web browsing are delay tolerant. Delay does not affect the usability of information but may cause frustration if users must wait an excessive amount time to receive a response from the server.

Inefficiencies arise when applications are implemented on unsuitable network systems. The PSTN system's switched connections maintain a high degree of synchronism and symmetry.[46] Such connections are unnecessary and expensive for many data based applications. The Internet, however, provides an efficient mechanism for asynchronous data transmission and replication, but is unreliable for video broadcast and real-time voice applications. An ideal network would provide an adaptive and flexible model to accommodate the distinct technical characteristics of each application. An IP network, such as the Internet, that exploits asymmetries, provides suitable capacity, and is augmented with the means to reserve resources may approach such a model.

1.3.3.1 Ease of Use

Users will be more likely to adopt new telephony technologies if they are easy to use and incorporate elements of familiar applications. PSTN telephony is becoming more complex with longer dialing strings and voice menus. Computer telephony integration allows these features to be better managed. As the functionality of communication networks is being shifted to the end-node, the user interface may be improved. [8] However, difficult setup or configuration may present a significant barrier in encouraging users to adopt easier to use applications.

1.3.3.2 Pricing

Currently, experimentation with IP telephony applications is driven by lower domestic and international long distance calling costs produced by the arbitrage opportunity to bypass international settlement payments and local service subsidies imposed by regulation. Most Internet Service Providers (ISP) charge a flat rate for unlimited Internet usage. Users may pay a single monthly fee per connection regardless of how and when bits are transferred. However, ISPs may not be able to maintain flat-rate fees if they are charged for access to local telephone company networks or traffic increases to the point that network quality significantly degrades and transport facilities must be upgraded. For example, Leida concludes that with only a moderate use of IP telephony, ISP revenue will increase slightly, while costs will increase by almost 50%. [30]

The marginal cost of each additional packet on a network is essentially zero except during periods of congestion where network performance decreases for all users. To manage congestion ISPs may choose to implement usage-sensitive or transaction based pricing. In usage sensitive pricing users pay based on the quantity of bits transferred and the prices may increase during peak usage periods. Transaction based pricing would be similar to the pricing for a traditional phone call. Users would pay based on the quantity and characteristics of network interactions.[31]

Neuman predicts that the cost of long distance telephony and Internet telephony will coincide sometime early next century. [53] More efficient data packet based networks, regulatory and settlement charge reforms, and competition will decrease the price of traditional telephony, while the decline of flat-rate billing will increase the price of Internet telephony. Most large ISPs exchange traffic from other networks on a peering basis. Real-time application's QoS requirements will allow ISPs to differentiate their networks and ISPs will seek compensation for higher levels of service. [52] As cost disparities are minimized, enhanced features will begin to attract users to IP telephony.

1.3.3.3 Ubiquitous access

A communications system is of little value if there are few users to call. The problem of creating a large user community is more severe in the case of peer-to-peer applications than client-server applications. In a client-server environment, the first users derive almost the same value from the features of the server as later users. In peer-to-peer environments, early adopters derive little value with only a small community with which to communicate. Common standards and access to gateways helps to alleviate this problem. Dynamic deployment of software is another potential solution. Languages such as Java allow new software to be installed as needed. Thus, end-nodes can be updated as new standards and interfaces become available. [34]

Issues of universal service and universal access have technical, economic, and policy elements. From 1907-1921 universal service policies sought to unify telephone services to produce a single interconnected telephone system. The second generation of universal service policy originated from the implicit intentions of the Communications Act of 1934. Cross-subsidies were designed to ensure affordable telephone service to all Americans. With the Telecommunications Act of 1996, the universal service obligations of common carriers were made explicit.[36] Universal service subsidies may serve to either accelerate or slow diffusion of network innovation. Fees imposed on ISPs that are classified as carriers may deter IP telephony use. At the same time, subsidies to provide greater Internet access will allow IP telephony to reach more potential users.

2. Adoption of Technology

2.1 Modeling Adoption Behavior

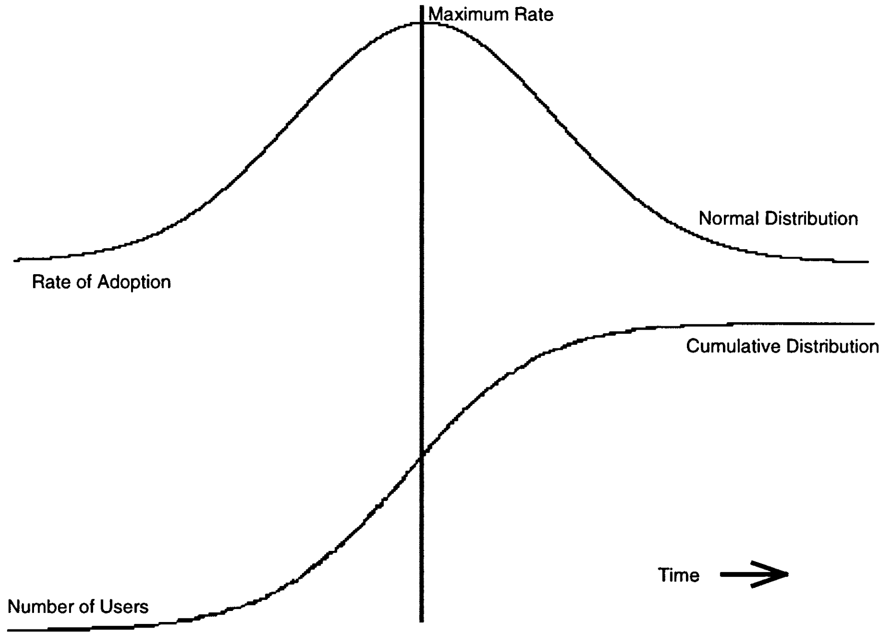

Figure 2.1: Diffusion and Adoption Curves

The two curves in Figure 2.1 characterize the adoption of technology. The normal Gaussian distribution curve describes the rate of adoption at time t. The bottom s-shaped logistic curve describes the cumulative number of users of the technology at time t. Adoption behavior can be divided into three stages: growth, maturity, and saturation. During the growth stage, the rate of diffusion and number of users grow as communication increases the knowledge and acceptability of the innovation. The earliest period of the growth stage may be approximated by the exponential curve, $N(t) = ae^{bt}$, where N quantifies the users at time, t. The rate of diffusion reaches a maximum at the halfway point indicated by the vertical line in Figure 2.1. The maturity stage surrounds the maximum point of the curve. The curve begins to level off during the saturation stage as all potential users have adopted the technology. The saturation stage

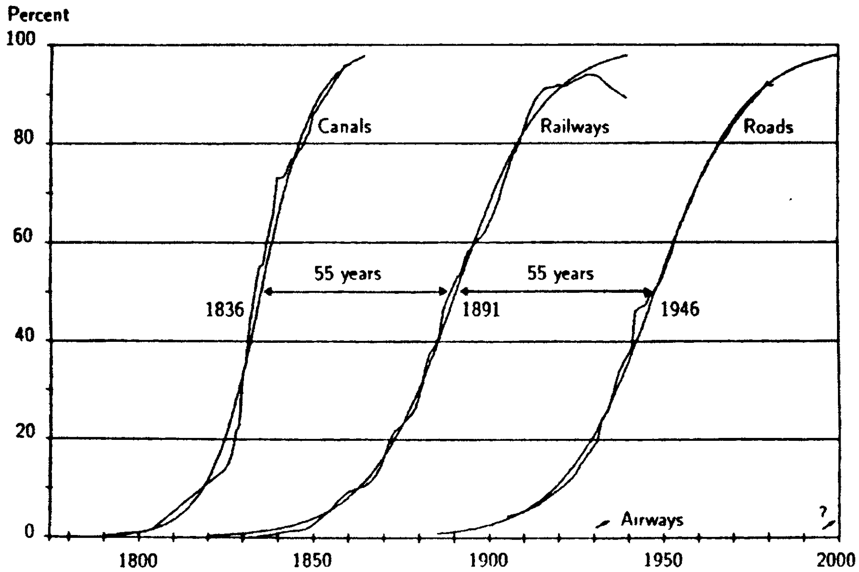

Figure 2.1: Growth of transportation technologies in the United States in terms of saturation limits, Source: Grübler [19]

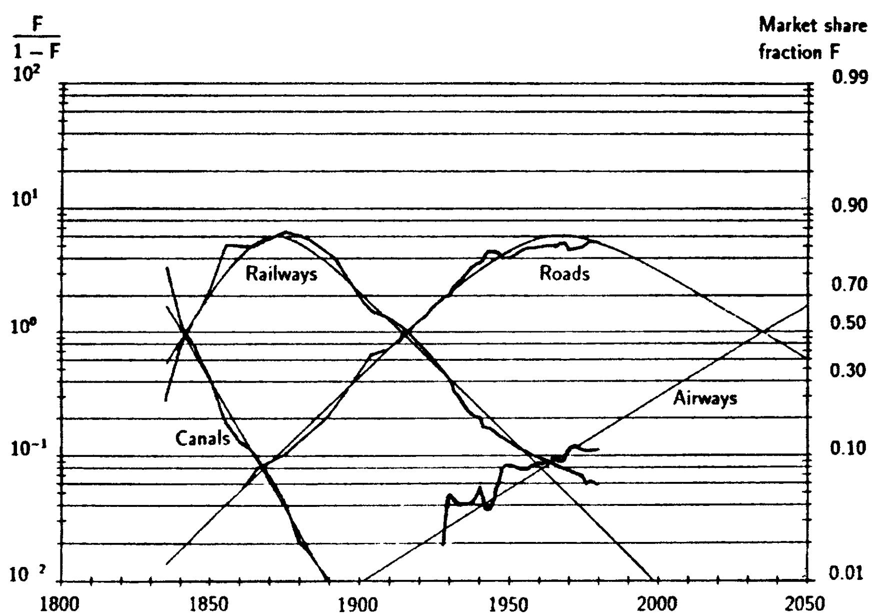

Figure 2.3: Projected growth and substitution of transportation technologies in the United States, Source: Grübler [19]

often coincides with the growth stage of a competing technology. An additional stage of decline occurs often as users substitute one technology for another. For example, transportation technologies grew to saturation along to an s-shaped curve in figure 2.2. Figure 2.3 displays the subsequent decline of older transportation infrastructures with the introduction of newer ones. In some cases, a new diffusion wave for each technology may build as additional uses are identified and current users replace or upgrade their existing equipment. Some technologies do not experience a significant decline with the introduction of newer technologies.

The rate of adoption can be described by the differential equation,

$$\frac{dN}{dt} \propto N(M-N) \quad (1)$$

where M is the saturation point of the diffusion process. Thus, diffusion is proportional to the amount of the innovation adopted and the amount remaining to be adopted. The solution to this differential equation is

$$N(t)=\frac{M}{1+e^{-(at+b)}} \quad (2)$$

where a describes the rate of adoption and b is the constant of integration. The halfway point of the process is identified by the relation,

$$t_{1/2} = -\frac{b}{a} \quad (3)$$

The halfway point is also the point of inflection of equation (2),

$$\frac{d^2N}{dt^2}(t_{1/2}) = 0 \quad (4)$$

A useful relation to compare the diffusion of different technologies is Δt, the time, in years, required for diffusion to proceed from 10% to 90% of M, or the takeover time.

$$\Delta t = \frac{1}{83.06 \cdot a} \tag{5}$$

Equation (2) can be manipulated to produce a form in which the parameters `a` and `b` can be calculated with linear regression methods,

$$\ln\left(\frac{N(t)}{M - N(t)}\right) = at + b \tag{6}$$

The variable, `N`, can be expressed either in terms of the percentage of the total market or the absolute number of users adopting the technology. The saturation level, `M`, can be expressed in terms of the total percentage of the market or the absolute number of users that the technology will reach. When an innovation acts as a simple substitute, substitutions have been observed to almost completely replace older technologies if substitution progresses a few percent. [14] In this case, `M` may be approximated as 100%. If `M` is not known beforehand, an `M` may be calculated that results in the best statistical fit of the model with existing data points. [18]

The mathematical equations make some assumptions that do not necessarily reflect actual adoption behavior. Specifically, the adoption curve is symmetric about the halfway point, an asymptote exists which diffusion can not proceed beyond, and adoption begins in the infinite past and goes to completion in the infinite future. The model is intended only to be a descriptive tool and provides no insight into driving forces or causality. The diffusion model describes the transfer of knowledge and experience from early adopters to the rest of the population. The innovation decision process consists of four steps: knowledge, persuasion, decision and implementation and confirmation. [47] Individuals obtain knowledge of the innovation and evaluate it in terms of perceived characteristics. The validity and reliability of the information is assessed during persuasion and then the decision to adopt or reject the innovation is made. This decision is reassessed and confirmed based on the actions of other individuals. The adoption rate increases as uncertainty decreases with a larger community to gather information concerning the innovation. Members of the community learn from the experiences of others and imitate the behavior of innovators. There may be a significant time lag between the point at which one learns and tries a technological innovation and actually adopts the technology by making some commitment and including the innovation as part of routine usage.

2.2 Factors Affecting the Adoption of Network Applications

As a communications medium, the Internet naturally facilitates rapid diffusion of novel network applications through the transmission of both information about applications and the applications software itself. In this section, the perceived characteristics of innovations are discussed according to a framework defined by Rogers. The most important attributes of innovations are relative advantage, compatibility, complexity, trialability, and observability. [47]

Innovation Attribute	Web	IP Telephony Software
Relative Advantage	Multimedia, hypertext information format	Cost savings call management features
Compatibility	Compatible with ftp, gopher	can interconnect with PSTN through gateways
Complexity	Easy-to-use graphical interface	varies by implementation
Trialability	Free client software requiring no commitment	Many implementations are free to download Some applications require service commitments
Observability	Highly observable URL's	Limited

Table 2.1: Summary of Innovation Attributes of the Web and IP telephony

Relative advantage is the degree to which an innovation is perceived as superior to its predecessor. Users migrate to applications that provide benefits over existing applications. Figure 2.4 illustrates the percentage of traffic originating from three popular applications on the NSFNET backbone. Note that on April 30, 1995, NSFNET was transitioned to a new architecture in which traffic is exchanged at four network access points and, therefore, comparable traffic data does not exist after this date. Traffic from World Wide Web browsers surpassed both ftp and gopher traffic. The advantages provided by the Web resulted in users substituting the Web for gopher and ftp.

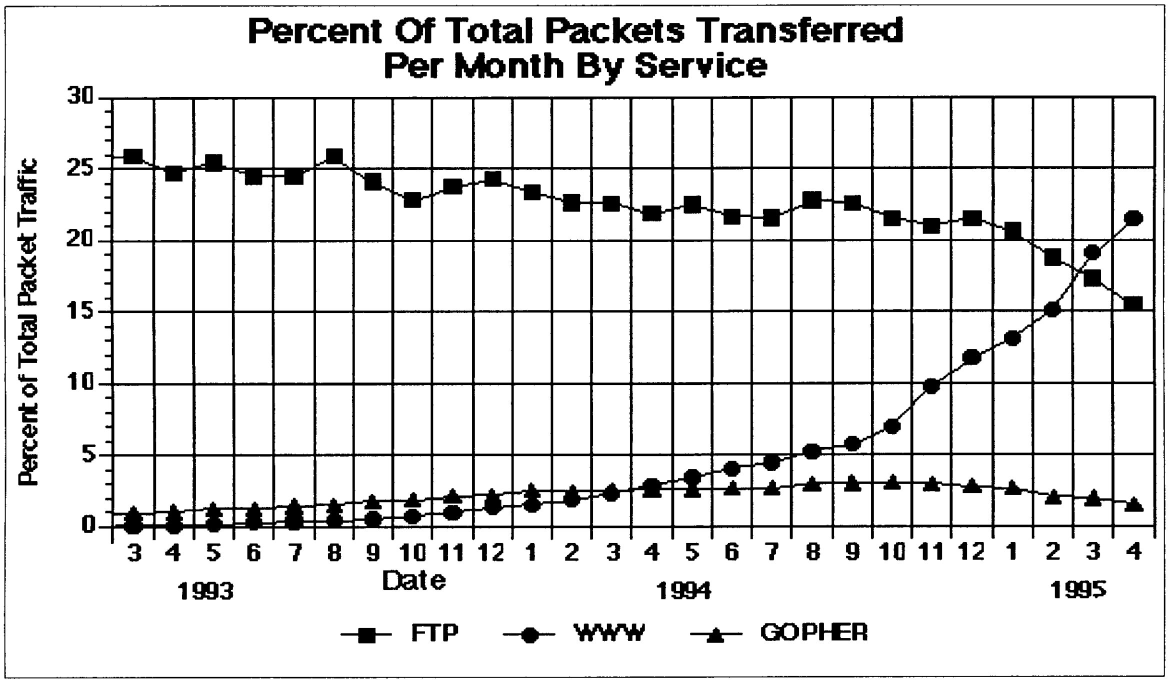

Figure 2.4: Traffic on the NSFnet backbone, Sources: Merit NIC, James Pitkow, GVU

IP telephony applications must present some benefit over traditional forms of telephony. Cost savings have attracted early adopters of these applications. Although cost savings do exist, quality tends to be much lower due to latency and other factors. Lower quality tends to be a result of network connectivity, or bitways, and not the application layer. However, the perception of overall poor quality may hamper future adoption even as bandwidth improves.

Compatibility is the degree to which an innovation is perceived as consistent with the existing values, past experience and needs of potential adopters. Interfaces that are compatible with familiar applications will positively affect the rate of adoption. Web browsers provided a similar interface and compatibility with ftp and gopher browsers. Users could continue to access ftp and gopher services as well as Web services. Class 2 and 3 telephony applications appear to be incompatible with methods of interacting with existing technology. Connecting with another party may require different directory lookup procedures, such as locating an IP address, and similar system platforms or software. Improved gateway services may help achieve more compatible telephony applications.

Complexity is the degree to which an innovation is perceived as relatively difficult to understand and use. Complexity impedes the adoption of innovations. The Web achieved widespread acceptance due to the easy-to-use interface of browsers. For users unfamiliar with computers these telephony applications have a more complex interface and are more difficult to setup than POTS equipment.

Trialability is the degree to which an innovation may be experimented with on a limited basis. Many successful network applications have been very trialable. Web and gopher clients could be downloaded for free and experimented without any commitment Most telephony applications, as well, do not require any commitment of the user and do not present any difficulties in discontinuing use. Users can simply install the software experiment without modifying their primary telephone system. Class 1 applications permit users to try Internet based services without switching their primary telephony service provider. Trialability is more important to early adopters who have less assurances of the viability of the applications. Late adoptions are assured of the applications success through observation of previous adopters.

Observability is the degree to which the results of an innovation are visible to others. Innovations that have observable benefits are adopted more quickly. Roger notes that software based innovations are less observable than hardware based innovations. Some software innovations such as the World Wide Web had certain aspects that were highly observable such as widely advertised URL's. New telephony applications may use existing addresses such as telephone number or host names that will not differentiate them. However, the peer-to-peer nature of telephony applications may cause early adopters to encourage others to try the applications.

2.3 Growth of the Internet

There are several factors that will drive and constrain the growth of the Internet. Communications systems are characterized by both positive and negative externalities.[2] Positive externalities arise when the total number of users affects the value of the network for individual users. New adopters derive more value from the network than early adopters because of the greater availability of information and number of users with which to communication. However, as the size of the network's knowledge base grows, information becomes more difficult to locate and organize. Such negative externalities arise when the performance or usability of the network degrades due to increased usage and traffic. Heightened costs, congestion, and complexity often occur in expanding networks. Each additional user produces a network with different qualities. New applications also change the nature of the network. For example, the demand for Web access created the need for direct connection to the Internet instead of simple access methods such as mail gateways.

2.3.1 Internet Hosts

Figure 2.3 describes the growth of hosts on the Internet from 1969 to 1998. The data was obtained from several sources and may not be consistent throughout the entire time-series because of different host count methods. From 1969 to about 1988 all Internet hosts were registered in host tables with the Network Information Center. In 1988, the Domain Name System (DNS) was implemented and deployed and host counts were performed by querying the DNS system. [27] Beginning in January 1998, the survey

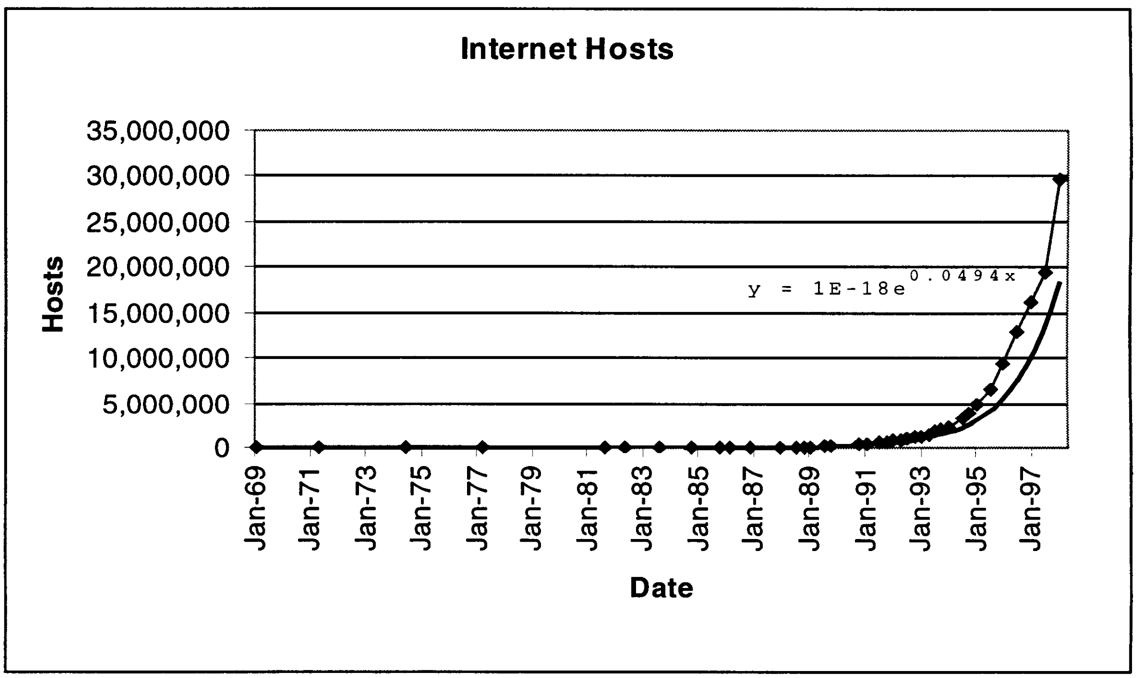

Figure 2.3: Growth of Internet Hosts, Source: Network Wizards

mechanism was modified to account for organizations restricting access to domain data. The new survey counts hosts by querying the domain systems to discover IP addresses assigned names. From 1969 to 1998 Internet host expansion exhibits an exponential growth pattern but growth rates during different periods are inconsistent due to different host count methods. The solid line in figure 2.3 illustrates the exponential regression curve for the data.

The host count only describes the number of visible machines connected to the Internet and does not provide information on usage. There exists no accurate calculation of Internet users. Multiple users accessing the network through the same machine obscure the actual size of the Internet community. For example, many individuals may read electronic mail through a single machine acting as a mail server or access the Internet using public terminals. Internet hosts that act as public file servers may have an unlimited

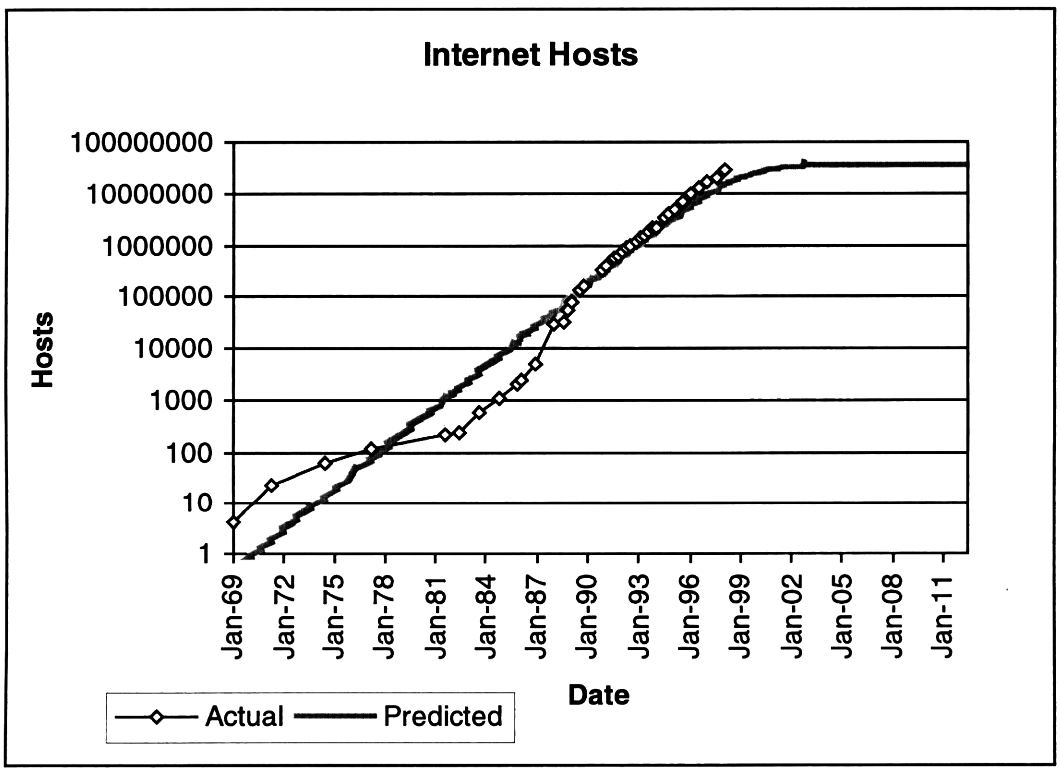

Figure 2.4: Predicted Growth of Internet Hosts

number of potential users. The ratio of users to machines has been decreasing as network services are being accessed with personal computers instead of timeshared mainframes.

Despite the fact that hosts may be private terminals or public servers, the Internet host count currently provides the most reliable measure of the size of the Internet.

Figure 2.4 projects the growth of Internet hosts by fitting data to equation (2). The upper limit of hosts, 39 million, was calculated by finding the best statistical fit. The logarithmic scale more clearly distinguishes several waves of Internet host growth in which hosts counts do not fit the predicted curve. The host count observations begin to converge on the predicted curve around 1989. This period of growth may represent the commercialization of the Internet or the implementation of the DNS. Although the growth of Internet hosts is predicted to saturate in the early part of the next century, this does not imply that expansion of the Internet will discontinue. The stabilization of the number of hosts may be coincidental with the growth of private networks, often called Intranets. [21] Hosts within these private networks are hidden from the surveying devices described earlier. Organizations that create Intranets isolate internal users from the rest of the Internet through firewalls, proxy servers, and gateways. These organizations decide what content and services from the external network to allow users to access and provide internal content on private servers. The rise of an Intranet based Internet may be a response to the need for improved security, filtering of content, or differentiated levels of service. Another trend that might also cause a slowdown in the growth of the number of hosts is the use of the Internet as a transport mechanism. Users can access a gateway device that utilizes the Internet for transport through terminals that are not Internet hosts, such as POTS equipment.

2.3.2 The Web

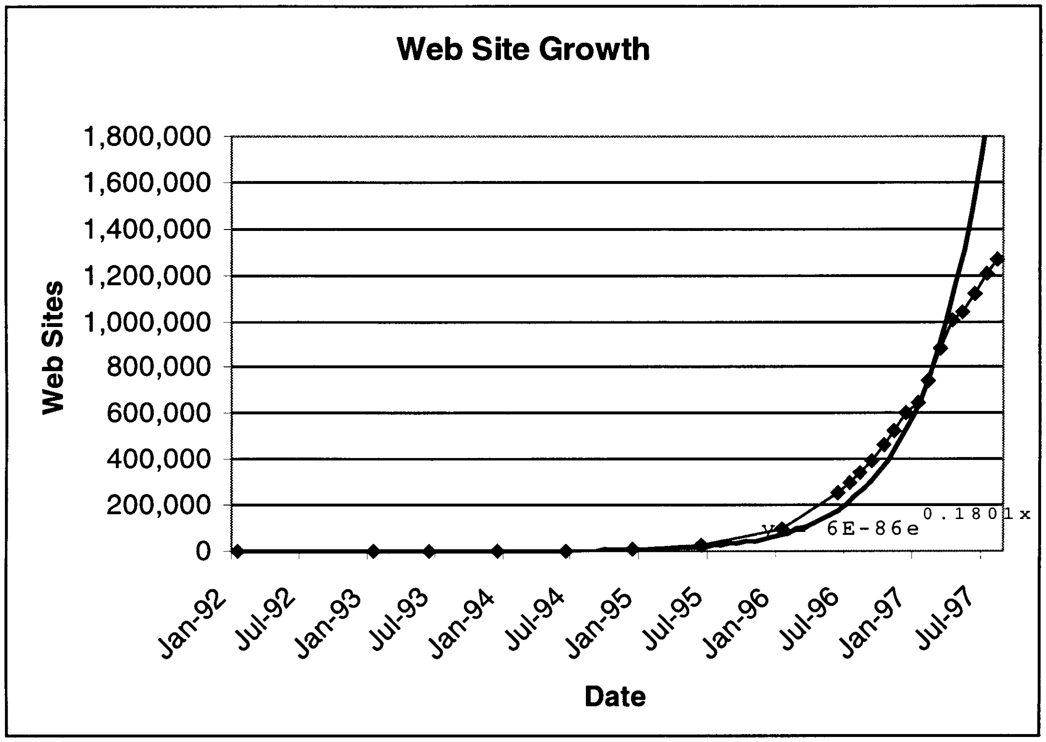

Figure 2.5: Growth of Web Sites. Sources: W3 Consortium, Matt Gray, MIT

In 1989, the World Wide Web (WWW or Web) was conceived at CERN as a distributed hypertext system to manage information about the lab's accelerators and experiments. The first multimedia browsers were introduced in 1992 and 1993. Although no accurate count of Web users exists, the number of Web servers or sites has been recorded and is displayed in figure 2.5. The Web has experienced tremendous growth but interception of the data with the exponential curve indicates that this growth is beginning to slow. To more accurately predict an upper limit on Web growth, web servers were plotted as a percentage of the total number of responding Internet hosts in figure 2.6. Responding Internet hosts were estimated by Network Wizards by querying a statistical sampling of the Internet. All public Web servers are responding Internet hosts. Other types of responding hosts include other forms of servers and networked machines that are always on and are outside of a firewall. The number of Web servers should not exceed the number of responding hosts. An upper limit of 40% of responding hosts functioning as Web servers was obtained. This is equivalent to approximately 8.6 million Web servers by the middle of year 2000. The halfway point of Web growth occurred in December 1996. These results are consistent with the fact that many organizations have already created a presence on the Web. A new wave of growth may occur if individuals were to setup private Web servers as personal computers gain the ability to be continuously connected to the network. Such a capability would enable the transition from web content hosted on a single server to content hosted on local personal computers. However, this would not necessarily increase the total information base of the Web.

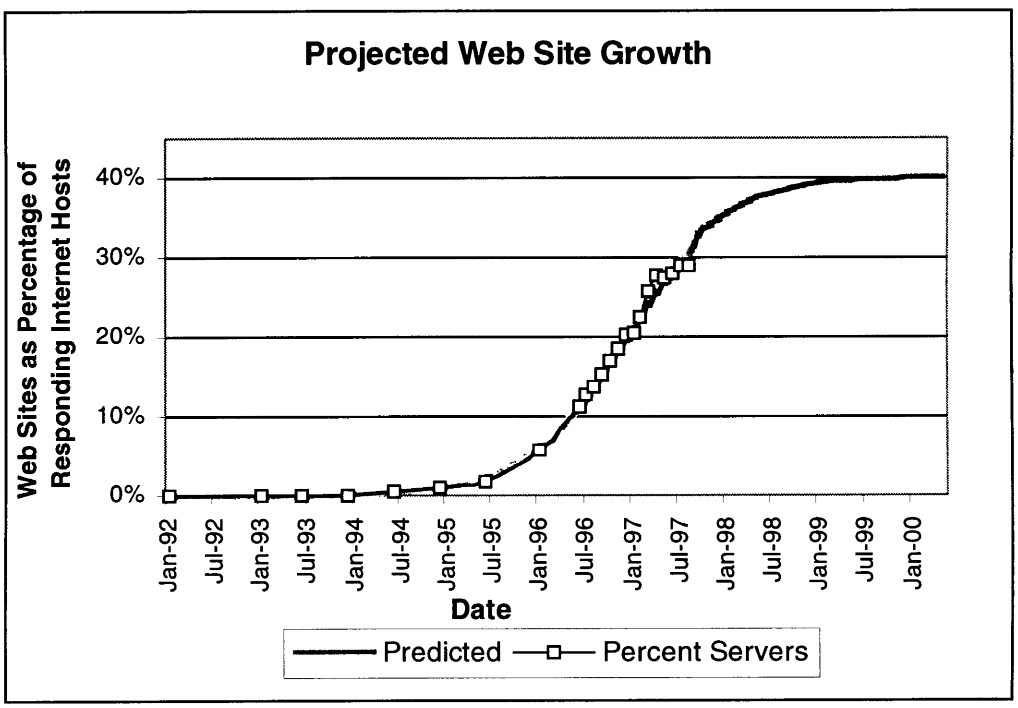

Figure 2.6: Predicted Web Site Growth as Percentage of Responding Internet Hosts

2.3.3 USENET

USENET was developed in 1979 as a distributed conferencing service or news system for UNIX machines. The distribution of news articles is supported by the decentralized interconnection of USENET servers. [45] Each machine replicates articles with its neighboring hosts. Thus, articles are propagated throughout the USENET system limited to news group subscriptions and distribution scope of articles. Although, records of the number of USENET servers exist, these records do accurately reflect growth of USENET usage. Unlike web servers, each USENET contains almost identical content. Old USENET servers are simply upgraded to accommodate increased traffic. New servers are added as new networks and groups of users become part of USENET.

The number of readers of USENET articles has been estimated by surveying news traffic. USENET readership from 1979 until 1988 is displayed in figure 2.7. Readership fluctuates as some users do not participate in news groups during some months. USENET continues to be an actively used application, however, frequent readership surveys are not available after 1988. The last readership survey was conducted in July 1995 with an

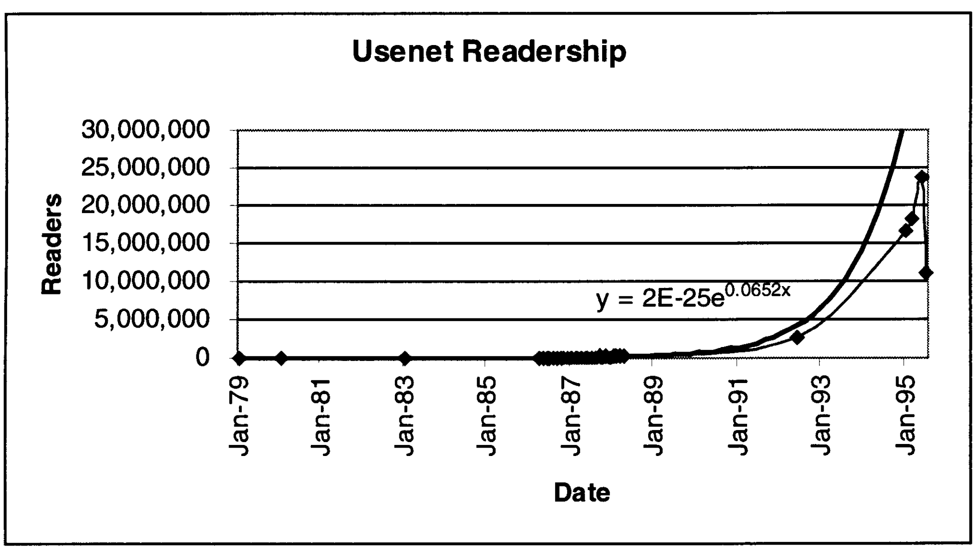

Figure 2.7: USENET Readership, Source: Brian Reid, Digital Equipment

estimated 11 million readers. Accurate projections and an upper limited on growth were not possible with the limited data set. USENET takeover of 5.6 years was calculated using initial growth patterns. Growth rate for applications are further discussed and compared in chapter 3.

2.3.4 Multicast Applications

The IP Multicast Backbone (MBone) is an early Internet based real-time video and voice application. The first multicast session was established between BBN and Stanford University in 1988. The MBone distributes information in a one-to-many fashion rather than a one-to-one fashion, as is the case with peer-to-peer IP telephony. Information about hosts participating in the MBone was collected using the *mlisten* tool that continuously monitors multicast addresses used to advertise MBone sessions. [1] The

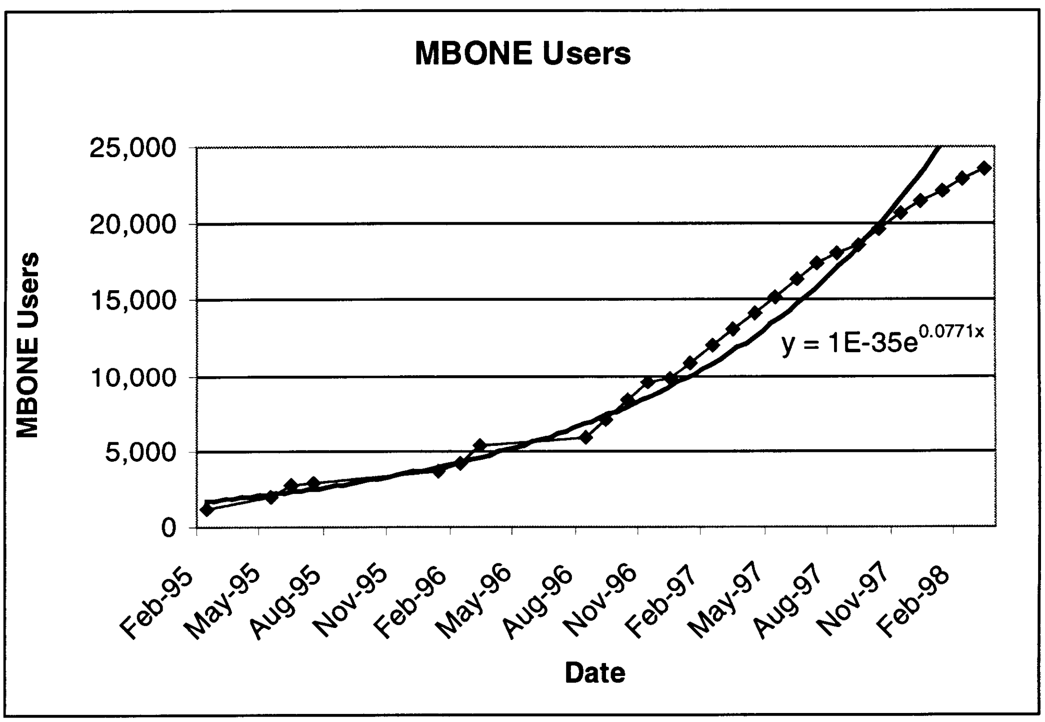

Figure 2.8: MBone Growth, Source: Kevin Almeroth, UCSB

data may not reflect the actual size the MBone user community. As described previously more than one user may use a computer with an assigned IP address. Problems in the collection method may also distort the results. Unreliable transmissions that cause packet loss may result in group members appearing to leave a session, but not actually doing so. In addition, abnormal MBone behavior may occur as a result of software bugs and performance experiments. Unique IP addresses were counted from the *mlisten* tool log

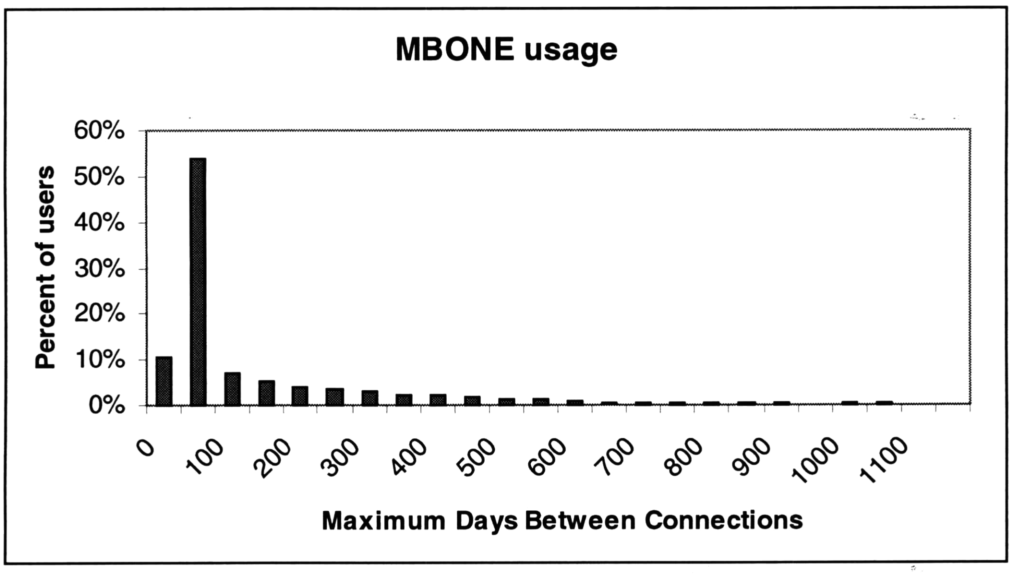

Figure 2.9: Histogram of maximum days between MBone connections

files. Figure 2.8 describes the usage of the MBone from 1995 to 1998 in terms of the cumulative number of distinct IP addresses identified. The MBone has experienced rapid exponential expansion, but this growth is beginning to slow based on the intersecting of the data with the fitted exponential curve.

The histogram in figure 2.9 describes the number of days between a user's first and last MBone connection. Each unique IP address appearing in the *mlisten* log files was considered to be an MBone user. The first bar in the figure represents the number of users having zero days between connection. Therefore, about 10% of the total number of users participated in the MBone only once. About 54% of the users used the MBone again within a 50 day or less period of time. These results suggest that most users tried the application a few times and then discontinued use. The remaining 36% of the total user population made use of the MBone within 50-day or more period of time. Of the users observed in figure 2.8, only a small percentage decided to actually adopt the technology. Most users experimented with the MBone over several days and then discontinued use.

The number of connections made by MBone receivers per month is displayed in figure 2.10. Instead of increasing in a regular manner, connections fluctuated and exhibited several peaks in usage. These peaks coincide with the presentation of events on the MBone such as IETF meetings or space shuttle or Mars exploration audio and video provided by NASA. The number of new users joining the MBone, in figure 2.11, fluctuates in a similar manner and peeks also coincide with the availability of certain

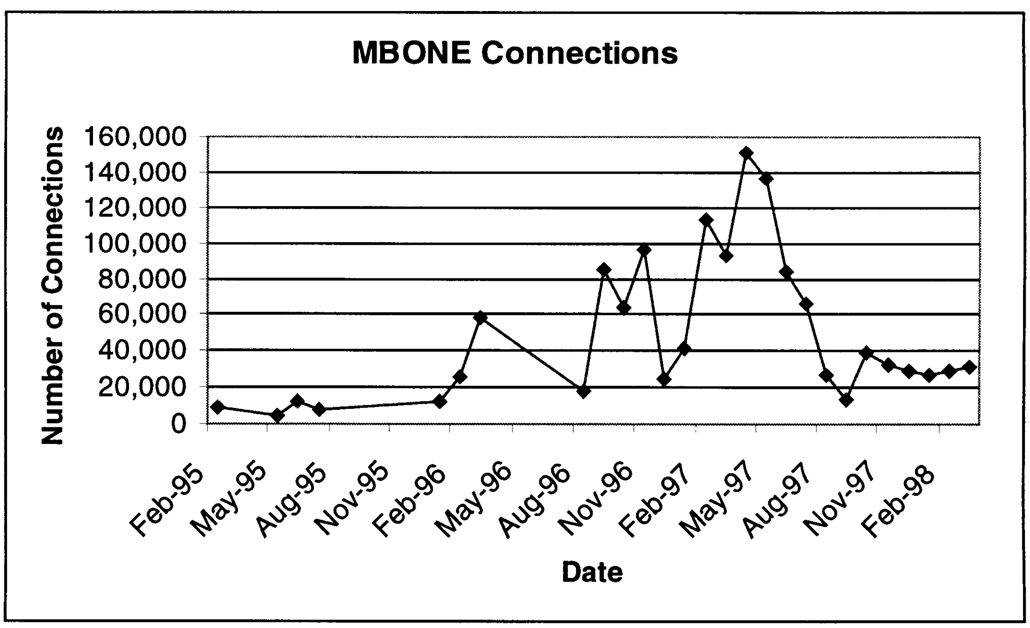

Figure 2.10: Number of MBone connections made each month

content. This suggests to date that new users join the MBone to participate in special sessions and find little reason to participate in subsequent sessions. Thus, the number of MBone adopters is very small compared to the number of users observed.

The number of MBone users is only expected to reach 36,500, see figure 2.12. The small size of the MBone user community can be attributed to the adoption patterns described above and competition from newer multicast and telephony applications. The MBone may also experience a decline in usage as users migrate to these newer applications.

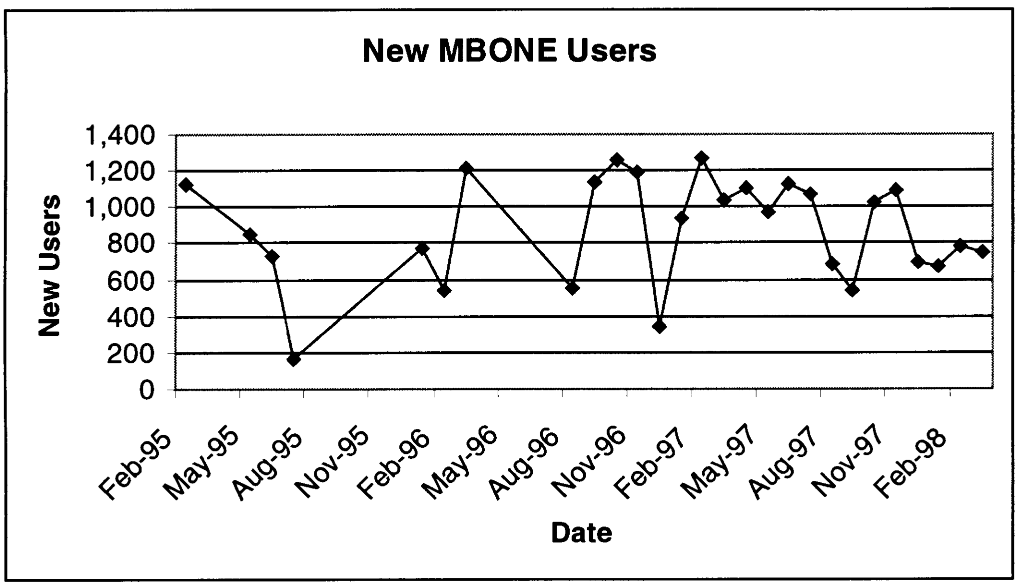

Figure 2.11: New MBone users by month

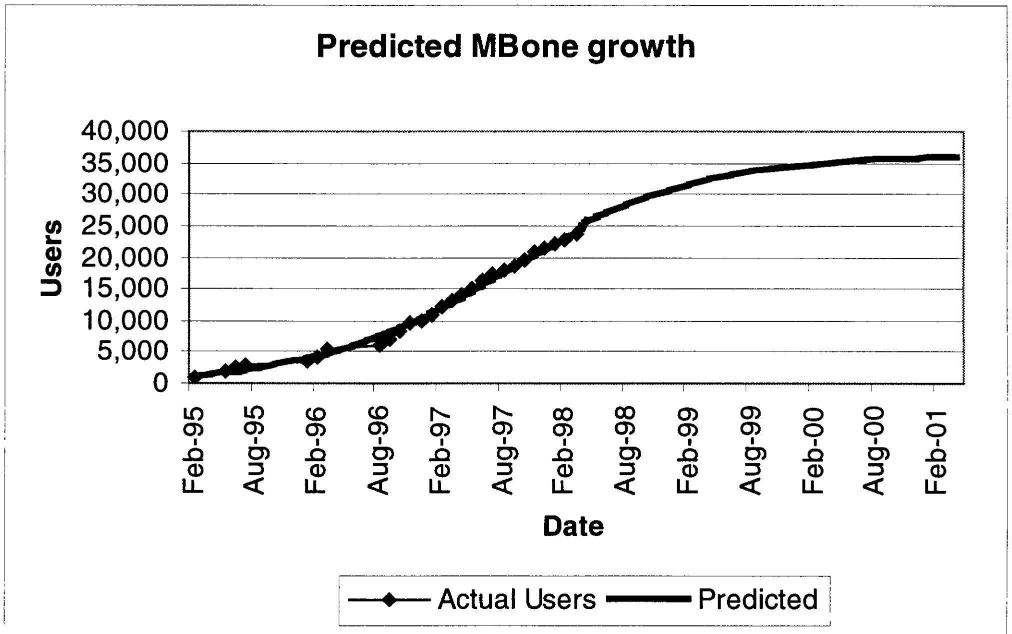

Figure 2.12: Predicted Mbone growth

2.3.5 IP telephony Applications

The number of IP telephony software users over a three-year period is displayed in figure 2.13. In this section, IP telephony software refers to class 2 and 3 applications. The

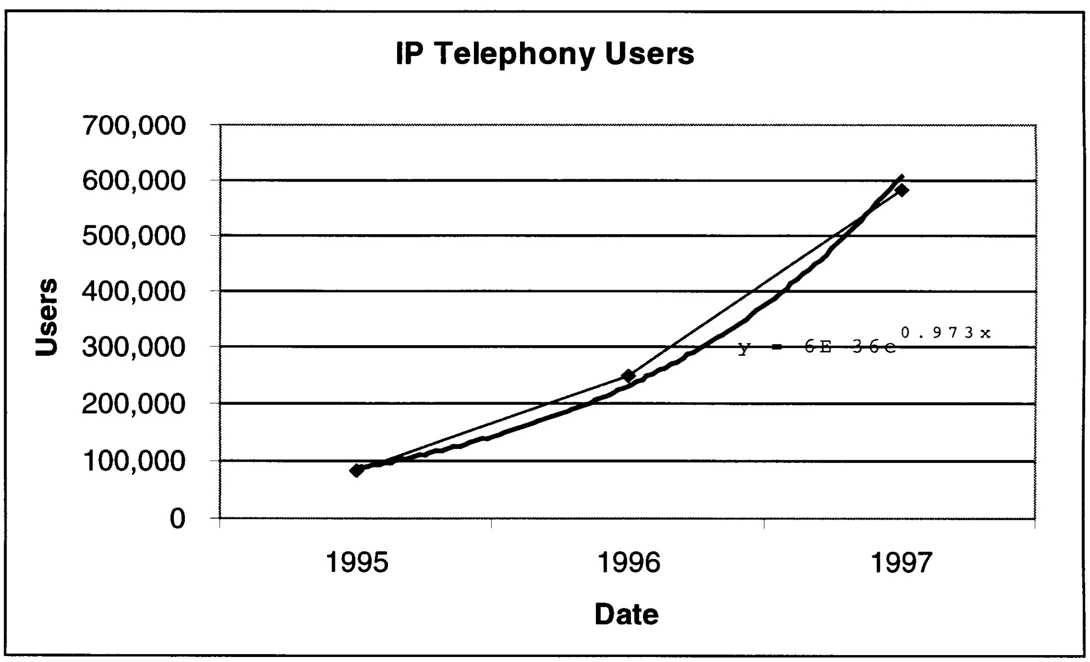

Figure 2.13: Growth of IP Telephony Users, Source: Scott Wharton, Vocaltec

data was approximated from software sales of Vocaltec's Internet Phone product that has an estimated 90% market share. IP telephony like the MBone appears to still be in an early exponential growth phase based on the close fit of the data in figure 2.13. Projections for IP telephony are likely to be very unreliable based on the limited availability of data.

A model for the growth of IP telephony was developed by analogy to other applications discussed. An upper limit was chosen as identical to the upper limit of Internet hosts. The saturation of telephony clients was approximated as not exceeding the total number of Internet hosts. A growth constant was then derived that best fit observed data points. IP telephony adoption was predicted to reach its halfway point in January 2002 and had a Δt value of 5.5 years. The growth of telephony software users displayed in figure 2.14 is not as dramatic as some other predictions. For example, International Data Corporation predicted there would be 16 million IP telephony users by 2000, whereas this

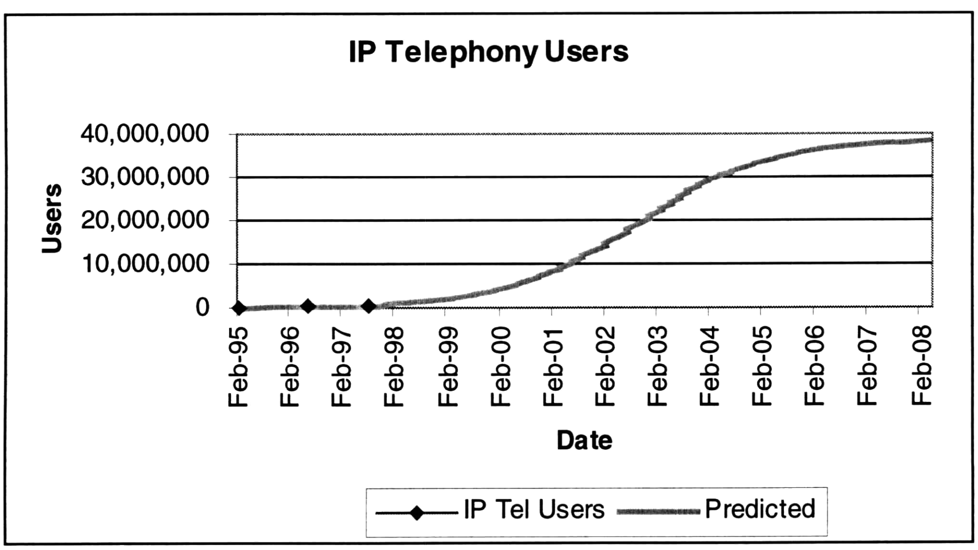

Figure 2.14: Predicted Growth of IP Telephony

model suggests telephony applications will still be in an early stage of growth at this point. The more conservative results of this model may reflect the exclusion of class 1 applications in which the Internet is used solely for transport and accounting only for active users of the software. According to Vocaltec, 3 million individuals have tried telephony software, but only .5 million are active users and make frequent calls. As is the case of the MBone, there are many users in the knowledge or trial stage of the adoption process who are not yet willing to adopt the technology.

3. Conclusions

Technology	Growth Constant	Halfway point	Δt in years
Internet Hosts	0.00162	October 1998	7.2
Web Servers	0.00501	December 1996	2.4
MBone users	0.00344	August 1997	3.5
IP telephony software users	0.00218	January 2004	5.5
USENET readership	0.00214	N/A	5.6

Table 3.1: Growth Rates of Network Applications

The growth rates for the Internet itself, based on host counts, were slower than for most applications. The expansion of the Internet was delayed by the arrival of easy-to-use software, such as Mosaic, and the commercialization of Internet backbones. For many years the Internet was restricted to academia and scientific research networks. The Web experienced the most rapid growth of the applications studied with a takeover time of 2.4 years. As discussed in chapter 2, the takeover time describes the time required for adoption to proceed from 10% to 90% of the saturation point. Information placed on Web was immediately accessible to all Internet users. The value of the Web to users was related to available content and the suitability and organization of information. The longer takeover time for IP telephony and network news can be attributed to the application's limited value during early stages of development. The similar growth rates of IP telephony and USENET may be related to the fact that the value of both applications is in proportion to the number of users participating. The MBone was determined to have a takeover value of 3.5 years. Although, MBone growth occurred quickly, the MBone was only attractive to a limited number of users. This growth rate reflects diffusion through a much smaller user community than other applications. There are several reasons that explain the MBone's failure to attract more users. Unlike the Web, limited content was available to MBone users. MBone sessions also tend to suffer from poor transmission quality. In a study performed by Handley, 80% of sites observed reported intervals with packet loss rates greater than 20%, which is regarded as the threshold above which audio without redundancy becomes unintelligible. [20] If problems related to poor transmission continue, the growth of IP telephony applications may slow as future users may be less tolerant to inferior performance than early adopters.

3.1 Technological Substitutions

Substitution	Half-way point	Δt in years
Synthetic/Natural Rubber	1956	58
Synthetic/Natural Fibers	1969	58
Water-Based/Oil Based Paint	1967	43
Plastic/Hardwood Floors	1966	25
Plastics/Metal in Cars	1981	16
Organic/Inorganic Insecticides	1946	19
Synthetic/Natural Tire Fibers	1948	17.5
Detergent/Natural Soap (US)	1951	8.75

Table 3.2: Technological Substitution rates
Source: Fisher and Pry [14]

The adoption of technology can be understood as the substitution of old technologies for newer more efficient ones. Although the diffusion of network innovations has not been explicitly analyzed as such in this thesis, underlying substitutions are present with network applications. Electronic mail acts as a substitute for postal mail, content available through the Web serves as a substitute for paper-based magazines and journals, and IP packet routed telephony substitutes for conventional switched telephone services. The overall trend of media convergence is driven by the underlying substitution of general-purpose programmable systems for special-purpose devices. [16] Substitution itself is catalyzed by the need to improve efficiency due to the depletion of resources and competitive pressures. [26] General-purpose computing equipment and network architectures more efficiently perform the tasks of separate dedicated infrastructures and specialized devices. Digitization permits more efficient delivery of information, increasing its availability in time and place. [5]

Based on the takeover times listed in table 3.1 and table 3.2, the Internet and network applications, on average, experienced much greater adoption rates than traditional technological substitutions. Advances in computing performance, rapid diffusion of information, standardization, and positive feedback, can explain the unusual rates of adoption for network applications. Positive feedback occurs as advances in networks and computing produce conditions that fuel further expansion. [56] The use of computers in the design and fabrication of semiconductor circuits sustains the current exponential evolution of computing performance. Such advances in computing have allowed higher-capacity networks to become available supporting the demand for bandwidth intensive applications. User participation also factors into positive feedback as users increase the value of the network and attract additional users. Users of the Internet have produced most of its content and developed many of its applications.

3.2 Standardization and the effect of gateway devices

The adoption of network innovations will likely halt if standards are not devised to permit incremental evolution, backwards compatibility and modular replacement. [39] Most of the applications observed in this thesis have incorporated standards with these characteristics. Telephony applications require standardized interfaces and protocols in order to facilitate the creation of large user communities. The International Telecommunication Union's (ITU) H.323 specification is emerging as the standard protocol for call control and audio/video CODECs for IP based telephony applications. [15] IP networks and the PSTN are incompatible, but gateways permit the interconnection of these systems. Web browsers provided backward support for old data retrieval applications such as gopher and ftp and the USENET operated over a variety of networks.

The hourglass shape of the Open Data Network architecture in figure 1.2 illustrates that at the "waist" a common bearer service, such as the Internet Protocol, isolates the applications and services from the details of the network transport mechanisms. At the ends of the hourglass, a diversity of applications, services and bitways are permitted. Although bearer services standards are intended to produce network interoperability, the shifting functionality of the network toward the end-node makes applications standards important as well. While standards promote the adoption of technology, incentives also exist to develop proprietary systems. Nonstandard applications can introduce new features without encumbering the costs of backward compatibility and innovators may receive greater rewards by locking out competitors. Many multicast applications, at this point of time, implement incompatible and sometimes proprietary video and audio encoding formats. Usage of the MBone may decline as it faces competition from these proprietary commercial multicast applications or may increase if common standards can be defined and further developed.

Incompatible variants tend be eliminated because of the economies of scale that result from a single or limited number of standardized systems. In the case of the VHS and BETA video recording formats, although the systems were technically similar, they were intentionally designed to be incompatible through different cassette sizes and video coding schemes. VHS eventually eliminated the arguably superior BETA due to the greater availability of pre-recorded material in VHS format and mass production and marketing of VHS equipment. Competing standards could not co-exist in a system with significant network externalities in the absence of a cost effective conversion device. [55] One can not assume that the emerging standard is superior. Due to feedback mechanisms, the decisions of early adopters are most critical in the determinations of de facto standards. The decisions of these early adopters are not always based on the technical superiority of a particular standard.

The interconnection of incompatible systems has the affect of nullifying competition between contending variants. For example, the interconnection of alternating and direct current electric power distribution networks through the rotary converter neutralized the rivalry between these competing systems.[10] Interconnection of the IP network and PSTN through gateways allows elements of both systems to co-exist. Gateways achieve compatibility and integrate different modes even if undesired or unintended by the designers of the original network. The early Bell telephone system could technically be interconnected with independent companies but interconnection was usually refused in order to control the telephone business and induce operating companies into becoming Bell licensees. [36] In modern telecommunications systems, the presence of voice transmissions over IP networks and interconnections of the PSTN with IP network are difficult to detect. The PSTN system does not derive any advantage over IP based systems from having a larger user base because traffic originating from IP networks can not easily be eliminated or treated differently. From the user's perspective, an Internet based telephone connection could appear identical to a PSTN based telephone connection.

Gateway devices do impose costs as a result of achieving compatibility. These costs arise in the form of speed, accuracy, capacity and availability. Additionally, the limited deployment of gateways provides IP telephony applications access to a small number of PSTN exchanges. Gateways will become bottlenecks, as they are more widely deployed and their usage increases. When gateway inefficiencies become more apparent, incentives to transparently interconnect IP networks and the PSTN will arise. Telephony applications will evolve such that the distinctions between application classes will be eliminated. The earliest adopters of IP telephony applications, Internet users and hobbyists, were restricted to communicating with other Internet users (class 3 applications). Later adopters, including corporations and Intranet users, could communicate with PSTN telephone users (class 2 applications). Subsequent adopters of class 1 applications used the Internet as a transport mechanism only and make calls through PSTN equipment by service arrangements with certain long distance carriers. New generations of telephony systems will transparently incorporate elements of all applications. Thus, computers will seamlessly provide voice and data services and telephone calls will be routed over the most efficient network.

3.3 The Dynamic Nature of Network Applications

The forecasting and modeling of innovation diffusion in the thesis have relied on a narrow definition of each application. A model that is too broadly defined is likely to incorporate elements of unintended technologies. For this reason, the IP telephony model only included software products and Internet hosts were modeled instead of all Internet users, as it is not precisely understood what qualifies as an Internet user. However, the Internet's emphasis on end-node processing and user participation is resulting in dynamic applications. The design and implementation of applications are rapidly evolving according to user requirements and the constraints of technology. Telephony applications will quickly change as network capabilities are upgraded and user needs are realized.

In the absence of frameworks to understand innovation, this evolution is often envisioned in terms of existing processes. Concepts based on and defined in terms of old technologies tend to hinder the development of new technologies. [46] Most telephony systems are still based on the assumption of technology as a scarce and expensive resource. The Internet has the potential of transforming communications services as antiquated notions of technology are discarded. IP telephony application not only can reproduce existing telephony features, but also incorporate multicast and information retrieval features to form new types of applications. The differences in the capabilities of Internet enhanced telephony and conventional telephony imply the path of innovation diffusion may not strictly adhere to the linear model of simple technological substitution. New applications will emerge that are not incremental improvements over current communication systems.

Network services have become increasingly difficult to classify as they are changing and diversifying. The nature of modern networks renders the distinctions between types of content, transport, and applications irrelevant. The Internets transports and processes bits without regard to distance or intended use. The breakdown of the barriers between services is beginning to reveal the irrelevance of regulatory and policy models that distinguish different modes of communications. Along with the convergence of technologies, it is necessary for regulatory frameworks to also converge. [32] Isolated regulations will hinder innovation in affected regions. Specific regulations will be ineffective. An attempt to regulate or impose fees on Internet telephony service providers will simply cause more users to migrate to PC based telephony applications. [9]

This thesis has demonstrated that open flexible networks such as the Internet have the ability to achieve rapid growth and innovation. The pace of innovation diffusion will present challenges as technological change becomes more difficult to manage. Future research should attempt to further understand what technical, policy, and social factors are required to continue to sustain the current growth of network application innovation.

4. Appendix A: Adoption Model

The model for innovation diffusion applied in this thesis was first proposed by Verhult in 1838 as a model for human population growth and then by Pearl in 1925 for the description of biological growth processes. Grilinches later used a similar model to study the diffusion of agricultural innovation by United States farmers. Mansfield applied the model in analyzing firm-level adoption patterns of technological innovations.

Data was fit to the s-shaped curve by performing a linear regression of the form in equation (6). The variable N(t) was transformed by the relation $N_1(t) = \ln\left(\frac{N(t)}{M - N(t)}\right)$. The variable for time t, was represented internally by Microsoft Excel as the number of days since January 1, 1900. The constant `a` was calculated using the Excel function `slope` and the constant `b` was calculated using the function `intercept`. If the M variable was not already known, it was determined by performing a goal seek function to set the correlation coefficient as close to 1 as possible. The correlation coefficient was calculated using the function `linest`.

The takeover time, Δt, was derived by subtracting the time in which the percentage of total diffusion, $\frac{N}{M}$, reaches 10% from the time which diffusion reaches 90%. The result could be expressed by the equation $\Delta t = 2 \cdot \ln(9)/a$ or in terms of years $\Delta t = \frac{2 \cdot \ln(9)}{a \cdot 365}$. This was simplified to produce equation (5).

5. Appendix B: Data tables

Date	Internet Hosts
Jan-69	4
Apr-71	23
Jun-74	62
Mar-77	111
Aug-81	213
May-82	235
Aug-83	562
Oct-84	1,024
Oct-85	1,961
Feb-86	2,308
Nov-86	5,089
Dec-87	28,174
Jul-88	33,000
Oct-88	56,000
Jan-89	80,000
Jul-89	130,000
Oct-89	159,000
Oct-90	313,000
Jan-91	376,000
Jul-91	535,000
Oct-91	617,000
Jan-92	727,000
Apr-92	890,000
Jul-92	992,000
Oct-92	1,136,000
Jan-93	1,313,000
Apr-93	1,486,000
Jul-93	1,776,000
Oct-93	2,056,000
Jan-94	2,217,000
Jul-94	3,212,000
Oct-94	3,864,000
Jan-95	4,852,000
Jul-95	6,642,000
Jan-96	9,472,000
Jul-96	12,881,000
Jan-97	16,146,000
Jul-97	19,540,000
Jan-98	29,670,000

Date	Internet Hosts	Adjusted Hostcount	Responding Hosts
Jan-93	1,313,000		
Jul-93	1,776,000		464,000
Jan-94	2,217,000		576,000
Jul-94	3,212,000		707,000
Jan-95	4,852,000	5,846,000	970,000
Jul-95	6,642,000	8,200,000	1,149,000
Jan-96	9,472,000	14,352,000	1,682,000
Jul-96	12,881,000	16,729,000	2,569,000
Jan-97	16,146,000	21,819,000	3,392,000
Jul-97	19,540,000	26,053,000	4,314,410
Jan-98	29,670,000		5,331,640

Date	Web Sites
Jan-92	26
Jan-93	50
Jun-93	130
Dec-93	623
Jun-94	2,738
Dec-94	10,022
Jun-95	23,500
Jan-96	100,000
Jun-96	252,000
Jul-96	299,403
Aug-96	342,081
Sep-96	397,281
Oct-96	462,047
Nov-96	525,906
Dec-96	603,367
Jan-97	646,162
Feb-97	739,688
Mar-97	883,149
Apr-97	1,002,612
May-97	1,044,163
Jun-97	1,117,255
Jul-97	1,203,096
Aug-97	1,269,800

Date	Mbone Membership
Feb-95	1,120
May-95	1,974
Jun-95	2,702
Jul-95	2,868
Jan-96	3,643
Feb-96	4,180
Mar-96	5,390
Aug-96	5,942
Sep-96	7,073
Oct-96	8,334
Nov-96	9,522
Dec-96	9,860
Jan-97	10,799
Feb-97	12,064
Mar-97	13,099
Apr-97	14,200
May-97	15,175
Jun-97	16,300
Jul-97	17,365
Aug-97	18,052
Sep-97	18,592
Oct-97	19,615
Nov-97	20,711
Dec-97	21,407
Jan-98	22,084
Feb-98	22,867
Mar-98	23,614

Date	Vocaltec Internet Phone Users
Feb-95	75,000
Jun-96	225,000
Aug-97	525,000

Date	USENET Readers
Jan-79	10
Jan-80	20
Jan-83	10,000
Apr-86	53,000
May-86	59,000
Jun-86	75,000
Jul-86	95,000
Aug-86	78,000
Sep-86	82,000
Oct-86	88,000
Nov-86	88,000
Dec-86	84,000
Jan-87	79,000
Feb-87	90,000
Mar-87	90,000
Apr-87	86,000
May-87	105,000
Jun-87	120,000
Jul-87	118,000
Aug-87	125,000
Sep-87	134,000
Oct-87	131,000
Nov-87	140,000
Dec-87	129,000
Jan-88	137,000
Feb-88	143,000
Mar-88	142,000
Apr-88	141,000
Jun-92	2,592,000
Jan-95	16,500,000
Mar-95	18,120,000
Jun-95	23,774,000
Jul-95	11,033,000

6. Bibliography

[1] Almeroth, Kevin, and Ammar, Mostafa, "Multicast Group Behavior in the Internet's Multicast Backbone (MBone)", *IEEE Communications*, June 1997.

[2] Antonelli, Cristiano, "The diffusion of information technology and the demand for telecommunications services", *Telecommunications Policy*, 13 (5), 255-264.

[3] Apostolidis, Kiriakos, Merakos, Lazaros, and, Xie-Hao, "A reservation protocol for packet voice and data integration in unidirectional bus networks", *IEEE Transactions on Communications*, 41 (March 1993), 478-485.

[4] Armbrüster, Heinrich, "Information Infrastructures and Multimedia Communications: Different Approaches of the Telephony, Data, and Radio/TV Worlds", *IEEE Communications Magazine*, September 1998, 92-101.

[5] Bane, William, Bradley, Stephen, and Collis, Davis, "The Converging Worlds of Telecommunications, Computing, and Entertainment", (Harvard University working paper 1997).

[6] Branden, R, et. al., "RFC 2205: Resource ReSerVation Protocol (RSVP): Version 1 Functional Specification" Internet Engineering Task Force, September 1997.

[7] Cairncross, Frances, *The Death of Distance*, (Boston: Harvard Business School Press, 1997)

[8] Clark, David, "A Taxonomy of Internet Telephony Applications, (paper presented to MIT Internet Telephony Consortium 1997).

[9] Crawley, Richard, "Internet, lies, and telephony", *Telecommunications Policy* 21, no. 6 (1997), 513-532.

[10] David, Paul and Bunn, Julie, "The Economics of Gateway Technologies and Network Evolution", *Information Economics and Policy*, 3, (1988), 165-202.

[11] de Sola Pool, Ithiel, *Forecasting the Phone*, (New Jersey: Ablexx Publishing, 1983).

[12] de Sola Pool, Ithiel, *Technologies of Freedom*, (Cambridge: Harvard University Press, 1983).

[13] Farell, Joseph, and Saloner, Garth, "Standardization, compatibility, and innovation", *Rand Journal*, 1, (1985), Vol 16, 70-83.

[14] Fisher, JC, and Pry, RH, "A Simple Substitution Model of Technological Change", *Technological Forecasting and Social Change* 3, 1971, 75-88.

[15] Fromm, Larry, "Interoperability is the foundation for successful Internet telephony", *Telecommunications*, 10, (Oct 1997), Vol 31, 99-101

[16] Gaines, Brian, "The Learning Curves Underlying Convergence", *Technological Forecasting and Social Change*, 57, 1998, 7-34.

[17] Greenfield, David, "IP Telephony Gateways", Data Communications, June 1997, 97-106.

[18] Griliches, Zvi, "Hybrid Corn: An Exploration in the Economics of Technological Change", *Econometrica*, 4, Vol 25, 1957, 501-522.

[19] Grübler, Arnulf, *The Rise and Fall of Infrastructures*, (New York: Springer-Verlag, 1990).

[20] Handley, Mark, "An Examination of MBone Performance", UCL and ISI Research Report, January 10, 1997, http://northeast.isi.edu/~mjh/papers.html

[21] Hilgemeier, Mario, "Internet Growth", http://www.is-bremen.de/~mhi/inetgrow.htm

[22] Kavassalis, Petros, Lee, Thomas, and Bailey, Joseph, "Sustaining a Vertically Disintegrated Network through a Bearer Service Market", (paper presented at the biannual meeting of the Internet Telephony Consortium, Cambridge, Massachusetts, November 6, 1997).

[23] Kelly, Tim, Sharifi, Shawn, and Pentrazzini, Ben, *Challenges to the Network,* (ITU: 1997).

[24] Lazarus, William and McKnight, Lee, *The Design and Forecasting of the New Media,* (Cambridge: MIT Research Program on Communications Policy, February 1984).

[25] Lee, Hokyu, "Retrospective Technology Assessment", *Telecommunications Policy,* 21, no 9/10 (1997), 854-859.

[26] Linstone, Harold, and Sahal, Devendra, *Technological Substitution,* (New York: Elsevier, 1976).

[27] Lotter, Mark, "Network Working Group Request for Comments 1296: Internet Growth", SRI International, January 1992, http://www.nw.com/zone/rfc1296.txt

[28] Majumdar, Sumit K., Venkataraman, S., "New Technology Adoption in US Telecommunications", *Research Policy* 22: 521-536.

[29] Mansfield, Edwin, "Technical Change and the Rate of Imitation", *Econometrica,* 4, (1961), Vol 29, 741-763.

[30] McKnight, Lee and Leida, Brett, "Internet Telephony: Costs Pricing and Policy", (paper present at the Telecommunications Policy Research Conference, Alexandria Virginia, September 27-29, 1997), MIT.

[31] McKnight, Lee, and Bailey, Joseph, eds., *Internet Economics,* (Cambridge: MIT Press, 1997).

[32] McKnight, Lee. "Internet Telephony and Open Communications Policy", paper presented to The Impact of the Internet on Communications Policy, Harvard University, December 1997.

[33] Mehta, Stephanie, "Bells Seek Advanced Networks as Entry into Long Distance", *Wall Street Journal,* February 19, 1998.

[34] Messerschmitt, David, "The future of computer telecommunications integration", *IEEE Communications Magazine* 34 (April 1996) 66-69.

[35] Modis, Theodore, *Predictions,* (New York: Simon & Schuster, 1992).

[36] Mueller, Milton, *Universal Service,* (Cambridge: MIT Press, 1996).

[37] Mutooni, Philip, *Telecommunications @ Crossroads: The Transition from a Voice-Centric to a Data Centric Communications Network,* (MIT Masters Thesis May 1997).

[38] Nakicenovic, Nebojsa, and Grübler, Arnulf, eds., *Diffusion of Technologies and Social Behavior,* (New York: Springer-Verlag, 1991).

[39] National Academy of Sciences, *Realizing the Information Future: The Internet and Beyond,* (Washington DC: National Academy Press, 1994).

[40] Neuman, W. Russell, McKnight, Lee, Soloman, Richard Jay, *The Gordian Knot: Political Gridlock on the Information Highway,* (Cambridge: MIT Press, 1997).

[41] Nixon, Toby, "Design Considerations for Computer-Telephony Application Programming Interfaces and Related Components", *IEEE Communications Magazine,* April 1996, 43-47.

[42] Noam, Eli, "The public telecommunications network: A concept in transition", *Journal of Communications,* 37, no 1, 30-48.

[43] Ohrtman, Frank, "Internet Telephony", *Boardwatch,* Feb 1998.

[44] PhoneZone.com, "Comparative Analysis of Internet Telephony Gateways", http://www.phonezone.com/tutorial/ip.htm

[45] Quarterman, John, *The Matrix: Computer Networks and Conferencing Systems Worldwide*, (Digital Equipment Corporation, 1990).

[46] Rockström, Anders, and Zdebel, Bengt, "A Network Strategy for Survival", *IEEE Communications Magazine*, January 1998.

[47] Rogers, Everett, *Diffusion of Innovations*, (New York: Free Press, 1995).

[48] Scalera, Nicholas, "Quantifying the Effect of Internet Telephony from both Telecommunications and Internet Service Provider Perspectives", (paper presented at the Telecommunications Policy Research Conference, Alexandria Virginia, September 27-29, 1997), Bell Communications Research.

[49] Schoen, Ulrich, et al., "Convergence Between Public Switching and the Internet", *IEEE Communications Magazine*, January 1998, 50-65.

[50] Sears, Andrew, *Directory Services for Internet Telephony*, (MIT Masters Thesis September 1997).

[51] Sherif, Mostafa, "Convergence: A New Perspective for Standards", *IEEE Communications Magazine*, January 1998, 110-111.

[52] Staple, Gregory, "The New Demand for Telecoms Traffic Data", *Telecommunications Policy* 20, no. 8 (1997), 623-631.

[53] Telecommunications Survey, "A Connected World", *The Economist*, September 13 1997.

[54] Turing, Alan, "On computable numbers : with an application to the Entscheidungsproblem", *Proceedings of the London Mathematical Society*, 2, Vol. 42, pt. 3-4 (November-December 1936)

[55] Tushman, Michael, and Anderson, Philip, *Managing Strategic Innovation and Change*, (New York: Oxford University Press, 1997).

[56] Werbach, Kevin, "Digital Tornado: The Internet and Telecommunications Policy", (Washington DC: FCC Working paper, March 1997), NTIS PB97 161905.

[57] Zakon, Robert. "Hobbe's Internet Timeline", The MITRE Corporation, version 3.1, http://info.isoc.org/guest/zakon/Internet/History/HIT.html