# AN EVALUATION OF THE ECONOMIC AND SOCIAL CONSEQUENCES OF EXTREMELY HIGH FREQUENCY DIGITAL CELLULAR TELEPHONY

by

Frederick T. Moore

A dissertation submitted in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

(Business)

at the

UNIVERSITY OF WISCONSIN - MADISON

1999

Information contained in this work may be subject to the Part 379 provisions

(Export control of technical data) of Federal Law 96-72 (1979).

**AN EVALUATION OF THE ECONOMIC AND SOCIAL CONSEQUENCES OF EXTREMELY HIGH FREQUENCY DIGITAL CELLULAR TELEPHONY**

Frederick T. Moore

Under the supervision of Professor Rodney Stevenson

At the University of Wisconsin - Madison

This thesis explores the potential of digital pseudonoise modulation and uncoordinated assignment of cellular provider networks to address rural telecommunications issues. Those issues include affordability, quality of service, and universal service. In particular, an analysis is conducted of the economic, strategic, and social implications of Extremely High Frequency (EHF) Digital Cellular Telephony (EDCT) as a proposed new class of fixed wireless service.

A new approach to allocating radio frequency spectrum among EDCT service providers is developed,

based on a spectral congestion toll, rather than on spectrum auctions, as has occurred in cellular PCS telecommunications. The revenue stream such a toll might produce is estimated.

The potential for EDCT is examined in a number of ways. A technological analysis is conducted on the extent of the
expanding radio frequency spectral resource, which together with the potential for low cost EHF communication links, promise the availability of spectrum needed for EDCT. The analysis shows that EDCT can provide an increase in capacity and reduction of monthly cost of service for local wireless telecommunications. The strategic management technique of stakeholder analysis is used to understand EDCT industry formation and industry - government relations.

The cost of service of EDCT is estimated for three rural Wisconsin counties, and compared to the Hatfield Model estimate of the cost of wireline service. The results show that EDCT is a cost

competitive technology, with costs in rural areas comparable to wireline costs in high density, metropolitan areas.  Thus, EDCT appears to offer the delivery of high quality and low cost telecommunications service to rural areas.  The multivariate technique of principal components analysis is applied to survey data concerning Wisconsin local service infrastructure deployment, to aid incumbent providers in understanding how best to make a transition to a future competitive environment for rural local service.

Advisor___________________________

# TABLE OF CONTENTS

# PREFACE

> “Because current spectrum management policies have promoted commercial allocations and auctions to the exclusion of nearly all other services and licensing schemes, a spectrum crisis has developed. In the commercial services, there is a tremendous surplus of spectrum, while the private services ... continue to struggle to sustain both credibility and unfettered access to their existing allocations...”
>
> - Reply comments of the Industrial Telecommunications Association to the 1998 FCC petition of the Land Mobile Communications Council concerning reallocation of spectrum to the Private Mobile Radio Service, as cited in QST 82:9, 15.

> “It is well known that the office of the chief priest was sold by the Romans to the highest bidder, who was thus required to come from a wealthy priestly family; and that rural priests were impoverished by the inequities created by the greed of the priestly aristocracy...”
>
> - Walter Wink, Engaging the Powers, Minneapolis: Fortress Press (1993).

The task at hand is both scholarly and spiritual in nature. It is to create an alternative institutional choice to both the “land rush” and auction theoretic approaches to electromagnetic spectrum allocation, to create a new kind of digital wireless telephony that serves the interest of people, especially in rural areas, and so restore an institution which has fallen into serving the self-interest of a few.

## ACKNOWLEDGEMENTS.

I wish to thank the members of my committee.

A special thanks to Jim Neighbors and Dr. Robert Boomer for proofreading and encouragement.

My family has been incredibly kind and supportive during my studies.

Clarence Mougin and Phil Jenkins, formerly of the Wisconsin Public Service Commission, Harry Hegna and members of the Wisconsin State Telephone Association, and the Public Utility Institute of the University of Wisconsin School of Business helped with acquiring the data used in the multivariate analysis.

> "Let your light so shine before others that they may see your good works and glorify your Father in heaven."
>
> - From my Baptism.

For the benefit of all.

# CHAPTER 1. INTRODUCTION.

> **"You've said the established telephone carriers will be out of business in five years. Why?**
>
> "It may sound absurd, but it's really based on my honest assessment of their potential market. Competition is a fact, and it's coming faster than they are prepared to deal with. They must take their business model and -- in real time -- change it to a new business model."
>
> - An interview with William Schrader,
>
> CEO of PSINet, Inc. (Brown, 1999).

> "They chose to live out there [in the countryside], so to hell with them!"
>
> - A former mayor of Washington, D.C.,
>
> as cited by an FCC official.

Where will change leave rural telephone customers, whose high cost traditional service is at present cross-subsidized to the extent of tens of billions of dollars per year? Deregulated markets cannot coexist with intensively regulated markets -- contestable market theory rules out cross-subsidies[1] (Baumol,

---

[1] The term cross-subsidy is often used a bit loosely in connection with markets for telephone service, perhaps because of the power of language to reframe issues. The precise meaning of the term in managerial economics is for a diversified firm to prop up a product offering in which revenue is less than the direct cost (marginal cost, including any customer-specific capital costs), by allocating the firm's common costs in support of that activity. Also, note that

1982). Also, the will to regulate is ebbing.

Is it possible to design a new class of telecommunications service that achieves the social benefits of the delivery of a merit good[2] provided at marginal cost pricing, but without the need of intensive regulation? Is it possible to design a market for radio frequency spectrum utilization and couple the market design with technology choices, such that wireless universal telephone service can be provided in traditional high cost areas without incurring the distributional shortcomings of the very limited competition that occurs in rural markets with other existing choices?

For several decades telephone service has been provided by intensively regulated monopolies. Changes in technology and growth in total market size have together overcome the structural advantage of monopoly provision of infrastructure goods on which the traditional approach was based. At present institutional choices for alternative markets involve various forms of imperfect competition -- that is, competitive forms where a small number of competitors (generally two to five) engage in inter-firm rivalry in an attempt to improve price and output quantities from the monopolistic result. But

---

perfect contestability assumes costless entry and exit.

[2] A merit good is a private good we agree everyone ought to have available to them.

unfortunately from the perspective of consumer welfare, the outcomes of choices based on imperfect competition are inferior to what could be attained in theory under intensive regulation. Additional choices are needed that can make the best use of the technology of digital modulation from the perspectives of promoting competition, minimizing costs, and delivering benefits to the public.

I investigate in this study whether the theoretical limitations and practical shortcomings of imperfect competition underlying the existing institutional choices of cellular and PCS radiotelephony can be overcome. Radio frequency spectral auctions have certain distributional shortcomings and are economically efficient only in a narrow sense. Severe restrictions on the number of players in cellular and PCS service territories create competitive conditions in which economic rents are inevitable. Moreover the spectrum regulatory model of one licensee per frequency slot is no longer necessary or socially optimal with the availability of at least some types of digital modulation, rendering the extant approach to licensure increasingly inappropriate.

The central idea behind a new approach to spectrum pricing is that with digital modulation the spectrum can now be thought of as having not only breadth (already embedded in the extant approaches to spectral resource allocation) but depth, which allows multiple transmitters (and even multiple organizations) to efficiently share the same frequency bands (Bromley, 1998).

At the same time that a new way of thinking about wireless spectral resource allocation becomes feasible, the emergence of the competitive provision of local telephone service in the most populous areas has rendered practically unsustainable the traditional cross-subsidization of local basic universal service in high cost (mostly rural) areas. While the Telecommunications Act of 1996 (1996 Act) protects small telephone local exchange carriers from certain deleterious effects of competitive entry, the shrinkage of traditional cross-subsidization of those firms is now resulting in substantial increases in local service charges in rural areas.

The challenge is to determine whether a new institutional choice that carries forward the societal virtues of the marginal cost pricing of an essential public good as has occurred under rate of return regulation of local telephone service can be developed.  The alternative institutional choice proposed will be assessed for distributional consequences and pricing efficiency.  The approach I suggest may have lower costs and be distributionally superior to that of auction theory, while efficiently pricing the spectral resource.

A key tenant in my thinking about the design of an institutional choice is that while microeconomists and lawyers have as a rule become accustomed to regarding technology as a sealed black box when understanding industry behavior, good institutional choice design must raise technology to assume the role of a choice variable, placing technology alongside the existing orthogonal considerations of economic efficiency and distributive fairness (Moore, 1995). Technology choices can no more be allowed to remain exogenous to institutional choice design than can consumer welfare, if the proposed choice is to be socially beneficial.

**Methodology of institutional choice design.**

An institutional choice is an interwoven blend of enabling technology, a market mechanism design for delivering the new good, enabling legislation, and a regulatory / policy approach that seeks to overcome the subtle limitations of markets.[3] A good share of the undertaking is beyond the scope of an individual effort, and more properly flows out of a process of governance.

[3] See especially Griffiths, 1984, Ch. 18 for a critique by a free market advocate of free markets.

(One might envision the following algorithm:

Technology pathway º Cost beneficiality º Pricing model º Institutional and regulatory choices.)

Designing an institutional choice to provide an essential infrastructure good like telephony necessarily involves striking a balance that attempts to simultaneously provide for the market need of efficient pricing and the moral commitment to universal service.

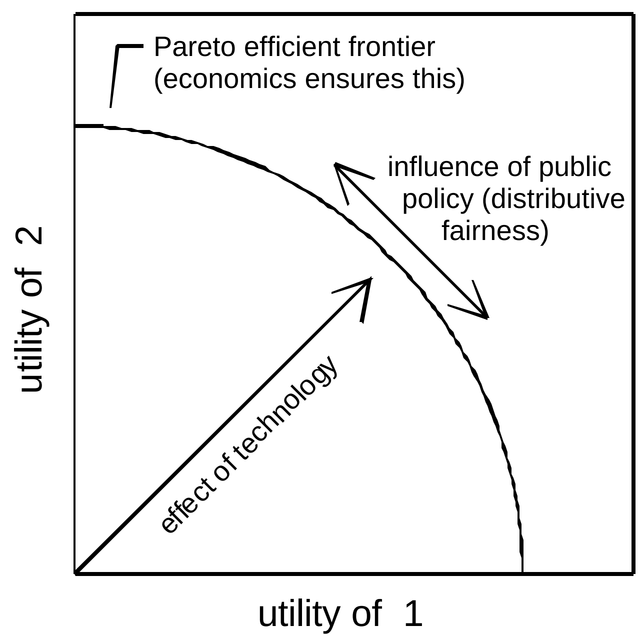



Figure 1.1. Efficiency, fairness and technology. We must master all three simultaneously. (Derived in part from Kreps, 1990, 154.)

For the present I wish to focus on the new technology of digital modulation and what is now possible by way of private markets that fully utilize the character of digital wireless communications. Then the cost characteristics of a possible new class of digital wireless telephony can be compared with the existing institutional choices for providing local telephone service.

**The basic research question.**

Is it possible to design a market for radio frequency spectrum utilization and couple the market design with technology choices, such that wireless universal telephone service can be provided in traditional high cost areas without incurring the distributional shortcomings of the very limited competition that occurs in rural markets with other existing choices?

(Or simply restated)

Can emerging technology be combined with an institutional design to fully deliver the promise of an affordable telecommunications service for rural customers?

Two sub issues exist:

1. Can a congestion pricing model for radio frequency spectrum be developed? What core technologies would be needed to achieve a product realization?
2. Can a new class of wireless local phone service be developed, targeted for the needs of rural markets? How would the cost of this new institutional choice compare to a wireline cost of service proxy model, like the Hatfield Model?

**Significance of this work.**

I propose a new class of service provider with a novel system architecture, choice of modulation scheme and attendant pricing model that promotes the price / output vector of perfect competition, especially in thinly populated markets for local telephone service.

For rural wireless markets, I propose an end to the traditional approach to radio frequency spectrum regulation involving one license holder per frequency assignment. The approach fit the technology of analog modulation, but is no longer necessary for services employing digital modulation.

I suggest approaches to enforcing efficiency in radio spectrum utilization and to industry structure in the proposed EDCT service that together are intended to mostly eliminate the need for ongoing governmental regulation.

**Organization of the thesis.**

Telecommunications begins with the underlying technology. In the next chapter I introduce some of the basic ideas concerning the radio frequency spectral resource. I will then examine how the digital wireless era reframes the institutions of radio spectrum regulation and creates a new opportunity for spectral resource allocation. I next develop a radio frequency spectral pricing model based on fundamental engineering relationships for digital modulation. The form of this new model will be briefly compared and contrasted with the extant literature on congestion pricing.

Analytical tools are needed to understand the cost structure, business strategy, and performance of the existing industry. In that way the need for a new institutional choice will be most clearly understood. Existing industry participants and policy makers can be guided in developing approaches to incorporate the new technologies of the wireless era in their business models. In chapter three I explore the technology of the existing telephone infrastructure, for universal wireline telephone service and for cellular telephony. The strategy and performance of the existing industry that provides local wireline telephone service for the State of Wisconsin is examined, in terms of measures of infrastructure deployment and service features.

The technique of multivariate analysis (principal components, or PCA) is used first, to explore the key dimensions along which existing firms or entrants with new technology might compete in a future competitive market for rural local telephone service. Potential competitive strategies are identified, that firms might be best positioned to initially employ. As such, the PCA model is primarily a gift to the industry, it being only tangentially related to the immediate purposes of this work. In addition, however, one might learn about the effectiveness with which individual firms have been regulated, illuminating the wisdom of the existing order. Specifically, a few small firms have been providing unusual value to their customers -- has regulation had a role to play in the differential performance of the independent service providers? Finally, the PCA model highlights the advanced service features that form the contemporary foundation of universal telephone service.

In a second section of chapter three, the cost of providing wireline basic universal service will be estimated for the State of Wisconsin using the Hatfield Cost Model v.4 (Hatfield, 1997). The Hatfield Model was recently developed by an industry consortium, for the purpose of understanding the cost structure of the U.S. telephone infrastructure. The Hatfield Model is of particular interest in the context of the present work, because it reveals the effects of subscriber line density and incumbent service provider firm size on the cost of providing rural local service. The Hatfield Model also reveals the way cost of service is allocated between switching and outside plant (the wires), underscoring the need for a replacement for outside plant. The cost structure of the proposed new class of service, EDCT, can be directly compared to the Hatfield Model predictions for specific geographic areas.

In the final section of chapter three service characteristics and the cost of service for cellular and PCS service providers will be estimated. In a later chapter, the resulting information about the existing cellular industry forms an additional basis for distinguishing between EDCT and the array of existing service options.

Chapter four focuses on technology. We must understand how to place rural telephony firmly into the realm of the economics of silicon. It is first necessary to develop a deep intuitive understanding of the trajectory of the technology of silicon, particularly in regard to the strategic implications of semiconductor linewidth. Continued industry movement along the path of Moore’s law impacts the costs of switching and digital signal processing hardware. The extent of the total available radio spectral resource, key to the deployment of new wireless technologies, is intimately tied to the intentionality of Moore’s law. I explain the connection between linewidth and new consumer uses of the radio spectrum near the middle of chapter four.

In the second half of chapter four a proposed new institutional choice for basic universal service based on the spectral pricing model of chapter two will be developed in some detail, so that its service characteristics can be evaluated. The question of the best choices of radio spectrum for this new class of service will then be addressed, based on our understanding of the unfolding of the spectral resource.

In chapter five a strategic analysis of the proposed EDCT industry structure is conducted. A business model for EDCT is developed and the cost of service is estimated. The federal revenue stream from an EDCT spectral congestion toll is estimated. I examine a practical implication arising from the potential existence of a new institutional choice -- the crossover between optimal choice of the existing less than two Gigahertz cellular telephony and the new technology as a function of increasing population density, as one approaches an urban area. It will become clear that EDCT has a unique competitive role to play, in relation to other choices, in ensuring universal access to advanced telecommunications services, including high speed Internet access, particularly in rural areas.

**EDCT: A convergence of need, technology, and institution.**

At present, those who live in cities are still mostly constrained by analog modem Internet data rates. Over the next one to two years, Ethernet-like speeds will become much more available to urban residential customers. Subsequently, Web content will evolve to become dependent on higher bandwidth, as it has once before, to take advantage of the popularity of 56 Kbps modems. Over the next few years, ways must be found to extend wider bandwidth to rural customers, so that everyone might enjoy the social benefits, and to avoid stranding rural communities.

As the transition to competition in local markets for telecommunications continues to unfold, the previous institutional arrangement that made rural local wireline service affordable will become untenable. That time is perhaps five years hence. The desire of some to continue the old order will not stand, because at a minimum, technology change will make available to the businesses and residents of the built-up areas of rural communities competitive options, like cable telephony, PCS, and decent Internet access. Rural telecommunications markets will be bifurcated, and the outlying customers potentially isolated.

Fortunately the pieces of technology needed to craft a new kind of rural telephony are just now emerging from research laboratories. In perhaps five years, EDCT could be made into a viable service alternative. The radio frequency circuits needed for use at the frequencies I propose for EDCT are already being made in modest quantities. Micromechanical antennas exist as prototypes. The signal processing circuits needed for low cost voice grade and first generation data service are here now.  There remains much engineering to be done, but the hard parts have been accomplished.

It is time to begin crafting the institutions of EDCT -- an enabling regulatory environment and a mechanism for affordably allocating spectrum to EDCT service providers. There is an opportunity to create a good fit between the needs of rural customers, the emerging technologies of fixed wireless communications, and the needed social structures. The spectral congestion pricing I explore in the next chapter is the core around which the various aspects of EDCT converge.

**A tribute to spread spectrum's inventors.**

I am grateful for a concept that was developed decades ago, and now stands ready to provide widespread benefits. Spread spectrum was conceived by the movie star Hedy Lamarr and her composer friend George Antheil over dinner one evening.

Originally termed frequency hopping, the modulation scheme was intended to make allied torpedo guidance signals immune to enemy jamming. The idea was to have a transmitter and receiver shift frequencies in synchrony, according to a prearranged pattern. In this way the communication could only be detected by the intended receiver. They were awarded patent number 2,292,387 (1942) for their idea, which they assigned to the U.S. government. Antheil was invaluable in creating a physical realization of Lamarr's idea, one related to his concert performances of synchronized player pianos.

Last (1998) perhaps best tells the story of Hedy Lamarr. Hedy was born (under a different name) in Austria and began her career there as a movie star in the early 1930s.[4] Her first marriage was to a Viennese munitions tycoon. The arms dealer and Nazi sympathizer wanted his wife constantly by his

[4] She regrets having made some of those early movies. As Hedy once said, "Any girl can be glamorous. All you have to do is stand still and look stupid." (Flippo, 1997)

side.  As a result, Hedy sat through innumerable meetings with weapons developers and buyers.  Not merely a beautiful woman, she paid close attention.  She was able to escape to England, later coming to America to begin a second film career here. She seemed to carry with her from her encounters an understanding of the nature of weapons systems, as well as a determination to do good.  Today she lives modestly in Florida.

Because of the difficulty of implementing the frequency hopping scheme with the analog technology of the day, just one use was possibly made of it during World War II -- a secure voice circuit from the White House to Churchill.  The second reported use was for the telemetry link for a pilotless surveillance drone used over Vietnam in the 1960s (Pessar, 1998), the first digital implementation.

In the 1990s, with the advent of low cost silicon-based frequency synthesis and signal processing, spread spectrum has become comparable in cost to traditional analog approaches to designing radio communications systems.  The frequency hopping scheme of Lamarr and Antheil heralds a new era of wireless. For her breakthrough work, Hedy Lamarr received an Electronic Frontier Foundation 1997 Pioneer Award.

**A layman's overview of EDCT technology.**

As an aid to the nontechnical reader, I explain EDCT -- what's new and how it is tied to an emerging need for improved rural communications. EDCT is first and foremost designed from the ground up to move rural telephone service fully into the age and economics of silicon. EDCT has a network approach like cell phones. The link to customers is wireless. But because EDCT operates on EHF frequencies, where waves are very short, the antennas can be made the size of ping pong balls. Customers can add service features and links to competing service providers by plugging in modular components.

EDCT is tailored to the needs of rural residential users, rather than urban mobile users. EDCT is intended to make rural voice and high speed Internet access as affordable and of the same quality for rural residents as it is for city dwellers. Voice service quality is designed to be equal to the best wireline service, rather than the Spartan character of mobile phones. Entry level Internet connections comparable to 56K modem speeds are included. Optional high speed Internet access at 14 times that rate is priced not by the month, but according to the megabytes of data exchanged, in order to promote affordability and adoption. A new software-defined radio technology could give EDCT customers premium cordless service at home, while enabling the same handset to be used everywhere.

The EDCT service provider business model centers on a hardware architecture that uses PCS with plug-in digital signal processing cards to make extremely low cost switches. The antennas house the fully integrated radio frequency electronics.  As a result cell site cost is kept below that of a half way decent tractor, enabling anyone with a high spot on their land and the inclination to get in the business.

The needed radio spectrum is allocated in an uncoordinated fashion, using digital spread spectrum techniques.  Spectrum pricing is on a pay-as-you-go basis, using a spectral congestion toll.  The combination of simple, low cost cell sites, and the alternative to lump sum payments for spectrum rights smash barriers to entry and artificial restrictions on competition.  Even rural areas should now be able to enjoy the benefits of competition, while facilitating local ownership of service providers.  Allocating spectrum by using a congestion toll facilitates reshaping the FCC for the digital wireless age.

EDCT may grow to perhaps five percent of the U.S. market for telephone service.  For each one percent of market share, and at a one cent per minute toll, the new spectral congestion toll would bring about $280 million annually to the treasury.

# CHAPTER 2.

# A RADIO FREQUENCY SPECTRAL CONGESTION PRICING MODEL.

The analog world of telecommunications has certain physical characteristics that inform and shape its institutions. When instead we use digital approximations of reality to convey information, the physical characteristics of telecommunications are altered. Institutions dealing with telecommunications need to be reshaped to take full advantage of digital telecommunications and the private markets they engender, while still striving to attain the universal service goals of the traditional approaches to regulation.

In this chapter I explain what has been fundamentally altered in the transition to the digital era of telecommunications. I propose a new approach to pricing the radio frequency spectral resource that forms a basis for a new institutional choice for telephony.

## 1. Need for regulation of the radio spectrum.

### 1.1. Institutional choices enveloping analog modulation.

Essentially all of the existing kinds of telecommunications service that make use of electromagnetic radiation (radio waves) to convey information employ analog modulation to attach the information to a carrier wave of fixed frequency. Analog communications systems include 800 megahertz (MHz) cellular, land mobile radio, ship and aircraft communications, radio and television broadcasting, and multipoint distribution service.

**Physical characteristics of analog modulation.** An unfortunate but inherent aspect of analog modulation is that if two senders use approximately the same carrier frequency, they will cause mutual interference to each other. For example in television broadcasting, in which video information is conveyed in a manner quite similar to amplitude modulation (AM), one can observe two superimposed images with the interfering signal slowly drifting about in relation to the desired signal. With the frequency modulation (FM) employed for FM broadcasting, land mobile radio and analog cellular, the effect of interference is slightly different. FM receivers will tend to lock onto, or capture, the strongest carrier while preventing the signal which is weaker at that instant from being heard at all. You may have noticed this effect while driving on a rural highway between two cities that each have an FM broadcast station assigned to the same frequency.

These characteristics of AM and FM analog modulation are not necessarily bad -- who wants to listen to two FM stations at the same time? On the other hand just one public safety worker who accidently sits on their microphone can render a whole network inoperable. But the fundamental point is that in institutions built around the technology of analog modulation it is essential that this potential for mutual interference be well taken into account. Apart from frequency re-use,[5] only one transmitter can occupy a frequency assignment.

Two additional and more often discussed characteristics (at least in polite scholarly circles) of analog modulated signals are

1. Non-excludability, which means that no receiver can be prevented from enjoying the content of a transmission, except through artificial constraints; and
2. Non-diminishability, which means that one person's enjoyment of a transmission does not reduce the enjoyment of another.

Economists regard economic exchanges that have these two properties as pure public goods. The clear implication of these two characteristics is that the realm of analog modulation is one in which the goods and services provided

---

[5] Which means that sufficient physical separation of transmitters is maintained during the process of frequency assignment to individual transmitters.

have the character of public goods, and are converted to private goods only through the somewhat artificial action of law, and not the true underlying reality of the physics of radio communications.

Finally the number of different frequencies available for transmitters, the total available spectral resource, is constrained by the ever increasing costs of attaining higher frequencies in realizable systems. It is not that the spectral resource has a firm limit, but more so that the economics of system design sets limits to the upper bound and frequency spacing of the services. Traditionally this has meant that highly specialized or strategic systems have been the first to make use of the upper reaches of spectrum available at a given point in time.[6]

**Implications.** The implications for institutional choice of the technology of analog modulation are manifold. First and foremost the practical engineering limit on the available spectrum make it in most cases a scarce resource. Scarcity immediately suggests to a contemporary economist that a price should be attached to the spectral resource to bring about

---

6 But as will be explained in chapter four, this long held assumption about how to best allocate spectrum between governmental and consumer uses is turned on its head by the new realities of the trajectory of silicon.

efficient use. But because the physical nature of analog modulation imparts the character of a public good to the spectral resource, the institutions that have grown over the last decades to envelop that part of the electromagnetic spectrum called radio[7] have taken a public interest approach to regulation. By that I mean in the U.S., for example, that license holders have been required to serve the “public interest, convenience, or necessity” (1934 Act).

Regulation of the spectrum is by expert agency. In many nations a bureau is attached to the ministry of post. In the U.S. there is a stand-alone federal agency called the Federal Communications Commission (FCC), which preempts lower units of government in the regulation of radio communications, except in regard to land use and matters of public safety. Application for renewable right-to-use licenses that are essentially free has until recently (1996 Act) been on a first-come-first-serve basis, with competing applications

[7] To now in the emerging digital age revert from the name radio to the name wireless seems an assault on the institutions that administer the spectral resource. With some thought it is hoped that many will see it is neither necessary or wise to destroy the analog world to make way for the digital age. Analog modulation continues to have inherent advantages in certain classes of service. For example field tests of COFDM digital audio broadcasting appear less than satisfactory if there is a breeze (Thibault & Lee, 1997). Recently a broadcast engineer assessed HDTV initial field tests as providing but a fraction of the service area of analog television (Eliason, 1998).

decided on a comparative worth basis in an administrative law proceeding. No property rights are conveyed in the U.S., either traditionally or in spectral auctions. But then, on the other hand, no U.S. broadcast station or cellular carrier has ever failed to have its license renewed (Smith, 1995).[8] In at least one country (El Salvador) property rights to spectrum are indeed conveyed, but this is best viewed as non-physical and inconsistent with the international law concerning telecommunications (Stockwell, 1998, 3).

A cooperative model has evolved for international regulation of the electromagnetic spectrum in the analog era. The international law of communications (includes transport and mail) is most highly advanced in the area of telecommunications (Alexandrowicz, 1971), precisely because telecommunications has evolved to a cooperative approach, as opposed to the awkward bilateralism of transport and mail.[9]

---

8 The cellular industry reportedly makes a careful habit of settling wrongful death actions out of court, so that there is never an adverse finding that could subsequently be used to challenge a carrier’s license before the FCC (Smith, 1995).

9 It is interesting to contrast the cooperative model used in the international regulation of telecommunications with the bilateral interconnection agreements now required nationally under Sections 251 (c) and 252 of the Telecommunications Act of 1996 (1996 Act). Is this an advancement in regulation? They have generally been far less contested than rate-of-return proceedings, so they may indeed represent an incremental improvement in some ways, and form a basis for future advancement.

The International Telecommunications Union (ITU) meets periodically to fine-tune frequency allocations on a collegial basis best described by Price & Rinaldo (1998, 31).

## 1.2. Evolution of institutional choice upon introduction of digital modulation.

What is most notable about the effects of the revolutionary transformation of telecommunications from the analog to the digital age is how little the foundations of the institutions of spectrum management have been altered. Changes embodied in the Telecommunications Act of 1996 do promote an increased reliance on private markets to deliver both basic and advanced telecommunications services, certainly, the one key exception at present being rural basic universal telephone service.[10] Private markets are wonderful inventions in that they enforce operation at the efficient frontier, thereby providing the greatest possible total quantity of telecommunications services, and so are to be preferred to the greatest extent possible.

---

[10] The exemption for those local providers with less than 50,000 lines (1996 Act) is not written as if it is but a temporary protection for rural local providers, but given the presence of analog cellular, telephony over cable systems, and the eventual build-out by PCS Block C license holders, the protection will prove infeasible (Vedro, 1995). Already the FCC’s Universal Service Board is beginning to explore alternatives.

In the area of international regulation of telecommunications, the ITU continues to embrace a cooperative model of regulation, but for the first time is being lobbied and petitioned directly by large equipment manufacturers, who hurriedly seek allocations for products to be marketed in more than one nation (Price & Rinaldo, 1998). The effect of the private interests is to bypass and ultimately diminish the role of national governments in spectral resource allocation.

**What hasn't changed.**

The underpinning that has not changed is the doctrine of the exclusive frequency assignment of transmitters. Before, exclusive assignment followed fundamentally from the physical character of the modulation scheme, but now there is no such hard constraint. The reason for a now-possible lifting of the constraint of exclusive use lies in the fact that with digital spread spectrum modulation, transmitters using different modulation spreading codes cannot be heard, except by a receiver set to a specific desired spreading code, even though the transmitters share the same frequency allocation (Milstein & Simon, 1996, 152-3). There remains only a subtle justification for exclusive assignment, there being somewhat of an improvement in spectral utilization efficiency (Yue, 1983). I explain how the small efficiency advantage that a centrally administered frequency assignment approach like exclusive right-to-use has to offer is only significant under certain conditions.[11]

The economic principle of non-excludability is also no longer operative, again because a receiver needs to know a particular (proprietary) spreading code in order to receive a transmission. Therefore the spectral resource need no longer be considered as a public good, in the traditional institutional sense concerning the regulation of broadcasting. Scarcity still applies, so that allocation mechanism design remains important to efficient use.

I will next explain how spectral auctions largely but not fully capture the new physical realities of the digital telecommunications regime and leave open an opportunity for improvement of societal welfare.

## 2. The need for a new institutional choice.

Spectral auctions for wireless telephony are not Pareto optimal, because they do not fully capture the underlying physical nature of digital spread spectrum modulation. My assertion may surprise some, and I hasten to point out that I

---

[11] The key argument is contained in my development of a radio frequency spectral pricing model at the end of chapter two and summarized in figure 2.3, which shows that for SNR > 10 dB, spectral utilization efficiency is relatively unimportant.

do not propose the wholesale replacement of spectral auctions with something different, but rather the delineation of regimes in which an additional spectral pricing option promises to improve the lot of classes of customers who are otherwise excluded by the workings of imperfect competition.

The 1993 introduction of spectral auctions created a private market for digital wireless telephony, with the granting of a ten year renewable exclusive right to use an assignment.  An oligopolistic price / output vector has been established in each served market.

That auctions are an efficient mechanism design for the allocation of a good, within the confines of the behavioral underpinning of microeconomics,[12] is universally accepted. Economic rents (profits in excess of the weighted average cost of capital) are inevitably present in the oligopolistic PCS market created, but it was hoped by the architects of that institutional choice that by having five competitors (rather than the duopoly of analog cellular) that the rents would not be objectionable.

I feel the existence of some rents in urban service territories where there are a multiplicity of providers and sufficient average income levels is acceptable, at least in a utilitarian sense.  Of course the urban poor lie outside such

---

[12] The assumption of rationality.

rationalization (see King, 1998), and I revisit this special case in chapter five. My proposed new class of service might also be viewed as a truly low cost “provider of last resort” in urban service territories, solving a heretofore intractable problem in establishing markets for competitive local access. I should mention that the original motivation has always been to provide affordable local service in mostly rural areas where wireline service is costly to provide and the traditional cross-subsidy of local service in the U.S. is being withdrawn.

**Wireless telephony: The next local loop.**

Wireless telephony is now showing the potential of substantially displacing wireline service, especially in high cost areas, but also as a means of quickly providing competitive residential local access to end the historical monopoly provision of local service in urban areas. As this happens radio spectrum allocation choices will move to eventually displace the traditional regulation of wireline common carriers as the key to attaining public interest goals of universal service (see Arellano, 1998). I anticipate that sea change by providing a choice for wireless local access that intrinsically provides for universal service goals. Unfortunately analog cellular and PCS classes of service by design do not fully meet the needs of universal local access to voice and data services.

**Cellular.** Analog cellular has the greatest number of shortcomings, both technical and service related. First, in rural areas it is usually deployed so as to best serve mobile users, leaving rural customers with spotty or non-existent coverage, by employing highly directional antenna patterns located almost exclusively along major roadways.

Second, the engineering assumptions made in the early 1970s at the inception of the service to assure a reasonable level of privacy have long since been overcome. Prior to the invention of the microcomputer few individuals could afford to possess sufficient computing power to overcome encryption of supervisory data streams. Also at that time good performing 800 MHz receivers were costly. The Communications Privacy Enhancement Act of 1998 (HR 2369) does nothing to alter these facts (Mansfield, 1999).

Third, the channel characteristics of analog cellular, while sufficient for voice, are insufficient to provide Internet connectivity at what are now routine wireline speeds (56 Kbps analog modems and 64 Kbps ISDN basic rate). For a given rated modem speed, throughput is much worse over a cellular connection than a wireline connection.[13] Also the channel bandwidth limits data rates to about 9.6 Kbps.

**PCS.** The institutional choice created for PCS differs in its effects from the intent of basic universal service provision of wireline telephony. From a technical perspective, voice and data performance are very much like wireline universal telephone service. The difficulties lie in the regulatory model. Instead of marginal cost provision, there is oligopolistic pricing. There is no obligation to provide service. In fact in rural areas there is little service buildout planned, due especially to the financial difficulties of Block C winners. There have been reports to the FCC of defaults on auction payments, with the prospect that bankruptcy proceedings could encumber for years the use of licenses that were awarded. It appears likely that in rural areas nowhere near the intended five competitors will ever be realized.[14] Thus PCS is also a flawed option for wireline replacement in traditional high cost areas.

---

[13] The problem is that modem data compression algorithms assume a virtually noiseless channel. The radio channel is highly imperfect, thus attainable compression ratios are < 2:1.

[14] At the time of writing this section Bell Atlantic, which recently acquired GTE, is reported to be in talks to buy out Airadigm (dba Einstein PCS, which holds the rights to most of rural Wisconsin). The prospect, thus, is a future deregulated monopoly for many Wisconsin rural customers.

**A new approach.** In the transition to digital wireless telephony, instead of proceeding incrementally from a regulatory regime developed for the technology of analog modulation,[15] we need to think more fundamentally about the role of regulation of the digital wireless industry. In doing so it would be advantageous to tailor resource pricing to the needs of rural markets. Specifically, the need for large up-front cash payments might be replaced with a pay-as-you-go approach, collecting similar total revenues over the long run. Engineering decisions could be made to minimize the fixed cost of entry, to engender competition even in sparsely populated regions.

Let's try starting with a clean sheet.

## 3. Back to basics: Coupling between users.

Regulation arises because of the need to make optimal use of a scarce resource, given that one person's use of the spectral resource has an impact on the quality of use experienced by others. But the functional form of the coupling between users differs with the chosen technology:

1. For analog modulation, central coordination of users on a mutually exclusive basis is an inherent

[15] An approach that would perpetuate rents and leave under-provided the full technical potential of digital telephony.

requirement of the technology.

2. For channelized digital modulation schemes (like TDMA 800 MHz next generation digital cellular and COFDM broadcasting (see Thibault & Li, 1997)), exclusive right-of-use is not essential, but allows a higher spectral utilization efficiency.
3. For direct sequence pseudonoise modulation, any number of transmitters may share the same band of frequencies in an uncoordinated manner, with a spectral utilization efficiency of 72% of what is theoretically possible for centrally administered spectrum (Rowe (1982) and Viterbi (1982), as cited in Yue, 1983).

Case three above suggests that there are some geographic areas where a new pricing mechanism might be devised, based on the externalities created by the existence of multiple transmitters. Spectral utilization efficiency in this case could be traded off for some other societal benefits without suffering any disadvantage to users.

## 4. Implications for digital wireless telephony.

It is possible that urban (high traffic density) and rural (low traffic density) users will be best served by distinct institutional choices for radio frequency spectrum management. First, given high traffic density, spectral utilization efficiency dominates wireless spectrum allocation considerations, so that channelized networks are the best choice for the bulk of urban customers. Second, urban users attract a sufficient number of service providers to force price / output vectors to at least the oligopolistic result. Third, for urban fixed wireless networks the sunk cost of the existing wireline infrastructure might afford a future opportunity for contestability between competing technologies.

For rural users the regime is different. Low population density makes the incremental efficiency advantage of channelized operation unimportant. Markets are too small to attract competitors when there is a substantial fixed cost of entry. Affordability is a critical issue with the fading of cross-subsidization of local service in high cost areas. Equity is of increased importance, because of lower income levels and the anticipated increasing dependence on wireless for basic service.

The key questions are then:

1. Can a new spectral pricing model, a new wireless system design engineering specification, and enabling legislation engender competitive access in rural markets?
2. Would the new choice also be applicable to other

countries with largely rural populations or to urban core customers dropping off the network?

## 5. A Radio Frequency Spectral Pricing Model.

Many of the terms I am about to use are explained in the table on the next page. In general the ideas I discuss have to do with the theory of information conveyance in communication systems, a specialized area of electrical engineering. These concepts form the basis for an economic model that allocates a resource efficiently using a dynamic price mechanism.

### 5.1. Engineering basics of digital communication.

In a low user density environment, consider what can be achieved with multiple transmitters using pseudonoise modulation and sharing the same frequency assignment. Each user's transmitter will degrade the reception of the other users. Each transmitter appears to other users as an additional increment of noise above the background thermal noise level. The combined effect can be well modeled as additive Gaussian white noise (AWGN), especially for the circuit conditions present in a rural environment (direct spreading modulation in the intended architecture, weak signals) (Yue, 1983, 103).

| | |
|---|---|
| Bit rate. | Information transfer rate (bits / second). |
| Baud rate. | Signaling rate (coding elements / second) (Baud). |
| Bit error rate. | Fraction of bits which the receiver demodulator falsely decodes (dimensionless). |
| Chip rate. | A spreading code element. For direct sequence spread spectrum modulation, the number of pseudonoise chips / baud >= 1. |
| Code rate. | Number of bits per baud; a measure of the extent of insertion of forward error correction code into the information stream. ($0 < r < 1$). The r parameter directly affects spectral utilization efficiency. Adding error correction improves system performance in the presence of noise and does not degrade throughput (See Viterbi, 1979). |
| Pseudonoise. | A method of information encoding (modulation) that appears to other receivers not using the same code as a very good approximation of noise. |
| Spreading factor. | Signal-to-noise improvement brought about through the use of spread spectrum techniques (dB). |
| Gaussian white noise. | Noise with no frequency or phase dependence. |

Table 2.1. Useful measures of information flow.

Viterbi (1985, 12) developed a model for the mutual interference of M Earth station digital uplinks as experienced by a single orbiting multiple access receiver. It is directly applicable to the case of a terrestrial cell site receiver (and of further value in the case of adjacent uncoordinated cell sites). I next describe Viterbi's model and explain its utility in the development of a spectral pricing model.

---

| | |
|---|---|
| M | Number of transmitters of equal [received] power. |
| $N_o$ | Background thermal noise [spectral power] density. |
| $N_o'$ | Total received noise spectral density. |
| $E_s$ | Received energy in one pseudonoise chip of duration $T_s$. |
| $W_s$ | $= 1 / T_s$. Chip bandwidth (Hz). |
| $E_b$ | Received energy per bit of information of duration $T_b$. |
| $R_b$ | $= 1 / T_b$. Bit rate (bits / second). |
| $T_b / T_s$ | $= W_b / R_b$. Spreading factor. |
| k | Number of pseudonoise chips per baud (k >= 1). |
| r | Number of information bits per baud. |

---

Table 2.2. Some spread spectrum variable definitions (Viterbi, 1985, 12).

As Viterbi explains, the total noise power at the receiver on a per-user basis is the sum of the background noise and interference from the other users. The mutual interference in an uncoordinated environment will also appear to the receiver as random noise (AWGN), as does the background noise. The noise and interference add.

The background noise power is the product of the background noise spectral density function and the receiver information bandwidth: $N_oW_s$.

The energy received from the (M - 1) other users is $(M - 1)E_s$, so the received power density of the interference becomes $\dfrac{(M - 1)E_s}{T_s W_s}$ .

The total received noise spectral power density is

$$N_o' = N_o + (M - 1)E_s \ .$$

The signal-to-noise ratio $E_b / N_o'$ can then be calculated as follows. The ratio of signal energy per chip (spreading code element) to total noise is

$$\frac{E_s}{N_o'} = \frac{E_s / N_o}{1 + (M - 1) E_s / N_o} \ .$$

The code rate (bits / baud) is

$$r = kE_s / E_b = kT_s / T_b = kR_b / W_s \ .$$

$E_s$ can be rewritten in terms of $E_b$ and the system design parameters (r and k) or ($R_b$ and $W_s$):

$$\frac{E_b}{N_o'} = \frac{E_b / N_o}{1 + (M - 1) (r / k) (E_b / N_o)}$$

$$= \frac{E_b / N_o}{1 + (M - 1)(R_b / W_s)(E_b / N_o)} .$$

In turn the signal-to-noise ratio determines the system bit error rate (BER) that can be attained in practical implementations.

The literature suggests that a BER <= $10^{-2}$ is the maximum commercially acceptable for a voice channel and that a BER = $10^{-5}$ is judged by end users to give good signal quality (satisfactory for data). (See Yue (1983, 103-4), Viterbi (1979), and Kucar (1996, 252-3)).

Viterbi (1985, Table I) estimates the signal-to-noise ratio required to achieve a BER = $10^{-5}$ for a practical communications system in which various degrees of forward error correction are present. Note however that there is a tradeoff between the benefit of forward error correction and spectral utilization efficiency (SE), which I illustrate in table 2.3:

| r (bits/baud) | $E_b$ / $N_o'$ (decibels)[1] | SE (%)[2] |
|---|---|---|
| 1 (no FEC) | 9.6 | 72 |
| 0.875 | 6.4 | 63 |
| 0.75 | 5.5 | 54 |
| 0.5 | 4.5 | 36 |
| ~0 (limit) | 3.4 | 0 |

[1] For a realizable system using convolutional encoding and soft decoding. (The r = 0 entry is an estimate.) All $E_b$ / $N_o'$ contain a 2 dB margin, reflecting the imperfections of physical implementations (see Viterbi, 1985, 13 footnote 1). (© 1985 IEEE.)

[2] Relative to a fully utilized ideal channelized scheme. (See Yue, 1983, 101 and Viterbi, 1985, figure 1.)

Table 2.3. Required $E_b$ / $N_o'$ for BER = $10^{-5}$ for various r and SE. (Based in part on Viterbi, 1985, 13.)

What Table 2.3 doesn't reveal, because it only contains the threshold $E_b$ / $N_o'$ for the target BER, is the highly nonlinear nature of the way that BER degrades with declining signal-to-noise (SNR) ratio. The behavior is best summarized graphically in the SNR - BER performance of digital communications receivers (Bhargava & Fair, 1996, 142):

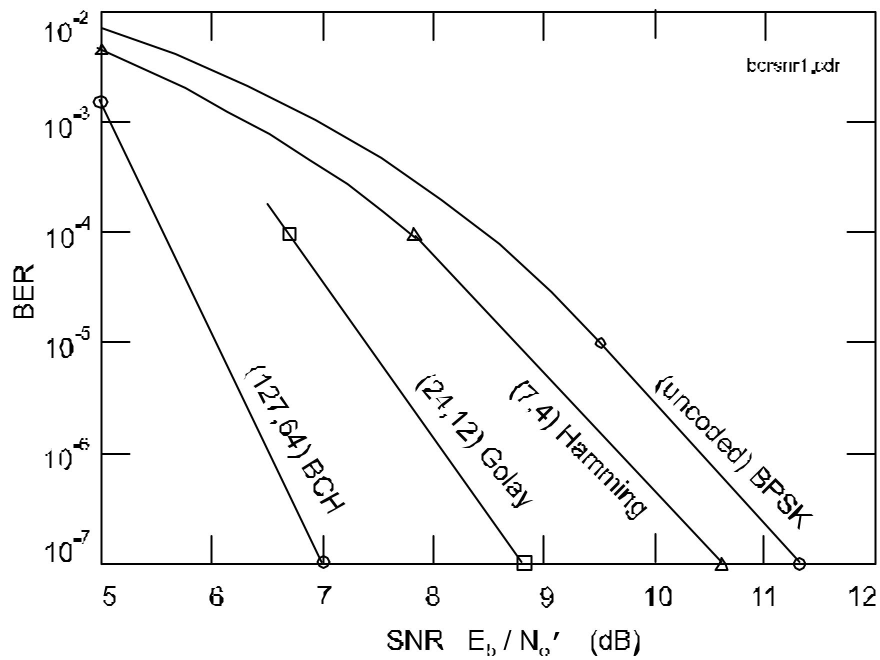



Figure 2.1. Signal-to-noise performance of various digital modulation forward error correction coding schemes. (Simplified, based on Sklar, 1988, 300, as cited in Gibson, 1996, 142.) All curves tend to converge to BER = $10^{-1}$ at SNR = 0 dB (see Orsak, 1996, 129).

**5.2. Analogy to optimal toll: The foundation of a pricing mechanism.**

The most striking thing about this figure is that on a log - log plot the relation between BER and SNR is for all practical purposes a straight line for BER better than $10^{-3}$

(the poorest commercially viable performance). The line shifts to the left depending on the extent of error correction coding (the value of the r parameter). A straight line on such a plot reveals that the bit error rate rises according to a power law relation with declining signal-to-noise ratio.

**Congestion costs in a communications network.** As message traffic builds on the block of spectrum assigned to these uncoordinated users, each new user establishing a connection degrades the quality of communications for all users. An equivalent way of expressing the effects of one user on the other users is in a monetary equivalent form as an increasing marginal cost of message traffic in the face of declining circuit quality. One might imagine in the case of data transmission an increasing number of corrupted packets that need to be resent, or in the case of voice traffic, increasing listener effort leading to difficult conversations. Ultimately users would begin switching to higher cost alternatives.

**Similarity to vehicular traffic congestion.** The situation is highly analogous to the increasing costs that occur in the case of vehicular traffic congestion. That close similarity suggests that a pricing mechanism can be designed to optimize the utilization of the spectral resource, and that the establishment of a market based on spectral congestion pricing can essentially replace the need for traditional forms of spectrum regulation, while avoiding the “tragedy of the commons” (FCC, 1998). As will be seen shortly there are but two essential deviations from an existing model setting an optimal congestion toll:

1. The exact functional form of the marginal cost curve is set by the technology of pseudonoise modulation, rather than the physical behavior of a roadway.
2. Vehicular traffic toll models tend to be static, both because of the difficulty of measuring the instantaneous degree of congestion and the difficulty of finely tailoring toll collection to the route traveled. But spectral pricing can be made fully dynamic, as I propose below.[16]

**Optimal toll in vehicular traffic congestion.** My discussion of urban transport closely follows Sharp (1966) and Smeed (1964). In figure 2.2 below I show the relation of costs and demand for a typical urban trip on a congested road.

---

16 See St. Clair (1964, 66): Dynamic pricing is the much sought-after goal of congestion theory.

The demand for trip making is determined by how people would value making trips in relation to their total cost. The average cost (AC) and marginal cost (MC) per vehicle will vary with the amount of traffic.

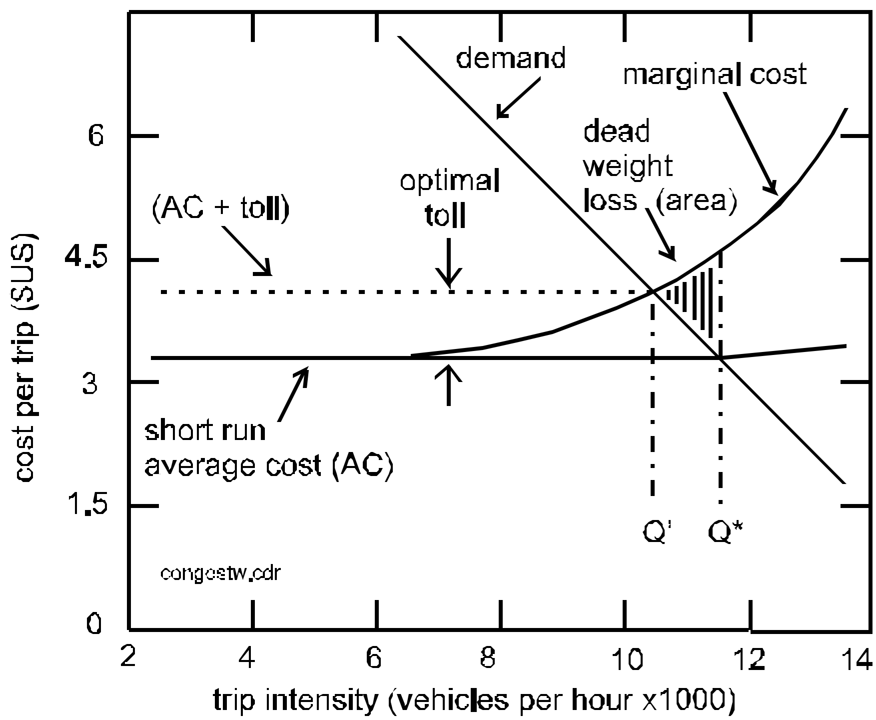



Figure 2.2. The social welfare implications of traffic congestion: Optimal toll. (Harmatuck, 1994 and Sharp, 1966.) See also Mohring & Harwitz (1962) as cited in St. Clair (1964, 78).

If the average cost per vehicle is X, then adding one more to the N vehicles on the road causes the marginal cost of the added car to be

$$(N + 1)(X + aX) - NX = X + aX + NaX$$

So the marginal cost for the $(N + 1)^{th}$ vehicle will be above its average cost by $NaX$. This means that the travel demand curve will intersect the marginal cost curve at Q′, before intersecting the average cost curve at Q*. The implication is that the $(N + 1)^{th}$ vehicle, who would be willing to pay the average cost to make the trip, is imposing a higher marginal cost on all other users. The difference $MC_N - AC_N$ is the amount that could be charged back in the form of a toll to that person to motivate optimal decision making. Once a toll is charged to all users the amount of traffic will shift from Q* down to Q′ and users who valued the trip at less than its true cost will forgo making it.[17]

**5.3. Optimal spectral resource pricing on an uncoordinated network: Objectives of a radio frequency spectral pricing model.**

In the remarks I make here concerning the development of

---

[17] Incidently such a toll is usually collected in the form of a downtown parking fee, in the case of trips to the urban core, the reasons being that a parking fee has a lower transaction cost than toll collection and simultaneously sets a non-zero price on the parking resource. As a result traffic toll collection is a static pricing mechanism. By contrast electronic billing of calls has such a low transaction cost that dynamic pricing is readily attainable.

a spectral pricing model one can see the interplay between efficiency, fairness, and technology that I alluded to earlier, and the essential nature of the simultaneous consideration of an allocation mechanism, the underlying technology of an industry, and the enabling regulatory environment that make for sound and enduring institutional choice. Other sections of my thesis will take up the related aspects of a new class of service.

I now investigate the essential core -- whether a suitable pricing model can be developed for the spectral resource that meets the following criteria:

1. Prevents the occurrence of the “tragedy of the commons,” by promoting efficient use of the spectral resource.
2. Minimizes the need for regulatory oversight.
3. Encourages Pareto-optimal spectral resource utilization.[18]
4. Provides for universal service, including Internet access at various bandwidths.
5. Optionally allows for a model of broadcasting which provides for the added value of individually tailored content for rural and low income customers.
6. The model “should be a dynamic model, taking account of

---

[18] The paradigm to be used here might be Mohring’s one-road variable-demand theorem (Mohring & Harwitz, 1962, as cited in St. Clair, 1964, 78).

variations over time, rather than a static model, expressing only the relationships existing at one time" (St. Clair, 1964, 66).

These criteria can be fulfilled by using the following approaches: Employ a congestion pricing scheme utilizing pseudonoise modulation and a spot survey of the background noise spectral density. A usage charge could be assessed, based on the connection bandwidth and tied to the noise congestion caused. Service provider equipment would conduct a spot survey of noise power spectral density to set spectral tolls for end-user sessions.

The regulatory oversight role of the FCC can now be fundamentally redefined as it pertains to this class of service. The FCC would be needed only to conduct area long term noise surveys to estimate total revenue flows for use of the resource and ensure efficient use of the spectral resource.

In addition to the six criteria above, the proposed pricing model would also enable the following:

7. Provides for socially optimal network deployment, while avoiding the undesirable aspects of rent extraction by

oligopolistic competition.[19] The challenge is "how to decentralize the socially optimal solution" (Economides, 1996, 682).

8. Provides a secondary market for service reliability, to substitute for the reliability inherent in traditional rate-of-return regulation.
9. Avoids standards coordination games and enforces the socially optimal long-run outcome of compatibility.

These additional criteria can be fulfilled by using the following approaches: As I illustrate with photographs of antenna structures in chapter four, and for other reasons, at extremely high frequencies (EHF) equipment costs can plummet. A hardware architecture that fully exploits the cost trajectory of EHF can therefore provide an extremely low fixed cost of entry.

A secondary market for service reliability could readily be established by encouraging end users to contract for alternate service providers to provide service on a standby basis. End user equipment could automatically switch to alternate providers as needed to cover for outages. In rural areas, where electric power tends to fail for longer periods,

---

[19] Note that if positive network externalities are present, marginal cost pricing is not socially desirable.

battery backup tailored to expected electric outage duration could also supplement the traditional service reliability of wireline telephony.

Cooperative ownership of intellectual property by the service providers, perhaps through a technology management body, could provide for private governance of most aspects of the operation of the industry. There are already two excellent models of cooperative governance of the spectrum in the operation of the ITU and the amateur radio service (which is largely self-regulating). But in addition a cooperative model of industry structure could help to avoid the socially costly game of technology churn, in which individual firms intentionally introduce incompatible technologies to hold captive classes of customers.[20]

## 5.4. The marginal cost of spectral congestion.

Let us now consider the functional form of the marginal cost curve. As noted earlier

1. The BER - SNR relation degrades exponentially as the SNR falls below about +10 dB.
2. The target BER for a good quality voice channel and

[20] See Katz & Shapiro (1985) and Berg (1988), as cited in Economides (1996) for a discussion of compatibility in markets where there is imperfect competition.

a serviceable data channel is $10^{-5}$.

3. The minimum BER for voice is $10^{-3}$.

The implication is that the marginal cost of spectrum to the next additional transmitter remains near one cent per minute, until SNR declines to about 10 dB, which corresponds to a BER of $10^{-6}$ for an r = 1 (SE = 72%, no FEC) network, or a BER of $10^{-8}$ for an r ~ 0.5 (SE ~ 36%) network design. Then the marginal cost rises exponentially until at a BER of $10^{-3}$ it is bounded by the price of a competing technology, like a wireline or analog cellular call.

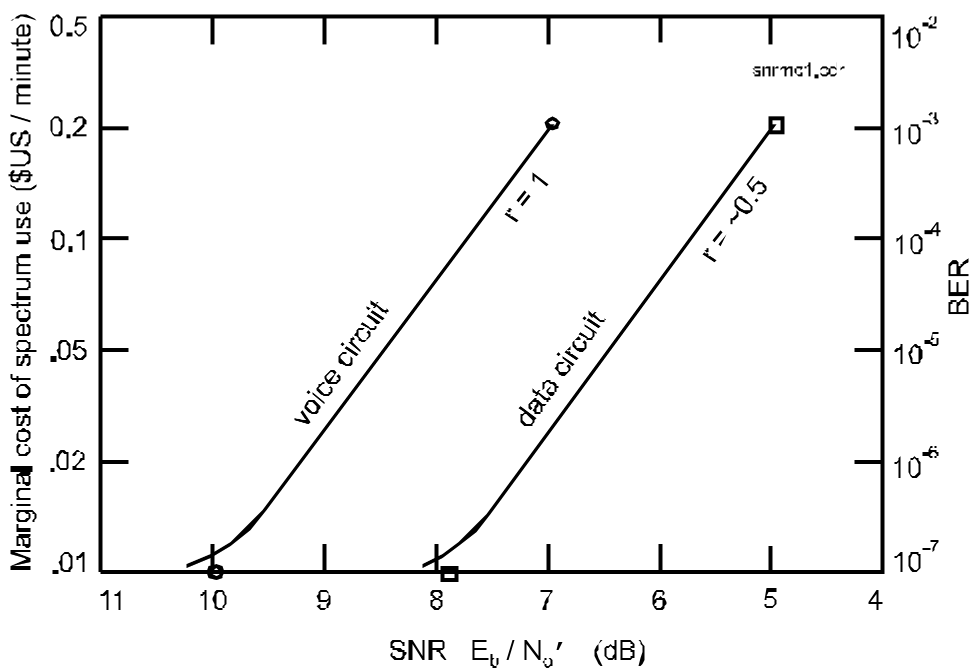



Figure 2.3. Marginal cost curves for spectrum use in an uncoordinated pseudonoise radio network.

The following engineering assumptions are present in the representative curves of figure 2.3:

1. The model is based on a centrally located receiver able to decode all connections simultaneously (like Viterbi, 1985).
2. The value of r is set to 1 for voice circuits and 0.5 for data in this example, in order to give data links the lower BER desired for computing sessions, while holding received power levels the same for each class of service. As a result, SE for data will be lower, which might be reflected in differential pricing for voice and data.
3. The upper bound of the marginal cost curves is the current price level of a competing technology.

## 5.5. Dynamic pricing of spectrum usage.

The background noise spectral power density (thermal + interfering) can be measured in real time by anyone, using a radiometer. Essentially a radiometer is a broadband receiver whose passband corresponds to the band of spectrum assigned to the network, the output of which is connected to an integrating voltmeter to produce a rolling time-averaged measure of the noise level.

In a deployed system for providing rural voice and data telephony, it is intended that there will be any number of geographically disbursed cell sites in competition with each other, in as uncoordinated an architecture as is practical. Each cell site can be equipped with a radiometer to give a dynamic measure of the spectral congestion experienced locally. Each cell site can then instantaneously set a usage charge for air time. At any given time different providers' sites may be expected to see different levels of congestion, depending on the pattern of utilization of capacity in a geographic region. Since all providers are sharing the same frequency assignment and only the spreading codes will differ for each individual user account, handsets can be designed to sample each provider's air time price and select the lowest available from the providers with whom a user has registered in advance.

It is envisioned that the connection price is set at the beginning of a session and holds or is updated only infrequently during a given session, so that only new users face the prospect of being tolled-off. The handsets would display the total per-minute price for a session, which is the sum of various charges that occur elsewhere on the network, plus the congestion toll.

**A note about congestion price levels.**

I mentioned above in section 5.2 of this chapter that each additional user in an uncoordinated pseudonoise environment degrades the quality of the communications of all users. The effect is perceived by end users as a deterioration in the bit error rate of the decoded baseband information stream. For example, in voice service for signal-to-noise ratios of better than 10 dB at radio frequencies, the decoded BER is better than $10^{-7}$ (see figure 2.3). Speech quality will be perceived by users as being excellent. As the signal-to-noise ratio declines at radio frequencies, however, the decoded BER climbs, and users are relatively less satisfied with speech quality. The degradation experienced by users takes several forms, all of which make understanding the speech more arduous -- the speech is more “hissy,” less natural, maybe gap-filled (like early RealAudio™ was). Eventually customers begin switching to other communications modes or other activities that compete for their time.

Thus there is a real cost to spectral congestion, measurable in the aggregate, as in vehicular traffic congestion. For spectral congestion, the cost of congestion at the limit of a fully degraded circuit is roughly equal to the price level of the next best alternative. At intermediate levels of congestion the cost varies according to a power law relation. In the limit of no congestion there remains a non-zero cost of spectrum usage, as can be seen in figure 2.3 above.

It is tempting to immediately translate the engineering relation of figure 2.3 into an analytic expression that economists would use to predict the optimal toll, as is done in the case of vehicular traffic congestion theory. But in transportation policy, the existence of a definite toll price prediction conceals the fuzziness of the underlying inputs. The value of time prediction of commuters makes some sense in the composite, but limited sense to the individual. The practical lack of alternate routes for many commuters can make a toll look like a mere tax to many. Analogous considerations would come into play for a spectral congestion toll. In reality the toll price level must be set within a social context. Chapter five contains a further discussion of the many factors related to setting congestion toll price levels.

# CHAPTER 3. EXISTING INSTITUTIONAL CHOICES FOR RURAL TELEPHONY.

## Introduction.

The telecommunications industry in Wisconsin is analyzed by way of example to help understand the benefits of developing a new institutional choice for the provision of universal telephone service. Wisconsin is an interesting candidate for the study of new approaches to providing telecommunications service because the state has a diverse mix of urban and rural customers (about 50 percent), agriculture and industry, population density and geographic features that inherently affect the cost of service.[1]

Analyses focused on an industry rather than on the level of an individual firm are inherently strategic in nature, which simply means that the results of the investigation have to do more with the interface between firms and their external stakeholders, rather than with the internal processes of individual firms. The various analytic models used in business and economics illuminate in differing ways the strategic relations of firms in an industry. For example,

[1] Many other less populous states and some small countries that are now considering how to first provide universal service for their citizens are not unlike Wisconsin in certain essential ways.

figure 3.1 below shows strategic relationships for the EDCT industry I propose and analyze in chapters four and five.

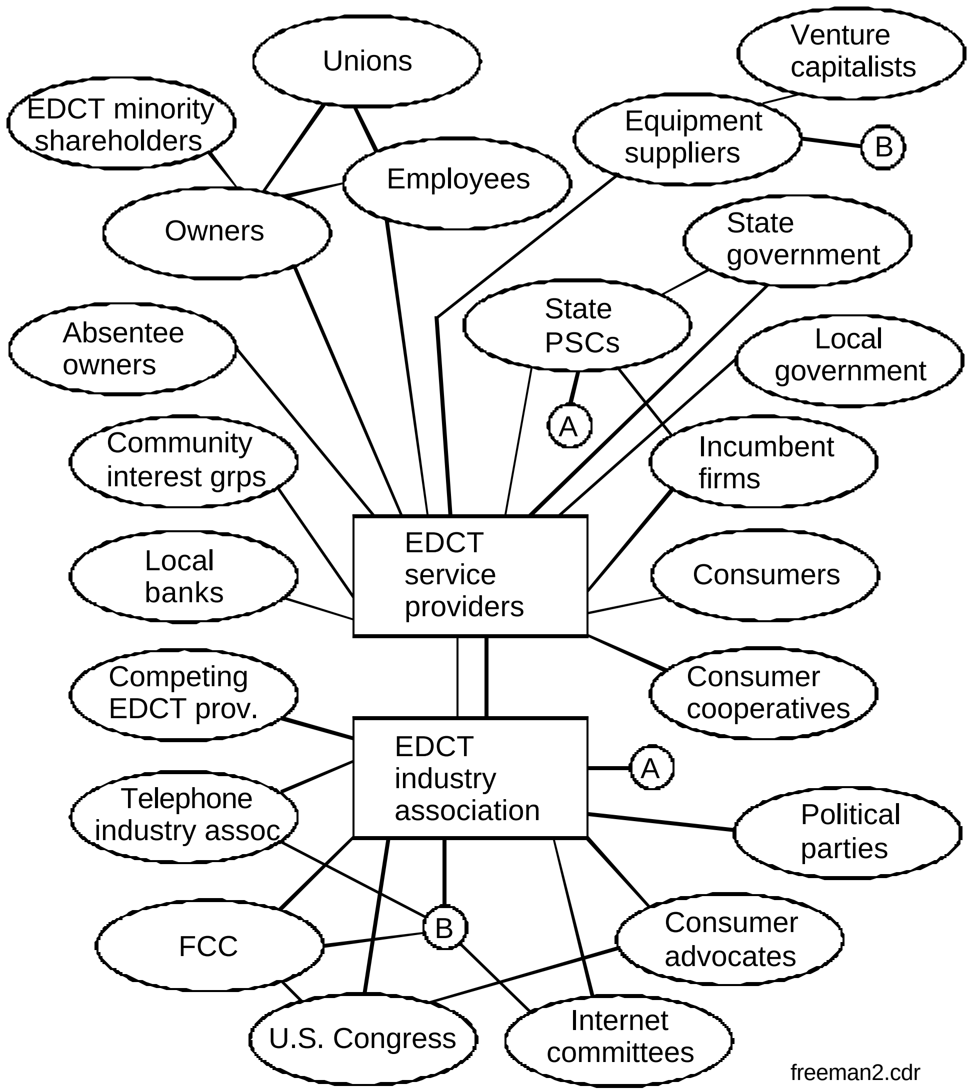



Figure 3.1. Stakeholder map of the proposed EDCT industry. (Line intersections are not connected; A and B are line connectors.)

I wish to focus in this chapter on two key views of investments in infrastructure made by providers of local telephone service. The first view is a multivariate statistical analysis model that provides competitive insight into the services that infrastructure investment makes possible. The second is an engineering and accounting-based model that describes the cost structure of wireline local service.

**Measures of infrastructure investment.**

**The role of infrastructure investment in competition and social welfare.** Adequate infrastructure capacity is the engineering foundation of universal basic service and profitable enhanced service features. Capital intensity is much higher in the infrastructure industries like telecommunications than it is in other sectors of the economy. For example in the manufacturing sector, about 25 cents of capital produces about one dollar of revenue on average, whereas in telecommunications and electricity capital outlays the range is one to three dollars per dollar of gross receipts. That is why in the infrastructure industries assessment of the effectiveness of infrastructure deployment is key to strategic management and regulatory oversight.

**Sources of information.** Under intensive regulation, monopoly providers have long been subject to detailed uniform reporting requirements concerning the financial, physical infrastructure, and quality of service aspects of firm activities. A uniform chart of accounts and technical standards in the public domain have made the public utilities amenable to regulatory oversight and scholarly study -- no other industry has been so open and orderly.

But both traditional providers of local telephone service and their regulators have fallen into a psychic prison of sorts, imagining that the accounting and engineering measures so conveniently provided adequately comprise a strategic view. I hope to aid stakeholders in the industry providing local telephone service by showing what multivariate analysis can do, in addition to using the results of the model within the context of this particular work.

By contrast firms in competitive markets reveal to the public only what is required in reports to shareholders and the SEC. Instead, technology becomes a more dynamic dimension of firm and industry strategy. As a result more sophisticated metrics and analytic models like multivariate analysis are essential to adequately understand and assess the quality of firm behavior in a transition to a deregulated business environment for local telephone service.

**Measurement.** Economic measurement alone, while usefully serving as a simple check of the quality of regulation and firm rational behavior, is far too narrow a measure. Infrastructure has several aspects that in total determine its capacity to adequately serve the public interest, convenience, and necessity. The telecommunications infrastructure consists of switching, local loop, terminal equipment, long distance, and services. For each element of infrastructure, a different metric is most appropriate. In a newly competitive environment the data needed to gain a full picture are either scattered about or in need of collection by researchers. The challenge is how to analyze the collected data, making the best use of the available information.

Multivariate model. I use multivariate analysis in the next section of this chapter to map the strategic positioning of providers in relation to each other. The multivariate (principal components analysis) model can be seen as an attempt to view the present industry structure in terms of those ingredients that best distinguish groups of firms. Which providers are giving their customers the most infrastructure at the least cost then becomes newly apparent. Such a competitive mapping becomes a summary measure of the quality of the management of providers, yet can be assembled from disparate metrics. I am then in a position to best comment on the effectiveness of regulation of the incumbent firms. Moreover the multivariate model illuminates the inputs that a proxy cost model like Hatfield can analyze.

Hatfield Model. The second part of Chapter three is a presentation of the Hatfield Model results for the State of Wisconsin. The Hatfield Model is an engineering-based model[2] that asks the question, ‘how much would it cost to rebuild the U.S. telephone system from scratch, using current technology?’ The answer is intended to be used by the FCC and state public service commissions to set the amount of universal service support money for local phone service. The Hatfield Model uses an adjustable set of input parameters and certain exogenous aspects (population and geography). The Hatfield Model is a proxy cost model in that the industry is modeled using a uniform set of technological assumptions that are applied hypothetically to all provider firms. Because all firms use the same technology by assumption, all must be equally efficient. The Hatfield Model affords an opportunity to approach the cost of service of individual providers from a more “forward looking” perspective.

**Key results of the models.** By pulling forward and reproducing here some of the results of the models I can give the reader a capsule overview of Wisconsin local telephone service providers.

---

[2] The Hatfield model is implemented in Microsoft Visual Basic for Office 95.

Hatfield Model results. The most basic result is the number of customers and their distribution among the providers.

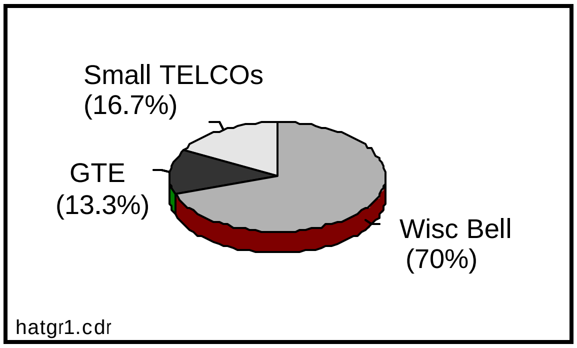



Figure 3.2. 1997 Market share of Wisconsin local telephone exchange carriers, on a per-line basis (Hatfield, 1997).

In Wisconsin in 1997 there were about 3.43 million telephone lines. A little over two thirds of these are owned by Wisconsin Bell, which does business as Ameritech. As figure 3.2 illustrates, GTE owns almost half of the remaining lines not owned by Ameritech. Dozens of small telephone companies provide the remainder of service to Wisconsin residents.

The key prediction of the Hatfield Model is an estimate of the cost of providing local telephone service to Wisconsin residents. The statewide average is $31.10 per month, but there is quite a bit of structure that the average would otherwise obscure.

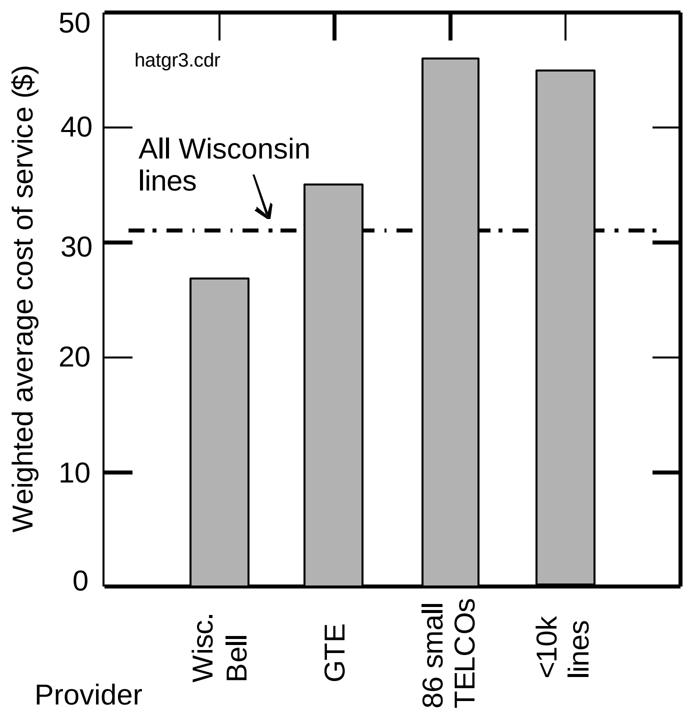



Figure 3.3. Weighted average cost of service (WACS) predicted by Hatfield (1997).

Multivariate model results. Table 3.1 summarizes the key competitive implications of both models. Table 3.1 shows the firms individually identified by the multivariate model as conforming to one of the possible strategies of table 3.2. (shown following table 3.1), together with the Hatfield predicted cost of service for those particular firms.

| Provider name | Hatfield WACS ($) | | No. of Lines | Multivariate identified strategy (See Tbl. 3.2.) |
|---|---|---|---|---|
| GTE North (Wisconsin) (76) | 35 | | 456,000 | 1 |
| All in mass of points in Figure 3.4. | 46 (approx.) | | 452,252 | 1 |
| All in Strategy 1 (wt. ave.): | | 40.50 | | |
| Century of Wisc. (19) | 38 | | 102,282 | 2 |
| Mt. Horeb Telephone Company (44) | 39 | | 4,000 | 2 |
| Lakefield (31) | 84 | | 1,493 | 2 |
| All in Strategy 2 (wt. ave.): | | 38.67 | | |
| Tri-County (66) | 71 | | 3,684 | 3A |
| Chibardun (14) | 69 | | 5,281 | 3A |
| All in Strategy 3A (wt. ave.): | | 69.82 | | |
| Riverside (54) | 53 | | 3,008 | 3B |
| Wisconsin Bell (77) | 26.80 | | 2,397,000 | Focus |

Table 3.1. Hatfield (1997) predicted cost of service for strategic groupings of Wisconsin firms that had been previously identified using principal components analysis. (Analysis using the Hatfield Model appears later in this chapter.)

The Multivariate and Hatfield models are then compared and contrasted in a later section to gain insight into the quality of traditional rate-of-return regulation for the Wisconsin telephone industry.

**Cellular telephony.**

Finally the service characteristics, pricing, and cost of service of cellular telephony are examined in a third section of this chapter. One key objective in that section is to estimate the marginal cost of a cellular call when the existing institutional choices of analog cellular and PCS are utilized.

| Strategy | Relation to Porter | Characteristics |
|---|---|---|
| 1 | Low cost. | Fewer service features, lower investment. |
| 2 | Low cost. | Fewer service features, higher investment. |
| 3A | Differentiation. | Many service features, higher investment. |
| 3B | Differentiation. | Many service features, lower investment. |
| case 77 | Focus. | (Wisc. Bell -- see conclusions.) |

Table 3.2. Competitive strategies identified by the multivariate model.

**Intended uses of the analysis.**

For the immediate purposes of this work the multivariate model will show what service features I will need to emphasize in the design specification for a new kind of local service. The Hatfield model will describe the cost of switching and outside plant separately, so that I might compare and contrast costs for the various service options that would be available to customers. I intend to make these comparisons in subsequent chapters.

In chapter five, table 5.7 provides a top level overview of the various service options. The cost comparisons shown in that table are obtained from the Hatfield Model and cost of wireless service estimates performed elsewhere in this work.

# 1. Plain old telephone service: A strategic analysis.

## 1.1. A multivariate analysis of Wisconsin telephone local exchange carriers: Infrastructure deployment and implications for business strategy.

### Introduction.

The technique of multivariate analysis of principal components (PCA) will be used to look for strategic dimensions along which Wisconsin telephone local exchange carriers (LECs) might differentiate themselves. This may provide evidence of grouping of the Wisconsin telephone local exchange carriers into distinct industry subsets. Next such possible strategic groupings are considered in relation to Porter's three competitive strategies.[3] The implications for firms in the local telephone industry are explored.

### The data set.

Cross-sectional data were collected for the 77 large and small telephone local exchange carriers with business operations in the state.[4] The data set consists of physical

---

[3] See Porter (1985).

[4] In the summer of 1993 I conducted an empirical study of the telecommunications industry infrastructure currently deployed in Wisconsin, while serving as a consultant to the Governor's

(plant and equipment), service (features provided customers), and financial (accounting) measures of the telecommunications network. In addition longitudinal data was collected for financial measures of infrastructure investment.

All but two of the local service providers are small. One large local service provider is the regional Bell operating company (RBOC) Ameritech, whose Wisconsin subsidiary is incorporated as Wisconsin Bell and does business as Ameritech in the cities of Madison and Milwaukee. Ameritech has a common administrative structure. The remaining large firm is GTE North, which has a single administrative structure, but which operates in various service territories similar to the service territories of the small firms. By contrast the small firms are typically locally owned and managed and thus are not able to fully realize economies of scale in their operations. The small firms, GTE and Ameritech each have about a one third share of the Wisconsin telecommunications market. The LECs have been intensively regulated for many years by the Wisconsin Public Service Commission (PSCW).

---

Blue Ribbon Telecommunications Infrastructure Task Force. The data has been published by the Task Force (1993a, 1993b) in summary form, and so is practically in the public domain.

**Approach to analysis.**

To date only a cursory univariate analysis of the data set exists (Task Force, 1993b), conducted essentially for purposes of benchmarking. In fact the data under investigation begs a proper statistical analysis, because conclusions to be drawn about industry structure and strategy could aid both the Wisconsin State Telephone Association (WSTA) and the Public Service Commission (PSCW) in the development of an optimum transitional regulatory framework.

A central question to ask of this data set is what might be learned about the possible impact of changes in the regulatory environment, to be brought about by the state legislation, on the business environment of the firms under investigation. A thorough answer is beyond the scope of this paper, but preliminary conclusions can be drawn by applying the framework of Porter's (1985) typology of competitive strategies.

Porter (1985) identifies three competitive strategies which successful firms tend to adopt: 1) being the low cost producer in that industry, 2) differentiation from competitors, or 3) focus on a specific subset of that industry's customers. Porter goes on to explain that firms which fail to clearly adopt exactly one of the three competitive strategies tend to under perform relative to their rivals. Porter calls this being “stuck in the middle.”

The multivariate technique of PCA will be used on the industry data set to identify key underlying dimensions along which these firms may be able to differentiate themselves. Next I will look for evidence of grouping of the Wisconsin Telephone LECs into distinct industry subsets, in the manner of Carter, et al. (1994). Finally I will consider these groupings in relation to Porter's three competitive strategies, and consider the implications for firms in this industry.

**Survey variables.** For the 77 local service providers surveyed, there are 31 (mostly discrete) variables, of which 20 are candidates for multivariate analysis. Variable definitions and notes about the individual variables and cases are contained in Appendix A. The data set is rich and of a high quality, due to uniform reporting requirements in this segment of the telecommunications industry, although the data were not collected specifically for multivariate analysis.

Of the 31 variables on which information was collected, 13 were chosen for their descriptive power in a multivariate PCA model of industry structure. The decisions about which variables to screen at this early stage were made by the author, who possesses 'expert' knowledge of this industry. The variables not chosen are considered to be primarily of value as simple comparative measures.

The total number of residential and business subscriber lines (Rtotal and Btotal) and switches are useful as measures of firm size, but are not explicitly included in the multivariate analysis. The reason is that because there are but two large firms, the distribution by firm size is highly skewed. Therefore conducting PCA using firm size (number of telephone lines) as a variable would produce a trivial and potentially invalid result. Instead the two cases of the large firms will be examined in light of their principal components scores to gauge their positioning in relation to each other and the other firms.

The subscriber line variables and the number of (central office) switches variable (Switches) are used to convert the other variables used in the PCA model into fractions (range of 0 to 1), which represent the diffusion of the various product technologies into a firm's service territory. In so doing all of the other variables used are made independent of firm size. The 11 variables used in the PCA model are shown in Appendix B. Assignment of individual firms to case numbers is shown in Appendix C.

When conducting an economic analysis at the industry level, firm profits are normally taken to be of central importance. Firms are considered to act rationally; that is, they are postulated to engage in profit-maximizing behavior, with cost-minimization equivalent by corollary (Varian, 1992). But in the intensively regulated Wisconsin telecommunications industry, profits and minimum service standards are fixed by PSCW. Thus the key strategic variables firms can manipulate are limited to deployment of advanced service features and levels of dollar investment per subscriber. Accordingly these are the variables to use as inputs to the analysis.

**Principal components analysis.**[5]

**Methodology of PCA.** Our main interest is to identify key features that make the telephone firms different. Principal component analysis provides this information by projecting a high-dimensional set of data into a few dimensions. PCA is performed by maximizing variances in mutually orthogonal dimensions. First, the eigenvalues and eigenvectors of the correlation or covariance matrix are found. Each eigenvalue gives the variance of the data on the axis corresponding to the respective eigenvector, and each eigenvector provides the coefficients of the linear combination of the original data.

To develop a graphical representation of the data, two dimensions with the largest spread (variances) are first chosen. Reification of the dimensions can provide a basic understanding of relationships. Formally, the number of dimensions to include in the PCA model can be chosen by selecting a cut off at the elbow point of a scree plot. From this multidimensional plot, a more precise model can be obtained than could be from a plot portraying just two dimensions. One could also look for some groupings in the multidimensional plot to see which firms are clustering together. The clustered firms have similar features and

---

[5] The principal components analysis in this subsection is extracted from Moore, et. al. (pending).

performance. Finally, a residuals plot can show us some discrepancies of the projection into lower dimensional space, and also outliers which don't have similar performance as the other cases.

**Results.** The results of the principal components analysis are as follows. Because PCA attempts to maximize variance in all dimensions for all cases, those cases for which missing data existed were omitted from the analysis. There were five such cases. All of these were smaller firms, and the final data set consisted of 70 small, and two larger telephone companies.

Figure 3.4 below shows a scree plot of the principal components. The scree plot follows a fairly typical pattern in which the initial sharp decline is followed by a much more gradual decline. However, the "flatter" portion of the plot quickly falls into a moderate pace of decline. The point at which the graph initially flattens is close to the customary eigenvalue cutoff for retention ($l = 1$). This plot suggests that a four or five component solution should best fit the data.

The principal components analysis revealed four components with eigenvalues greater than one. Employing the arbitrary, but common practice of retaining components

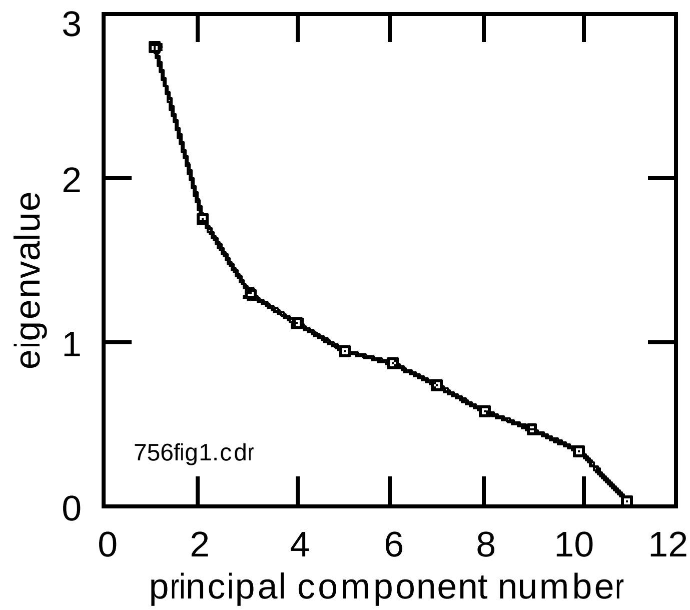



Figure 3.4. A scree plot of the principal components.

with eigenvalues greater than one, a four dimensional solution was initially chosen. However, the fifth principal component loaded heavily on the one variable which loaded only moderately on the other variables. Further, the inclusion of the fifth dimension added 8.6% to the explanatory power of the model. In total, the first five principal components accounted for 71.87% of the variance in the data.

**Description of the observed principal components.** An examination of the loadings on the chosen components suggests that each component can be considered as a bundle of firm resources allocated in a common way.

| Loading on principal component: | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Variable:** | | | | | |
| **Component #1** | | | | | |
| Fraction of all switches that are digital | .5256 | | | | |
| Fraction of residential lines served by digital switch | .8391 | | | | |
| Fraction of business lines with digital switches | .6400 | | | | |
| Fraction of business lines with narrow band ISDN | -.718 | | | | |
| Average subscriber distance to switch | .5596 | | | | |
| **Component #2** | | | | | |
| 5 year average transmission investment | | .4858 | | | |
| 5 year average switch investment | | .6336 | | | |
| **Component #3** | | | | | |
| Average miles of digital lines / customer | | | .6211 | | |
| **Component #4** | | | | | |
| Enhanced 911 | | | | .6251 | |
| Signaling System 7 switches | | | | .5395 | |
| **Component #5** | | | | | |
| Fraction of business lines | | | | | .6253 |

Table 3.3. Maximal loadings of variables on first five principal components.

As table 3.3 shows, the first principal component loads positively primarily on the fraction of firm owned switches that are digital, the fraction of residential and business lines served by digital switches, and the average subscriber distance to switch in miles. This component also loads negatively on the fraction of narrow band ISDN business lines. Thus, the first component is essentially digital in its measure, but also with subscribers tending to be farther from switching facilities.

The second principal component loads strongly positively on both measures of financial investment. The third component loads strongly positively on only the average digital transmission line length per subscriber. The fourth component loads positively only on the advanced features of enhanced 911 service and Signalling System 7. Finally, the fifth component loads only on the fraction of subscriber lines that are business lines.

Because two dimensions can easily be understood by visual examination, a plot of the first two principal components is often informative. In this case, with a five dimensional solution, it might be profitable to look at the first two principal components, locate the outliers, and assess how these differ from the other points on the plot. The first two principal components are plotted in figure 3.5 below. This plot reveals a relatively homogenous cluster that is differentiated almost solely by the second principal component, or the level of financial investment. The large companies are indicated by their case numbers of 76 and 77.

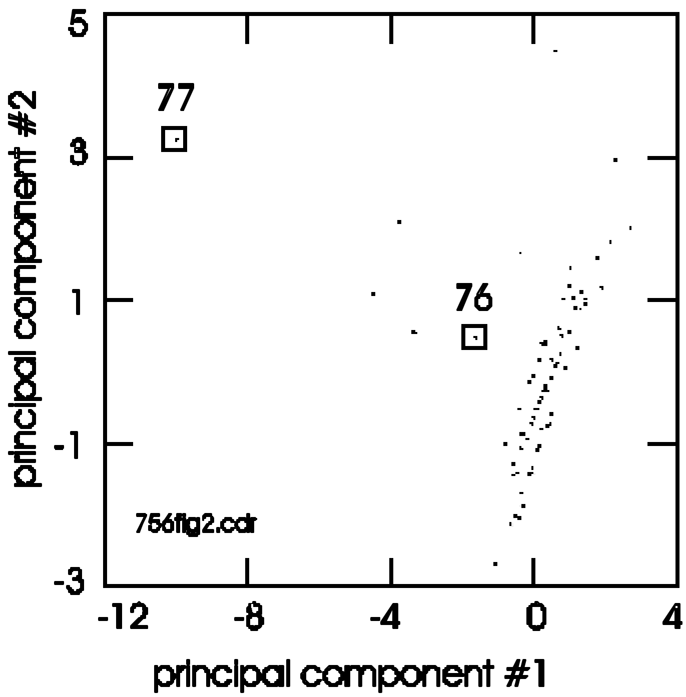



Figure 3.5. Plot of first two principal components.

To locate outliers, the residual sum of squares for a model composed of the first two principal components was calculated. A plot of the case numbers against the residual sum of squares can reveal outliers as those points with unusually large values of RSS (Krzanowski, 1993). This plot is shown in figure 3.6 below. An arbitrary cutoff value for RSS of ten was chosen to determine outliers. This revealed 11 outliers for a two dimensional model.

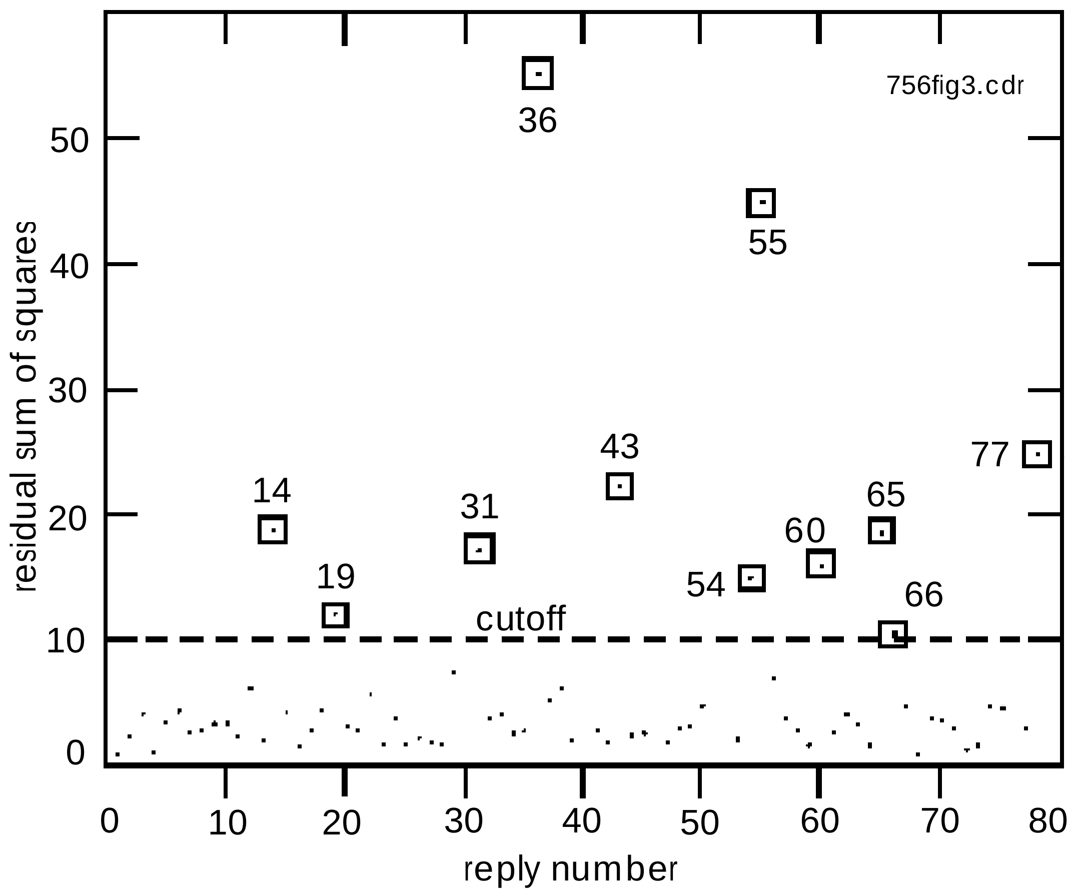



Figure 3.6. Outlier plot for a model comprised of only the first two principal components.

**Identification of firm strategies.** To gain insight into the nature of the deviations from the low dimensional model, a four dimensional plot was constructed (see Krzanowski, 1993, for discussion of the technique). This plot, shown in figure 3.7, both locates a point in two dimensional space, and provides two additional vectors representing the third and fourth dimensions respectively. The third dimension is plotted horizontally, and positive values are indicated by a rightward, or easterly, orientation. The fourth dimension is plotted vertically, and positive values point upward, or north. Case numbers of outliers are indicated on the plot.

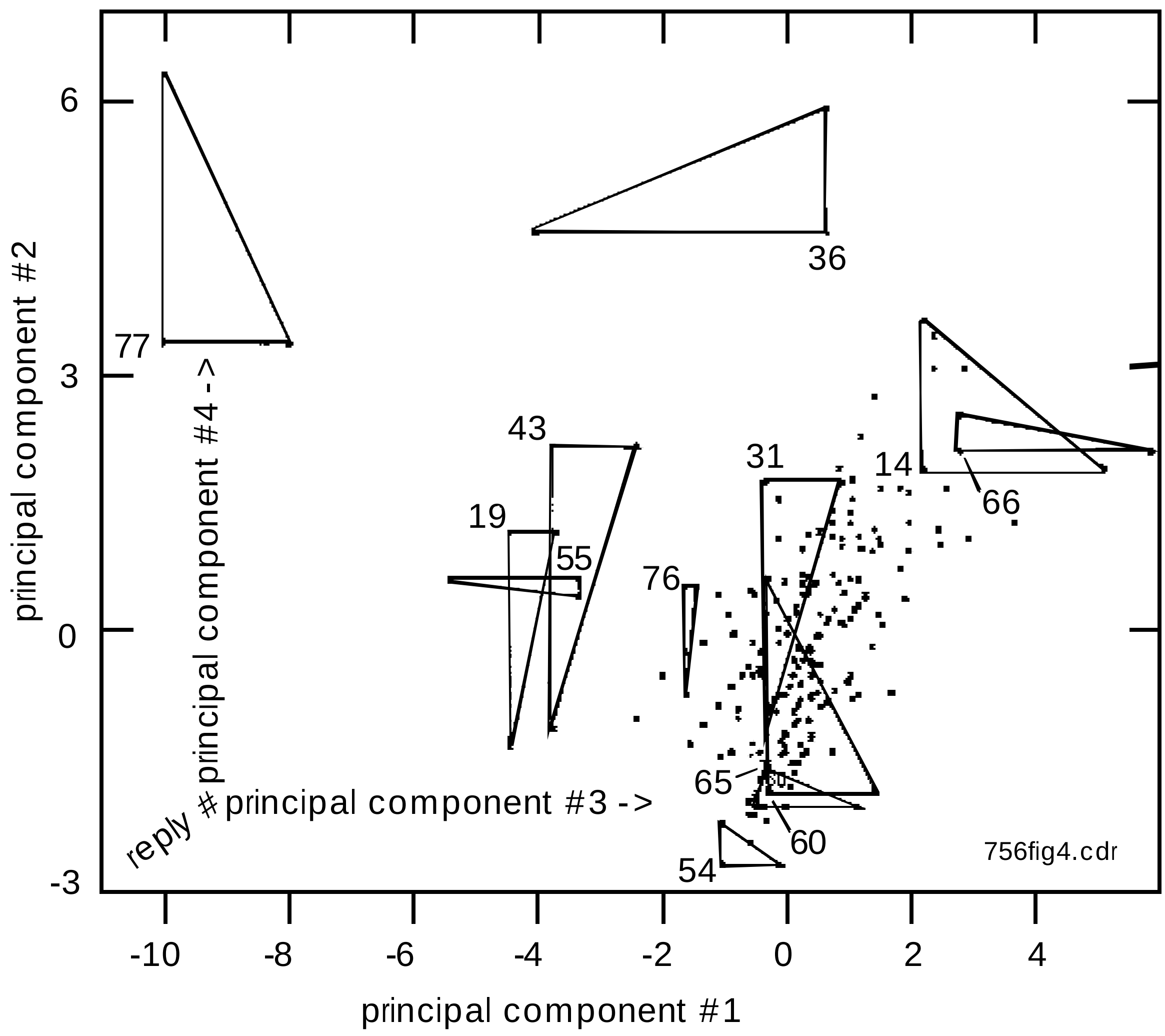



Figure 3.7. A four-dimensional plot of the first four principal components.

The point closest to the number is the company's position along the first two principal components.

Strategy 1. Figure 3.7 reveals that the mass of points differentiated by investment level tend to be adequately represented in two dimensions. Those farther removed from the mass tend to have more complex strategies. Thus companies who fall into the mass of points will be referred to as those companies characterized by STRATEGY 1, a 'feature-poor' or virtual lack of advanced service feature defined strategy. This makes up 75 % of the telephone companies in the state.

Strategy 2. Of the remaining companies, an examination of the four dimensional plot suggests that the companies Century (19), Mount Horeb Telephone (44), and to a lesser extent Lakefield Telephone (31), seem to be similar to each other in four dimensional space. This second group seems to share a strategy characterized by slightly higher investment, little use of digital switches and narrow band ISDN lines in business service, short subscriber distance to switches, a preponderance of digital transmission line, and light use of enhanced 911 and Signalling System 7 in switches. Thus, STRATEGY 2 shows little attention to advanced switching services, but a somewhat higher level of investment in transmission.

Strategies 3A and 3B. The remaining companies seem to have individually defined strategies. One possible exception to this is a cluster of similar businesses composed of the companies Chibardun Telephone (14), Tri-County Telephone (66), and Riverside Telcom (54). These companies are similar in dimensions three and four, and are differentiated by investment level. This differentiation splits the group into two. The first sub-group (STRATEGY 3A) is made up of Tri-County Telephone and Chibardun Telephone. These companies are generally slightly oriented toward increased investment, with heavy use of digital switches and narrow band ISDN lines in business service, and general use of digital transmission. They have unusually high proportions of enhanced 911 and Signalling System 7 switching, and customers are generally close to, to fairly far from switches. The other sub-group consists of only Riverside Telcom (STRATEGY 3B). It employs a very similar strategy to Tri-County Telephone and Chibardun Telephone, however its level of investment is low, and it is slightly negative on the first principal component.

However, it is important to note that in general the vast majority of the small firms have virtually indistinguishable line, switch, and special service allocation strategies.

The larger companies, Wisconsin Bell (77) and GTE North (76), have very different strategies. While Wisconsin Bell is far removed from the other firms, GTE North employs a strategy very similar to STRATEGY 1. Wisconsin Bell on the other hand is characterized by high investment, very light use of digital switches and narrow band ISDN lines in business service, very short subscriber distance to switches, a preponderance of digital transmission line, and unusually frequent use of enhanced 911 and Signalling System 7. GTE North on the other hand can be differentiated from STRATEGY 1 only by a slightly negative position along the first principal component, and moderately light use of enhanced 911 and System 7 switching. Thus, there does not seem to be support for the notion that large companies would have a common competitive strategy. Rather, it seems that complex competitive strategies tend to be individually determined by the companies regardless of firm size.

The first four principal components explain a total of 63.2% of the variance in the data. While examination of the information contained in these dimensions shed considerable light upon the competitive strategies employed by Wisconsin telephone companies, the inclusion of a fifth component would add an additional 8.6% explained variance to the model. The utility of including a fifth dimension was confirmed by examination of the RSS plot for a model consisting of only the first four principal components. This plot is shown in figure 3.8. It reveals that seven points can still be considered to be outliers.

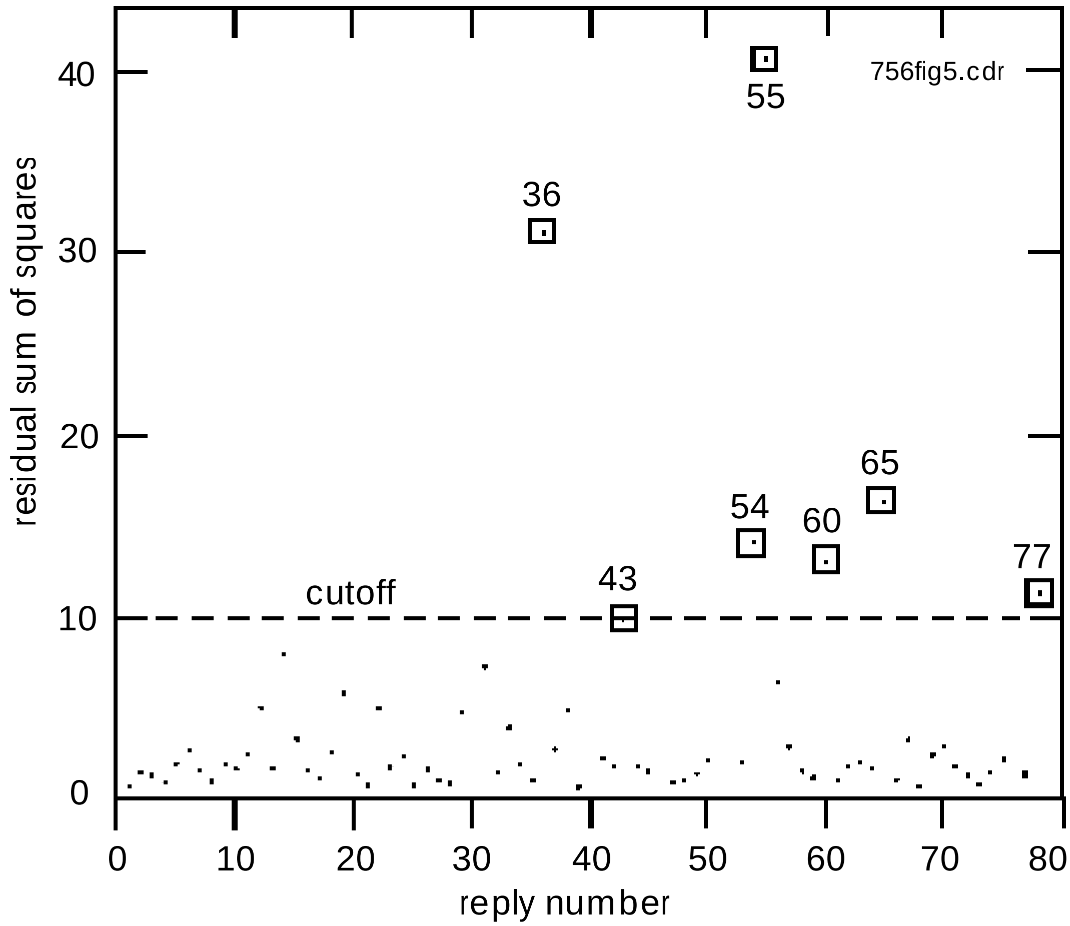



Figure 3.8. Outlier plot for a model composed of the first four principal components.

Inclusion of the fifth principal component in the model removed three of the seven companies from outlier status. These are Riverside Telcom, Siren Telephone, and Wisconsin Bell. Of these, Riverside Telcom and Siren Telephone (60) position moderately negatively on the fifth principal component (coordinates: Riverside Telcom = -2.03, Siren

Telephone = -2.17), suggesting that they can be characterized by slightly smaller proportions of business customers. Wisconsin Bell positions slightly on the positive side of this component (coordinate = 1.18), suggesting that it has slightly more business customers than the norm, in addition to the profile offered above. It is important to note that thus far, the proportion of business customers has not broken up any of the strategies outlined above. Of the remaining outliers from the four dimensional model, only Mount Horeb Telephone was previously included in a strategy (STRATEGY 2). Its position on the business customers dimension (coordinate = .499) is so slight that although it has more business customers than the norm, it is unfair to say that this dimension breaks up the strategy. Finally, Maple Telephone Cooperative (36) (coordinate = 2.47) has a moderately strong business customer base, while Rhinelander Telephone (55) and Tenney Telephone (65) have moderately weak business customer bases (coordinates = -3.58 and -2.33 respectively).

Finally, it is useful to point out that all but Rhinelander Telephone are removed from outlier status when a model consisting of the first six principal components is constructed. This suggests that this company has the most complex strategy, based upon the variables included in this analysis.

**Conclusions.**

**Identification of competitive strategies of Porter (1985).**

Principal components analysis of the structure and strategy of an industry enables the identification of the particular strategies which are operative in a specific industry.  For example in the Wisconsin telephone industry a small number of strategies are identified, which have been summarized in table 3.2 below.[6]

| Strategy | Relation to Porter | Characteristics |
|---|---|---|
| 1 | Low cost. | Fewer service features, lower investment. |
| 2 | Low cost. | Fewer service features, higher investment. |
| 3A | Differentiation. | Many service features, higher investment. |
| 3B | Differentiation. | Many service features, lower investment. |
| case 77 | Focus. | (Wisc. Bell -- see conclusions.) |

Table 3.2.  (Reproduced.)

Competitive strategies identified.

Casting the strategies identified in terms of the three competitive strategies of Porter (1985) may next be of value,

[6] More will be said about the utility of the identified strategies as they pertain to the Wisconsin telephone industry about 30 pages hence, after there has been an opportunity to explore the predictions of the Hatfield Model.

because it permits a simple metaphor for the strategies identified. For example, STRATEGY 1 and STRATEGY 2 appear most like Porter's competitive strategy of low cost. STRATEGIES 3A and 3B are most like Porter's differentiation. The two main components from which the allusion to Porter is constructed relate to the number of service features and level of investment, as shown in table 3.2. Within the low cost and differentiation strategies, STRATEGY 1 appears to be a fuller expression than STRATEGY 2 and similarly 3B than 3A, because 1 and 3B achieve the desired service levels at lower levels of investment within each strategy.

Finally Wisconsin Bell (Ameritech) (77), which is far removed from the other firms with respect to its principal components scores and which serves two large urban areas, can be thought of as exhibiting Porter's focus strategy. Wisconsin Bell scores high in certain service features, like enhanced 911 & Signalling System 7 (both principal component (PC) 4), and digital transmission (PC 3). Also Wisconsin Bell scores high in level of investment (PC 2), all of which is consistent with a focus strategy designed to best serve the demands of its urban customers. And yet Wisconsin Bell was found to score low overall on the variables relating to digital service features (PC 1, the most significant).

Given the strong economy of density in its urban service territory and the economy of scale present for such a comparatively large firm in this industry, one ought to wonder why Wisconsin Bell should score so high in investment and yet so low generally in service features (see figure 3.5). Furthermore, why should there be a high score on digital transmission facilities on a per-customer basis, when economies of density are also present for the firm in switch location and interconnection with the long-distance network? Possible explanations for such deviation from industry mean behavior may reside in the presence of rents, I/O inefficiency, or some strategy for this firm which is not articulated by the set of industry measures used here. (Could Ameritech be cross subsidizing the construction of its cellular “local calling area?”)

**Limitations of Porter (1985).**

A strong note of caution is in order with regard to inter-firm differences generally and their use as a basis for identifying strategic groupings along the lines of Porter. For most of the firms differences are slight, especially for principal component 1. Alternate explanations may exist for much of the variation displayed for principal component 2 (see figure 3.5). In particular each individual rural service area can be expected to impose its own demands on the level of transmission investment. So there is little basis for a strategic grouping approach without further taking into account certain dynamics of individual firms.

Using the language of Porter to describe firms rather than directly examining the scores on principal components resulting from a proper multivariate analysis can be misleading. The effect of the Porter (1985) model is to reduce to a single dimension a firm behavior that is actually better described by the interplay of two or more principal components, as is seen for example with Wisconsin Bell. And yet judging by a reading of the periodical "MIS Quarterly" in recent years and observing industry presentations, Porter is used almost exclusively in the telecommunications industry to describe firm strategy. I see little empirical support in this study for such reliance on Porter by the industry.

**A top performer.**

A bright spot in the analysis is the identification of Riverside Telcom (54), STRATEGY 3B, as exhibiting a high score in service features and a low score in level of investment. This firm is the best performer, in that it has achieved a high level of service at low cost. Other firms might benefit from this paradigm as they prepare for the changing competitive environment ahead.

What has been accomplished so far is a static analysis, rich in implication, and which makes optimal use of the various kinds of information available about the firms in this industry.  Principal components analysis appears to hold much promise as an additional tool for improving the quality of policy formulation in this industry.

## 1.2. An estimate of the cost of universal wireline telephone service for the State of Wisconsin, utilizing a cost-proxy model.

### Introduction.

What does it cost to provide telephone service? This question is important, because the cost of the existing institutional choice of basic universal wireline service serves as a benchmark by which proposed alternatives can be evaluated.

There are a number of different approaches to understanding the cost of providing a merit good such as the public switched telephone network. One approach might be to value the network at its historical cost of acquisition, as reflected in the accounting records of the providers, net of depreciation. In turn there are various methods for understanding the useful service life of the capital stock of the firms, for applying depreciation, and for risk spreading in projects undertaken to provide service to customers. But while a historical methodology reflects well the decision history of management and regulators overseeing the good, the trajectory of technology, particularly with regard to declining cost curves of the core technologies of the firms, is ignored. In the next chapter I explore the implications of the trajectory of silicon with regard to cost and the feasible set of radio frequency spectrum for providing service. Similarly the technology of glasses has yielded to date a ten-fold reduction in the cost of bulk transmission of messages. The historical cost method is ignorant of these revolutions in the technology of telecommunications.

The Bellcore model is a second approach to estimating the cost to construct a system that exactly replicates the geographical configuration of the existing network, but which makes use of present-day "off-the-shelf" equipment and labor costs. Because this method estimates cost using a surrogate for the capital stock actually in place, it constitutes a "proxy"-cost model. In addition the substitution of current technology choices for the historical capital stock makes this method "forward looking."[7] The Bellcore model is popular with incumbent firms, which find in it a way to include their past judgements about deployment decisions made over the course of building their systems, while taking into account changes in technology.

A third method relaxes the constraint that the geographic

---

[7] I would have preferred that it be termed "present looking," to acknowledge the validity of a possible additional method using R&D-established technologies planned by industry for future roll-out. A possible difficulty with the Bellcore model is that this method relies on a proprietary data set describing the physical infrastructure of the regional Bell operating companies.

arrangement of the network elements must mimic that currently in place. The method posits a network optimally arranged to service the present-day distribution of customers. Past decision making is now largely erased. This is the approach taken in the Hatfield Model and the various generations of the Benchmark Cost Proxy Model (BCPM).[8]

Other cost estimation methodologies exist, but these have not gained wide acceptance by regulatory agencies.[9]

**Characteristics of cost-proxy models.**

As mentioned, the fundamental approach of the dominant cost-proxy models is to estimate the cost to construct a system that exactly replicates the service extent and characteristics of the existing network, using “off-the-shelf” capital equipment and labor. In addition the use of current technology makes these models “forward looking.”

A compact overview of the Hatfield Model appears in New York Public Service Commission Opinion Number 97-2 (95-C-0657) at 135 and 143:

---

8 The Hatfield Model is jointly sponsored by AT&T and MCI, both potential entrants into markets for local telephone service. The BCPM is sponsored by Bell Atlantic and others who in part represent incumbent providers.

9 Some of these methods are described in the public record of the hearing in a Pennsylvania Docket (I-00940035) concerning the cost of basic universal telephone service in that state.

"To estimate demand, the Hatfield Model's first module starts with data regarding each state's census block groups [CBGs], each of which is assumed to be served from the nearest existing [sic] wire center of the incumbent LEC. Through a variety of calculations, which take account as well of access line and usage demand data reported by New York Telephone, the model determines the number of residential, business, special access, and public lines in each CBG. [¶] In its next module, the model uses the distance between each CBG and its serving wire center as well as topographical considerations, to estimate feeder and distribution cable lengths. It does so on the basis of a variety of assumptions, such as the existence of four main feeder routes leaving each wire center, with subfeeder routes placed at 90-degree angles from the main feeder routes, and the uniform spacing of customer premises across a CBG. On the basis of geometric relationships, it calculates average distribution distance within a CBG to equal five-eighths of the length of one side of the CBG.[103]

To estimate switching, signaling, and transport investment, the model's wire center investment module uses the total line counts for each wire center along with data on inter-office distances and the distribution of total traffic among varying services as well as assumptions regarding traffic. On that basis, it calculates such items as the size of the switches to be placed in each wire center and the amount of trunk capacity needed.[104]"

... (continuing in p. 143) "The Hatfield model's 'BCM-PLUS loop module' estimates loop cable facilities investment via a ' "bottom-up" network design process that uses forward-looking loop plant engineering and planning practices, publicly available information on component prices, and least-cost cable sizing algorithms to estimate the outside plant investment appropriate to a TELRIC-based analysis[10].' [139] Recognizing that prices paid for loop components may vary from carrier to carrier, the model allows these values to be adjusted by the user but employs default values based on Hatfield's best estimates. As already noted, it assumes that fiber feeders would be used above a crossover point to be set

---

10 Hatfield Model Description (1997a, 15).

by the user (the default value is 9,000 feet); for shorter feeder lengths it assumes copper cable.

The model's wire center investment module produces investment estimates for, among other things, switching and wire centers, the signalling network, including STPs, SCPs, and signalling links, and transport investment."

... "In its convergence module, the model combines the loop cable investments with those for the other elements and produces the complete collection of network investments stated by density range."

... "It also provides a user defined input for the fraction of structure investment that should be assigned to local telephone service as distinct from other utility services (such as electric and cable television) that share poles, trenches, or conduits."

**Selection of a particular model.**

Both the BCPM and Hatfield Models rely in part on firm-proprietary data. The Hatfield Model also relies on proprietary information about price levels of equipment, based on discussions with equipment suppliers about closing prices in equipment sales to LECs (I-00940035, 1995). The intent of Hatfield apparently is to introduce still greater realism into the cost estimate.

The BCPM as a whole is a proprietary and closed model, in that persons using it are not allowed to make any modifications to the data set beyond those permitted by the sponsoring telecommunications companies. In addition the BCPM must be used in its entirety -- Users of the BCPM may not entertain technology choices beyond those currently identified by the regional Bell operating companies (RBOCs).

The BCPM doesn't constitute a proper basis for scholarly study, because the model restrictions prevent the insertion of the cost characteristics of new technology for providing outside plant.[11] In addition the BCPM restriction that the location of switches and wire centers be identical to that historically in place would violate the duty of firms to their shareholders to optimally arrange their network elements when hypothetically faced with a decision to build a network. (Optimal network element arrangement is consistent with profit maximization, given a hypothetical rebuilding.)

Though the Hatfield Model contains proprietary data, users of the model remain free to replace sections of the model with new ones that are not proprietary and to explore other technology choices within the framework of the model. Thus the Hatfield Model can become truly "forward looking." Given these advantages and the fact that the model has achieved widespread respect in regulatory settings,[12] I have

---

[11] Whether the BCPM remains a proper object of regulatory decision making is a question left to others.

[12] The BCPM dominates recent discussion. The FCC has been considering both the BCPM and the Hatfield Model as contenders for the mechanism by which to allocate federal universal service support, and was to have made a final determination by August, 1998 (FCC DA 97-1912 in CC Docket Nos. 96-45 and 97-160). I understand that a final decision has been delayed (Wiecki, 1998).

chosen to employ the Hatfield Model in my estimate of the cost of universal telephone service for the people of Wisconsin.

The Pennsylvania docket (I-00940035) contains testimony concerning the detailed methodology of the Hatfield Model design. In addition that design is critiqued at length in New York Public Service Commission Opinion Number 97-2 (95-C-0657). The authors of the model describe it fully in Hatfield (1997a). The input data set is shown in Hatfield (1997b).

**Discussion of the predictions of the Hatfield Model for Wisconsin.**[13]

The Hatfield Model was run for each of the telephone companies providing local service to Wisconsin residents, using the default scenario assumptions concerning the prices of equipment and labor, the determination of the amount of fiber to include in trunks, information about the local land conditions and census data concerning the population distribution.

A summary of the results of each run appears below in

---

13 The Hatfield Model Release 4.0 (dated 080197) used in this study is copyrighted (1997) and owned jointly by Hatfield Associates, Inc., AT&T Corporation, and MCI Telecommunications Corporation. The antecedent BCM-PLUS Model is owned by MCI. The model may contain licensed, proprietary information of Bellcore or PNR & Associates, Incorporated. (Dale Hatfield is currently employed at the FCC as chief technologist in the Office of Plans and Policy (QST, Feb 98, 76).)

table 3.4. An overall summary appears on the final page of that table. The right half of the table is comprised of logical variables representing the existence of certain ranges of customer density in each service territory. Note that the %_DLC variable represents that fraction of the customer lines provided using digital loop carrier technology, which is a kind of multiplexing. The Per Unit Cost of Service variable is the sum of outside plant (loop), switching, signaling, transport, operator systems and public telephones.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hatfield Model, V. 4 Summary of Wisconsin TELCOs using default scenario. | | | | | | | | | | | |
| 2 | ..\hat4sum1.wb2 | | | | | | | | | | | |
| 3 | A1..O144 | Number | Per unit cost | | % | Density (lines terminated per square mile): | | | | | | |
| 4 | Company name | of lines | of service ($) | | DLC | 0 to | 5 to | 100- | 200- | 650- | 850- | > 2550 |
| 5 | All lines | 3,426k | total | switch | | 5 | 100 | 200 | 650 | 850 | 2550 | |
| 6 | Large TELCOs: | | | | | | | | | | | |
| 7 | Wisc. Bell (Ameritech) | 2,397k | 26.8 | | | | | | | | | |
| 8 | GTE Wisconsin | 456k | 35 | 1.17 | 0.71 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | Small TELCOs | 572k | | | | | | | | | | |
| 10 | All non-RBOC companies | 1,028k | 40 | 1.94 | 0.7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 11 | | | | | | | | | | | | |
| 12 | Small TELCOs: | | | | | | | | | | | |
| 13 | Amery | 5824 | 49 | 2.31 | 0.8 | | 1 | | 1 | | | |
| 14 | Amherst | 4373 | 60 | 2.62 | 1 | | 1 | | | | | |
| 15 | Badger Telecom | 6828 | 49 | 2.43 | 0.74 | 1 | 1 | 1 | | 1 | | 1 |
| 16 | Baldwin Telecom | 3500 | 46 | 2.43 | 0.36 | | 1 | | 1 | 1 | | |
| 17 | Bayland Telephone | 1682 | 72 | 2.48 | 1 | | 1 | | | | | |
| 18 | Belmont Telephone | 792 | 108 | 2.53 | 0.6 | | 1 | 1 | | | | |
| 19 | Bergen | 185 | 361 | 4.08 | 1 | | 1 | | | | | |
| 20 | Black Earth | 1419 | 62 | 2.58 | 1 | | | 1 | | | | |
| 21 | Bloomer | 2955 | 41 | 2.34 | 0.35 | | 1 | 1 | 1 | | | |
| 22 | Bonduel | 1740 | 45 | 2.59 | 0 | | | | 1 | | | |
| 23 | Bruce | 1534 | 79 | 2.59 | 0.54 | 1 | 1 | 1 | | | | |
| 24 | Burlington, Brighton & Wheat. | 3378 | 46 | 2.57 | 0.47 | | 1 | 1 | 1 | 1 | | |
| 25 | Casco | 1112 | 100 | 2.75 | 1 | | 1 | | | | | |
| 26 | Cencom dba PTI | 26910 | 53 | 2.49 | 0.76 | 1 | 1 | 1 | 1 | | 1 | |
| 27 | Central State | 9432 | 61 | 2.54 | 1 | 1 | 1 | | | | | |
| 28 | Century of North Wisc. | 13909 | 76 | 2.71 | 1 | 1 | 1 | | | | | |
| 29 | Century of Northwest Wisc. | 17685 | 57 | 2.53 | 0.91 | 1 | 1 | 1 | 1 | | | |
| 30 | Century of Larsen - Readfield | 2442 | 76 | 2.71 | 1 | | 1 | | | | | |
| 31 | Century of Monroe County | 10309 | 41 | 2.46 | 0.6 | 1 | 1 | 1 | 1 | | 1 | 1 |
| 32 | Century of Wisconsin, Inc. | 57937 | 21 | 2.26 | 0.45 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 33 | Chequamegon Telephone Coop. | 8656 | 86 | 2.76 | 1 | 1 | 1 | | | | | |
| 34 | Chibardun Tele Coop. | 5281 | 69 | 2.68 | 1 | 1 | 1 | 1 | | | | |
| 35 | Citizens Tele Coop | 2008 | 87 | 2.63 | 1 | | 1 | | | | | |
| 36 | Clear Lake Tele Co. | 1322 | 77 | 2.62 | 1 | | 1 | | | | | |
| 37 | Cochrane Cooperative Tele | 1178 | 87 | 2.7 | 1 | | 1 | | | | | |
| 38 | Coon Valley Farmers Tele Co. | 2128 | 87 | 2.6 | 1 | 1 | 1 | | | | | |
| 39 | Crandon Tele Co. | 3395 | 62 | 2.34 | 1 | 1 | 1 | 1 | | | | |
| 40 | Cuba City Tele Exchange | 1647 | 59 | 2.58 | 0.25 | | 1 | | 1 | | 1 | |
| 41 | Dickeyville Telephone Corp. | 1154 | 96 | 2.72 | 1 | 1 | 1 | | | | | |
| 42 | Eastcoast Telecom, Inc. | 6055 | 46 | 2.55 | 0.83 | | 1 | 1 | | | | |
| 43 | Fairwater- Brandon- Alto Tele | 1219 | 86 | 2.68 | 1 | | 1 | | | | | |
| 44 | Farmers Independent Tele Co. | 2244 | 65 | 2.77 | 1 | 1 | 1 | 1 | | | | |
| 45 | Farmers Tele Co. | 6295 | 46 | 2.49 | 0.55 | 1 | 1 | 1 | 1 | | | 1 |
| 46 | Forestville Tele Co., Inc. | 2180 | 76 | 2.79 | 1 | 1 | 1 | | | | | |
| 47 | Frontier Comm. of Lakeshore | 1922 | 69 | 2.42 | 1 | | 1 | | | | | |
| 48 | Frontier Comm. of Mondovi | 2423 | 60 | 2.36 | 0.64 | 1 | | 1 | | 1 | | |
| 49 | Frontier Comm. of St. Croix | 7803 | 36 | 2.42 | 0.44 | | 1 | 1 | 1 | | 1 | |
| 50 | Frontier Comm. of Viroqua | 3659 | 37 | 2.26 | 0.6 | | 1 | 1 | 1 | | | 1 |
| 51 | Frontier Comm. of Wisconsin | 22953 | 38 | 2.43 | 0.51 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 52 | Grantland Telecom, Inc. | 3853 | 58 | 2.58 | 0.86 | 1 | 1 | 1 | 1 | | | |
| 53 | GTE Wisconsin | (See above) | | | | | | | | | | |
| 54 | Hager Telecom, Inc. | 1751 | 96 | 2.45 | 1 | | 1 | | | | | |
| 55 | Headwaters Telephone Co. | 4611 | 72 | 2.69 | 1 | 1 | 1 | | | | | |
| | | Number | Per unit cost | | % | Density (lines terminated per square mile): | | | | | | |
| | Small TELCOs: | of lines | of service ($) | | DLC | 0 to | 5 to | 100- | 200- | 650- | 850- | > 2550 |
| | | | total | switch | | 5 | 100 | 200 | 650 | 850 | 2550 | |

Table 3.4. (Continues)

| | Small TELCOs: | Number of lines | Per unit cost of service ($) total | switch | % DLC | Density (lines terminated per square mile): 0 to 5 | 5 to 100 | 100-200 | 200-650 | 650-850 | 850-2550 | > 2550 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56 | Hillsboro Telephone Co., Inc. | 1578 | | | 0.32 | | 1 | 1 | | | | |
| 57 | Indianhead Telephone Co. | 2040 | 88 | 2.62 | 1 | 1 | 1 | | | | | |
| 58 | Kendall Telephone, Inc. | 581 | 153 | 2.67 | 1 | | 1 | | | | | |
| 59 | La Valle Telephone Coop. | 1823 | 79 | 2.69 | 1 | | 1 | | | | | |
| 60 | Lakefield Telephone Co. | 1493 | 84 | 2.53 | 1 | | 1 | | | | | |
| 61 | Lemonweir Valley Telephone Co | 3091 | 70 | 2.55 | 1 | 1 | 1 | 1 | | | | |
| 62 | Luck Telephone Co. | 2202 | 82 | 2.58 | 1 | 1 | 1 | 1 | | | | |
| 63 | Manawa Telephone Co., Inc. | 2268 | 64 | 2.6 | 0.56 | | 1 | | 1 | | | |
| 64 | Marquette- Adams Tele Coop | 3360 | 56 | 2.68 | 0.72 | | 1 | 1 | | | | |
| 65 | Mid- Plains Telephone, Inc. | 29866 | 21 | 2.23 | 0.44 | | 1 | 1 | 1 | | 1 | 1 |
| 66 | Midway Telephone Co. | 7824 | 45 | 2.43 | 0.83 | 1 | 1 | | 1 | | 1 | |
| 67 | Milltown Mutual Telephone Co. | 2277 | 63 | 2.59 | 0.55 | | 1 | | 1 | | | |
| 68 | Mosinee Telephone Co. | 4588 | 50 | 2.18 | 0.64 | 1 | 1 | 1 | 1 | | 1 | |
| 69 | Mt. Horeb Telephone Co. | 4000 | 39 | 2.24 | 0.46 | | 1 | 1 | 1 | | | |
| 70 | Mt. Vernon Telephone Co. | 8141 | 39 | 2.46 | 0.54 | | 1 | 1 | 1 | | | |
| 71 | Nelson Telephone Coop | 3682 | 64 | 2.61 | 0.74 | 1 | 1 | | 1 | | | |
| 72 | Niagara Telephone Co. | 3956 | 63 | 2.69 | 1 | 1 | 1 | 1 | | | | |
| 73 | North-West Tele Co. dba PTI | 75299 | 36 | 2.41 | 0.71 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 74 | Northeast Telephone Co. | 6647 | 48 | 2.44 | 0.78 | | 1 | 1 | 1 | | 1 | |
| 75 | Peoples Telephone Co. | 6422 | 51 | 2.73 | 0.54 | | 1 | 1 | | 1 | | |
| 76 | Platteville Tele Co. dba PTI | 8961 | 31 | 2.31 | 0.4 | | 1 | 1 | 1 | 1 | 1 | 1 |
| 77 | Price County Telephone Co. | 4483 | 70 | 2.37 | 0.83 | 1 | 1 | | 1 | | | |
| 78 | Rhinelander Telephone Co. | 13263 | 33 | 2.21 | 0.66 | 1 | 1 | 1 | | 1 | 1 | 1 |
| 79 | Rib Lake Telephone Co. | 1248 | 98 | 2.66 | 1 | 1 | 1 | | | | | |
| 80 | Richland- Grant Telephone Coop | 2502 | 86 | 2.84 | 1 | | 1 | | | | | |
| 81 | Riverside Telcom, Inc. | 3008 | 53 | 2.63 | 0.59 | | 1 | | 1 | | | |
| 82 | Scandinavia Telephone Co. | 2559 | 67 | 2.54 | 0.48 | | 1 | 1 | | | | |
| 83 | Sharon Telephone Co. | 985 | | | 1 | | 1 | | | | | |
| 84 | Siren Telephone Co. | 2340 | 50 | 2.4 | 0.47 | | 1 | | 1 | | | |
| 85 | Somerset Telephone Co. | 1907 | 68 | 2.41 | 1 | | 1 | | | | | |
| 86 | Southeast Telephone Co. | 7890 | 38 | 2.38 | 0.73 | | 1 | 1 | 1 | | | |
| 87 | Spring Valley Telephone Co. | 958 | 88 | 2.47 | 0.39 | | 1 | 1 | | | | |
| 88 | State Long Distance Teleph. Co. | 8387 | 30 | 2.41 | 0.49 | | 1 | 1 | | 1 | | 1 |
| 89 | Stockbridge&Sherwood Tel. Co. | 2855 | 87 | 2.75 | 1 | | 1 | | | | | |
| 90 | Tenney Telephone Co. | 1011 | 104 | 2.37 | 1 | 1 | 1 | | | | | |
| 91 | Thorp Telephone Co. dba PTI | 2151 | 72 | 2.43 | 0.51 | 1 | 1 | | 1 | | | |
| 92 | Tri-County Telephone Coop, Inc. | 3684 | 71 | 2.86 | 0.79 | 1 | 1 | 1 | | | | |
| 93 | Union Telephone Co. | 4061 | 63 | 2.79 | 1 | 1 | 1 | | | | | |
| 94 | Wisconsin Utelco, Inc. | 15054 | 34 | 2.4 | 0.58 | | 1 | 1 | 1 | 1 | 1 | 1 |
| 95 | Vernon Telephone Coop | 6104 | 63 | 2.74 | 0.87 | | 1 | 1 | | | | |
| 96 | Waunakee Telephone Co. | 6190 | 33 | 2.32 | 0.67 | | 1 | 1 | 1 | | 1 | 1 |
| 97 | Wayside Telephone Co. | 1335 | 176 | 3.52 | 0.87 | 1 | 1 | | | | | |
| 98 | West Wisc. Telcom Coop | 5106 | 57 | 2.73 | 1 | | 1 | 1 | 1 | | | |
| 99 | Wisconsin Bell | (See above) | | | | | | | | | | |
| 100 | Wittenberg Telephone Co. | 2556 | 58 | 2.56 | 0.57 | | 1 | | 1 | | | |
| 101 | Wood County Telephone Co. | 25046 | 30 | 2.24 | 0.58 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| | Small TELCOs: | Number of lines | Per unit cost of service ($) total | switch | % DLC | Density (lines terminated per square mile): 0 to 5 | 5 to 100 | 100-200 | 200-650 | 650-850 | 850-2550 | > 2550 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 102 | | ====== | | | | | | | | | | |
| 103 | Small TELCO total lines (all 86): | 572,465 | | | | | | | | | | |
| 104 | | ====== | | | | | | | | | | |
| 105 | | | | | | ==== | ==== | ==== | ==== | ==== | ==== | ==== |
| 106 | Number of small companies with density shown: | | | | | 37 | 84 | 44 | 36 | 13 | 16 | 14 |
| 107 | | Fraction thereof (of 86): | | | | 0.430 | 0.98 | 0.511 | 0.42 | 0.151 | 0.186 | 0.16 |
| | | | | | | ==== | ==== | ==== | ==== | ==== | ==== | ==== |

Table 3.4. (Continues)

| | | | | |
|---|---|---|---|---|
| 108 | Small TELCO total lines (all 86): | | 572,465 | |
| 109 | Total number of small companies. | | 86 | |
| 110 | Number of companies with <10,000 lines: | | 75 | |
| 111 | Number of customers they serve: | | 339,533 | |
| 112 | Their combined market share on a per-line basis (%) | | 9.9 | |
| 113 | | | | |
| 114 | Weighted average cost of service (WACS) ($) (inclusive of switching)* | | | |
| 117 | | | | |
| 118 | WACS for all Wisconsin lines: | ($) | 31.1 | |
| 119 | WACS for all 86 small TELCOs: | | 46 | |
| 120 | WACS for TELCOs with <10,000 lines only: | | 45 | |
| 121 | WACS for GTE: | | 35 | |
| 122 | WACS for Wisc. Bell: | | 26.8 | |
| 123 | | | | |
| 124 | | | | |
| 125 | | | | |
| 126 | Weighted average cost of switching (WACSw) ($) (switching only)* | | | |
| 129 | | | | |
| 130 | WACSw for all Wisconsin lines: | | | |
| 131 | WACSw for all 86 small TELCOs: | ($) | 2.44 | |
| 132 | WACSw for TELCOs with <10,000 lines only: | | 1.95 | |
| 133 | WACSw for GTE: | | 1.17 | |
| 134 | WACSw for Wisc. Bell: | | | |
| 135 | | | | |
| 136 | | | | |
| 138 | | | | |
| 139 | Weighted average cost of service (WACS) ($) by population density* | | | No. of lines |
| 140 | WACS for TELCOs with only density <101 lines/mi2: | ($) | 78.8 | 83105 |
| 141 | WACS for TELCOs with only density <201 lines/mi2: | | 73 | 131317 |
| 142 | WACS for TELCOs with only density <651 lines/mi2: | | 65.2 | 211276 |
| 143 | WACS for TELCOs with only density <2551 lines/mi2: | | 60.2 | 282418 |

* Each firm's cost per line is multiplied by the number of total lines. Result is summed across all firms in that group, and then divided by the total number of lines served in that group.

---

Table 3.4. (Three pages.) A summary of simulations of the cost of universal telephone service for the State of Wisconsin, using the Hatfield Model Release 4.0.

**Basic predictions.** In Wisconsin in 1997 there were about 3.43 million telephone lines. A little over two thirds of these lines are owned by Wisconsin Bell (Ameritech). As the figure below illustrates, GTE owns almost half of the remaining lines not owned by Ameritech. Dozens of small telephone companies provide the remainder of service to Wisconsin residents.

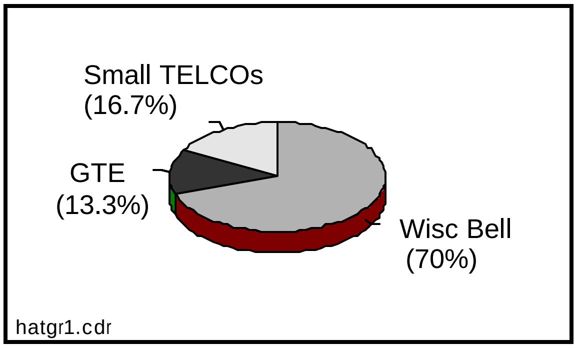
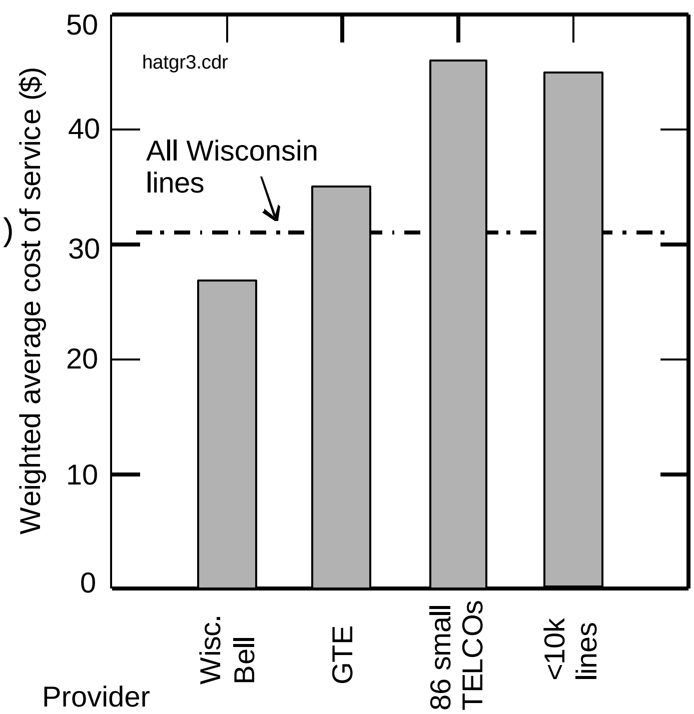



Figure 3.2. (Reproduced.) 1997 Market share of Wisconsin local telephone exchange carriers, on a per-line basis (Hatfield, 1997).

The key prediction of the Hatfield Model is an estimate of the cost of providing local telephone service to Wisconsin residents. The statewide average estimated cost is $31.10.

Figure 3.3. (Reproduced.) Weighted average cost of service (WACS) predicted by Hatfield (1997).

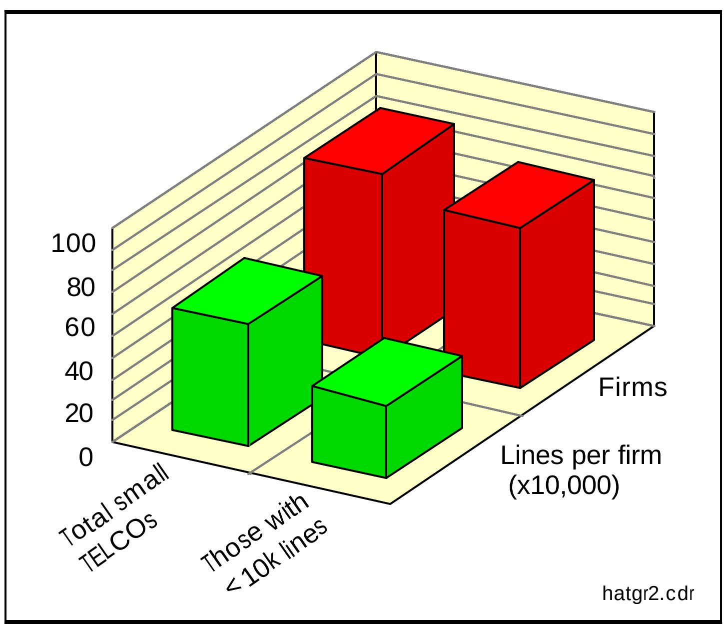


But there is quite a bit of structure that the average costs would otherwise obscure, as I explain in the next few pages.

Wisconsin Bell’s weighted average cost of service (WACS) is substantially below the predicted statewide average cost. The WACS of GTE is very close to the state average. More interesting however, is how the other 86 small telephone companies (TELCOs) stand in relation to the statewide average and to each other.

The 75 smallest TELCOS, those with less than 10,000 lines, each have a WACS slightly less than the whole ensemble of 86 small TELCOs. The advantage is slight, WACS for the smallest 75 firms is $45, as opposed to $46 for the entire 86 small firms. Interestingly, the smallest 75 providers also have a disproportionally smaller share of the number of lines.

Figure 3.9. A comparison of the 75 smallest TELCOs, having less than 10,000 lines each.



The implication is that the smallest of the small firms are able to enjoy a structural cost advantage of some sort. Note that the providers with less than 10,000 lines each together have 340,000 customers, a market share of 9.9 percent.

The firms with less that 10,000 lines have a lower cost of switching than all the small TELCOs taken together, in spite of there being an economy of scale in switch sizing.

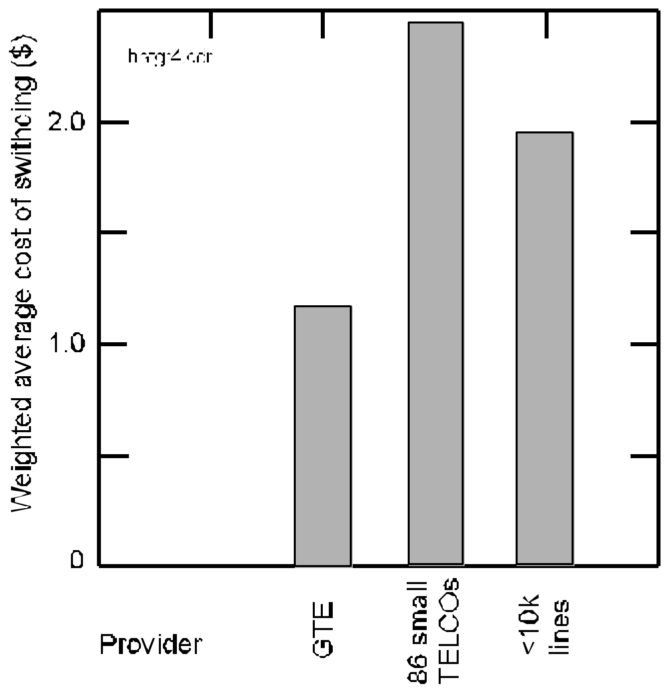



Figure 3.10. Weighted average cost of switching for Wisconsin telephone service providers. (Switching as portrayed here is central office only, not inclusive of tandem. Wisconsin Bell data is not represented in a comparable way.)

**Univariate analysis.** Simple univariate statistical analysis of the predicted WACS for the small TELCOs can demonstrate whether the predicted cost of service for each of the firms forms a more or less normal distribution. Univariate analysis also provides insight into possible outliers that might skew the WACS. A “dot plot” made for the 86 small firms is shown below:

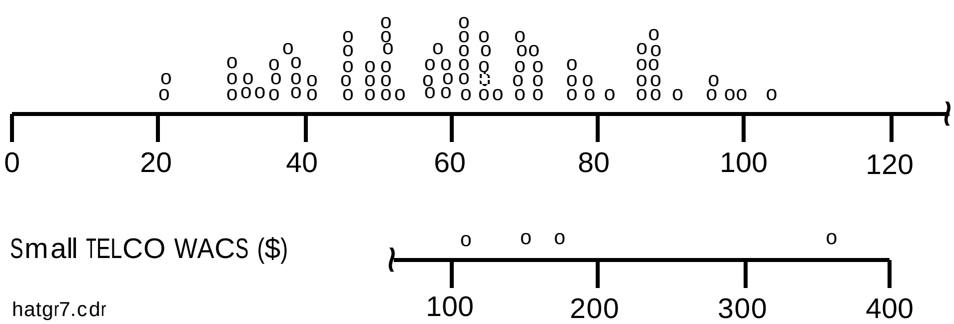



Figure 3.11. A dot plot of the cost of service for each of the small TELCOs.

| Provider | Cost of service | No. of lines |
|---|---|---|
| Bergen | $ 361 | 185 |
| Wayside Tel. Co. | 176 | 1,335 |
| Kendall Tel, Inc | 153 | 581 |
| Belmont | 108 | 792 |
| Tenney Telephone | 104 | 1,011 |

Table 3.5. The highest cost service providers.

As shown in table 3.5 above, there are five providers with a predicted cost of service above $100. Table 3.6 below shows what effect the highest predicted cost firms might have on the character of the distribution and on the small TELCO composite WACS. The standard deviation and WACS are calculated with outliers removed as follows:

| Configuration | WACS | Std. dev. | Simple ave | No. Lines |
|---|---|---|---|---|
| All 86 small | $45.97 | 40.9 | 66.9 | 572,465 |
| Less 1 highest | 45.87 | 25.6 | 63.4 | 572,280 |
| Less 3 highest | 45.46 | 20.4 | 61. | 570,364 |

Table 3.6. Effect of small TELCO outliers on standard deviation and weighted average cost of service (WACS).

By discarding the three highest predicted cost firms, the standard deviation declines markedly to a value that one’s intuition would expect for the plotted distribution, but the effect on WACS without the three highest cost firms is only about one percent. The five highest cost firms are all firms with less than 10,000 lines. Thus excluding three outliers from a reported WACS makes clearer the cost advantage of the 75 smallest firms.

**Effect of density in service territories.** The Hatfield model also reports the range of population densities that providers experience in their service territories. (See figure 3.12.) One can use this information to gain additional insight into the role that the firms that service the most thinly populated service territories play in the industry.

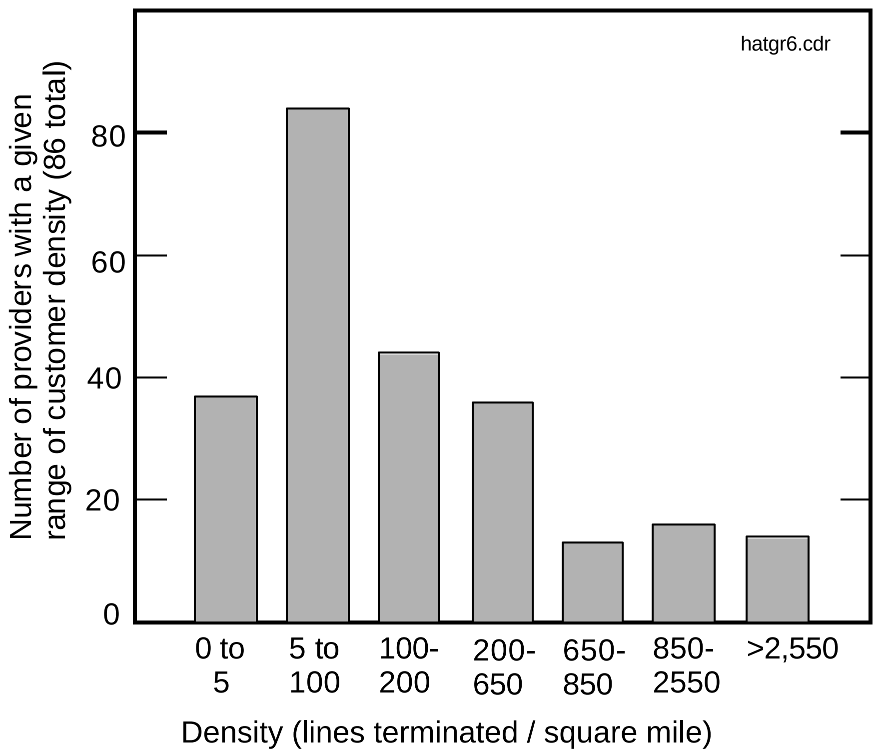



Figure 3.12. Distribution of population density in service territories of small TELCOs.

Nearly every firm has areas where the customer density is less than 100 lines per square mile, and a little over 40 percent of the small TELCOS experience areas where there are less than six lines per square mile. Areas with densities of less than ten lines per square mile are obvious candidates for wireless local loop. GTE reportedly now offers analog cellular phones to new customers in the lowest density regions of its service territories (PSCW, 1997). The universal prevalence of regions with less than 100 lines per square mile suggests that nearly every one of the small providers in Wisconsin could benefit from a low cost alternative to wireline technology.

Next, figure 3.13 shows the relation between firm size and cost of service. For the small TELCOs, those firms are identified that operate only at customer densities below certain threshold values. The result is that the very smallest firms are progressively isolated. For example, the firms that experience only customer densities up to 100 lines per square mile have a combined total of only 83,100 lines, or 2.4 percent of all Wisconsin lines. The weighted average cost of service for those firms is $79. As the maximum served density increases (roughly in factors of four) the WACS declines quasi-linearly. With the possible exception of the most egregious outlier, Bergen, which has a maximum customer density of 100, in Wisconsin at least there is no explosion in cost of service at the low end of density. However the three outliers excluded previously all have a maximum density of 100 lines per square mile. For densities below 650 the WACS rises from two to 2½ times the statewide average WACS. With this information about cost and density one can better gauge opportunities for providing wireless alternatives to basic telephone service in the most thinly populated regions of Wisconsin.

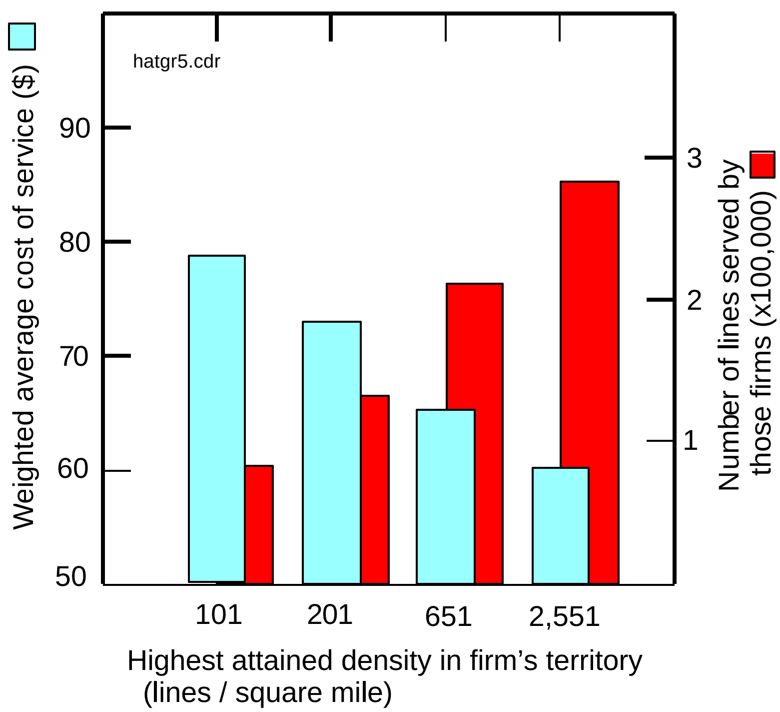



Figure 3.13. Effect of density on cost of service.

**1.3. Comparison with the multivariate model.**

The Hatfield Model is perhaps best understood as an algorithmic attempt to optimally construct the present using an input set consisting of technology (capital deployed in fixed assets of firms), a transfer function of the industry (which converts assets into usage), and certain exogenous aspects (population and geography). Because all firms use the same technology by assumption, all are assumed to be equally efficient.[14] The multivariate (principal components) model can be seen as an attempt to view the present industry structure in terms of those ingredients that best distinguish groups of firms. The multivariate model is alive, in the sense that it illuminates the inputs that a proxy cost model like Hatfield can analyze, commingled with subjective aspects like the quality of management and the effectiveness of regulation that have shaped the present. The two models only partially overlap, affording an opportunity to compare and contrast their views.

As noted above, the 75 smallest TELCOs enjoyed a slightly lower WACS than the other small TELCOs, even though the 75 have a disproportionally smaller share of customers of those

---

[14] Assuming all are equally good at obtaining management talent, which it turns out is a key determinant of firm efficiency.

served by small TELCOs. Because of the “scorched earth”[15] nature of the Hatfield Model, this predicted advantage cannot be due to the history of the relation between the Wisconsin industry and its regulators. By contrast, the multivariate model developed from survey data shows that cost differentiation among small providers could easily be due in some subtle way to the role of regulation.

The cost advantage of the smallest firms merits further investigation. One approach would be to list several firms which the Hatfield Model predicts would have the lowest cost and explore the correlation with the firms that the multivariate model revealed to be differentiated on the basis of low cost.

| **Provider name** | **WACS** ($) | **WACSw** ($) | **No. of Lines** | **Multivariate identified strategy** (See Tbl. 3.2.) |
|---|---|---|---|---|
| Century of Wisc. (La Crosse area only) | 21 | 2.40 | 57,937 | n/a |
| Mid-Plains Telephone, Inc. | 21 | 2.23 | 29,866 | 1 |
| State Long Distance Telephone Co. | 30 | 2.41 | 8,387 | 1 |
| Wood County Telephone Co. | 30 | 2.24 | 25,046 | 1 |
| Platteville Telephone DBI PTI | 31 | 2.31 | 8,961 | 1 |
| Waunakee Telephone Co. | 33 | 2.32 | 6,192 | 1 |
| Rhinelander Telephone Co. | 33 | 2.21 | 13,263 | 1 |
| Wisconsin Utelco, Inc. | 34 | 2.40 | 15,054 | 1 |
| North-West Telephone DBA PTI | 36 | 2.41 | 75,299 | 1 |
| Frontier Communications of St. Croix | 36 | 2.42 | 7,803 | 1 |
| Frontier Communications of Viroqua | 37 | 2.26 | 3,659 | 1 |
| Frontier Communications of Wisconsin | 38 | 2.43 | 22,953 | 1 |

15 By this term I simply mean that the model rebuilds the network from scratch.

| | | | | |
|---|---|---|---|---|
| Century of Wisc. (statewide wt. ave.) | 38 | 2.40 | 102,282 | 2 |
| Southeast Telephone Company | 38 | 2.38 | 7,890 | 1 |
| Mt. Horeb Telephone Company | 39 | 2.24 | 4,000 | 2 |
| Mt. Vernon Telephone Company | 39 | 2.46 | 8,141 | 1 |

Table 3.7. Small TELCOs with the lowest WACS, in ascending order, predicted by Hatfield (1997). (Century appears twice -- see text.)

**Strategies 1 and 2 compared.** Table 3.7 shows the fifteen lowest cost providers that the Hatfield Model predicts, those with a predicted cost of service of less than $40. All but two of the firms listed are identified by the multivariate model as following the “fewer service features, lower investment” STRATEGY 1. The two STRATEGY 2 firms (... ”higher investment”) are grouped near the high end of the list, and are closer to the state average WACS for small TELCOs. So far the agreement between the two models, for strategies 1 and 2 appears to be excellent. Note that of the fifteen firms listed, just about half have under 10,000 lines and the other half have more than 10,000 lines.

Century Telephone of Wisconsin, with its 58,000 lines serving just the La Crosse area, has a WACS of just $21, making it one of the very lowest cost providers in the state. For Century Telephone, all the different service territories modeled individually by Hatfield were combined into a single weighted average, in order that the result can be compared with the accounting data maintained by the Wisconsin Public Service Commission and used in the multivariate model. That explains the second entry for Century in the above table with a WACS of $38. In composite Century is a strategy 2 firm.[16] There is no particular correlation between WACS and WACSw for the small TELCOs.

Table 3.2. from the multivariate model, which summarizes the strategies identified, is reproduced below for reference.

| Strategy | Relation to Porter | Characteristics |
|---|---|---|
| 1 | Low cost. | Fewer service features, lower investment. |
| 2 | Low cost. | Fewer service features, higher investment. |
| 3A | Differentiation. | Many service features, higher investment. |
| 3B | Differentiation. | Many service features, lower investment. |
| case 76 | Focus. | (Wisc. Bell -- see conclusions.) |

Table 3.2. (Reproduced.) Competitive strategies identified by the multivariate model.

16 Even though it has an enviable WACS, perhaps in reality Century of Wisconsin (La Crosse) has tried to be a little too low cost. I recall a strike in about 1970 against the company predecessor, La Crosse Telephone, in which scores of its customers eventually were motivated to slam their old black Automatic Electric phones into the wall, creating many barrels of scrap. The problem wasn’t the phones, so much as the switch, whose maintenance was being neglected. For nearly a decade afterwards the firm continued to use that same switch, then the oldest rotary crossbar still in operation in the U.S. I imagine that by now the analog SPC switch that replaced it has become yet another museum piece.

Table 3.1, reproduced below, shows the firms individually identified by the multivariate model as conforming to one of the strategies of table 3.2., together with the Hatfield predicted cost of service. Since the Hatfield Model assures that each firm makes optimal use of technology and is therefore equally efficient, while the multivariate model reflects what has been deployed by real firms, the two models can be compared and contrasted to gain insight into the quality of traditional rate-of-return regulation for the Wisconsin telephone industry.

| Provider name | Hatfield WACS ($) | | No. of Lines | Multivariate identified strategy (See Fig. 3.2.) |
|---|---|---|---|---|
| GTE North (Wisconsin) (76) | 35 | | 456,000 | 1 |
| All in mass of points in Figure 3.4. | 46 (approx.) | | 452,252 | 1 |
| All in Strategy 1 (wt. ave.): | | 40.50 | | |
| Century of Wisc. (19) | 38 | | 102,282 | 2 |
| Mt. Horeb Telephone Company (44) | 39 | | 4,000 | 2 |
| Lakefield (31) | 84 | | 1,493 | 2 |
| All in Strategy 2 (wt. ave.): | | 38.67 | | |
| Tri-County (66) | 71 | | 3,684 | 3A |
| Chibardun (14) | 69 | | 5,281 | 3A |
| All in Strategy 3A (wt. ave.): | | 69.82 | | |
| Riverside (54) | 53 | | 3,008 | 3B |
| Wisconsin Bell (77) | 26.80 | | 2,397,000 | Focus |

Table 3.1. (Reproduced.) Hatfield (1997) predicted cost of service for strategic groupings of Wisconsin firms that had been previously identified using principal components analysis.

The most apparent result is that strategies 1 and 2 identified by the multivariate study appear negatively correlated with the Hatfield Model prediction of WACS, though by only about four percent ($40.50 vs $38.67). Since the WACS for STRATEGY 2 consists of (by weight) essentially only Century of Wisconsin, however, the lower Hatfield prediction for the STRATEGY 2 group is most likely to merely reflect the extremely low predicted cost of service of $21 for those lines in the La Crosse area.

In general one can only conclude that the Hatfield Model does not distinguish between strategies 1 and 2 on the basis of cost of service from a forward-looking perspective. Therefore the distinction between strategies 1 and 2 that principal components analysis demonstrates must have some historical basis. A possible explanation might be GTE’s continued and extensive use of older switches, which are feature-poor and more fully depreciated. Another possible explanation might be differences in the history of regulatory treatment of Mt. Horeb Telephone or Century in relation to the mass of small TELCOs. Lakefield (31), however, has a predicted cost of service of $84, almost two standard deviations above the small TELCO WACS, and is appropriately placed in STRATEGY 2.

**Strategies 3A and 3B compared.** We next turn our attention to strategies 3A and 3B. The Hatfield Model predicts a difference in WACS of $13 ($69.82 - $53), nearly 2/3 of a standard deviation, between the two substrategies. This is clearly statistically significant, in terms of the forward-looking costs that distinguish the two groupings of providers. I conclude that the way that the providers grouped into strategies 3A and 3B have deployed their assets and their past regulatory treatment are in accord with the underlying costs of providing service to their customers. Beyond that the multivariate study also revealed that all three firms in strategies 3A and 3B are providing their customers with a rich set of service features. All three firms are to be commended for providing excellent service in a cost-based manner.

**A second look at the top performer.** The STRATEGY 3B firm that the principal components analysis identified as the top performer, Riverside Telcom (54). The cost of service of $54 predicted by Hatfield is slightly above the statewide WACS for the small TELCOs. However, for a firm serving a maximum population density of 650 lines per square mile, figure 3.13 shows an expected WACS of $65. So indeed the multivariate model has isolated a firm with much lower than average investment. The cost advantage for Riverside Telcom might be in the geographic configuration of its customers or soil conditions for laying outside plant, which can be further understood by examining the model run for that provider. The multivariate model further identified Riverside Telcom as providing its customers with a rich set of service features, a testament to the quality of management that the Hatfield Model alone could not reveal.

With regards to the STRATEGY 3A firms, Tri-County (66) and Chibardun (14). Both of these providers experience maximum customer densities of just 200. Figure 3.13 suggests that they could normally be expected to have a cost of service that is $18 above Riverside ($73 - $65.20). Therefore the three firms together appear to be all equally well managed.

**Concluding remarks.**

The two studies together suggest that the three providers offering their customers the most service features at the best value are small firms with only a few thousand customers each. Most of the small TELCOs were identified as pursuing a strategy of fewer service features and lower investment compared to the outstanding small providers.

By contrast GTE appears to have simply under invested in infrastructure. The STRATEGY 2 firms Century of Wisconsin and Mt. Horeb Telephone might merit closer individual consideration. In all the quality and cost-effectiveness of service of three very small firms in relation to GTE is striking. The multivariate study shows Wisconsin Bell to be a firm pursuing a distinct strategy, and the Hatfield Model predicted its cost of service to be below the statewide average.

The Hatfield Model predicts the statewide weighted average cost of service to be $31.10 per month for all Wisconsin lines and $46 per month for the small TELCOs only, on a per-line basis. The standard deviation in the predicted cost of service for the small TELCOs is $21. Only a few percent of the cost of service is in central office switching, well under $2.50 per month in most cases. The Hatfield Model results show the overwhelming portion of the cost of local service to be in the outside plant.

It appears that the intrinsically high cost of providing conventional wireline service in rural areas (as revealed by the Hatfield Model) is burdensome to the small TELCOs and essentially locks them into the feature-poor STRATEGY 1. The implication is that a technology to replace the outside plant, combined with appropriate policy to address the sunk cost of the existing capital stock, could enable the bulk of the small TELCOs to strategically reposition themselves and move to STRATEGY 3B or the focus strategy of Wisconsin Bell. Customers in rural areas might be very well served by reinventing the cost structure of the small TELCO.

Some small providers have begun to partner with analog cellular providers in an effort to reduce service costs for those customers farthest from the central office. But is analog cellular a direct substitute for wireline service? In the next section I survey cellular telephony to show its service characteristics and unmask its cost of service.

## 2. Cellular telephony.

At the time data were being gathered about Wisconsin local exchange carriers for the Governor’s telecommunications task force, a survey was also conducted of the state cellular telephone service providers (Task Force, 1993b). Unfortunately the state analog cellular service providers as a whole were unwilling to disclose anything to the governor’s task force. That silence included the locations of cellular towers, visually apparent as they are! I will try to accomplish much with what I am given.

In this section, I describe the technology and service characteristics of wireless telephony, survey consumer prices and estimate the marginal cost of service for wireless service providers. Finally I explore the relation of cost and pricing.

### The underpinnings of cellular telephony.

First I want to give an overview of the trajectory of the product realizations of land mobile telephony, which we now commonly refer to as cellular telephony. Rather than dwelling here on analog cellular or PCS or the other more specialized classes of wireless service, with their various technical distinctions, I want to examine first the very idea of mobile telephony and how it translates into customer service.

**Service characteristics of PCS.** Ricci (1997, 2) says

> "We generally think of PCS as a mobile telephone service characterized by low-cost pocket telephones with service that is associated with a person instead of a place or a vehicle. Such a service could provide different services, such as voice, data and fax, to its users."

Garg & Wilkes (1996, 6) explain that the three key ingredients of PCS are:

"1. An easy-to-use, high-functionality handset
2. A single, personal number that can reach the subscriber anywhere
3. An individualized feature profile that follows the user and provides a customized set of services at any location".

Clearly the service characteristics these authors mention constitute a long sought-after vision of system architects, at least as regards the class of urban customer at which land mobile telephony has been targeted since its inception.

I contend that a long-held vision of a personal communications service has informed all of the classes of mobile service instituted since the inception of mobile telephone service (MTS) in 1946 (Stone, 1994). That vision has remained fairly constant over the decades, increasingly distilled into products as the trajectory of the technology of silicon has permitted.[17] In figure 3.14 is the first realization of personal communications for the urban mobile user.

Figure 3.14. An MTS (Mobile Telephone Service) telephone. The price? Ten cents a minute! (For three minute calls)(Sands & Tellet, 1968).

---

[17] I explain the trajectory of silicon and its implications for wireless telephony in chapter four below.

At this point in time a human operator was still required to handle certain aspects of a call, as was the case with the early 1960s design iteration, IMTS, shown in the next figure.

Figure 3.15. Improved mobile telephone service (IMTS) control head (Sands & Tellet, 1968).

**Evolution of underlying technical standards.** The Bell Labs development in 1979 of the first cellular telephone system architecture (AMPS) enabled fully automatic completion of calls, much improved spectral utilization efficiency through the splitting-up of urban areas into smaller “cells” that reuse channels, and portable handsets for personal use (Stone, 1994). Ever decreasing costs of signal processing and operation at ultra-high frequencies have made possible the transition to digital modulation and the realization of the service features of PCS. Technology standards of the wireless industry have evolved along the path shown in Table 3.8 below:

| **Era** | **Dominant deployed technology** |
|---|---|
| 1946 | Mobile Telephone Service (MTS), based on Major Edwin Armstrong's 1930s work on frequency modulation |
| Mid-60s | Improved Mobile Telephone Service (IMTS) |
| 1979 | Advanced Mobile Phone System (AMPS), FM analog modulation with 30 KHz. channel spacing, 800 MHz., (first true cellular architecture). |
| Late-80s | Time-Division Multiple Access (TDMA), digital cellular began replacing analog in selected areas. |
| 1992 | Digital European Cordless Telecommunications (DECT) adopted continent-wide at 1.9 GHz. |
| Now | Code-Division Multiple Access (CDMA) using channelized approach on existing allocations (PCS and 800 MHz.). |
| Future | CDMA using spread spectrum. |

Table 3.8. Time line of U.S. wireless technologies (based largely on Garg & Wilkes, 1996).

**Undesirable service characteristics of cellular telephony.** The existing choices for cellular telephony, especially analog cellular, have certain limitations that render these classes of service marginally useful for providing data service to subscriber dwellings. Particularly for providing Internet access, the 9.6 Kbps maximum data rate of analog cellular has long been outstripped by consumer expectations and the demands of content-rich Web sites. For PCS GSM technology, the data rate currently offered is 9.6 Kbps, which has an actual throughput of about 14 Kbps (Scott, 1999). For mobile urban customers reading e-mail or modest file attachments, these data rates are satisfactory, and perhaps all that can be achieved, given the propagation characteristics of mobile radio links in dense urban environments. But Internet commerce and other promised uses require more bandwidth. Thus the vagaries of these two channelized radio system architectures withhold the promise of respectable Internet access for rural customers, because of certain technical realities I discuss briefly below:

Handoff burst.

Analog cellular uses a supervisory channel pair to track available handsets and signal calls. But once a call is underway, the cell site must use the voice channel for any further signaling required. When a “handoff” of a call to a neighboring cell is needed as a subscriber moves out of range, the cell site controller temporarily mutes the conversation (for a large fraction of a second) and sends a packet of data used to switch the handset to a new channel pair (Stone, 1994). This so-called handoff burst is acceptable for speech, but disastrous for computing sessions. Special, more expensive cellular modems ($200 for Ameritech's Mobile Partner™ package) are needed to avoid dropped calls.

Data compression ratio.

The data compression algorithms used in analog wireline modems take full advantage of the reliable 30 - 40 dB signal-to-noise ratio typical of wireline service to achieve compression ratios of as much as 4:1. So while the published speed of a particular modem might be 28 Kbps, throughput rates are often around 100 Kbps.[18] But radio communication links are inherently noisy. The same data compression algorithms are hardly able to achieve a 1.5:1 throughput gain over a cellular link. Thus the same published data rates for wireline and wireless modems yield dramatically different system level performance.

Fading and delay spreading of the bit stream.

For mobile customers, and to a lesser degree for fixed subscribers, the realities of radio wave propagation can

---

[18] At least over the "last mile" of an Internet session, that is.

result in short term and long term fluctuations of up to 30 dB in received signal strength. For fixed links an adequate signal strength margin can usually be designed into the system.[19] The problem of signal strength fluctuations (and resulting signal-to-noise deterioration) is worst for dense urban customers, where rapid fades of up to 60 dB are observed.[20]

In addition to fading effects, multipath propagation leads to delay spreading of the information bit stream. Delay spreading varies from under 200 nanoseconds (RMS) in open areas, to 3 microseconds in urban areas (Garg & Wilkes, 1996, 51). The worst observation of delay spreading is 25 microseconds in San Francisco, CA (Rappaport, 1996, 162).

The strategic implication of delay spreading is that it sets an upper bound on system data rates for wireless institutional choices targeted at particular geographic settings. Rural customers will be far better served by a wireless telephony system tailored to their setting.

---

[19] Though the FCC regulations strictly limiting handset power and prohibiting external directional antennas often prevent analog or PCS cellular fixed installations from offering a sufficient fade margin.

[20] See Rappaport, 1996, chapters 3 & 4 for an excellent discussion of radio propagation at 1 GHz.

**Universal Service Fund (USF) money for the cellular industry?** In spite of these many architectural limitations and the unsuitability of cellular for Internet connectivity in accord with fixed user expectations, the U.S. cellular industry has been pressing FCC Chair Kennard for access to USF support (Glassner, 1999), and with apparent success. I conclude that to date a satisfactory solution to universal voice and data service in rural areas has not existed, or the FCC would not choose to cross-subsidize a class of service exempt from intensive regulation and from any state oversight.

**Pricing of service.**

Because cellular providers utilize the radio spectrum and provide an enhanced telecommunications service, they are not required to file tariffs with the FCC and consider themselves to be entirely exempt from state regulation as telecommunications service providers.[21] Information about prices charged to customers is nevertheless available in various ways. For example, in mid-1998 Consumer Reports Magazine (various, 1998) conducted a nation-wide survey of price offerings. The reader should independently refer to

---

[21] There is partial federal pre-emption of the regulation of radio telecommunications. The FCC further considers land mobile telephony to be an enhanced service not subject to intensive regulation.

that compilation, but I wish to extract some basic statistics from that survey now for industry analysis, and for use again in chapter five.

**One estimate of wireless airtime.** In the Consumer Reports survey, in order to isolate the unbundled average price of airtime, it is necessary to subtract the embedded price of the included handset from service bundles offered to consumers. I also wish to subtract out the price of roaming minutes (at one dollar per minute) that had been included in the offering bundles published in their survey. Table 3.9 below is an estimate of the embedded price of the single mode handsets included in 800 MHz analog offerings and the dual mode handsets bundled with digital service provider offerings (an effort by the authors to construct equivalent offers in terms of coverage areas). Table 3.10 then estimates the unbundled mean price of airtime alone in several major U.S. cities.

Handset price. Analog service providers were reported to charge from zero to fifty percent of the stand-alone retail price of a handset when it is included with a service contract (various, 1998). Since a non-zero additional price of a handset applies to an upgraded model, I conclude that a fair correction would be based on the embedded price of a basic single band analog handset, an amount I estimate by taking the lowest quoted price offered without a contract and subtracting the lowest contract price cited. The handset price corrections are estimated in the table below:

| **Model handset** | **Price, w/o contract** | **Price, w/ contract** | **embedded price** |
|---|---|---|---|
| **Single mode:** | | | |
| Nokia 918+ | $149 - 309 | $ 0 - 150 | $149 |
| StarTAC 6500 | 349 - 799 | 199 - 550 | 150 |
| Nokia 252 | 249 - 400 | 49 - 180 | 200 (big batt.) |
| StarTAC 3000 | 251 - 499 | 99 - 280 | 152 |
| Profile/300 e | 167 - 300 | 0 - 130 | 167 |
| MicroTAC/Piper | 215 - 245 | 24 - 160 | 191 |
| Ericsson AH630 | 179 - 399 | 69 - 119 | 110 |
| | | | ----- |
| **Dual mode:** | | | |
| Sony CM-B3200 | $179 - 249 | $119 - 409 | $ 60 |
| Qualcomm QCP820 | 399 - 649 | 129 - 399 | 270 |
| Audiovx CDM3000 | 349 - 399 | 150 - 199 | 199 |
| Nokia 2160i | 249 - 500 | 49 - 250 | 200 |
| Erics. DH368vi | 300 - 400 | 49 - 129 | 251 |
| | | | ----- |

Mean single mode handset embedded price: $160
Mean dual mode handset embedded price: $196

Embedded price on a per-minute basis, based on average monthly usage of 80 minutes and an engineering product lifetime of 3 years (based on useful life of habitually overcharged NiCd battery packs):

| | | |
|---|---|---|
| Single mode handsets: | $0.056 | per minute |
| Dual mode handsets: | 0.068 | per minute |
| | ------ | |
| Mean per minute: | $0.062 | |

Table 3.9. Estimated price of handsets that have been included in service bundles of existing wireless providers. (Based on various, 1998.) Model names listed are trademarks of their respective manufacturers.

| City | Monthly offer price Gross[1] | less roaming[2] | Per minute[3] | Airtime only[4] |
|---|---|---|---|---|
| Baltimore/D.C. | $37.04 | $32.04 | $0.427 | $0.365 |
| Boston | 37.60 | 32.60 | 0.435 | 0.373 |
| Chicago | 27.82 | 22.82 | 0.304 | 0.242 |
| Cleveland | 35.86 | 30.86 | 0.411 | 0.349 |
| Dallas/Ft Worth | 37.33 | 32.33 | 0.431 | 0.369 |
| Detroit | 32.34 | 27.34 | 0.364 | 0.302 |
| Houston | 35.14 | 30.14 | 0.402 | 0.340 |
| Los Angeles | 32.61 | 27.61 | 0.368 | 0.306 |
| Miami | 36.56 | 31.56 | 0.421 | 0.359 |
| Minneapolis | 34.42 | 29.42 | 0.392 | 0.330 |
| New York City | 42.40 | 37.40 | 0.499 | 0.437 |
| Philadelphia | 34.06 | 29.06 | 0.388 | 0.326 |
| Pittsburgh | 33.73 | 28.73 | 0.383 | 0.321 |
| San Francisco | 36.17 | 31.17 | 0.416 | 0.354 |
| St. Louis | 29.78 | 24.78 | 0.330 | 0.268 |
| U.S. mean:[5] | $34.84 | $29.84 | | $0.336 |

[1] Usage assumed to be 30 minutes/month peak, 45 minutes/mo. off-peak, plus 5 minutes/mo. roaming. Handset included.
[2] I estimate per minute charge for roaming to be one dollar.
[3] Based on monthly less roaming, divided by 75 minutes.
[4] Net of estimated embedded $0.062 per minute handset price.
[5] Based on the 15 metropolitan areas listed here.

Table 3.10. Estimated mean price of airtime only, on a per-city basis. (Based on various, 1998.)

**Additional estimates of wireless airtime.** First, while walking in a local shopping mall past a provider’s booth in December of 1995, I overheard a sales person offer a per minute rate of 14 cents to an employee of a major Madison, Wisconsin, area employer for a group calling plan. The sales person represented that this was the best per minute rate available to any consumer in the Madison area. Second, in early 1999 in Madison, WI, Einstein PCS was offering 300 minute calling card packages at $0.399 per minute, with or without a bundled free handset (same price) (WSJ, 1999).

Hobica (1998) has conducted a limited informal survey of consumer prices. They reported that Sprint PCS had offered 400 minutes of talk time for $50 (12.5 cents per minute, customer-supplied handset). They further observed that a three-minute call from San Francisco to Boston using Cellular One™ was $7.92. I speculate that they were roaming outside of their normal service territory, which should normally have cost them about a dollar per minute, plus a toll charge.[22]

Finally, consumers in Thailand have recently been reported to be charged three cents per minute for analog cellular airtime, exclusive of handset, using the same Motorola cell site technology as is in use in the U.S. (Moore, J., 1996). In Thailand there was at the time but one service provider, a well-connected individual whom I believe to

---

[22] So the possibility of what traditionally would be called undue price discrimination exists here, with the cell sites that provide service to roamers in the airport hotel district possibly charging higher prices to those customers.

possess a vision of making affordable wireless service available to all, as an alternative to under-provided wireline service. While it is unlikely that this individual experiences effective regulation of the kind U.S. customers would associate with the provision of universal service, I speculate that they have partly for altruistic reasons chosen to price their service at close to marginal cost.

**Cost of service.**

I next turn my attention to estimating the marginal cost of wireless service in the U.S. market. Two approaches can be used to estimate the economic cost of providing cellular telephone service. The first is based on interconnection agreements filed with the Wisconsin Public Service Commission. The second approach involves an accounting estimate for a prototypical firm, based on equipment and land use prices.

**Cost of service, based on call termination agreements.** Starting in the first quarter of 1998 and lasting for much of that year, there was a flurry of activity to put in place bilateral interconnection agreements of the type envisioned by the Telecommunications Act of 1996 (1996 Act) and Wisconsin Act 496 (Act 496, 1993), according to administrative rules established in Wisconsin Public Service Commission docket number 05-TI-0140 (1997). A number of these interconnection agreements dealt with setting a price for reimbursement of the costs associated with transporting and terminating calls made or received on a wireless service provider with a wireline local exchange carrier serving a similar geographic area. Usually, but not always, the agreements are symmetric with respect to the party terminating a call. In general interconnection agreements were arrived at voluntarily during this period, a few notable exceptions being between wireline carriers. (See especially CTC vs GTE North (05-TD-100.)

Table 3.12 two pages hence lists most of the agreements from that period that include a wireless service provider. In figure 3.16 and table 3.11 below I show the results of a simple univariate analysis of those agreements:

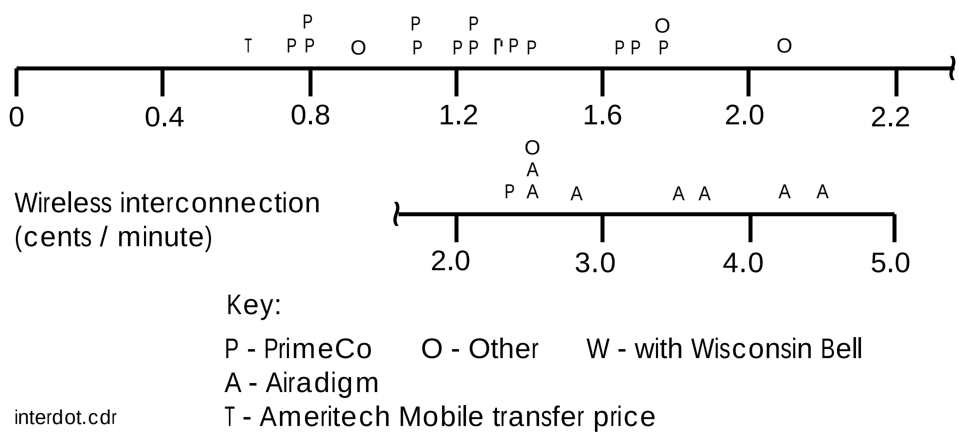



Figure 3.16. Bilateral interconnection agreements reached in 1997 or 1998 involving a Wisconsin wireless service provider: Statistics.

Industry-wide behavior. Reimbursement ranges from $0.0074 to $0.0424 per minute for all carriers. The mean rate is $0.0195, and the standard deviation is $0.01. The mean Airadigm rate is $0.0339, but that is about 1.5 standard deviations above the mean rate for all carriers.

| **Provider** | **Range**, $/min | **Mean**, $ | **Std. Dev.**, $ |
|---|---|---|---|
| All wireless | 0.0074-.0424 | 0.0195 | 0.010 |
| All less Airadigm | 0.0074-.025 | 0.0144 | 0.005 |
| PrimeCo / TDS | 0.0074-.0235 | 0.0137 | 0.004 |
| Airadigm | 0.0250-.0424 | 0.0339 | 0.0075 |
| Ameritech | transfer pr. | 0.00634 | n/a |

Table 3.11. A summary of bilateral interconnection agreements reached in 1997 or 1998 involving a Wisconsin wireless service provider.

By contrast the mean PrimeCo rate is $0.0137 for all 15 of the cities served by TDS Telecom and covered by docket 05-TI-0195, a full two standard deviations below Airadigm. Moreover by visually examining the dot plot in the above figure of the agreements, one can see that the Airadigm rates appear to be outliers. But I will be generous and include them in my estimate of the cost of cellular airtime.

Airadigm. At least four possible reasons exist for the departure of Airadigm from the group statistical behavior: First, Airadigm may be operating below efficient scale for its Einstein Wisconsin subsidiary. Second, the agreements might be erroneously high and might perhaps best be revisited with a view toward bringing them into line with the industry average. Third, the possibility of an agency problem exists. Fourth, the rate may in some benevolent way be seen by their board of directors as being in the firm's overall best interest.

| **Rate, Cents /min.** | **Wisc. Docket** | **Wireless provider** | **Other party** |
|---|---|---|---|
| 0.63 | 05-TI-149 | Ameritech Mobile | Wisc. Bell dba Amer. |
| N/A | 05-TI-173 | Airadigm | Century Service Grp. |
| 2.5 | 05-TI-175 | Airadigm | Wittenberg Telephone |
| 4.5 | 05-TI-176 | Airadigm | Headwaters Telephone |
| 3.68 | 05-TI-177 | Airadigm | Rhinelander Telephone |
| 3.51 | 05-TI-178 | Airadigm | Amherst Telephone Co. |
| 4.24 | 05-TI-179 | Airadigm | Mt. Horeb Telephone |
| 2.5 | 05-TI-198 | Airadigm | Mosinee |
| 2.80 | 6770-MA-100, 7989-MA-104 | Airadigm | Wood County Telephone Company |
| 2.1 | 05-MA-108 | New-Cell, Inc. | Frontier Communicat. |
| 1.75 | 05-TI-193 | American Cellular | Northeast Telephone |
| 2.5 | 05-TI-199 | American Cellular | Mosinee |
| 0.93 | 05-TI-204 | NEXTEL West Corp. | GTE North (not symmetric) |
| 0.79 | 05-TI-195 | PrimeCo. | Burlington, Bright.&Wh |
| 0.80 | " | " | Waunakee |
| 0.74 | " | " | Mt. Vernon |
| ... | (15 cities on this docket, all TDS) ... | | |
| 1.68 | " | " | UTELCO |
| 1.76 | " | " | Scandinavia |
| 2.35 | " | " | Badger |
| | 6720-TI-140, 8037-TI-101 | Airadigm | Wisconsin Bell |
| | 275-TI-100, 6720-TI-147 | WinStar Wireless | Wisconsin Bell |
| | 6720-TI-142 | US West Communic | Wisconsin Bell |

Table 3.12. Bilateral interconnection agreements reached in 1998 involving a Wisconsin wireless service provider: A nearly complete listing of the initial agreements.

Ameritech Mobile. Perhaps the most interesting interconnection agreement is the docket (05-TI-0149, 1998) concerning Wisconsin Bell and Ameritech Mobile Communications, in that it sets a (fully costed) transfer price between two affiliated entities. (Because the companies are related, the agreed rate is called a transfer price.) The agreed price for call termination between these two entities is not symmetric. Table 3.13 below shows Attachment A of that agreement:

| "**Reciprocal Compensation:** | **Per minute of use:** |
|---|---|
| For calls originated on Ameritech's network and terminated on Carrier's network: | $0.004839 |
| For calls originated on Carrier's network and terminated to Ameritech's end office via: | |
| Type 2A Service, local call: | $0.006341 |
| Type 2B Service, local call: | $0.004839" |

Table 3.13. Wisconsin PSC 05-TI-149 (1998) interconnection agreement involving Ameritech and its cellular subsidiary.

What can be concluded about the marginal cost of wireless telephone service from these interconnection agreements? The Telecommunications Act of 1996 is reasonably specific about the nature of the charges to be included in interconnection agreements between providers of local service, as New-Cell, Inc. explains in Wisconsin docket 05-MA-108 (1998, 4):

> “The FTA [1996 Act] prescribes that charges for call transport and termination shall be cost-based (47 U.S.C. §252(d)(2)(A)(I)). The FTA specifically limits the relevant costs to ‘the additional costs of terminating (CMRS / LEC) calls’ (47 U.S.C. §252(d)(2)(A)), and specifies that a ‘reasonable approximation’ standard is to be applied in the determination of such costs (Id.).”

The clear implication is that the per minute rate of reimbursement is intended to be in principle identical to the incremental cost of a local call. While not equal to the marginal cost of a call in a strict sense, in aggregate the interconnection agreements provide an excellent surrogate for the marginal cost of providing local service using the current classes of wireless service. I think a best estimate is that the marginal cost of wireless service is two cents per minute, based on Wisconsin wireless interconnection agreements.

**Cost of service, based on costs experienced by providers.** In their discussion paper on collusive conduct in the U.S. mobile telephone industry, Parker & Roller (1994, 17) describe their approach to making estimates of the cost structure of cellular telephone providers. Also, McKenzie & Small (1997) have performed an econometric study of the cost structure of the U.S. cellular industry. Shortly I will discuss their work, but first a more casual approach to cost estimation, based on simple business principles and the basic characteristics of cellular equipment, might better serve to inform our intuition about the conduct of this industry.

As an elementary approach to cost estimation, let us construct a business model of a cellular service provider in equilibrium. The resulting accounting estimate will be based upon simple and conservative assumptions that do not require a detailed insider knowledge of their affairs (as no such knowledge has been forthcoming). The model will take the form of a pro forma income statement for some year in which it is assumed that the business has been in operation for an indefinite period. After making such a cost estimate, I will then use the theory of imperfect competition to predict the optimal price, and compare that to the actual prices experienced by consumers.

It will be helpful to first acquaint ourselves with the productive assets of cellular service providers. A provider will want to have a retail outlet for sales, handset programming and customer service. In addition to a storefront, a provider would operate one or more cell sites, linked by a leased line to a switch. Figures 3.17 - 3.21 below on the next few pages depict the cell site assets to cost:



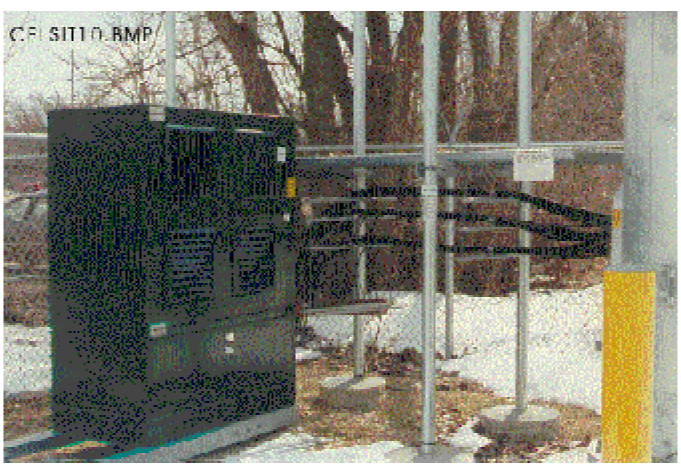


**Figure 3.17.** (Above left) An urban cell site antenna support structure (25 M high).
**Figure 3.18.** (Above right) Antenna array, with mast-mounted low noise amplifier.
**Figure 3.19.** (Lower left) Equipment cabinet housing for

transmitters, receivers, control and power supply.


**Figure 3.20.** (Left) A rural cell site antenna support structure (60 M high). Note that competitive providers have co-located at 25 and 50 meters, and that the 25 meter high antennas are rotated to optimize coverage for urban mobile users.

**Figure 3.21.** (Below) Equipment housing.


I make the following assumptions about the prototypical firm whose business activity I project (see table 3.14):

1. The provider is a stand-alone business. That is, I ignore economies that arise from the management of networks of cell sites and from the joint provision of several kinds of telecommunications service.[23]

2. I use the cost of a standard analog cell site provided by an equipment supplier (Prakash, 1997), who assured me that cell site equipment package cost varies little by modulation scheme or allocation at 0.8 or 1.9 GHz.

3. I use a circuit capacity of 24 channel pairs, an occupancy of 50 percent averaged over 24 hours, and a useful service life of ten years.

---

23 Interestingly, McKenzie & Small (1997) report decreasing returns to scale for all the large U.S. cellular providers.

4. I assume that the cost of the antenna, antenna support structure, building, land, and legal costs are together about equal to the cell site equipment cost. Only in the highest land cost areas is this assumption likely to fail. I have not heard of side payments for cell siting exceeding $100,000 in the Midwest.[24] Another reason why this assumption is conservative is that increasingly several competing providers are finding ways (or being required) to share the same antenna support structure.

5. I include revenue and costs of providing local service only.

6. Spectrum costs are set to zero in this equilibrium analysis. Why? 800 MHz. spectrum licenses were granted by lottery for a small application fee. 1.9 GHz. spectrum ten year (infinitely renewable) exclusive right to use licenses were sold at auction for princely sums. But either license may be sold on a secondary market for at least what was paid for it, and neither license is consumed in use. In fact the 800 MHz. licenses constitute a windfall.

7. Cost of call termination is set to zero, since such agreements are usually symmetric and average to zero over time, except in unusual cases.

____________________

Table 3.14. Accounting model assumptions.

[24] The most extreme side payment I encountered in the literature concerns a $500,000 side payment to a city golf course to site two antenna support structures (Moss, 1998, 121). (Moss also feels that subsidizing rural telecommunications is unfair to people who live in cities (p. 122).)

Crudely, the cell site equipment capital cost could be converted to a per minute cost as follows:

$250,000 equipment bundle divided by (525,960 minutes per year X 24 channels X 0.5 occupancy X 10 years life) = $0.004 per minute.

This will give the reader an immediate sense of how things will turn out.

If on average a customer uses their handset 80 minutes per month, then based on the assumptions above each site will support about 6,500 customers.[25] Each site would then require about the full-time equivalent of one administrative assistant, one service technician, and one half sales person. There would need to be a storefront (leased), and the usual small business expenses. Again, a somewhat larger organization with many cell sites could operate more efficiently than the firm I model here. (As I have modeled a provider, the firm would expand by mere replication of this business model.) Based on these considerations the income statement resulting from such a static analysis appears below and on the next page in table 3.15:

---

[25] Parker & Roller (1994) use in their cost estimate a monthly average usage per customer of 500 minutes, which would result in about 1,100 customers per cell site. The two usage estimates both represent the capacity of the site equipment. I believe that 80 minutes better accounts for non-business customers and 500 minutes for business users.

________________________

Pro Forma Income Statement for a Hypothetical Cellular Provider

**Assumptions**
Scenario:
1. A hypothetical stand-alone provider with a single cell site.

2. Costs are converted to a per-minute basis by dividing by
   the following factor:

6311520 = factor for 24 ch. pairs x 50% 24 hr ave occupancy x 525960 min/yr
80 = minutes per month average usage per customer.
Therefore cell site services: 6574.5000 customers

3. Input coefficients are: Income (per-minute), COG (annual), expenses (annual).

0.336 = Airtime retail price per minute ($).
250000 = Site equipment cost ($), with 10 year life, straight line.
250000 = Facilities cost ($), with 20 year life, straight line depreciation.
160 = Handset retail price ($), and have a useful life of 3 years.

| | Annual ($x1000) | Per-minute basis (dollars/min) | Per-customer basis ($) | % of sales |
|---|---|---|---|---|
| **Income** | | | | |
| Airtime | 2120.67 | 0.3360 | 322.56 | 86% |
| Handset sales | 350.64 | 0.0556 | 53.33 | 14% |
| Sales | 2471.31 | 0.3916 | 375.89 | 100% |
| **Cost of Goods Sold** | | | | |
| Site equipment | 25.00 | 0.0040 | 3.80 | |
| Site facilities | 12.50 | 0.0020 | 1.90 | |
| Handsets | 210.38 | 0.0333 | 32.00 | |
| COGs | 247.88 | 0.0393 | 37.70 | 10% |
| **Labor** | | | | |
| Salesperson (half time) | 32.00 | 0.0051 | 4.87 | |
| Technician | 40.00 | 0.0063 | 6.08 | |
| Administrative assistant | 33.00 | 0.0052 | 5.02 | |
| Total wages | 105.00 | 0.0166 | 15.97 | 4% |
| **Gross Profit** | 2118.43 | 0.3356 | 322.22 | 86% |
| **Expenses** | | | | |
| Rent of storefront | 19.20 | 0.0030 | 2.92 | |
| Advertising (5 % of sales) | 123.57 | 0.0196 | 18.79 | |
| Telephone (office use) | 3.60 | 0.0006 | 0.55 | |
| T1 line lease (site use) | 12.00 | 0.0019 | 0.00 | |
| Software lease (office use) | 6.00 | 0.0010 | 0.91 | |
| Janitorial | 1.70 | 0.0003 | 0.26 | |
| Insurance | 2.00 | 0.0003 | 0.30 | |
| Supplies and Maintenance | 7.00 | 0.0011 | 1.06 | |
| Misc. business supplies | 3.00 | 0.0005 | 0.46 | |
| Entertainment | 1.00 | 0.0002 | 0.15 | |

| | | | | |
|---|---|---|---|---|
| Total expenses | 179.07 | 0.0284 | 25.41 | 7% |
| **Net Profit Before Taxes** | 1939.36 | | | 78% |
| taxes of a standard corporation | 969.68 | | | |
| profit after tax | 969.68 | | | 39% |

cellpro1.wb2 A1:I55 14 APR 99

Table 3.15. Pro forma income statement for a hypothetical cellular provider.

What we now want to extract from this income statement is an estimate of the accounting (i.e., incremental) cost of a phone call. We have, exclusive of handset and advertising:

| | |
|---|---|
| Site equipment and facilities | $0.006 / minute |
| Wages | 0.017 |
| Business expenses | 0.006 |
| Accounting cost of a call | $0.029 / minute |

Under the circumstances this compares favorably with the mean value of the interconnection agreements discussed earlier. The elements I have included are quite analogous to the transport and termination charges that form the basis of the interconnection agreements. Handset cost is not included here, because the cost is borne by the consumer in my model.

Advertising is excluded, in order to facilitate comparison with interconnection agreements. Moreover the cost of switching, not included here, is known from the Hatfield cost study examined earlier in chapter three to be quite small in comparison to all other relevant costs.

Two possible points of interest come immediately to mind in relation to the accounting approach I have taken. The first is the possible effect of economies of scale on cost. Surprisingly in their econometric study of the U.S. cellular industry, McKenzie & Small (1997) note that for all but one of the firms they studied, there were decreasing returns to scale present. A clear implication of their work is that a small business approach to providing cellular service may in fact be preferred, at least if network economies can be achieved through cooperative agreements that build competing virtual networks covering wide areas. Such agreements are possible, and suggest that the concentration of ownership that now exists serves no social purpose.

A second point of discussion has to do with the handsome profitability of the provider modeled. Of course this profitability accounts for the initial keen interest in cellular licenses and the ensuing secondary market in cellular properties. Danner (1991) points to two underlying causes of economic rents: scarcity of the spectral resource and various forms of cooperative behavior that keep prices near monopoly levels (Danner, 1991, footnote 2). But Danner is quick to point out that accounting profits in themselves cannot reveal whether the origin of rents is a true underlying scarcity or a result of industry conduct.

Parker & Roller (1994, 15) are less diplomatic -- they see evidence of “outright cartel pricing” practices among the independent providers (but not among the firms owned by wireline providers). The arrival of PCS providers in urban markets appears to have had no discernable effect on price levels, as gauged by the price offers discussed earlier in this section. Moving from two to five players should have dramatically lowered prices -- at least that was the intention of the regulatory model of PCS. Such conclusions may not seem so surprising, given the obvious lack of decline in price levels over the years, even though the number of customers has grown markedly.

There is but one ray of hope in cellular pricing: the AT&T surprise announcement of ten cents a minute pricing (Sandberg, 1999). AT&T’s move heralds a return to the simplicity of the MTS pricing of the 1950s (Sands & Tellet, 1968). Ten cents a minute -- now they’re doing it again! Maybe AT&T will start something, like Sprint did with dime a minute long distance pricing. Such a move begs the question:

Is there a best price to offer, given what is known about costs and industry structure?

**Implied game theoretic pricing for the U.S. cellular oligopoly.** The U.S. cellular telephone industry has a unique structure that originated in explicit institutional choice,[26] and that unfortunately seems to have predestined a pattern of industry conduct that under provides the social benefits of wireless telephony, particularly to fixed customers.

If the cellular markets for analog and PCS were untainted by distinct mechanism designs (which they certainly are not), it would be possible to use contemporary industrial organization theory to predict the profit maximizing price / output vectors for each competing player in a given service area. Another fatal impediment to application of the standard theory of imperfect competition is that the service offering bundles that the various technical standards create differ enough to make strict application of competitive models problematic, though some decline over time in the price of simple voice service is likely to have occurred (Samuelson, 1999). Nevertheless, I will mention that I recall hearing that for a Cournot-like oligopoly with five entrants, with

[26] See Calhoun (1988) for a discussion of the history surrounding AMPS cellular telephony regulatory design.

“imperfect information,” and with identical technologies, each firm’s equilibrium price should be 15 % above their costs, when the sum of firm outputs equals market demand.

Because pricing in the U.S. cellular industry differs so profoundly from what theory predicts, I conclude that price setting in this industry is not rational.[27] My critique is simply theoretical, and yet is reinforced by the cellular industry econometric studies I discussed previously.

Could the departure from rationality be the result of a lack of strategic vision on the part of the key players in the cellular industry? Could this serious distortion in price levels be caused by the market design mechanisms for analog cellular and PCS employed by the FCC? If it is the latter, it is in need of redress. If it is the former, it is perhaps understandable, given that the industry tends to view itself as the provider of a luxury to urban dwellers.

---

[27] By rational, I simply mean that sellers engage in profit maximizing behavior, according to the ways of economists.

# CHAPTER 4. CHARACTERISTICS OF THE PROPOSED EDCT SERVICE.

## Introduction.

The motivation for the development of EDCT is twofold: First, there is the need to continue to provide affordable telephone service in areas where decreasing subscriber density results in a mounting cost of service, once the historical cross subsidy of local service proves unsustainable. Second there is increasingly a need to provide Internet connectivity at speeds comparable to those promised in the immediate future to urban residential customers, in order that rural communities retain their economic vitality.[1] Both objectives need to be met with technology choices that produce low cost networks and inherent distributive fairness, as EDCT is intended to provide a new kind of universal service in a deregulated environment.

The difficulty of continuing to use wireline technology in rural areas is clear from the Hatfield prediction of rising monthly cost of service as subscriber line density declines, as figure 3.13 (reproduced below) revealed. That figure shows

---

[1] I discuss the service characteristics of residential alternatives for high speed Internet access in the second half of this chapter. The bottom line is that urban consumers will shortly have megabit per second access rates available to them. Small towns would then look increasingly stranded, unless a new alternative can be developed.

that the cost of serving the lower density areas is several times what people are accustomed to paying for basic local service. The Hatfield Model also showed that for Wisconsin there were 75 firms with less than 10,000 lines each, serving 340,000 customers, or about ten percent of all of Wisconsin. As Figure 3.12 showed, nearly all service providers experience subscriber line densities of under 100 lines per square mile. The implication is that nearly every one of the small local service providers in Wisconsin could benefit from a low cost alternative to wireline technology.

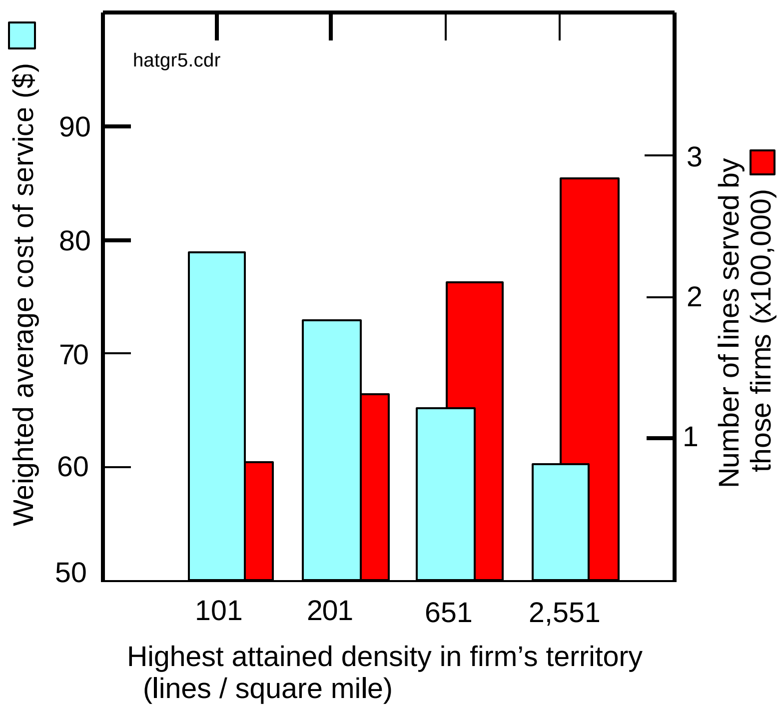



Figure 3.13. (Reproduced.)

Effect of density on cost of service.

The multivariate analysis of chapter three revealed how firms might differentiate themselves from their potential competitors by providing advanced service features to their customers and by investing in digital switching and transmission to provide those highly desirable features. But it now becomes clear that the traditional technologies of telephony will not provide the desired features in a competitive environment, because of the technology cost curve for outside plant that the incumbent providers now exploit.

Solving the challenge of providing low cost service that has advanced service features, including high speed Internet access, requires a strategic shift from the traditional technologies of wireline telephony to what telecom industry CEO Jim Crowe of Level 3 Communications (Brown, 1999) calls “silicon economics.” Industry CEO William Schrader feels that competitive pressures are now so intense, that the established telephone carriers as we know them will be out of business in five years, unless they reinvent their business models “in real time” (Brown). The reality is simply that the trajectory of silicon has made unsustainable the existing order that for decades had provided affordable universal service under intensively regulated monopolies. Reality can be held at bay for just a bit longer for the smaller local service providers.

Understanding how to deliver rural local service in a future competitive environment is a two-fold challenge: We must first turn our attention to the silicon era, to acquire a deep intuitive understanding of the implications of the unprecedented trajectory of microelectronics. Our thinking must extend beyond the oft-repeated implications of Moore's law for computing power and cost (which indeed impact switching mightily). What is new about the trajectory of silicon is how it will impact the provisioning of outside plant. Wires in rural areas cannot provide the connectivity data rates customers are about to demand. Emerging wireless technology promises to revolutionize the "last mile" in rural areas, but only if coupled with a new radio spectral resource approach that keeps airtime costs low. Thus, the second half of the challenge is to understand the shape and potential of the new wireless era for residential service.

This chapter begins with insights into the force of change silicon brings to telecommunications -- insights gleaned from direct contact with the technology of the semiconductor industry. Next, the unfolding of the radio spectrum is explained in terms of the march of decreasing semiconductor linewidth. The emergence of extremely high frequency technology for consumer applications is explained. In the second half of this chapter, the architecture of a new class of telephone service, EDCT, is explored. The service characteristics of EDCT are developed, and an allocation of radio spectrum to EDCT is proposed. In chapter five the discussion of EDCT will continue with an exploration of costs, competitive positioning with respect to existing wireless choices, and business strategy for a new EDCT industry.

## 1. Implications of the trajectory of silicon for spectral resource utilization.

The purpose of this section is to explain the strategic relation between the U.S. semiconductor industry, the technology of radio communications in the digital era, and the continuously expanding radio spectrum. In this way the possibilities for new uses of the radio spectrum resource can be understood by policy analysts and decision makers.

### 1.1. Trajectory of silicon.

The behavior of the semiconductor industry is summarized in Moore's law (Service, 1996), in which Gordon Moore in 1965 asserted that digital circuit complexity would double approximately every 18 months. For that portion of the Moore's law curve in which circuitry is implemented in silicon integrated circuits, the driving force behind improving cost and performance is the continual adoption by the industry of manufacturing process technologies that are capable of replicating designs at finer pattern linewidths.

As a simple example, Kane (1998) describes the plans of Digital Equipment Corporation (DEC) to manufacture the Alpha™ 64-bit microprocessor at ever decreasing linewidths over the product design's life cycle. The DEC Alpha is projected to have linewidths and clock speeds as shown in table 4.1.

| Date | Linewidth (microns) | Clock speed (MHz) |
|---|---|---|
| July, 1998 | 0.35 | 600 |
| -- | 0.25 | -- |
| 2000 | 0.18 | 1000 |

Table 4.1. The trajectory of silicon in the digital realm: DEC Alpha 21264 CPU performance (Kane, 1998).

Already one can appreciate the relation that exists between the design linewidth of the manufacturing technology employed and the speed of circuitry so implemented. (For the analog circuitry employed in wireless transmitters and receivers, the details of the relation are slightly different, however, and will be discussed shortly.)

The availability of improvements in process technology is far from accidental. In fact the semiconductor industry worldwide has, during the intervening decades since the invention of the transistor, perfected the art of taking public investment and using that investment for private profit -- a kind of reverse “taking,” if you will. Instead I suggest that by understanding the connection between public R & D investment and the ensuing industry trajectory, the public benefit can be maximized.

Moore’s law implies a continually unfolding trajectory of increasingly complex digital circuitry with sophistication limited only by fundamental physical constraints of transistor design with features consisting of mere clusters of atoms. (Such theoretical limits appear to be about 20 years distant, with linewidths of perhaps 100 Angstroms (0.01 microns) and gate oxide thicknesses of about 30 Angstroms.) Figure 4.1 shows how the trajectory has unfolded. The slight difference in growth factors for memory and central processors is believed by Taylor (1998) to be due to more order in the circuit topology for memory.

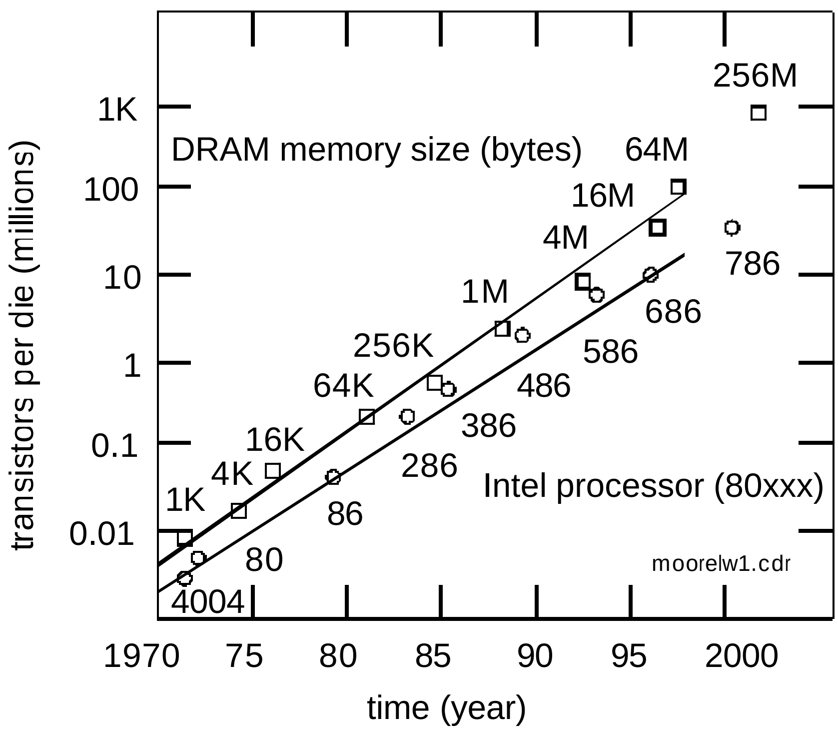



Figure 4.1. Backward-looking depiction of Moore’s law. (VLSI Research, Inc., as cited in Service, 1996.)

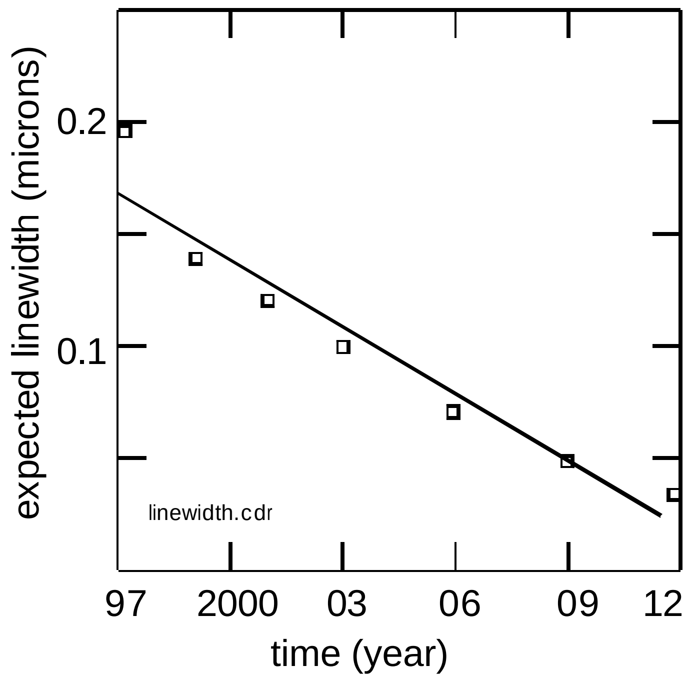



Figure 4.2. A forward-looking view of Moore’s law, based on semiconductor industry technology roadmap for MPU transistor gates (based on Gargini, Glaze, and Williams, 1998, 74).

To understand how the semiconductor industry desires to continue this march, consider figure 4.2 (see Gargini, et. al., 1998). What is fundamentally different in their look forward from the history presently embodied in Moore’s law is that Gargini, et. al., is reporting on industry plans to deploy in sequence specific photolithographic technologies that have already been shown in the laboratory to produce circuits with these projected linewidths.

What is revealed here is not at all a physical property of silicon, but instead the continually unfolding outcome of a series of (mostly public) investments in photolithography.  In other words, Moore's law is a collective behavior that shapes and is shaped by semiconductor industry strategy, structure, and conduct (Chandler, 1962).  Public R&D investments in photolithography, device design modeling, and materials research move the industry along a trajectory summarized in Moore's law.

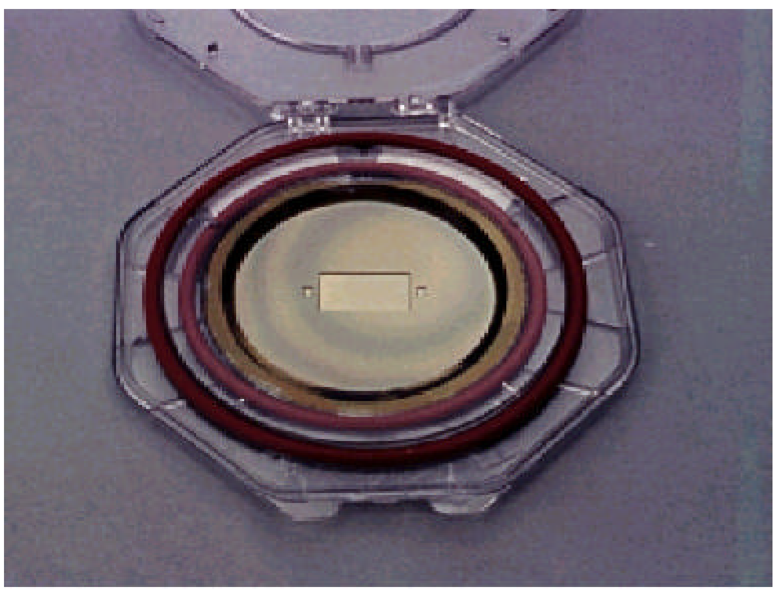


Figure 4.3.  X-ray lithographic mask blank of a type suitable for fabrication of 0.18 micron linewidth devices (Moore, et. al., 1997).

Moore’s law has become a mechanism for the extraction of economic rents for those firms which understand that managing a firm’s product technology for greatest profit means moving each newly feasible linewidth to product realization as soon as the manufacturing tools can be put in place, and then abandoning the existing linewidth manufacturing technology in synchronization with rivals. Note that while technology change is rapid, the *rate of change* is constant. Any firm that falls out of step with Moore’s law is punished with extinction. Therefore it becomes crucial to employ Moore’s law as a kind of signaling behavior to achieve strategic coordination within the industry to protect incumbents and to raise barriers to entry based on the increasing capital intensity of the photolithographic process technology employed. (See Porter (1985) for a discussion of the role of competitive signaling in facilitating coordination.)

Is Moore’s law really that intentional? The intentionality embodied in Moore’s law falls short of perfection, because the scale and difficulty of the applied research efforts that cause movement along the curve take considerable time, effort and capital, making the trajectory a noisy process. Success is far from assured at each stage. But what is important is summarized in three main points:

(1) The industry understands the opportunities for

rents that the high rate of change of circuit density enables.

(2) Technology management is simplified for industry participants if the rate of change is held nearly constant, which facilitates strategic coordination among the various segments of the semiconductor industry (process equipment manufacturers, silicon wafer vendors, chip foundries, product distributors, OEMs), and mitigates risk.

(3) The industry whenever possible pushes the R&D costs of moving along the trajectory of Moore's law onto the public, enabling private rents and risk reduction based on public inputs to the science and technology base.

The recurring justifications for point three are national security and national competitiveness. For example note the change of wording in the U.S. Department of Defense Advanced Lithography Program when control of Congress recently passed from the Democrats to the Republicans (PL 103-337, 1994 (S 2182) and PL 104-106, 1996 (S 1124)):

> "SEC. 216. ADVANCED LITHOGRAPHY PROGRAM (1994).
> (a) PURPOSE. The purpose of the Advanced Lithography Program ... ("ALP") is to fund goal-oriented research and development to be conducted in both the public and private sectors to help achieve a competitive position for lithography tool manufacturers in the international market place.
> (b) CONDUCT OF PROGRAM. --(1) The program shall be

> conducted in accordance with ... plans developed by the Semiconductor Technology Council...
> (2) The interim plan ... shall be the Semiconductor Industry Association 1994 development plan for lithography.
> (C) PROGRAM MANAGEMENT. --The Advanced Research Projects Agency (ARPA) shall be the executive agent for the ALP and shall ensure seamless, fully integrated incorporation of the program planning of the ALP into the full range of ARPA core electronics development programs.
> (D) Funding. -- (1) ... $60,000,000 ... for ALP ... (2) ... for the Semiconductor Manufacturing Technology Consortium...

And now the 1996 rewrite:

> "SEC. 271. ADVANCED LITHOGRAPHY PROGRAM (1996). Section 216 of the National Defense Authorization Act for Fiscal Year 1995 (Public Law 103-337; 108 Stat. 2693) is amended --
> (1) in subsection (a), by striking out "to help achieve" and all that follows through the end of the subsection and inserting in lieu thereof "to ensure that lithographic processes being developed by United States-owned companies or United States- incorporated companies operating in the United States will lead to superior performance electronics systems for the Department of Defense."
> (2) ... add "... and shall consider funding recommendations made by the Semiconductor Industry Association as being advisory in nature."
> (3) ... by inserting "Defense" before "Advanced"; ...
> (4) ... "(C) that affords adequate and effective protection for the intellectual property rights of United States- owned companies."

At the same time that the purpose of the U.S. Advanced Lithography Program changed from national competitiveness to national defense, the new language apparently endorsed industry rents from the work products of this publicly funded R & D activity.

But is defense funding of semiconductor industry R&D central to the needs of the industry? Consider points (1) and (2) above that relate to industry structure and coordination in regard to Moore's law. Ferguson (1985) of the MIT political science department analyzes the performance of the U.S. semiconductor industry in the early decades, from its inception through about 1980.

Ferguson (1985) has an altogether different take on the question of the intentionality of Moore's law. Ferguson observes on page 17 and on:

> ... "In several respects, the semiconductor industry established patterns of industrial conduct which had never been seen before, but which have since spread to other sectors, and particularly high technology sectors of the American economy. ... -- the industry also began to show, and then institutionalized, several unusual structural patterns which resulted in a novel structural and strategic equilibrium. ... The unique dynamic equilibrium of American semiconductor production had its origins in the 1950s, but was not fully developed and explicitly understood within the industry until the middle to late 1960s[2]. ... The structure was one of ... [summarizing pp. 19-29]
>
> 1. Continuous formation of new firms. [The key inbreeding is detailed on page 19.]
>
> 2. Transitory market power.
>
> 3. High employee turnover, individualistic corporate culture, and unique incentive structures.
>
> 4. Extensive licensing and rapid intraindustry

---

[2] Which was then most memorably articulated by Moore (Service, 1996).

diffusion of technology.

5. Generational crises and self-limiting firm-level success.

6. Extreme vertical and functional disaggregation.

> “... however it is far from clear that the effect of the industry’s structural / strategic equilibrium on its performance has been positive. Indeed I will argue that precisely the reverse is the case.”

Ferguson goes on to explain later in his thesis what he sees as a behavioral origin to these structural characteristics -- residing in the essence of the industry founders themselves. Ferguson observes that the principal cause of structural harm to the domestic industry is simply due to the inability of the key players of the industry to get along with each other: a constant series of business divorces among company founders resulting in the inability of firms to manage technology beyond a single product generation, retain key employees, or organizational learning. He relates that this key structural flaw contrasts sharply with the business strategy of overseas competitors to grow semiconductor divisions within large diversified firms that offered buffering from the external environment and access to patient, low cost capital. The behavioral shortcomings of American semiconductor industry executives is traced back to the formation of Fairchild, Inc. in his report. Interestingly, a fresh biographical sketch of Shockley by Riordan & Hoddeson (1997) reaches back to the root of these behavioral shortcomings, pointing out the behavioral tendencies of this founding father of the industry and their profound impact on Shockley’s business relations. In fact Shockley developed a theory of compensation of researchers which he used to motivate people to join him, and which he later published (Shockley, 1957) -- and which to this day appears to weigh heavily in the selection of talent. One has to wonder if the American industry could ever be competitive, with a leadership so driven by individual monetary reward, yet possessing not enough business acumen or moral restraint, were it not for an ongoing dependence on public investment to coordinate and steer the industry along the trajectory of Moore’s law.

In summary the U.S. semiconductor industry has had an unfolding strategic self-understanding, consisting of three stages:

1. An early entrepreneurial phase, centered around Shockley. This early phase appears to have predestined subsequent strategic conduct.
2. A second phase in which the industry learned the value of achieving coordination using Moore’s law. In this early period the industry had yet to thoroughly master the strategic dimensions of public investment and risk-shifting to the public using the

defense budget.

3. A fully mature period in which the industry is able to intimately connect with the civil religious tradition of the American culture. The industry's spot on the National Technology Roadmap (Gargini, et. al., 1998) is a sign of that sense of a shared destiny.

To further illustrate my point that Moore's law exists as a means to achieve industry coordination (and here especially risk reduction) using public resources, see Goldsmith, et. al. (1998). Figure 4.4 shows that Goldsmith's group at Sandia National Laboratory has demonstrated (1997) the lithographic technology needed to produce the commercial device linewidths projected for 2009, a full twelve years hence. What the industry has to do is to insert Goldsmith's technology at the proper moment. Working transistors have already been fabricated using this equipment (see references 3 and 4 in Goldsmith et. al., 1998). The business relationships of the national laboratories, industry, and funding sources needed to produce the results shown is interesting in itself and is partly described in Goldsmith's (1998) introductory section.

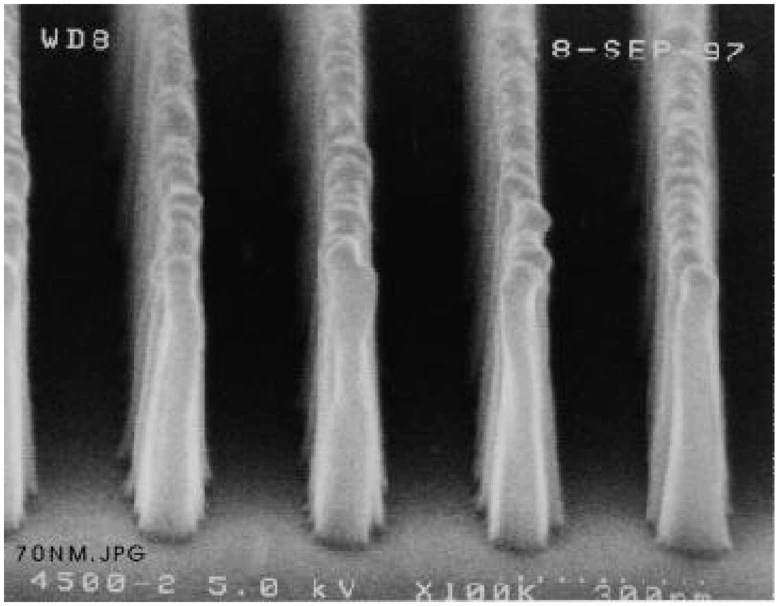



Figure 4.4. Early results of the extreme ultraviolet lithography (EUV) 10x micro-stepper at Sandia, showing 0.07 micron wide lines (Goldsmith, et. al., 1998).

My purpose in surveying the extent of public investment in the semiconductor industry is to suggest that the public should be entitled to a majority of the surplus generated by the trajectory of Moore’s law. Whenever our nation’s defense is not compromised, the public should receive the full social benefit of the expansion of the spectral resource the trajectory of silicon makes possible. Those benefits can only be fully realized by merging technology with the design of institutions that inherently engender vigorous competition. New choices for wireless telecommunications services need to replace the flawed mechanism designs for wireless service in which we are mired.

**1.2. Connection with the technology of semiconductor device design for radio communication.**

I will now explain the relation between Moore’s law and the opening of new portions of the radio spectrum for private use. At any given moment in time the linewidth that can be attained in the manufacture of semiconductor devices determines the upper limit of the frequency at which the devices may be utilized in practical radio circuit designs. In turn the high frequency limit of a device design based on a particular linewidth manufacturing process technology determines the upper bound of the radio frequency spectrum that may be placed into public use at any given point in time.

For a wireless digital telephone system the relation between technology employed and highest useable frequency allocation actually centers on key bits of the analog subsystems of transmitter and receiver. For the receiver section of a handset (or cell site for that matter) the key quality characteristic is the noise figure (NF), which together with an incoming signal of a certain field strength, establishes the signal-to-noise ratio (SNR) of the received signal. Finally, for a given digital modulation scheme, the SNR determines the bit-error rate (BER). The SNR - BER relation forms the basis for the spectral pricing model I describe elsewhere in this work.[3]

**Noise.**

All physical systems have noise associated with them, caused by one or more underlying processes. In an experimental setting the structure of the observed noise helps us develop models to explain their underlying behavior. At a theoretical level however, models of underlying physical processes that cause noise in systems are not altogether satisfying. Noise has a cosmological significance that has fascinated many a researcher over the last few decades. The study of noise in semiconductor devices has in particular brought one expert in that field to ponder the nature of God

---

[3] Once again my undergraduate advisor's admonition (Olson, 1976) that all digital representations are at their deepest level mere approximations of an analog reality rings true.

(Van der Ziel, 1979).[4]

That having been said its time to get practical. The ideas of noise figure and signal-to-noise ratio in wireless communications systems can be most easily explained by using the approach of Schetgen (1994, p. 12-2) in what follows.

**Receiver noise figure and signal-to-noise.**

Consider a radio receiver connected for the moment not to an antenna, but to a perfect resistor which simulates the characteristics of the antenna. The block diagram below (figure 4.5) shows the various stages of a receiver together with various input signal options.

[4] It is important to keep in mind that chaos theory, no matter how taken with it academicians and the business community may be, is but the current attempt to attain a deep understanding of nature through noise. But I dare say that chaos theory paints a view of nature without a divine presence, assuming the role of a creation myth of the enlightenment. Chaos theory may also be applied outside its domain to detriment as have earlier physical theories, like the Heisenburg uncertainty principle and special relativity.

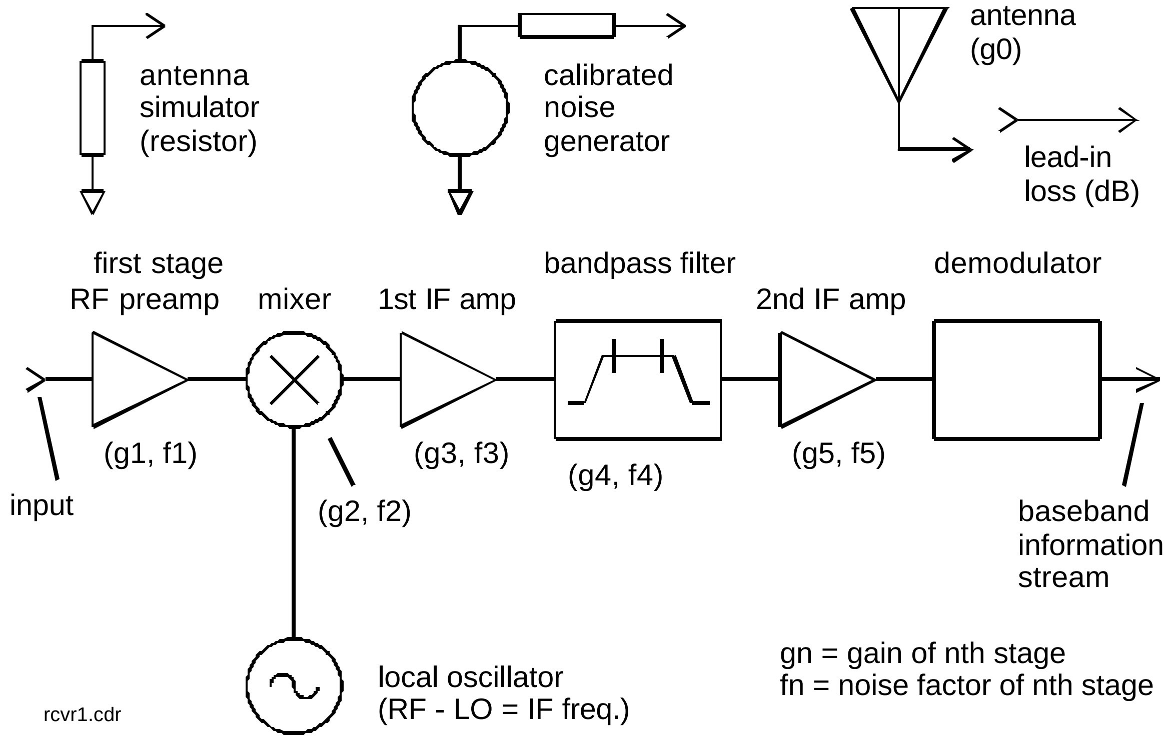



Figure 4.5. Radio receiver block diagram (superheterodyne receiver for data, configured for noise figure measurement).

Each stage of the receiver as well as the antenna simulator has an associated noise, and each stage of the receiver has a gain, or amplification factor. The challenge to the wireless engineer is to maximize the sensitivity of the receiver consistent with cost and packaging objectives.

Receiver sensitivity is understood as how many microvolts of incoming signal intensity are required to produce a minimum acceptable signal-to-noise ratio in the baseband information stream at the receiver output. For a specified SNR, the required signal level can be found from

$$\text{SNR (dB)} = 10 \log_{10} \frac{\text{signal level + noise level}}{\text{noise level}}$$

(S + N / N convention)

Note that the incoming signal level is determined upstream from the receiver by transmitter power, transmitting and receiving antenna siting, and propagation losses. The noise level is the sum of noise external to the communications circuit (atmospheric noise, which dominates only at frequencies far below those of interest here) and internal noise generated within the receiver itself. So now the receiver design task becomes one of minimizing internal noise contributions for a desired receiver overall gain.

A useful engineering convention for evaluating the relative merits of various design alternatives is to refer back to the antenna input terminal the various internal noise contributions of the individual stages, rolling them up into a single overall number. If $f_i$ is a noise factor representing noise added by an individual stage I, and $g_i$ is the gain of that stage, then

$$f_i = \frac{SNR_{input\ I}}{SNR_{output\ I}}$$

and F, the receiver noise factor is

$$F = f_1 + \frac{f_2 - 1}{g_1} + \frac{f_3 - 1}{g_1 g_2} + \ldots + \frac{f_n - 1}{g_n \ldots g_2 g_1} .$$

The usually quoted noise figure NF is

$$NF\ (dB) = 10 \log_{10} F \qquad \text{(dB is decibel).}$$

How does one measure the noise factor of a receiver? The antenna simulator we had connected to the receiver in the figure above is a resistor, which generates a thermal noise (i.e., white or Johnson noise) power per unit bandwidth of

$$p = kT$$ , where $k = 1.38 \times 10^{-23}$ joule per Kelvin, and T is temperature.

When that resistor is connected to the input of a receiver under test, the noise power N which would appear at the output of a noiseless receiver is

$$N_{input} = kTGB$$ , where G = receiver gain, and B = receiver bandwidth.

One observes in reality $N_{total}$ , so that

$$NF\ (dB) = 10 \log_{10} \frac{N_{total}}{N_{input}}$$

(After Van der Ziel, 1957).[5]

---

[5] An alternative method better suited to the bench exists which utilizes a calibrated noise generator (Schetgen, 1994).

**Implications.**

The equation above for F, the receiver noise factor in terms of individual stage contributions, has a strategic implication. Receiver mixer stages (generally the second stage) inevitably have noise factors that are many times worse than would an RF preamplifier stage. That means that the gain $\mathbf{g_1}$ of the first stage must be sufficient, so that its noise factor will predominate the receiver noise performance in order to avoid serious noise degradation by the mixer. Generally $g_1$ = 10 dB is the practical minimum useful first stage gain used in commercial designs at modest frequencies. The table below shows receiver noise figure as a function of first stage gain for the case where $f_1$ = 1 dB, $f_2$ = 12 dB, $f_3$ = 0.5 dB, $g_2$ = -6 dB:

| | | | | | |
|---|---|---|---|---|---|
| Gain $g_1$ (dB) | 0 | 3 | 6 | 10 | 20 |
| Noise figure (dB) | 12.2 | 9.5 | 7 | 4.5 | 1.5 |

Table 4.2. Receiver noise performance as a function of first stage gain.

The receiver noise figure is practically determined by the noise figure of the first stage preamplifier transistor, which operates at the signal frequency. So not only should this transistor have an architecture which has a favorable noise figure at the frequency of interest, but the transistor must exhibit a sufficiently high gain, so that the first stage noise figure dominates over the internal noise figures of all subsequent stages of the receiver design as intended. (By a different line of thinking a transmitter power amplifier should have a power gain of at least 3 dB.)

An interesting practical consideration is that the receiver noise figure is degraded by the signal loss of the antenna lead-in cable. For example an 800 MHz analog cellular base station might have a receiver with NF = 1 dB connected to an antenna located at 200 feet through 7/8 inch diameter cable (loss = 2 dB per 30 meters @ 850 MHz (Schetgen, 1994)), for a system noise figure of 5 dB. There is, therefore, a large advantage to placing at least part of the receiver right at the antenna, whenever it is economical to do so. If the antenna and receiver can be co-located, then the extremely high frequency application contemplated here will have system noise figures that compare very favorably with traditional analog cellular implementations, even with a lower first stage gain.

The implication is that the very highest frequency radio spectrum that can be employed in a wireless communication system is limited by the need to operate at or below a frequency where the transistors are able to exhibit a gain of at least 6 dB (voltage gain). Transistors have a gain that is constant over a wide frequency range, but which begins to deteriorate at higher frequencies due to internal stray impedances resulting from the finite physical structure of the device. Eventually the gain goes to unity (0 dB) at some frequency $f_t$ . Just below $f_t$ the gain declines at a rate of 6 dB per octave. Figure 4.6 shows the behavior.

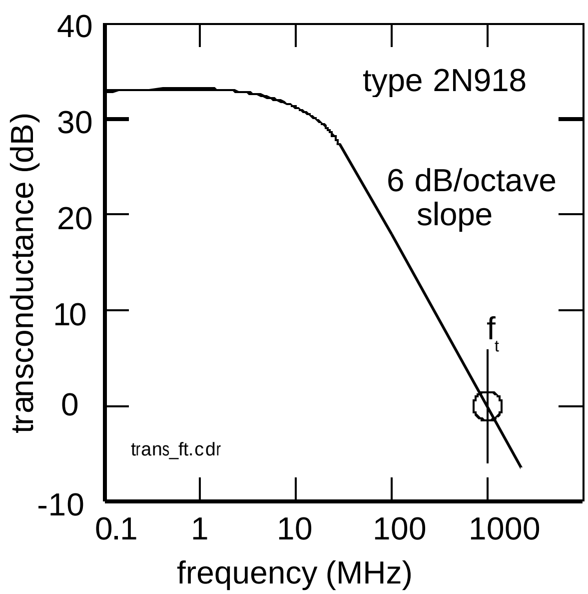



Figure 4.6. High frequency behavior of transistors (simplified, based on Cleary, 1964, p. 75)

**Choice of device technology.**

At extremely high frequencies the transistor architecture with the best inherent noise performance is the high mobility field effect transistor (HMFET), which is fabricated on a gallium arsenide (GaAs) substrate. $f_t$ performance as a function of transistor gate length for HMFETS fabricated with gate widths of 200 microns is shown in figure 4.7. Note that by extrapolation to the anticipated theoretical limit of gate length of 0.01 micron the maximum attainable $f_t$ would be about 280 GHz (Gigahertz).

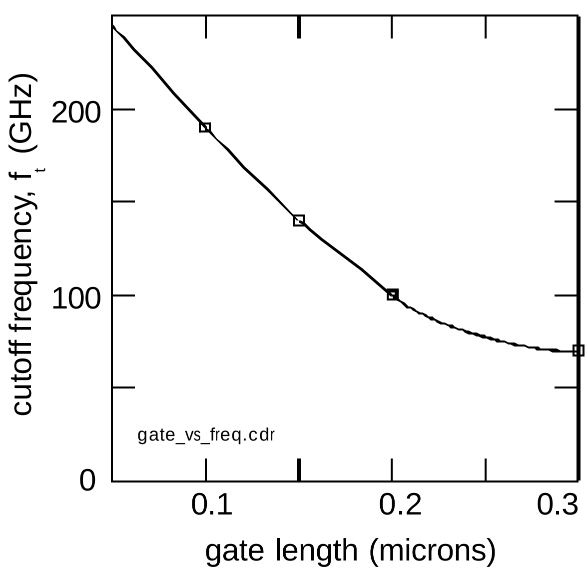



Figure 4.7. High frequency performance of millimeter wave HMFETs fabricated using X-ray lithography on GaAs substrates (Heaton, as cited by Taylor, 1998).

**Role of circuit topology on optimal design.**

There is but one final ingredient of receiver / transmitter design to consider, and that is the fit between the transistor device design and the design of the circuit in which it is employed. Operation of the proposed new class of wireless service at the efficient frontier requires that the best possible use be made of the devices that the semiconductor industry makes feasible. When used at the theoretical limits of their performance, the imperfections of real devices come to dominate the integration of transistors into circuitry. Performance can be maximized by cleverly using the “stray” impedances that devices have that would ordinarily limit their performance to advantage -- a kind of “jiatsu” of circuit design. The situation is precisely like that faced by designers of very high frequency vacuum tube amplifiers decades ago. The same circuit topologies may be adopted now.

I propose merging the two circuit topologies described below, which would make for an extremely manufacturable amplifier design using contemporary microelectronic methods. It appears that using these ancient approaches a good performance EHF front end can be designed with a device transconductance of only 1.5 dB, implying operation virtually at $f_t$.

The first ancient wisdom to employ is the push-pull radio frequency amplifier. At all frequencies push-pull amplifiers cancel out even harmonic distortion. But at high frequencies this architecture also halves the device interelectrode capacitance and series inductance (NAVSHIPS 92676, 1958, 2.4). The effect is to push out the $f_t$ of the device when it is employed in such an amplifier stage. Figure 4.8 below illustrates the design approach as it is used in a Korean war-era aircraft communications receiver. (The tube used is like a 12AT7. The frequency of operation is 400 MHz.)

The second wisdom is the distributed amplifier. Normally used in untuned amplifiers, the technique involves getting the best useable high frequency performance from an amplifier stage with a gain - bandwidth product limited by the available technology. The idea is in part to employ a large number of stages chained together, with each stage having a gain of just over unity. The overall gain is then the product of the gains of each individual stage. Perhaps the best example is of the vertical amplifier in a Tektronix 585, shown in figure 4.9, which interestingly makes use of its own unique approach to stray impedance cancellation. This amplifier has a stage gain of 1.5 (about 2 dB), for an overall gain of ~1000 in 16 stages. The 3 dB bandwidth is 90 MHz. (The tube used is a 6DJ8. The adjustable grid and plate capacitances are about 1 pF.)

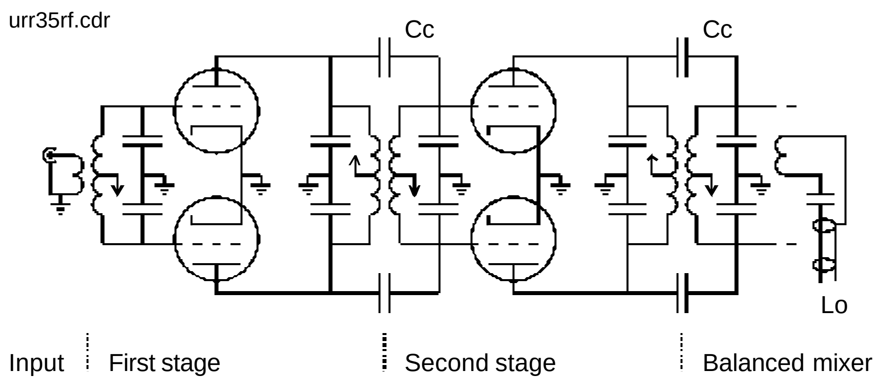



Figure 4.8. Receiver RF amplifier design of the URR-35. (Simplified, based on NAVPERS 92676 (1958, fig. 7-26).

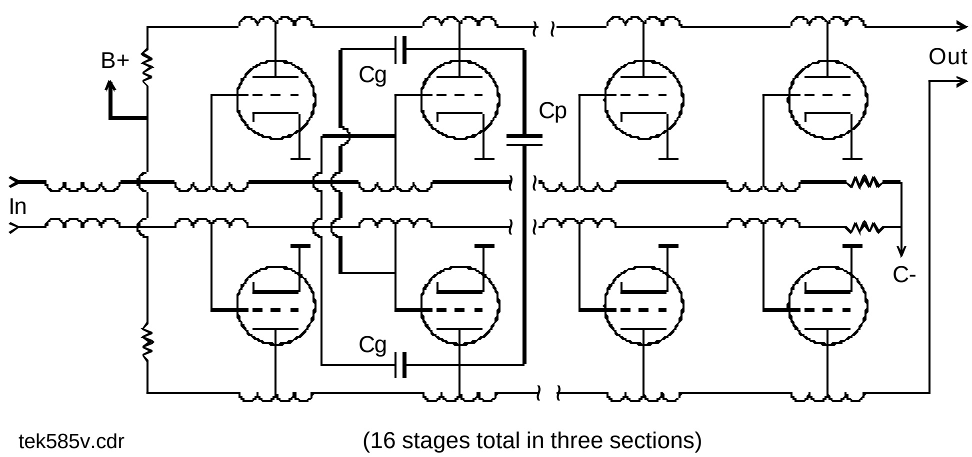



Figure 4.9. Distributed amplifier used in the Tektronix 585. (Simplified, based on TEK 82 (1963, 3.5).

**Estimating the total available spectral resource.**

Now all the details are in place to understand the implications of Moore's law for the spectral resource:

- Transistor performance for a given linewidth.
- The year a particular linewidth will become commercially feasible.
- The needs of wireless circuit designers for transistor performance.
- The art of integrating a transistor device design into a circuit environment.

From this information set we can project the total allocatable radio spectrum over time:

| Year | Linewidth, : | $f_t$ (GHz) | Maximum frequency | allocatable... |
|---|---|---|---|---|
| | | | for gain = 1.5 dB. | for gain = 6 dB. |
| 1999 | 0.14 | 150 | 120 (80% $f_t$) | 37 |
| 2003 | 0.10 | 190 | 150 | 47 |
| 2006 | 0.07 | 220 | 175 | 55 |
| 2009 | 0.05 | 240 | 190 | 60 |
| - | 0.01 | 280 | 224 | 70 |

Table 4.3. The trajectory of silicon for the analog

reality underlying the digital era of wireless communications: Total allocatable radio spectrum.[6] (Linewidth shown is that achievable for MPU gates.)

**1.3. The extent of the spectral resource.**

If the trajectory of linewidth is understood it becomes possible to design public policy concerning new uses for the spectral resource, so that spectrum can be allocated in a coherent and timely way coincident with the deployment of new products. Specifically, wireless digital telephony could be allocated spectrum that best facilitates a business model tailored to the need for universal connectivity. I propose such a new class of service in the remainder of this chapter.

In existing circumstances such is precisely the process employed in planning for new military applications of spectrum, usually by the National Telecommunications and Information Agency (NTIA) in collaboration with the military establishment (Bush, 1985, 2.4-2.5). The NTIA is charged with

[6] The cutoff frequencies shown are for high mobility field effect transistors fabricated on gallium-arsenide substrates, using X-ray lithography (Heaton). An emerging low cost alternate technology, especially suited for consumer applications, is that of silicon-germanium heterojunction transistors. The high frequency gain and noise characteristics for Si-Ge devices are likely to be somewhat different.

managing U.S. governmental uses of the radio spectrum, whereas the FCC manages civilian uses of the spectrum. The result is that at present the defense industry is the first to realize new uses for the high frequency limit of the spectrum, to acquire the spectral resources it wants, and to extract rents from the deployment of new telecommunications technologies in military systems. If one believes that resources should be employed to the highest and best use, and that the highest use of material things is to better the lot of humankind in times of peace, then the existing dynamic of allocating newly accessible spectrum must be turned on end. Besides, if pseudonoise digital modulation is employed in private market applications, the military could still, if needed in time of war, overlay its systems on the same spectrum. The whole idea of giving the most advanced spectral resources over to military uses then becomes superfluous.

The spectrum currently available for civilian use is managed by the FCC. The spectral allocation processes as utilized by the FCC are a little more complex and consist of a series of largely incompatible policy approaches:

- There is more that one FCC group looking at new technologies.
- Pioneer preference awards.
- Lotteries for the awarding of broadcast spectrum and

800 MHz cellular.

- Spectral auctions for PCS.
- As needed for land mobile. There are even FCC proposals to auction slices of the VHF public service band, those auction blocks being interleaved with traditionally allocated spectrum.[7]
- Performance bonds of billions of dollars for rights to satellite spectrum assignments.

I suggest that ending the bottleneck (Economics and Technology, Inc. & Hatfield Associates, Inc., 1994) to economically feasible competition in the market for local access to the telecommunications market, and keeping rural telephone service affordable are of such strategic importance that it is worthy of the application of the most advanced device technology and the accompanying highest frequency spectrum -- particularly in a peacetime marked by the absence of any sophisticated military threat. The difficulties with restricted competition in the existing choices for wireless telephony were discussed in chapter three. But unless the spectrum allocation is paired with a wise institutional choice for a market-based approach to deliver the benefits such technology promises, we will be doing little more than mirroring the monopolistic or oligopolistic abuses of existing

[7] Visit the FCC Web site Auction pages for information and proposed spectrum maps.

wireless mechanism designs, or replicating the information costs and attendant inefficiencies of traditional regulatory approaches.

**A fundamental policy implication of the trajectory of silicon for radio frequency spectral resource management: A final scarcity.**

Over the last few decades especially, the radio spectrum has been viewed as an ever-expanding resource, where the total available spectrum is taken to be largely a function of the economics of telecommunications equipment engineering. The development of integrated circuit techniques for microwave frequencies and the transition to digital modulation schemes have over the last two decades lent that view of a limitless resource a seemingly unshakeable realism.

But my explanation of the trajectory of the technology of microelectronics and its implications for radio frequency design demonstrate that the upper bound of the spectrum that will be economic for consumer products will be about 225 GHz, and that this limit will be attained just a single generation hence. At the same time digital encoding schemes that increase circuit capacity cannot do so without fundamentally trading off the human qualities of speech or visual images, setting limits to what the digital era can bring to the spectrum management table.[8] It is well understood that the demand for telecommunications grows exponentially.

The clear implication is that the scarcity doctrine that has empowered the FCC until now, and which many would prefer to cast off in the transition to the new era of digital wireless communications, appears only to those whose vision is clouded to be no longer operative. In just shy of a generation, as the digital age is fully upon us and we have finally traveled down the path of silicon, the scarcity of the spectral resource will once again be as apparent to us as it was prior to the 1970s. We will once again confront the need to design just institutions for the allocation of the spectrum resource to human needs.

There is a window of opportunity to design wireless telephony systems that serve the human need for genuine relation and beneficial markets and that make fair and wise use of the spectral resource that is of God and under the stewardship of people.

---

[8] Footnote: That limit appears to be about an eight-fold improvement in channel capacity at most (see Cox, 1996, 229 and Kucar, 1996, 252-3).

## Section 2. Technology for EDCT.

### 2.1. Service features desired.

The objective of EDCT is to provide universal voice and data connectivity at extremely low cost, so that competitive provision of telecommunications becomes practical, even in areas of low population density. I wish next to define the level of performance and service features for EDCT voice and data services. To create a “drop in” replacement for existing wireline rural local service, we can rely heavily on the measures of infrastructure deployment from the survey conducted of Wisconsin telecommunications service providers[9] for guidance concerning the kinds of service features desired.

For digital wireless provision of voice grade circuits, some consideration then needs to be given to the technical issues of data rate, acceptable signal-to-noise ratio, and encoding methods. For data service to provide, say, Internet access, there is considerable flexibility in defining data rates. A convenient starting point is to survey the performance of existing high speed alternatives for residential access. The data service bandwidth offered to subscribers is going to impact the fixed cost of the

---

[9] Chapter three contained a multivariate analysis of that survey. The advanced service features listed there are those which society has previously decided are key to attaining universal service goals.

subscriber equipment, as well as the spectral congestion charge for airtime. Finally there will need to be some discussion of other service characteristics that are unique to the new class of service envisaged.

**Voice service characteristics.**

As was discussed in the multivariate analysis, wireline service providers have as a strategic choice the extent to which they deploy advanced service features in their service territories. The multivariate analysis used the measures of infrastructure deployment listed in appendix B. The variables listed there can be condensed into the following measures of advanced service features for the existing wireline network, as shown in table 4.4 below. A digital wireless local loop either inherently provides for many of these service features or the features reside in the central office switch. As a result all of the advanced features of traditional wireline telephony are readily provided. With rural wireline service under rate-of-return regulation, substantial monies are being allocated to attain these universal service goals. EDCT would enable these societal goals to be realized privately and at a much lower cost.

| Service feature | Extent provided for in network: Wireline | Cellular | EDCT |
|---|---|---|---|
| Lines served by a digital switch | most | 100% | 100% |
| ISDN narrowband lines | little | N/a | 100% (1) |
| SS7 compatible switches | most | 100% | 100% (2) |
| Enhanced 911 capability | most | little (3) | 100% (4) |
| Digital transmission | 100% | 100% | 100% |

**Notes:**
1. EDCT can provide for ISDN data rates through an appropriate choice of voice channel bit rate, thus providing br1 service levels for voice or data.
2. For the most part, EDCT cell sites would act as tandem switches.
3. Cellular providers are under FCC mandate to provide radiolocation for 911 calls placed over their network, but little deployment has occurred to date.
4. EDCT is inherently a fixed wireless service, so subscriber location is known.

Table 4.4. Advanced service features for universal service.

Speech coding considerations.

The choice of the digital circuit data rate, acceptable signal-to-noise ratio, and encoding method not only establish the perceived quality of voice conversations, but for EDCT would determine the extent to which a voice-only customer would be able to press the link into service as a basic Internet connection. The existing wireless telephony standards trade voice quality for other factors, reflecting deliberate choices made to effect tradeoffs between signal processing requirements, network capacity, battery life, handset cost and the like. Cox (1996, 228-9) explains that if speech quality considerations are set aside, lowering the encoding bit rate to as little as 8 Kbps (as in IS-95) can result in a cell site capacity improvement of as many as 30 times over a low-tier PCS implementation. However, signal processing requirements are greatly increased, and speech quality is significantly degraded (See also Cox, 1992, as cited in Cox, 1996).

We are targeting customers with the following characteristics affecting the choice of speech coding rate:

- Low to moderate population density.
- Circuit congestion expected to occur only at peak times.
- Subscriber hardware cost is a major concern.
- Nearly all customers will want basic Internet access, while some will want high bandwidth connections.
- Customers will expect voice quality equal to wireline.

Given these needs I propose a bit rate equal to ISDN br1, which is 64 Kbps. All customers will then have the same entry level voice / data options as do wireline ISDN customers: that is, two excellent voice lines, voice plus fax, voice plus data at analog modem speeds, or FM broadcast grade audio. As a bonus, extending lifeline-like service to the lowest income residents would require only minimal hardware cost.[10] Finally, if the subscriber link operates without speech coding, then coding algorithms may be employed on the network backbone, sharing the costs of the additional signal processing that would be required among end users and improving network efficiency.[11]

**Data service characteristics.**

High speed Internet access to the home means different things to the purveyors of technology alternatives to analog modems. The principal alternatives at present are Integrated Services Digital Network (ISDN), Asymmetric Digital Subscriber Loop (ADSL), the cable industry @Home modem initiative, DirecPC, and Multipoint Distribution Service (MDS). I will look briefly at each of these in turn.

---

[10] Broadcast grade audio provides a way to originate feeds for school sporting events, religious services, town meetings and the like that help create community. If voice-only service can be provided at a low enough cost, then subsidizing lifeline service becomes unnecessary. Both imply a higher speech coding rate.

[11] Later I explain that the subscriber frequency “slices” are generally chosen where there is high atmospheric absorption, so that efficiency in end user links is of lesser importance. On the other hand, backbone frequency blocks will have a much larger frequency reuse range and aggregated traffic. (In an urban implementation speech coding in subscriber hardware may produce the lowest overall cost.)

ISDN and ADSL.

ISDN basic rate service at 64 Kbps has on average about twice the throughput of 56 Kbps analog modems. ADSL is not a single standard, but a series of largely incompatible standards falling under International Telecommunications Union (ITU) Group G.991. The various existing protocols have downstream (to the subscriber) data rates ranging from 768 Kbps to 8 Mbps (Raynovich, 1999), with 1.5 Mbps “G.lite” (G.992.2) possibly emerging as the most common. Regrettably, actual throughput data rates are not assured, as the network aggregation points (known as DSLAMs) do not have bandwidth management features. To date ADSL modem deployment has been considerably lagging that of cable modems, with but one tenth the installed base (Raynovich, 1999, 39), partly because a coherent standard won’t be available until the end of 1999, and partly because ILEC “foot dragging” on unbundled access to copper seems to be interfering with the formation of a market.

Cable industry @Home™ initiative.

Activity in cable modems is centered on a single technical standard, DOCSIS v1.1 (Weinschenk, 1999), with fifteen modem manufacturers scheduled to undergo certification testing in 1999. Data rate specifications are a little scarce at the moment, but a not certified product, the Motorola

CyberSURFR™ (Moto, 1999), has a downstream peak rate of 10 Mbps over a shared 30 Mbps channel and an upstream rate of 768 Kbps.

DirecPC™ satellite provision of Internet access.

Hughes Data services (HDS, 1999) has an offering that provides instantaneous download rates of 400 Kbps, and a continuous caching of most popular pages on the hard drive of the end user computer. The satellite terminal is similar to the Dish TV-like services, meaning that it is receive only. Thus data from end users must travel over a wireline link through a local Internet service provider.

Multipoint Distribution Service.

Zita (1999) is of the opinion that MDS is an especially promising architecture to provide Internet access, but that most deployments will be in countries with inadequate wired infrastructures. MDS operates at 10, 28, and 38 GHz. For the WinStar Communications product data rates are available from 8 Mbps up to T3 (in beta testing) (Zita, 1999).

Wireless modems.

Finally, with respect to wireless modem products offered for computer networking, Kucar (1996, 218) points out the considerable problems with product churn, lack of clear standards, and lack of appreciation by the computer industry of “the vagaries and needs of a reliable radio system.” Kucar observes data rates for wireless local area network (WLAN) products ranging from perhaps 768 Kbps to 15 Mbps (for the Motorola ALTAIR 18 GHz product), with the mean being about 1-2 Mbps. While never intended as a means of providing residential service, WLAN modem technology is nevertheless indicative of what can be presently attained using digital spread spectrum techniques.

Summary of data service offerings.

The data services that will be of interest to either consumers or small independent service providers are summarized here in table 4.5:

| **Type of Service** | **Data rates (Mbps) Max.** | **Typical (D / U)** | **Target customer** |
|---|---|---|---|
| ISDN | 0.12 | 0.064 | consumers |
| ADSL | 8 | 1.5 / 0.5 | consumers, small business |
| Cable modems | 10 | ?? / 0.768 | consumers |
| Satellite IP | 48 | 2 to 8 | ISPs, overseas or extreme rural |
| DirecPC | cache | 0.4 / 0.05 | consumers |
| MDS | 48 | 8 | business, CLECs for trunking |
| WLAN modems | 15 | 3 | business (campus environments) |

Table 4.5. Data service offerings for non-large customers.

Proposed data rates for EDCT.

Presently the objective is to extend “Internet I" (what is presently known as the Internet) to rural areas, but eventually “Internet II” connectivity will be expected.  Thus we will need a system architecture that can handle a migration from T1 rates to T3-like rates for high tier customers.  I propose three product generations of data rates: 768 Kbps, 6 Mbps, and 48 Mbps.

**Other service features of EDCT.**

I believe that only spectral congestion pricing affords sufficient flexibility in pricing high speed access to enable orderly growth, across generations of product realizations, of a seamless and enduring new rural network for voice and data. Below in table 4.6 is a summary of the key specifications for the proposed EDCT.  Some of the specifications have been discussed already, others are discussed below, and the rest in the final sections of this chapter.

Business model.

As I discussed in chapter two, the radio spectrum is to have a resource cost assigned, based on spectral congestion. Cell sites are to conduct spot radiometric measurements of excess noise in their service area and set airtime usage prices based on the present level of congestion and the bandwidth required by the pending subscriber connection.

The role of the FCC is to be that of conducting area noise surveys to prevent overuse and resulting deterioration of the spectral resource. Digital modulation inherently provides for full deployment of the advanced service features that have traditionally been seen as universal service goals in the wireline era. The other goal of regulation -- attaining marginal cost pricing in the presence of a natural monopoly -- is now best attained by exploiting the cost trajectory of silicon to bring the fixed cost of entry into the reach of the working class, while preventing government from establishing any criteria that restrict entry.

| | |
|---|---|
| **Voice service:** | |
| Voice channel encoding rate: | 64 Kbps. |
| Number of voice grade lines provided: | 2 (if only one circuit is in use, it takes all 64 Kbps). |
| basic data rate: | 32 - 64 Kbps (over 1-2 voice channels). |
| Universal service advanced features: | E911, SS7, digital switch, ISDN br1. |
| Modulation: | Pseudonoise BPSK, little to no FEC (r ~ 1). |
| Speech encoding: | 32 - 64 Kbps ADPCM (CCITT standard) |
| Minimum acceptable signal-to-noise: | 25 dB end-to-end (voice). |
| **Data service:** | |
| Data rate: | |
| first generation: | 0.768 Mbps. |
| second generation: | 6 Mbps. |
| third generation: | 48 Mbps. |
| Modulation: | Pseudonoise Golay, r ~ 0.5. |
| Data caching: | Service provider to cache data in local demand. |
| **Physical specifications:** | |
| frequency of service (subscriber): | |
| first generation (year 2000): | 55 to 65 GHz (slices therein). |
| second generation (2006): | 110 to 120 GHz. |
| third generation (2012): | 165 to 194 GHz. |
| Network backbone frequencies: | 134 to 151 GHz, plus near subscriber frequencies. |
| Size of transmitter / receiver modules: | About 4 cm (1.5 inch) in diameter. |
| Power requirements: | 12 volt, with local battery standby power. |
| **Business model:** | |
| Spectrum assignment method: | Uncoordinated; spectral congestion pricing. |
| Subscriber unit target cost / life: | $200 / 5 years (without data service capability). |
| Cell equipment target cost / life: | $10,000 / 10 years. |
| Ownership model: | (See text.) |
| Competitive access: | (See text.) |
| Service outages: | (See text.) |

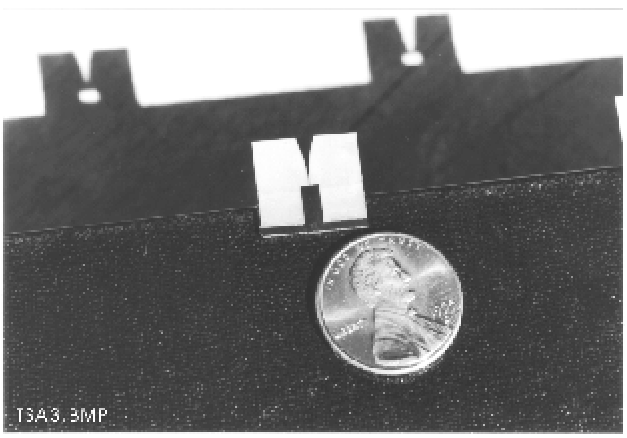
Table 4.6. EDCT: Proposed key service characteristics and specifications.

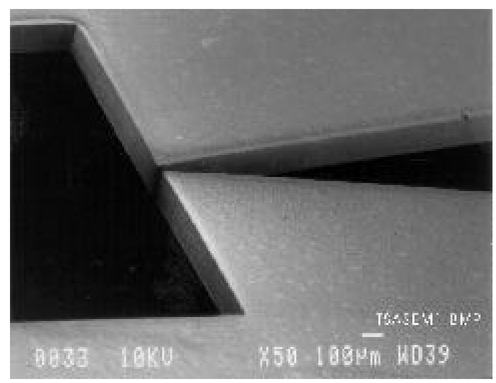
## 2.2. System architecture.

Traditionally the more specialized governmental services have been allocated to the highest frequency spectrum, because such services have been better able to justify the higher costs of utilizing radio spectrum frequencies at the upper limit of the spectral resource. While it has been true that it is more costly to design services for the upper bound of the spectrum, the trajectory of the technology of silicon ultimately undoes this assumption (below about 225 GHz), especially for mass markets. In addition to the increasing electrical circuit densities and performance that were chronicled earlier in this chapter, mechanical structures (i.e., antennas, disk drives, analytical instrumentation) fabricated using the technology of microlithography have their key quality characteristics of speed of operation, cost and reliability scale as the inverse fourth power of size (Guckel, 1990).

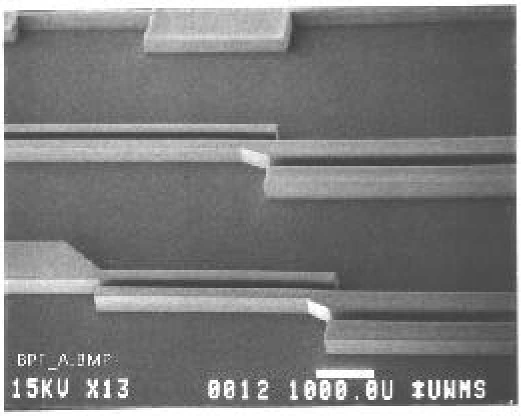
### Antenna structures suited to EHF.

Moreover the micromechanical devices so manufactured can be made with extreme dimensional accuracy and fully integrated with their associated electronics. Thus the cost of box-level consumer telecommunications products for EHF can in principle be much lower than for current design approaches that combine chips onto boards with discrete antennas. Two photos of a micromechanical antenna appear in the electron micrographs below, along with an example of a bandpass filter element (the key component of a diplexer).[12] All three examples are of electroplated gold and are suitable for use at 90 GHz. The required lithographic technique is less sophisticated than that illustrated in figure 4.3, the key requirement being dimensional accuracy over the total size of the structures.




[12] These three non-copyrighted images were obtained in a private communication on 04 MAR 98 from Prof. Steven S. Gearhart, Electrical and Computer Engineering, University of Wisconsin: Bpf_a.tif; tsa3.tif; tsasem1.tif.




Figures 4.10. through 4.12. A 90 GHz (15 dB gain) tapered slotline antenna (above two images) and a bandpass filter element (left) for 90 GHz (Gearhart, 1998).

It is interesting to compare the tapered slotline antenna shown above to the 2 GHz horn antennas mounted on top of the microwave relay tower shown in the next figure.  The 2 GHz antenna has an aperture of about 5 meters and a gain of about 30 dB.  The 90 GHz antenna isn’t directly comparable, but one can easily envision the scaling of cost and reliability as frequency increases.  More will be said about the cost structure of telephone service based on developments in the trajectory of silicon in chapter five.

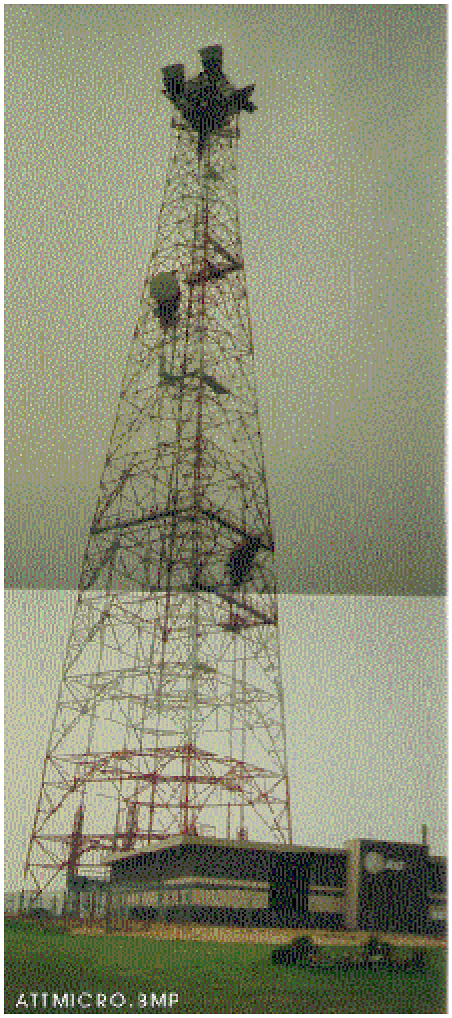



Figure 4.13. AT&T Longlines Division microwave relay tower.

**EDCT system design example.**

Next let's design a telephone system architecture for EHF that takes full advantage of recent developments in microelectronics and micromechanics. I discuss the propagation characteristics of EHF radio waves in chapter four, section 2.3 a few pages hence. I need to carry forward to the present discussion just two ideas: First, the working range of a subscriber communications link will vary from two to ten kilometers, depending on the precise frequency chosen. Second, there must be a clear line of sight to each subscriber. The task is to design a network that provides for the desired service features and takes into account these technical constraints.

Let us define four basic types of integrated antenna and transmitter / receiver (T/R) modules. The types are listed below in figure 4.14. Each module need be no larger than a ping-pong ball, given that moderate gain antenna structures at EHF frequencies are but a centimeter in size. It is best to locate the T/R electronics right at the antenna, in order to avoid degrading the system noise figure. The connection to the T/R module is a twisted pair wire or short-haul fiber optic cable that carries a digital information stream at baseband frequencies. (By baseband I mean directly encoded information prior to its attachment to a radio wave.) The standardized modules can be completely sealed and mass produced.

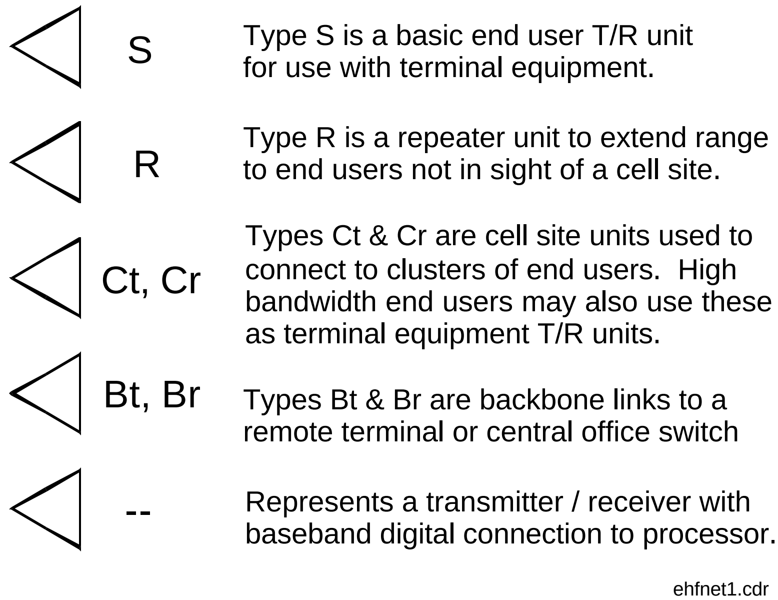



Figure 4.14. Type definitions of transmitter / receiver modules used in EDCT network topology.

The type S module would be the kind to be attached to subscriber dwellings. Cell sites would use type C modules to communicate with clusters of subscribers. In addition end users desiring the widest possible bandwidth connection may use a type C module on-premises to make a dedicated high speed link. Type B modules are used for network backbone links between cell sites or between a cell site and a central office switch.

The type R repeater module is unique to this proposed system architecture. In rural areas, particularly in hilly terrain or in the lowest population density areas, some subscribers will not be in direct view of a cell site. However the density of customers will make it not economic to deploy an additional cell site. By linking those customers instead to the nearest subscriber with a good view of a cell site, the range can thereby be extended. Because the repeater is a digital link, there is no degradation in circuit quality.

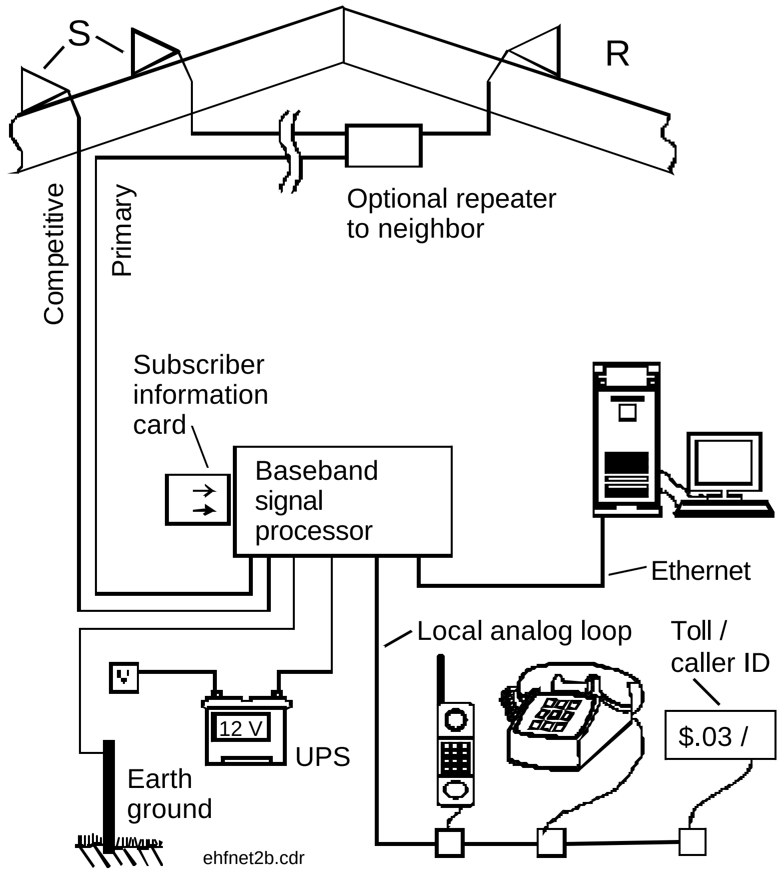



Figure 4.15. The future of fixed wireless: EDCT subscriber installation.

The type R modules are to be interconnected with type S modules in a way that is separate from a subscriber's baseband signal processor. Figure 4.15 above shows a typical subscriber installation.

In a subscriber installation it is anticipated that the baseband link will be copper twisted pair to minimize cost and reduce demands on installer skill. The baseband signal processor would look outwardly much like a contemporary wireline Network Interface Device (NID), except that here there would be an optional Ethernet port for data and some intelligence to manage account information, much like the Smart Card on GSM handsets. The various components would simply plug together, much like “Dish TV” subscriber terminals, but with even simpler antenna aiming requirements. The subscriber information card could, at least in areas of low fraud, be remotely managed. The voice port is intended to provide a powered analog local loop, so that the existing type of telephones, that all customers are familiar with, may be used.

In order to provide independence from electric utility service interruptions, an external 12 volt backup battery would be provided. The capacity of the battery could be tailored to the expected reliability of electric service in a given area. Additionally, if the subscriber package is designed to operate off of 12 volts, a cigarette lighter adapter could be issued for use during extended outages, as occurs during the occasional severe ice storm or tornado, thus giving people something useful to do with their cars when under siege by Mother nature.

Next let us look at a typical cell site, pictured below in figure 4.16:

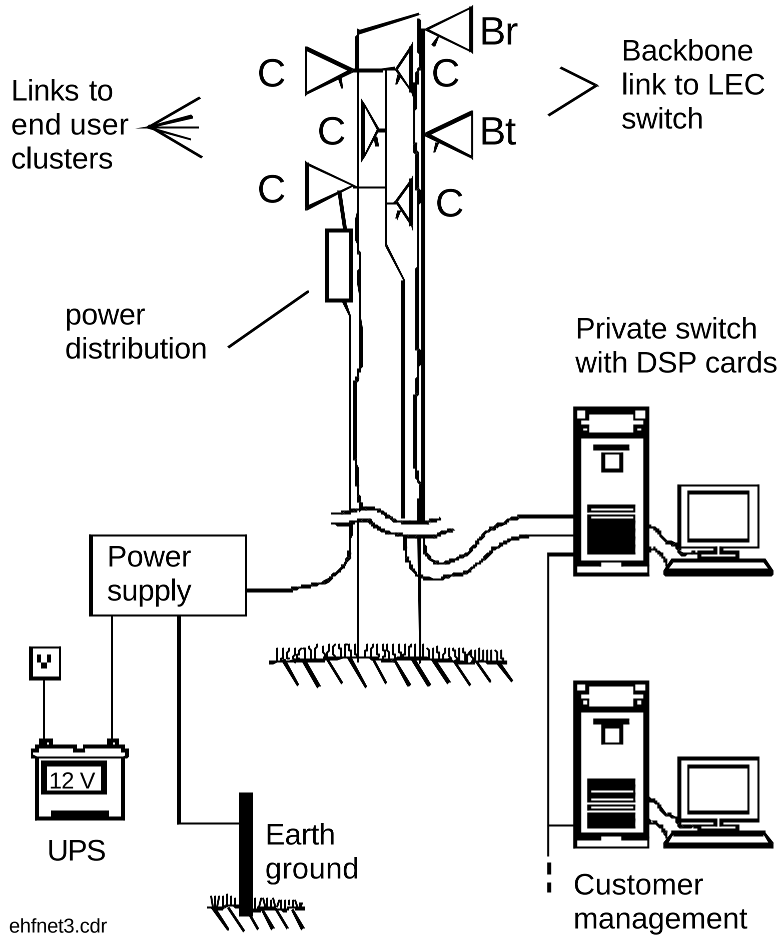



Figure 4.16. Joe's Cell Site and Data Sprayer Service.

The principle underlying the proposed cell site architecture is to minimize the fixed cost of entry for service providers, by taking full advantage of personal computer-based signal processing cards now available for computer telephony applications, and the extremely low cost of the T/R modules. (See Jainschigg (1999, 8) for a 60 channel PCI card using ITU G.723.1 speech encoding.) Then many people will find it within their means to provide service to their neighbors. A business of this type would be comparable to the other kinds of service businesses that operate in a rural economy. The antenna support structure could be a wooden telephone pole, or for that matter, a pretend tree. (See Locicero (1996, 21) for photos of commercially available antenna support structures that have the appearance of white pines.) The baseband data link would most likely be fiber optic, to provide immunity from lightning.

As envisaged a cell site would be similar in complexity to a cross between a business PBX, which requires some administration of individual customers, and an amateur radio packet bulletin board service (BBS), which involves the installation of off-the-shelf radio equipment, personal computers, and BBS software. For both the PBX and radio BBS, the level of provider skill required is a high school degree, a technical inclination, and some training or experience. An industry association could provide standard software packages and support to service providers. I propose the cooperative ownership of any such associations. University extension schools could provide operator certification, as has traditionally been done at the University of Wisconsin and elsewhere for analog cellular operators.

The next two figures, 4.17 and 4.18, illustrate the relation between the public switched telephone network and EDCT service providers. Some of the local traffic could be handled solely over EHF links between provider cell sites.

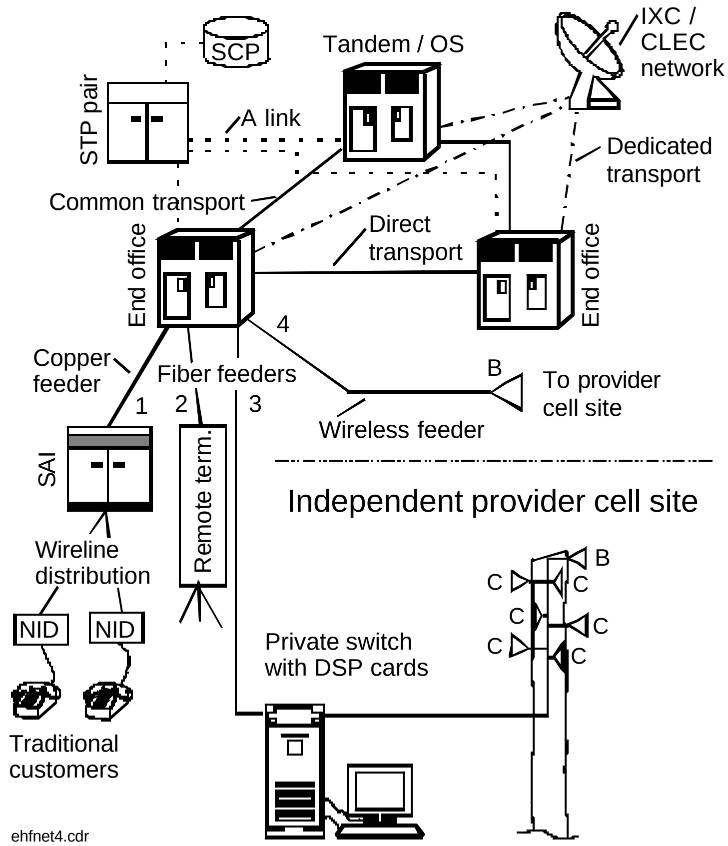



Figure 4.17. EDCT: Unbundled network diagram.

Access to the built-up areas of local communities and interexchange carriers (IXCs) would most likely be by interconnection with an existing wireline provider central office (CO) switch.  Signaling System 7 (SS7) functionality can be extended from the CO to the EDCT cell sites by a lower data rate secondary channel.

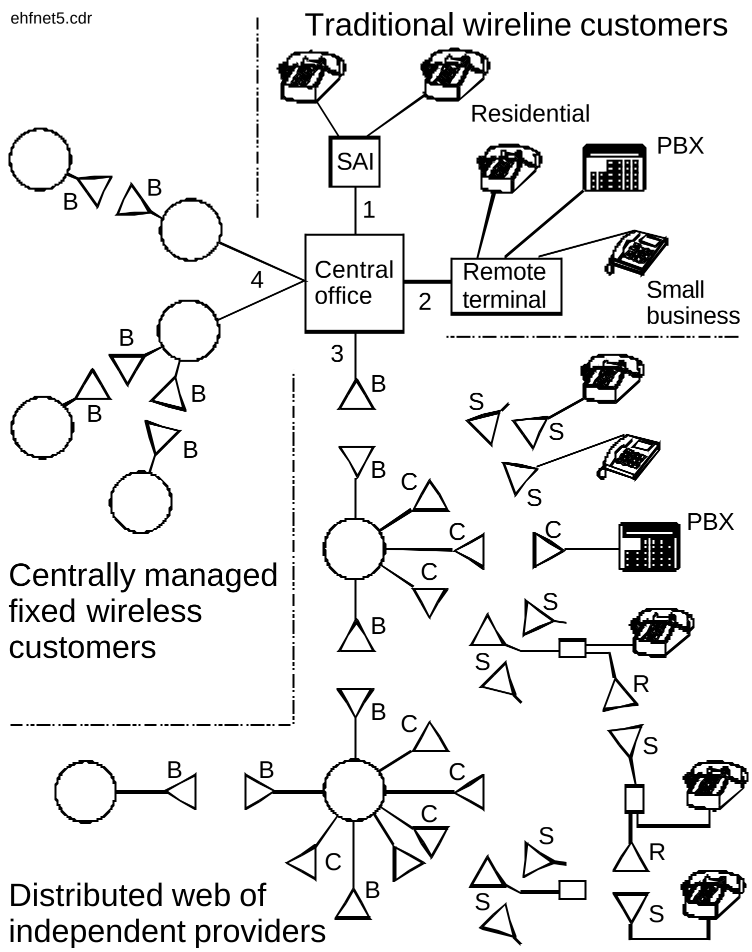



Figure 4.18.  An overall view of a rural telephone network that uses a mix of technology, including EDCT, and ownership.

Figure 4.18 above gives a global view of a rural network with various interconnected service providers. Note that there are four ways to interconnect to the incumbent firm's CO switch:

1. Traditional copper trunks to wireline customers in the build-up core of the community.
2. Fiber optic trunking to remote terminals in ex-urban developments.
3. Wireless EDCT provider owned backbone links that terminate at the switch.
4. Incumbent owned fiber optic or thin channel microwave trunks to incumbent or independent EDCT service provider cell sites.

The bottom line for EDCT is that a low-cost, feature rich network can be built that creates opportunities for small independent operators to provide advanced telecommunications service to the members of their local communities.

**2.3. Allocation of the spectral resource to EDCT.**

The unfolding of the extent of the radio frequency spectral resource in terms of the enabling trajectory of microlithography was explained in the first section of this chapter. Here we want to understand enough of the unique qualities of extremely high frequency (EHF) radio wave propagation, so that wise choices can be made about how to best use the resource for providing local telephony and the many other classes of telecommunications service that benefit from EHF frequencies. Then specific recommendations can be made about which portions of the spectrum might be allocated to this new class of service.[13]

**Overview of EHF spectrum usage.**

Administrative aspects of the allocation of radio spectrum were discussed in chapter two, but the basic principles in domestic affairs are “first-come-first-serve” and on an international basis collegial relations between nations.

---

[13] I must introduce a constraint at the outset. There are small slices of the EHF spectrum that have been set aside for amateur use, often on a non-exclusive basis. I feel these need to be left alone for the future benefit of society. The reason is simple: It is my love of the technology of radio communications, merged with a desire to create something better for others, that motivates my work. I am not the only one who will experience such a sparkle of inspiration. (See Pocock (1999, 85) for a list of the amateur bands above 10 GHz.)

Telecommunications services that have already been allocated slices of the spectrum are summarized below in table 4.7:

| Freq. (GHz) | Attenuation (dB / Km) | Use (See key.) | Freq. (GHz) | Attenuation (dB / Km) | Use (See key.) |
|---|---|---|---|---|---|
| 54.25-58.2 | 6-20 | EES, F, IS, M, SR | 150-151 | 1.8 | SR, EES, M, FS, F |
| 58.2-59 | 20-100 | EES, RA, SR | 151-164 | 3 | FS, M, F |
| 59-64 | 100 | F, IS, M, RL | 164-168 | 3-10 | SR, RA, EES |
| 64-65 | 100 | EES, SR, RA | 168-170 | 10 | M, F |
| 65-66 | 50 | M, F, SR, EES | 170-174.5 | 30 | IS, M, F |
| 66-71 | 20 | M, RN, MS, RNS | 174.5-176.5 | 50 | EES, IS, SR, M, F |
| 71-72.91 | 10 | M, F, RA, MS, FS, RNS | 176.5-182 | 100 | IS, M, F |
| 72.91-75.5 | 9 | M, F, MS, FS | 182-185 | 30 | EES, SR, RA |
| 75.5-81 | 6 | AMAS, AMA, RN | 185-190 | 8 | IS, M, F |
| 81-84 | 4 | MS, FS, M, F | 190-200 | 8 | RNS, RN, MS, M |
| 84-86 | 3 | BCST sat., BCST, M, F | 200-202 | 6 | EES, SR, M, F |
| 86-92 | 3 | EES, SR, RA | 202-217 | 6 | FS, M, F |
| 92-95 | 2.5 | FS, RL, M, F | 217-231 | 5 | EES, SR, RA |
| 95-100 | 2 | RL, RN, RNS, M, F | 231-235 | 5 | RL, FS, M, F |
| 100-102 | 2.5 | SR, EES | 235-238 | 5 | EES, SR, FS, M, F |
| 102-105 | 3 | FS, M, F | 238-241 | 5 | RL, FS, M, F |
| 105-116 | 3-20 | EES, SR, RA | 241-250 | 5 | AMA, AMAS |
| 116-126 | 20-100 | EES, SR, IS, B, M, F | 250-252 | 5 | EES, SR |
| 126-134 | 4-1.5 | IS, RL, M, F | 252-265 | 5 | RNS, RN, MS, M |
| 134-142 | 1.5 | RL, RNS, RN, MS, M | 265-275 | 6 | RA, FS, M, F |
| 142-149 | 1.8 | AMA, AMAS, RN | 275-300 | 9 | M, F |
| 149-150 | 1.8 | FS, M, F | | | |

**Notes:**
1. All uses above 32 GHz are considered as primary, except radionavigation.
2. All allocations are shared on a government / non-government basis, except 75.5-76, 142-144, and 248-250 GHz, which are non-government exclusive.
3. ISM bands appear at 122.5 +/- 0.5 GHz, and at 245 +/- 1 GHz.
4. Attenuation shown is total for all sources exclusive of rainfall, for a path normal to the surface (see Bulletin No. 70, 1997, figure 5), and a humid atmosphere.
5. Absorption peaks are at 60, 120, 180, 315 GHz, and are due to oxygen and water vapor.

**Usage key:**

| | | | | | |
|---|---|---|---|---|---|
| F | Fixed | EES | Earth exploration satellite (passive) | AMA | Amateur |
| M | Mobile | SR | Space research (passive) | AMAS | Amateur satellite |
| MS | Mobile satellite | IS | Intersatellite links | | |
| FS | Fixed satellite | RNS | Radio navigation satellite | BCST | Broadcasting |
| RN | Radionavigat. | ISM | Industrial, scientific, or medical | | |
| RL | Radiolocation | RA | Radio astronomy | | |

Alloc96.wpd

Table 4.7. U.S. radio frequency spectrum allocation table, 54 - 300 GHz. Slightly abbreviated and based on NTIA (1996), FCC (1996), and FCC (1997, 8).

While the spectrum may appear to be already “divvied up” among many different kinds of services, closer examination of the Spectrum Inventory Table (FCC, 1996) reveals that there is at present little congestion above 42 GHz. Besides, as we saw earlier in table 4.3, semiconductor linewidths just now make it economic to consider fielding products for the mass market at frequencies to 37 GHz. At the other extreme, spectrum above 225 GHz is likely to never be amenable to consumer products, according to the technology assumptions of this thesis. Note however that there are already passive imaging activities, including radio astronomy, underway throughout the spectrum.[14]

**Technical features of EHF radio propagation.**

EHF frequencies, also known as the millimeter waves, exhibit certain interesting characteristics when traveling through the Earth’s atmosphere. Such propagation characteristics can either be foolishly ignored or constitute unique advantages for telecommunications service stakeholders.

[14] A good example of current radio astronomy research activity is the MSAM2 millimeter wave telescope experiment of Cordone, Timbie, et.al. (Unpublished) This 1.3 meter dia. telescope operates at five frequencies from 65 to 170 GHz. The first balloon flight occurred in June, 1997. The objective is to observe the large scale structure of the universe to test various theories of the origin of the universe.

FCC Bulletin Number 70 (FCC, 1997) provides a good overview of the decades of empirical work concerning the various factors that affect EHF communications system design. There are three key attributes of millimeter wave propagation:

1. Line-of-sight communication.
2. Atmospheric absorption resonances at intervals throughout the spectrum, caused by both water and oxygen molecules.
3. Significant additional absorption caused by plant foliage and precipitation.

All of this may sound rather bleak, but much of it may be turned to advantage. The absorption peaks at 60, 120, and 180 GHz provide excellent opportunities for short range communication links that are relatively secure from eavesdropping and efficiently use the spectral resource.

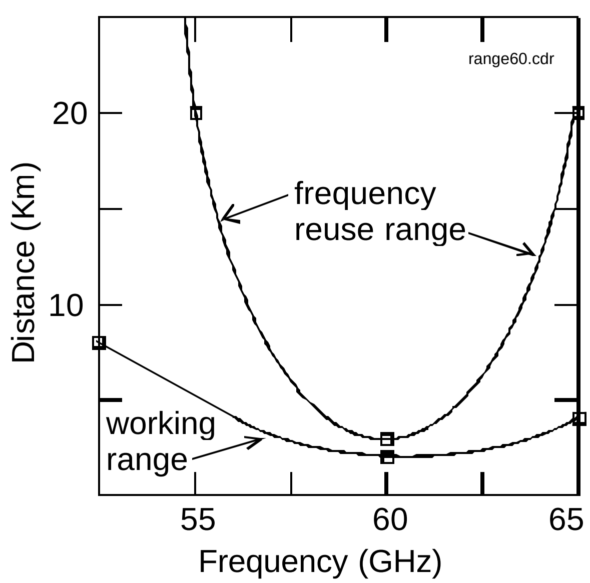



Figure 4.21. Practical working distance and necessary separation between transmitters sharing the same fixed frequency assignment for a hypothetical EHF system (based on FCC, 1997, 12).

For example, consider the impact of the absorption peak at 60 GHz on the design of a hypothetical eight Mbps digital fixed link (FCC, 1997, 12), portrayed in figure 4.21 above. The working range is the maximum practical distance over which the communications link can be maintained with an acceptable bit error rate and system availability. The key factors determining working range are the three key attributes of EHF propagation mentioned just above. For a system with antennas about ten meters above ground, antenna height caps the working range at a little under ten km. As one approaches the absorption peak, atmospheric absorption begins to dominate and further constrains the working range. The frequency reuse range is the separation distance between two (fixed frequency) users that assures that mutual interference will be below an acceptable level.

Intersatellite links are present for use in space at those frequencies where the total atmospheric absorption is high, effectively shielding those communications from ground-based interference or monitoring. Interestingly those same atmospheric absorption peaks centered at 60, 120 and 180 GHz would in a complementary way prevent space-based interception of private terrestrial telephone conversations. Thus private and governmental users may share the same bands without mutual interference.

On the other hand 134-151 GHz has very little absorption and would be especially good for network backbone links. In fact the discussion here about restricting the working range should not be taken as implying that EHF frequencies are only useful for short range communications. Recently a group of amateur radio operators in the Chicago, IL area used 24 GHz, 60 milliwatt T/R modules designed by station DB6NT and 1/3 meter dish antennas to span a 113 km path across Lake Michigan (Pocock, 1999a, 92). While not a long distance record, no mountains were used in this effort. They report typical results of 80 km over land paths.

**Spectrum management recommendations.**

Frequency choices for EDCT.

The frequency reuse range for subscriber communication links may be considerably reduced or eliminated by using directional antennas and unique digital pseudonoise spreading codes. I propose using both approaches to maximize resource utilization. Then the frequency offset from the absorption peaks at 60, 120 or 180 GHz can be chosen to set the working range for a particular group of subscribers. If there are a few (two to four) narrow “slices” of spectrum allocated in the vicinity of an absorption peak, then the exact link center frequencies can be matched to the geographic distribution and density of customers in a particular region.

For example for a first generation EDCT product design, a region of very low population density may use a single slice at about 52 GHz to cover widely separated users. A region surrounding a rural Midwestern community may use both 52 GHz and 57 GHz. A low income urban area may use 57 and 60 GHz for subscribers and reassign 52 GHz for a network backbone. Rural areas will need a backbone frequency allocation with a working range comparable to microwave frequencies, for which anything in the frequency range of 134-151 GHz will do. Successive product generations may use progressively higher absorption peaks.

Improving EHF spectral resource allocation.

The upcoming World Radio Conference 2000, to be held in May of that year, will consider new allocations for fixed wireless telephony in several new bands between 27 MHz and 66 GHz,[15] making it important that changes in the accompanying competitive model to be employed be considered in a timely manner (Staff, 1999, 89). It is no doubt too late to revisit

---

[15] This activity is being studied in Joint Rapporteurs Group JRG 8A/9B.

institutional choices made for services at microwave frequencies, but I would very much like to see fresh thinking applied to new service offerings at EHF frequencies.[16]

Summarizing my work to this point, I propose refinements in spectrum usage that I list below in table 4.8. The technical foundations for these recommendations are table 4.3 of this thesis, which summarizes the implications of semiconductor device linewidths for total available spectrum, together with the unique frequency dependence of atmospheric absorption at EHF frequencies, as explained in FCC Bulletin No. 70 (1997).

---

[16] Having a bit of the blood of the Vikings in me, when visiting new lands, I prefer to make camp where no one else is presently living (which contrasts with the approach of the Southern Europeans when the Americas were discovered). I suppose my ancestry accounts for my fondness for the upper reaches of the spectrum, and my hope that distributive fairness will this time not be neglected.

| Frequency range | Institutional design consideration |
|---|---|
| 42.2 to 225 GHz | National governments should consider spectral congestion pricing for designing markets for new telecommunications service offerings. |
| Above 225 GHz | Private fixed and mobile, both satellite and terrestrial, uses should be ruled out, in favor of governmental (i.e., military and research) uses. |
| 50 to 65 GHz | Allocate narrow slices of spectrum for first generation pseudonoise spectral congestion pricing based wireless local telephony. |
| 110 to 119.98 GHz | 2nd generation spectral congestion pricing based wireless telephony. |
| 134 to 151 GHz | Rural fixed wireless networking backbone terrestrial links. |
| 165 to 194 GHz | 3rd generation spectral congestion pricing based wireless telephony. |

Consid3.wpd

Table 4.8. New considerations for allocation of the radio frequency spectral resource.

**An example EDCT link analysis.**

I provide an elementary analysis of the communications link from an EDCT cell site to a subscriber, for purposes of illustration. The analysis is based largely on FCC Bulletin No. 70 and on Ricci (1997, 161-8). I make some preliminary assumptions about EDCT transmitter and receiver characteristics, included in table 4.9 below:

---

**Transmitter:**

| | |
|---|---|
| Transmit power (0.1 watt) | + 20 dBm |
| Antenna gain | + 6 dB |
| Feedline loss | 0 dB |

**Receiver:**

| | |
|---|---|
| Antenna gain | + 15 dB |
| Feedline loss | O dB |
| Noise figure | 6 dB |
| Noise floor (60 KHz instantaneous BW) | -117 dBm |

**Path loss** (52 GHz, one km link, one-way):

| | |
|---|---|
| Free space loss: 92.4 + 34 + 0 = | 127 dB |
| Total attenuation through atmosphere, (High humidity) (dB / km) | 3 |

(Specific attenuation @ 75 % humidity:
$O_2$: 0.3 dB / km
$H_2O$: 0.1 dB / km)

**Resulting signal-to-noise margin:** + 22 dB

**Effect of rainfall:**

99.9 % link availability implies an outage time of 8 hours per year.

Precipitation rates of greater than 10 mm / hour occur less than 0.1 % of the year in Wisconsin.

At 52 GHz, precipitation attenuation at 10 mm / hr is 4 dB / km.

---

Table 4.9. EHF link analysis example.

**Summary.**

In chapter three we saw the need for a new class of universal service for rural customers, in the high Hatfield predicted cost of service for those customers living away from built-up cores. We saw in the multivariate analysis of the Wisconsin telephone industry how service providers might use advanced service features made possible by investments in digital switching and transmission to differentiate themselves in the impending competitive environment of local service. Frankly we saw how some firms were better positioned to compete than others.

In this chapter we have come to deeply appreciate the force of the trajectory of silicon. The power of the silicon era is both a destructive force, as the age of the digital approximation displaces the more direct experience of the analog realm, and a creative force, making affordable the technique of pseudonoise modulation and a new way of approaching the problem of radio spectrum resource allocation.

I have built on the promise of silicon, designing a new class of rural fixed wireless telephony. EDCT is intended to place rural telephone voice and data service firmly in the camp of the economics of silicon, using the declining costs of EHF hardware, signal processing and packet switching to minimize the fixed cost of entry for EDCT service providers. In the next chapter we will explore the strategic implications of EDCT.

# CHAPTER 5. ECONOMIC AND SOCIAL ASPECTS OF EDCT.

## Introduction.

The inadequacy and unsustainability of the tradition of rural wireline telephone service has been explored. The engineering foundation of a new class of telephone service has been laid. Now it is time to explore the strategic implications of EDCT. There are several aspects to consider when examining the external environment of EDCT service providers, which I explore in turn:

1. Industry formation and structure. I employ the stakeholder strategic analysis of Freeman (1984).
2. EDCT cost of service estimation. I utilize the same approach as was employed in chapter three to estimate the cost of service for the existing cellular providers, so that direct intercomparisons can be made.
3. Estimation of the EDCT spectral congestion toll. Here I continue the development of the spectral congestion model developed in chapter two. I turn from the engineering foundation to the social considerations and economic impact of the resulting revenue stream.

4. A cost and feature comparison of EDCT and the other kinds of telephone service available to consumers.
5. An exploration of the uniqueness of EDCT, compared to wireless services targeted at mobile urban users.

The role and form of competition in rural markets for EDCT merits some discussion. Technology choices and the new pay-as-you-go approach to accessing the spectral resource fully actualize contestability of rural markets for rural voice and data service.[1] We will see that the fixed cost of entry for an EDCT service provider is a fraction of the price of an air conditioned tractor or a milk truck. EDCT promises to be a great second income for farm families. Local banks should come to see business lending to EDCT as very similar to agricultural lending. A used equipment market for EDCT cell site hardware should flourish, with an industry association enforcing open standards. If Susan doesn’t like Joe’s prices or quality or offering bundle, entry can occur. Subscribers can play Susan and Joe off against each other in real time by plugging in extra type S modules aimed at their favorite service providers.

At the Federal level, the revenue stream from EDCT

---

[1] See Baumol (1982) for an excellent intuitive introduction to contestability theory; and Baumol, Panzer, and Willig (1982) for the details.

spectral congestion tolls will be seen to have a net present value of several billion dollars, making this new approach to spectrum management quite attractive in relation to auctions. But EDCT compliments, rather than supplants the other wireless choices. The urban mobile user and rural fixed wireless subscriber will be seen to constitute wholly distinct technical regimes, calling for distinct institutions.

**1. A stakeholder analysis of EDCT industry relationships.**

The next task is partly to understand the relationships that will envelope EDCT upon the formation of that industry, and partly to tailor those relationships to best advantage. Note that I did not say to the best advantage of EDCT service providers. EDCT is from its inception an effort to privately provide an essential public good, making technology choices that inherently discourage sustainable rents or concentration of ownership, while engendering low cost entry and exit, in order to dramatically reduce the need for regulatory oversight. It is important to cultivate and nurture over time a strategic vision of the EDCT industry that will balance the interests of the service providers, subscribers, suppliers, the public, and others.[2]

**Introduction to stakeholder analysis.**

I propose using the stakeholder analysis method of Freeman (1984) to illuminate the strategic environment of EDCT. The first step in applying stakeholder analysis is to identify all the various parties that are affected by or that affect the activities of the organization under investigation. The affected parties are termed stakeholders. Next the individual interests and perspectives are identified for each stakeholder. Finally couplings (or interactions) among the stakeholders and the organization are explored.

The main objective of strategic management using the stakeholder analysis approach is to best provide for long-run outcomes for the organization by balancing the interests of the stakeholders. Stakeholder analysis is also a way to identify social concerns and impacts, and develop institutional arrangements to address them.

**Identification of EDCT stakeholders and their couplings.**

In the present analysis the focus will be not only on an

---

[2] The balancing of interests that is the objective of stakeholder analysis may surprise some. I believe it to be a better fit to the provision of essential goods.

individual firm supplying service, but also on the EDCT industry association. The process of identifying the stakeholders and their key interactions revealed that the two centers of activity were each significant. The EDCT industry itself is a subset of the telecommunications industry, represented here by various individual stakeholders. Figure 5.1 illustrates the result of conducting a stakeholder analysis for the proposed EDCT industry.

The process is as follows: First, I list as many of the stakeholders as can be identified. The most important relationships are then shown next to each stakeholder. (Because so many stakeholders interact with the EDCT service providers, that coupling is omitted.) The result of the stakeholder identification process is shown in table 5.1:

| Stakeholder | Dominant couplings |
|---|---|
| Absentee owners | |
| Equipment suppliers | |
| Local banks | |
| Venture capitalists | Equipment suppliers |
| Minority shareholders of EDCT service prov. | Owners |
| Employees | |
| Unions | |
| U.S. Congress | FCC, EDCT industry association |
| FCC | EDCT industry association |
| State government | State public service commissions (PSC) |
| State PSCs | Individual providers, EDCT industry association, incumbent firms |
| Local government | |
| Community interest groups | |
| Consumers | |
| Consumer cooperatives | |
| Consumer advocates | EDCT industry association |
| EDCT industry assoc. | (Several) |
| EDCT service prov. | (Several) |
| Competing EDCT prov. | EDCT industry association |
| U.S. Telephone Ind. Association (TIA) | EDCT industry association |
| Incumbent firms | State PSCs |
| Internet committees | EDCT industry association |
| Political parties | EDCT industry association |

Table 5.1. Identification of EDCT stakeholders and the predominant interactions (other than with EDCT service providers).

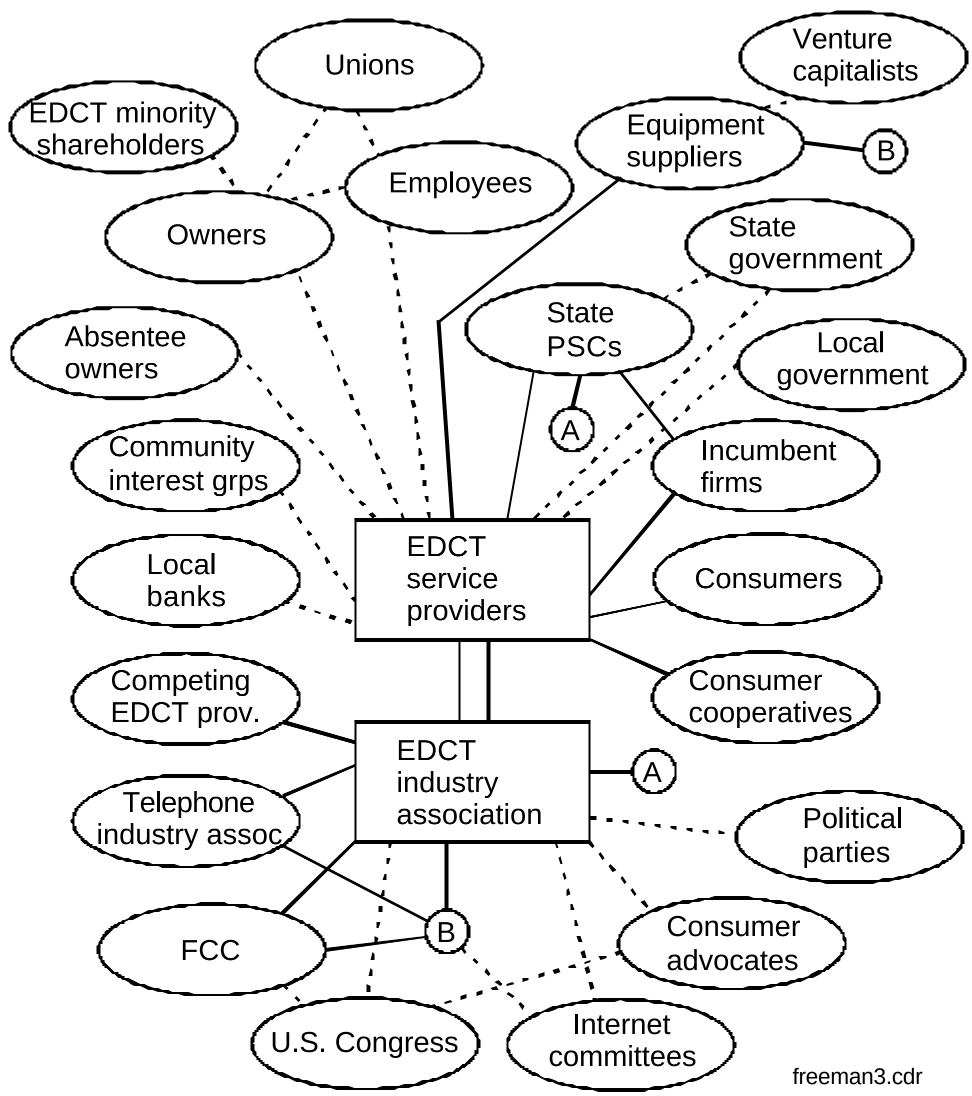



Figure 5.1. Stakeholder map of the proposed EDCT industry. Relations discussed here are shown in solid lines. (Line intersections are not connected; A and B are line connectors.)

Looking at the resulting stakeholder map, one can see that with the exception of the equipment suppliers, stakeholders interact primarily with just one of the two entities at the core of the model. State and local interactions tend to be with the service providers, whereas industry-wide and federal interactions tend to be with the EDCT industry association. All of these various interactions must work relatively harmoniously in order for service providers and subscribers to be served well by this new kind of telecommunications service.

**Discussion of stakeholder interests, strengths, and perspectives.**

Several of the stakeholders will have readily understandable relationships with the EDCT industry. There are however several service and consumer protection issues that merit further treatment. The stakeholders most closely connected to these issues are:

- The Federal Communications Commission.
- State public service commissions.
- Other telecommunications service providers, and their industry associations.
- Consumer cooperatives.
- The industry structure of equipment suppliers.

- The role of an EDCT industry association.

I will discuss each of these stakeholders briefly in turn. My assessment is based on my impressions about the organizational culture of each and its present "fit" to the needs of the other stakeholders surrounding the proposed EDCT service.

Federal Communications Commission.

The organizational culture. The FCC has certain essential roles to play in EDCT, but they are possessed by a structural shortcoming. The current mission statement of the FCC is:

> "to encourage competition in all communications markets and to protect the public interest. In response to direction from the Congress, the FCC develops and implements policy concerning interstate and international communications by radio, television, wire, satellite, and cable."
>
> - The home page of the FCC Web site, 1999.

Talk about competition and the public interest is laudable, but meaningless without a distinction between the various forms of industry competition and the resulting social outcomes. Only in the case of perfect competition are the benefits of low prices and complete delivery of technical innovation attained. In a monopoly (intensively regulated or not) and in imperfect competition (oligopoly), economic rents are present, delivery of innovation is inherently constrained, and some customers are unavoidably excluded. Unfortunately the FCC uses as guidance as to whether sufficient competition is present in a market the lowest possible test: the idea of market power as used in antitrust law.

The FCC appears not even to visit the thinking of economists as it regards the public interest, possibly because a deep understanding of the theory of competition seems to lie outside the expertise of that agency's managers, but certainly because the FCC is an agency rooted in the trappings of administrative law. Through the present time another foundation of the FCC's limited view of the public interest has been inescapable: The scarcity doctrine and the necessity of exclusive frequency assignment attendant an analog world has made limited competition necessary.

A changed regulatory role for the FCC. With EDCT's pseudonoise modulation and spectral congestion pricing, there is comparatively little scarcity, and the proposed market for spectrum is self-regulating. The FCC is not needed to design a market -- that would be the role of Congress. With EDCT the FCC does indeed have a role to play in promoting technology, efficiency, and fairness. For the first time the role of the FCC can be fundamentally recast to fully embrace the digital era:

1. Certain technical standards relating to spectrum usage, underlying the service, will need to be established by administrative proceedings conducted by the FCC.
2. A technical means (radiometric survey) to assess long run congestion levels will need to be fielded.
3. A method to collect congestion fee payments from service providers will need to be maintained.
4. A simple rule regarding EDCT subscriber repeaters will be needed: Subscribers will need to allow installation of repeaters, as reasonably needed by their neighbors (when certain neighbors do not have a clear view of a cell site).
5. As in other classes of service, the FCC may wish to consider whether it wishes to license individual provider firms, for non-spectral related reasons, and whether there is an administrative need to limit the number of sites owned by a single firm.

Federal regulatory matters addressed elsewhere. The relevant Telecommunications Act of 1996 provisions can be relied upon to address the following concerns:

1. Interconnection standards and arbitration.

2. Access to right-of-way.

3. Antenna siting rights.

There is certainly potential for abuse of EDCT providers, given their small size, as in the Wisconsin docket discussed in an earlier chapter. As elsewhere in the telecommunications industry, a watchful eye needs to be kept on events related to a transition to competition. With respect to price setting, EDCT markets are expected to be highly contestable. Thus there is no anticipated role for the FCC in pricing.

State public service commissions.

EDCT is expressly intended to provide intrastate telecommunications services to local residents and businesses. Thus State governments will naturally have an interest in seeing that these services are well provided in accordance with the needs of their locales. But the principal difficulty with the State public service commissions is regulatory capture by the existing telecommunications providers. A good example of capture by the firms being regulated is in Wisconsin, where that agency “hasn’t issued a single pro-consumer decision in the past several years” (Merritt, as cited by Fantle, 1999). Worse yet according to Fantle, the State commission chair is reportedly unwilling to publicly discuss the matter. I think we need to be very careful about what authority States are given to regulate an industry where there inherently isn't a problem with monopoly power.

Short of intensive regulation, a number of enabling roles exist for State PSCs. The first and most important would be to achieve coordination with PSCs from other States and the EDCT industry association, in order to establish and manage quality of service standards across generations of product realizations, and as consumer needs evolve. A second role would be to administer interconnection agreements, in the manner envisioned by the 1996 Act. A third role would be to receive and address concerns raised by consumers, though I think the mechanics of handling consumer disputes would need to be made real to individual consumers.

Other telecommunications service providers, and their industry associations.

At present the 1996 Act protects small TELCOs from the effects of competitive entry into their local service territories. But that protection must ultimately give way to competition, as discussed earlier in this thesis. It is hoped that EDCT will become a nucleating event in the opening up of rural markets for local service to the benefits of competition.

For incumbent local exchange carriers there are two key components to their continued success in their service territories: The issue of stranded investment, and finding ways to become players in their own right.  The key assets that ILECs possess already, are a core wireline set of customers in the built-up areas of towns and cities; traditional switches (modern or not); and existing interconnection agreements covering IXCs and SS7, suitable for all of the aggregated traffic needs of their area of the State.  ILECs and their investors may need help with stranded outside plant as their lowest density customers migrate to wireless service.  On the other hand, ILECs will be able to continue to serve many of their most profitable business customers, and resell blocks of long distance access to EDCT providers.  ILECs might become the Internet service providers (ISPs) of choice for rural customers, contingent on their ability to arrange higher bandwidth links to the Internet backbone than might individual EDCT providers.  State telephone associations could be very helpful in teaching ILECs how to make it all happen, including getting ILECs into business as EDCT service providers.

Frankly the initial responses of the ILECs to the prospect of competition in local voice and data services has been disappointing, as was seen in Wisconsin Docket 05-TD-0100 (1998) and in Raynovich (1999), both discussed earlier.

Specifically in the Wisconsin docket, GTE is alleged to have taken the position that no interconnection was possible anywhere in its system, because there was no spare room in its ducts or central offices.[3] Similarly in the hearing record of Wisconsin Docket 05-TI-0138 (1995), Ameritech was able to persuade the commissioners that there is no space available for interconnection at intermediate points in the outside plant.[4] The self-defeating nature of these obstructionist approaches should be obvious to anyone who is not an ILEC and who understands the trajectory of silicon. With demand for telecommunications growing exponentially (at about eight percent per year in the late 1990s), why waste years fighting?

Pricing practices of incumbents and ease of entry. ILECs could, if they so choose, make it very difficult for EDCT service providers to make competitive entry. Assume that an incumbent realizes that they are stuck holding an obsolete infrastructure, that they no longer wish to maintain. The assets of the ILEC consist almost entirely of the fixed cost associated with prior outside plant investment. That

---

[3] Maybe if GTE were to get rid of those clunker analog and crossbar switches it would free up some floor space, which it could then rent out.

[4] That position might seem reasonable to lawyers, but cable splicers would know that the problem could be handled by simply upgrading the enclosure or locating a CLEC enclosure nearby on the utility easement.

investment is a sunk cost. Viewed in this way, an ILEC could be justified in setting the marginal cost of any given call over its portion of the network at approximately zero. Rural customers might therefore be faced with the prospect of a collapsing infrastructure, unless certain uniform standards for price setting by incumbent providers in a deregulated regime can be agreed upon. That is so, unless enough rural consumers decide to simply up and leave, in order to enjoy greatly improved Internet access at what they are now paying for voice only service. ILECs would also be well advised to refine their business models to emphasize delivering high quality services to their customers in built up areas.

Consumer cooperatives.

Termed buyer cooperatives by economists, their role is to increase the bargaining power of individual consumers, relative to producers, in order to lower the closing price (or effect sharing of the surplus value created by a productive activity). EDCT consumer cooperatives may simply be groups of subscribers who can organize, if the information costs of achieving coordination are favorable. In addition local employers may sponsor cooperatives for their employees, to bargain with service providers for group discounts. Neighborhood associations might contract to provide service for their residents.

My concern is that exclusive dealing arrangements would tend to defeat the redundancy of providers that helps ensure reliability in the case of individual provider service outages. Thus side payments should be prohibited, along with exclusive contracts.

Equipment supplier industry structure.

Even though the manufacturing techniques needed to make the EHF antenna structures and transmitter / receiver circuitry have a certain capital intensity, there is no natural monopoly. Moreover, several nations (it is thought) have or will have the know-how to make the required devices. Nevertheless, the finite number of qualified firms make an oligopoly unavoidable.

X-ray lithography is a natural choice for the manufacture of EHF integrated circuits in moderate quantities. A synchrotron would not be required, with the anticipated commercial availability of a suitable X-ray point source.

The role of an EDCT industry association.

There is a danger that a vertical relationship may develop involving a hardware or software vendor and a service provider network, as in the old AT&T monopoly. I propose that rather than trying to regulate against such an event, that one to several nonprofit, cooperatively owned industry associations of EDCT service providers be sanctioned to develop product specifications for and procure equipment. Cooperative ownership is also intended to dissipate rents that such associations may generate, by returning profits to service providers (and ultimately to subscribers). Having just one such association might violate the Sherman Act of 1890. Also, having just one association to administer spreading code assignments might lead to controversy of the sort that engulfs the InterNIC (the assigner of Internet domain names).[5]

**Striking a strategic balance among stakeholders.**

Balancing the interests of stakeholders needs to be the subject of much dialogue. I am convinced that with EDCT everyone comes out ahead, even the ILECs over the long run. Here is a starting point:

The bottom line is that decisions about entry, exit, and network deployment are to be uncoordinated. Spreading code assignment and technical standards are to be jointly, but privately, administered. What levels of voice and data

---

[5] See Walsh (1999) for a recent spat.

service to offer and their terms of sale is to be a joint public - private decision, respecting the essential nature of local telecommunications service.

Small TELCOs will need help from their industry in recognizing the opportunities that movement along the trajectory of silicon will afford them.

What is gained by trading a bit of spectral utilization efficiency for uncoordinated assignment of pseudonoise transmitters is the ability to replace intensive regulation of local service with competitive provision, the opportunity to end the tens of billions of dollars of cross subsidy of local telephone service in high cost areas, while at the same time delivering the benefits of universal Internet connectivity.

Last but not least, the U.S. Congress can realize a perpetual revenue stream from spectral congestion fees, instead of one-time auction payments. Service providers need not be driven into bankruptcy by trying to make auction payments while deploying their networks. Pay-as-you-go is better than cash up front, when it comes to providing modern alternatives to traditional wireline service.

**Possible undesirable social effects of EDCT.**

Deployment of EDCT in rural areas promises to dramatically improve the delivery of services that are Internet-based or that can uniquely benefit from a packet switched network architecture. There are certain possible social ill effects that might be intensified by EDCT. The difficulties lie not with the technology itself, but with the introduction of technological change into an existing social matrix.

In addition to many anticipated consumer benefits, EDCT would also further the diffusion into rural areas of contemporary organizational structures, like flattened management structures or virtual organizations. For example, increasing the bandwidth to farms would facilitate the remote management and even the far-flung ownership of dairy operations. Farmers might take on the appearance of factory workers. Contract growing of genetically modified plants and livestock has already initiated such a trend. Concentration of ownership in agricultural production might be hastened. On the other hand it seems just as likely that groups of small farmers and their marketing organizations might take good advantage of reduced information costs and access to pooled managerial talent.

Rural downtowns might be adversely impacted by Internet commerce, as occurred with the introduction of suburban shopping malls. For urban dwellers, Internet commerce might next displace the mall experience. Rural consumers may find themselves able to bypass the mall and directly enter the next consumer culture. The effect on rural downtowns is far from clear. Local producers of handmade or specialty goods may make further use of improved connectivity to make a nationwide market for their goods, as is now beginning to occur.

**2. Cost of service estimates for EDCT service.**

Several approaches to cost estimation for EDCT are possible, just as for traditional wireline service. I want to discuss two approaches here, because they will give views of the cost structure of EDCT that can be readily compared to the cost of service estimates presented in chapter three. The first approach is to make a simple cost of service estimate, based on the cost of operating a prototypical service provider cell site. The result is directly comparable to my earlier estimate of the cost of cellular telephony. Moreover, taking a firm level perspective will help explain the business of EDCT.

A second approach to cost estimation is to construct an optimal network from the ground up for a given rural area. The result is similar to the Hatfield Model presented earlier. The view of EDCT afforded by this second estimate will be especially of value in the formulation of policy.

Before completing these estimates, we will first need some summary statistics for the existing U.S. telephone industry. Then we will return to the task at hand.

**Key statistical facts about the U.S. wireline telephone industry.**

The FCC has made available aggregated data for the wireline telephone industry that will be of value in estimating potential EDCT market size and other characteristics. The report Statistics of Communications Common Carriers (SOCC) for 1997 (FCC, 1999) reports that there were 517,249,240,000 ($5.17 \times 10^{11}$) local calls placed in the United States ($6.8 \times 10^{9}$ for Wisconsin) (SOCC table 2.6). Local call dial equipment minutes (DEMs) (SOCC table 8.7) for the nation for 1997 were 2,807 billion ($2.8 \times 10^{12}$) (based on the same 8 % growth factor as for the year before).[6] There are about 162 million switched access lines (SOCC table 2.5). There are about 100 million residences, about 94 percent of which are equipped with a telephone (as of 1997).[7]

In a similar way other derivative statistics can be estimated. Table 5.2 below summarizes the data of interest:

---

[6] As SOCC explains, “DEMs are measured as calls enter and leave telephone switches. Therefore, two DEMs are counted for every conversation minute.” But that is the number we want -- a congestion toll would occur for airtime involved with both the origination and the completion of a call, as is customary practice in the U.S. cellular and PCS industries.

[7] Just for fun, the average duration of a local call in 1997 was:

$$\frac{2.8 \times 10^{12} \text{ DEMs}}{5.17 \times 10^{11} \text{ calls}} \times \frac{1 \text{ call-minute}}{2 \text{ DEMs}} = 2.71 \text{ minutes.}$$

In a similar way one can compute other values shown.

| Statistic | Value |
|---|---|
| Dial Equipment Minutes (DEMs) | $2.8 \times 10^{12}$ |
| Growth factor (G) (%) | 8 |
| Number of residences | 100 million (approx.) |
| Number of local calls per year | $5.17 \times 10^{11}$ |
| Number of switched access lines | 162 million |
| Access lines, all types | 192.6 million |
| Universal Service Fund loops | 165 million |
| Total residential lines | 107.2 million |
| Number of local calls (per subscriber per month) | 266 [1] |
| Average duration of a call (Minutes) | 2.71 |
| Average usage per customer (Minutes per month) | 721 [1] |
| Number of lines per residence | 1.07 |

**Notes:**
1. Both business and residential calling.

Table 5.2. Some key U.S. wireline telephone industry statistics. (The first group is from SOCC 1997 (FCC, 1999), the balance are calculated.)

**EDCT cost of service, based on an example firm.**

The system architecture of EDCT was explained in the second half of chapter four. The cost structure of an EDCT service provider is intentionally designed to be lower than that of a cellular provider with mobile subscribers. The key distinctions are the use of off-the-shelf PCS and DSP cards, instead of custom signal processing hardware; the choice of

EHF frequencies, which lie further along the trajectory of Moore’s law; and other choices of scale matched to a rural fixed wireless environment. Based on several additional assumptions I list below in table 5.3, I have constructed a pro forma income statement for a hypothetical EDCT service provider.[8] The income statement follows in table 5.4.

---

1. The EDCT service provider is a stand-alone business. There are clearly economies of scale that would derive from operating clusters of geographically close cell sites, but no attempt has been made to capture those efficiencies.

2. The cost of the cell site hardware is based on the prices of comparable computer telephony (CT) hardware used in call centers. CT hardware has such a similar architecture that CT equipment manufacturers could easily enter the EDCT business as suppliers of baseband hardware and application software. The cost of T / R modules and support structure are included here.

3. I use a circuit capacity of 24 channel pairs, an occupancy of 50 percent averaged over 24 hours, and a useful service life of 10 years.

4. I price the land and a room to house the cell site equipment at the approximate price of a small residential lot with improvements. A separate business location for an office and customer service operation is leased and appears as an expense.

5. I include revenue and costs of providing local service only.

Table 5.3 (Continues).

---

[8] The model assumptions and income statement closely parallel the cellular provider model shown on about pp. 132 - 137.

6. Spectral congestion costs are set to zero in this equilibrium analysis. The reason is that they simply pass through the service provider in the same way as would a sales tax.

7. Cost of call termination is set to zero, since such agreements are expected to be approximately symmetric and average to zero over time. If an incumbent engages in a practice of charging above cost to terminate a call on its network, that per minute charge can be passed on to individual subscribers calling into that network. Time and the thirst for justice will need to be allowed to work their magic.

8. EDCT provides the additional feature of a high speed data service. I model the data service pricing on a fractional dollar charge per megabyte moved (up or down). There is further discussion below.

---

Table 5.3. EDCT provider model assumptions.

---

Pro Forma Income Statement for a Hypothetical Cellular Provider

**Assumptions**

Scenario:

1. A hypothetical stand-alone provider with a single cell site.
2. Costs are converted to a per-minute basis by dividing by the following factor:

6311520 = factor for 24 ch. pairs x 50% 24 hr ave occupancy x 525960 min/yr

721 = minutes per month average usage per customer.

Therefore cell site services: 729 customers

3. Input coefficients are: Income (per-minute), COG (annual), expenses (annual).

0.025 = Airtime retail price per minute ($).

25000 = Site equipment cost ($), with 10 year life, straight line.

50000 = Facilities cost ($), with 20 year life, straight line depreciation.

600 = Subscriber equipment price ($), and have a useful life of 10 years.

Table 5.4 (Continues).

| | Annual ($x1000) | Per-minute basis (dollars/min) | Per-customer basis ($) | % of sales |
|---|---|---|---|---|
| **Income** | | | | |
| Airtime (64 Kbps channel) | 157.79 | 0.0250 | 216.30 | 72% |
| Data service (768 Kbps ch.) | 17.51 | (~$0.35/MB moved) | 24.00 | 8% |
| Subscriber equipment sales | 43.77 | 0.0069 | 60.00 | 20% |
| Sales | 219.06 | 0.0319 | 300.30 | 100% |
| | | | | |
| **Cost of Goods Sold** | | | | |
| Site equipment | 2.50 | 0.0004 | 3.43 | |
| Site facilities | 2.50 | 0.0004 | 3.43 | |
| Subscriber Equipment | 26.26 | 0.0042 | 36.00 | |
| COGs | 31.26 | 0.0050 | 42.85 | 14% |
| | | | | |
| **Labor** | | | | |
| Salesperson (1/4 time) | 6.40 | 0.0010 | 8.77 | |
| Technician | 40.00 | 0.0063 | 54.83 | |
| Administrative asst (half time) | 16.50 | 0.0026 | 22.62 | |
| Total wages | 62.90 | 0.0100 | 86.22 | 29% |
| | | | | |
| **Gross Profit** | 124.90 | 0.0170 | 171.22 | 57% |
| | | | | |
| **Expenses** | | | | |
| Rent of storefront | 12.00 | 0.0019 | 16.45 | |
| Advertising (5 % of sales) | 10.95 | 0.0017 | 15.02 | |
| Telephone (office use) | 3.60 | 0.0006 | 4.93 | |
| T1 line lease (site use) | 12.00 | 0.0019 | 0.00 | |
| Software lease (office use) | 6.00 | 0.0010 | 8.22 | |
| Janitorial | 1.70 | 0.0003 | 2.33 | |
| Insurance | 2.00 | 0.0003 | 2.74 | |
| Supplies and Maintenance | 7.00 | 0.0011 | 9.60 | |
| Misc. business supplies | 3.00 | 0.0005 | 4.11 | |
| Entertainment | 1.00 | 0.0002 | 1.37 | |
| Total expenses | 59.25 | 0.0094 | 64.78 | 27% |
| | | | | |
| **Net Profit Before Taxes** | 65.65 | | | 30% |
| taxes of a standard corporation | 32.83 | | | |
| Profit after tax | 32.83 | | | 15% |

EDCTpro1.wb2 A1:I55 14 APR 99

Table 5.4. Pro forma income statement for a hypothetical EDCT service provider.

EDCT provides the additional feature of a high speed data service. Charging rural subscribers on a connect time basis for such a service, or similarly, a high fixed monthly charge, as for cable or xDSL modems, would likely forestall market penetration. Instead, I model the data service pricing on a fractional dollar charge per megabyte moved (up or down). For the EDCT data service I estimate that initially 20 % of the subscribers would be willing to buy $10 per month of high speed packets. Initially at least, then, most provider revenue is from voice service. But as Internet commerce moves to center stage, there is considerable growth potential for the data side of EDCT.[9]

At the voice per minute pricing and equipment cost assumptions of the above model, the EDCT service provider can be expected to show a profit that, while not as handsome as for an urban cellular provider, is appropriate for a craft-like business of this size. The subscribers enjoy local service at approximately the same monthly charge as they do now, but the universal service subsidy is no longer needed. In addition, customers who so desire can have xDSL data rates on a pay-as-you-go basis. In the next section the proto-

---

[9] Walmart (and shortly IBM) offers everything in its store over the Internet. I suspect Internet shopping will become the new Sears catalog for rural America. I think the transition will take just five years, if the connectivity can be provided.

typical EDCT provider business will be replicated over three Wisconsin counties to model the cost of universal service.

**EDCT cost of service, based on optimal network.**

As a specific example, let us design a system for Trempealeau County, Wisconsin and two adjacent counties. The county seat is Whitehall, with a population of about 1,000 persons. An interstate highway cuts diagonally across Jackson County, so that some residents will have analog cellular service available as an alternative to local service.

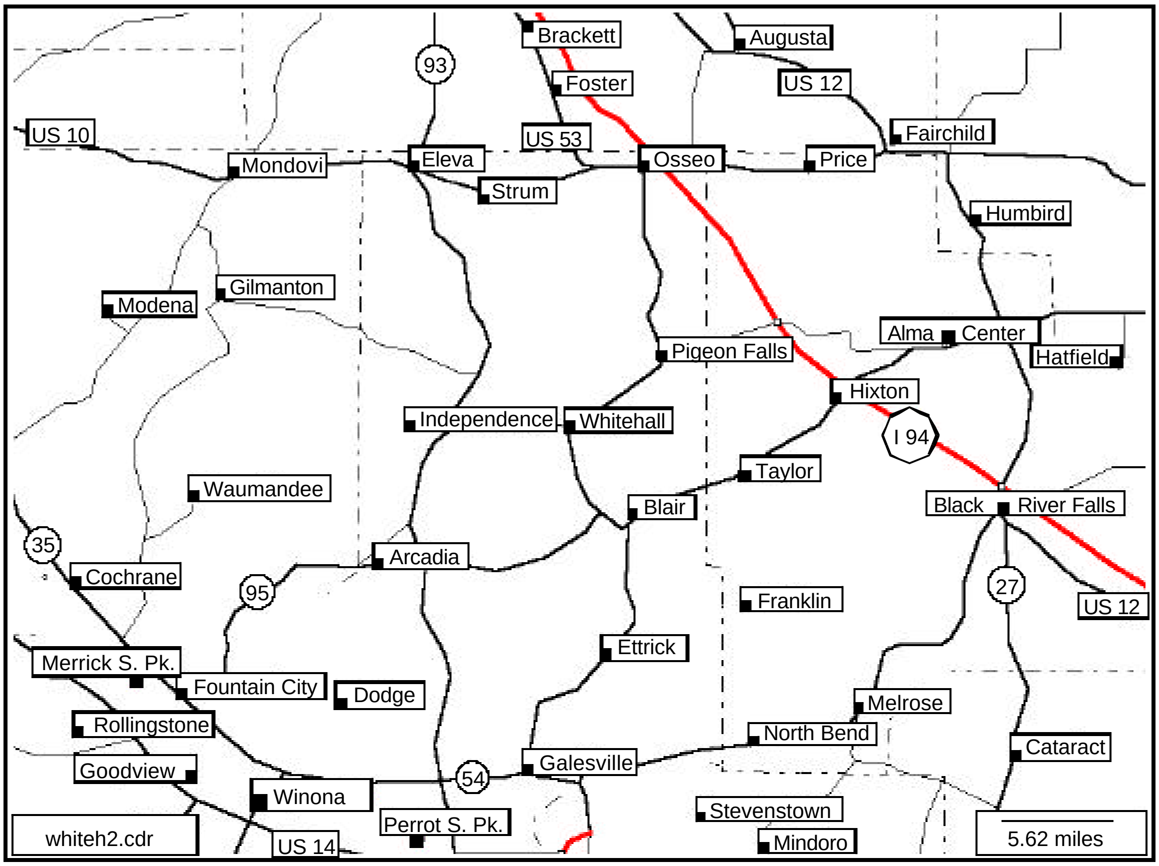



Figure 5.2. The Trempealeau county area of Wisconsin. (Trempealeau Co. is in the center, Buffalo Co. to the left, and Jackson Co. to the right.)

I should say a little about the demographics of this region of the state.[10] Trempealeau county has a mostly rural economy, consisting of dairy farms, logging, agriculture-related businesses, and manufacturing. The county just to the east, Jackson county, has some reservation lands, more poverty, and a more seasonal workforce. The county to the west and bordering the Mississippi river is Buffalo County, which has a completely rural character. During the recession of 1982, unemployment in this area reached about ten percent, and remained at that level throughout the 1980s, long after most of the nation had recovered.

In Black River Falls, WI, the largest community in Jackson County, the public schools did not have any computers for educational purposes until about 1995. In Eleva, WI, in northern Trempealeau county, elementary school computers currently in use are mostly Apple IIs. Each middle school classroom has one Power Macintosh™. By contrast in Madison, Wisconsin public schools, children in the elementary schools have Pentium™-based computers for their typing lessons. Obviously in these counties of Wisconsin, the Internet is not as well integrated into the learning experience. The statistical data of table 5.5 below further illuminates the disparities. Computer penetration rates in the homes of these three counties is also likely to be lower than in Dane County.

---

[10] A friendly troll told me some of these things.

| Statistic \ County | Dane | Buffalo | Trempealeau | Jackson |
|---|---|---|---|---|
| Population (persons) | 425K | 14,298 | 26,469 | 17,735 |
| Childhood poverty (%) (under 18 years old) | 9.1 | 14.5 | 14.2 | 17.0 |
| Household income (dollars x1000) | 44.4 | 30.1 | 29.4 | 28.2 |
| Manufacturing (jobs/1000 population) | 64 | 22 | 142 | 30 |
| Retail (jobs/1000 pop) | 100 | 40 | 49 | 74 |
| Service (jobs/1000 “ ) | 85 | 33 | 22 | 25 |
| Number of households | 143K | 5,123 | 9,495 | 6,253 |
| Married households (%) | 51 | 63 | 62 | 61 |

Table 5.5. Demographics of selected Wisconsin counties. (Source: U.S. Census Bureau, 1990, 1992, 1995, and 1998.) (Household data is from 1990.)

| Households by BNA xxyy | Buffalo (96yy) | Trempealeau (99yy) | Jackson (96yy) |
|---|---|---|---|
| 01 | 881 | 1,122 | 868 |
| 02 | 1,074 | 1,137 | 1,014 |
| 03 | 912 | 823 | 1,355 |
| 04 | 1,044 | 1,351 | 1,308 |
| 05 | 1,209 | 1,087 | 1,758 |
| 06 | | 1,265 | |
| 07 | | 1,367 | |
| 08 | | 1,340 | |

Table 5.6. Households by Census tract BNA No. (Source: U.S. Census Bureau, 1990.)

The U.S. Census Bureau divides these rural counties into census tracts, each containing an average of about 1,200 households (in 1990). Each tract has a four digit identifier, shown in table 5.6 above.

At a level of finer detail, figure 5.3 below shows the individual roads surrounding Whitehall, WI. The roads attest to the hilly terrain and rural character of this part of the state. By contrast, eastern Jackson County (not shown) is mostly forest and marsh.

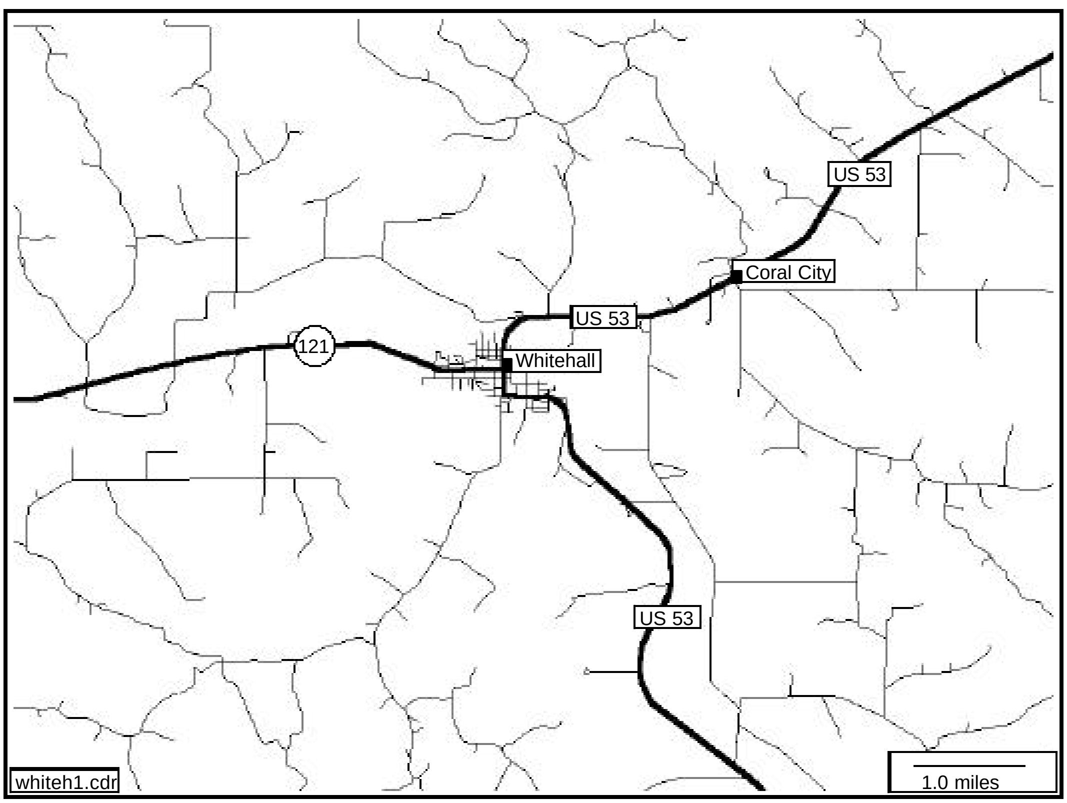



Figure 5.3. Immediate vicinity of Whitehall, WI.

An approach to planning an actual network buildout in an already populated area, using a geographic information system (GIS), is as follows: Overlaying the basic map with census data would yield the locations of individual dwelling units and businesses, which can then optionally be aggregated. Overlaying a second time with U.S. Geological Survey relief map data would suggest the best locations (i.e., hilltops) for cell sites to serve those potential customers. Looking for good cell sites is analogous to the Hatfield Model use of terrain data to estimate costs for laying outside plant cabling.

A perfectly competitive market ought to closely approximate such an optimal network, except that there would be redundant cell sites (and excess capacity). In EDCT the redundancy brings the benefits of competition, service reliability, and paths around localized congestion (using subscriber equipment that searches for and connects at the lowest per minute rate).

We can use an approach similar to the GIS method to size and cost infrastructure for the proposed EDCT service. For these rural counties, the way in which the census data is traditionally presented, aggregated by BNA number, is quite convenient for constructing a forward-looking cost proxy model for EDCT. Because each EDCT cell site can support about 700 customers (assuming a 24 circuit capacity), and each census tract contains one to three small built-up areas, it is about right to deploy one EDCT cell site per BNA number. The result of identifying each census tract area and optimally locating a cell site according to the terrain of each is shown in figure 5.4 below. A spreadsheet is used to tabulate total costs for the network in each census tract and estimate the per-subscriber monthly cost of service. These cost estimates are summarized in table 5.4 below.

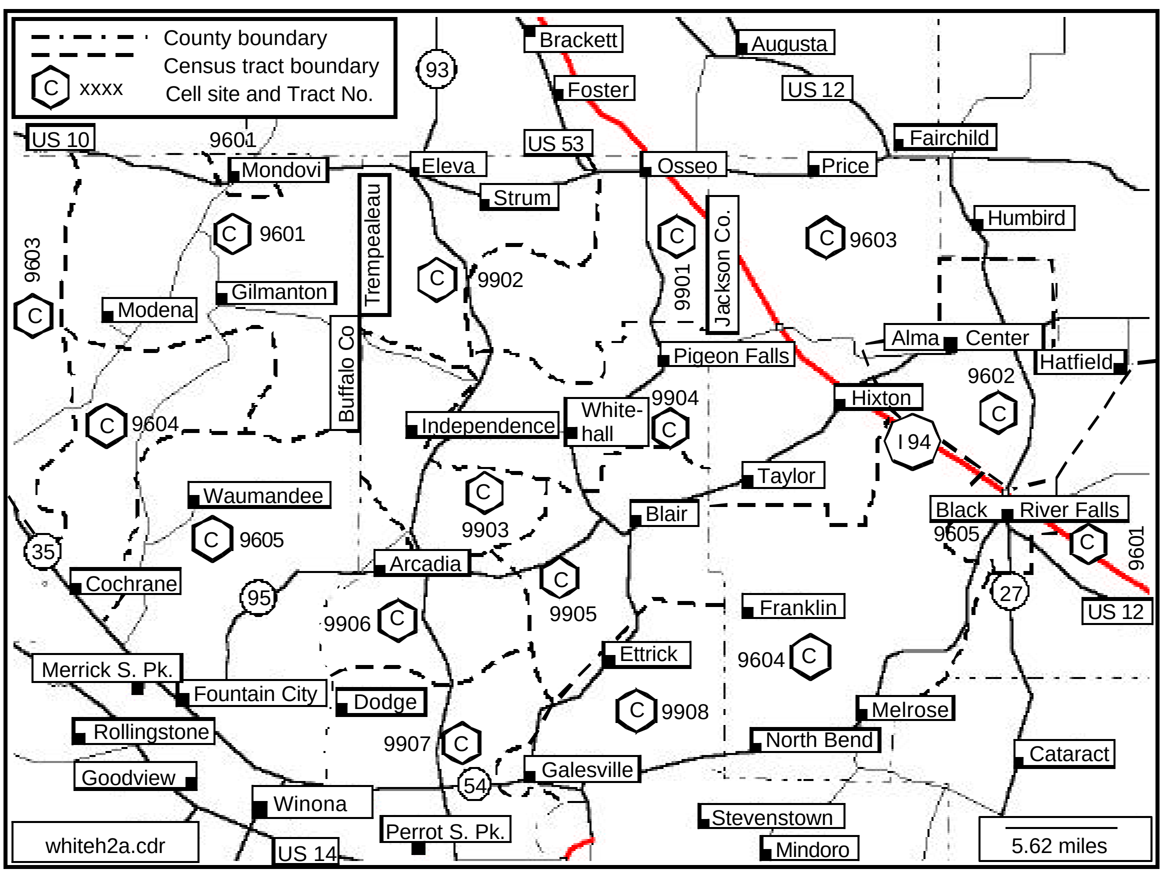



Figure 5.4. EDCT service design example for three rural Wisconsin counties.

________________________

EDCT forward-looking cost of service estimate for three Wisconsin counties.

**Estimated Cost of Service per Month:**

**Buffalo County**

| BNA | No. of H.hold | Subscriber Equipment | Cell cost [1] | Local air [2] | User taxes | Congestion toll |
|---|---|---|---|---|---|---|
| 9601 | 881 | 4.41 | 16.04 | 15.88 | 1.59 | 6.35 |
| 9602 | 1074 | 5.37 | 16.04 | 19.36 | 1.94 | 7.74 |
| 9603 | 912 | 4.56 | 16.04 | 16.44 | 1.64 | 6.58 |
| 9604 | 1044 | 5.22 | 16.04 | 18.82 | 1.88 | 7.53 |
| 9605 | 1209 | 6.05 | 16.04 | 21.79 | 2.18 | 8.72 |
| subtl: | 5120 | 25.60 | 80.19 | 92.29 | 9.23 | 36.92 |

Buffalo Co. cost of service (dollars per subscriber-month): 29.67

**Jackson County**

| | | | | | | |
|---|---|---|---|---|---|---|
| 9601 | 868 | 4.34 | 16.04 | 15.65 | 1.56 | 6.26 |
| 9602 | 1014 | 5.07 | 16.04 | 18.28 | 1.83 | 7.31 |
| 9603 | 1355 | 6.78 | 16.04 | 24.42 | 2.44 | 9.77 |
| 9604 | 1308 | 6.54 | 16.04 | 23.58 | 2.36 | 9.43 |
| 9605 | 1758 | 8.79 | 16.04 | 31.69 | 3.17 | 12.68 |
| subtl: | 6303 | 31.52 | 80.19 | 113.61 | 11.36 | 45.44 |

Jackson Co. cost of service (dollars per subscriber-month): 26.73

**Trempealeau County**

| | | | | | | |
|---|---|---|---|---|---|---|
| 9901 | 1122 | 5.61 | 16.04 | 20.22 | 2.02 | 8.09 |
| 9902 | 1137 | 5.69 | 16.04 | 20.49 | 2.05 | 8.20 |
| 9903 | 823 | 4.12 | 16.04 | 14.83 | 1.48 | 5.93 |
| 9904 | 1351 | 6.76 | 16.04 | 24.35 | 2.44 | 9.74 |
| 9905 | 1087 | 5.44 | 16.04 | 19.59 | 1.96 | 7.84 |
| 9906 | 1265 | 6.33 | 16.04 | 22.80 | 2.28 | 9.12 |
| 9907 | 1367 | 6.84 | 16.04 | 24.64 | 2.46 | 9.86 |
| 9908 | 1340 | 6.70 | 16.04 | 24.15 | 2.42 | 9.66 |
| subtl: | 9492 | 47.46 | 128.30 | 115.54 | 11.55 | 46.22 |

Trempealeau Co. cost of service (dollars per subscriber-month): 24.60

**Worksheet.**

Cell site cost estimate: ( Annualized basis)

| | |
|---|---|
| 2.5 | equipment cost |
| 2.5 | facilities cost |
| 62.6 | labor |
| 59.25 | expenses [3] |
| 32.8 | income taxes |
| 32.8 | profit, accounting |
| 192.45 | Total cell site cost ($x1000) |

Table 5.4 (Continues).

**Assumptions:**

| | |
|---|---|
| 721 | Average local usage (minutes per month). |
| 192.45 | Cell site annualized cost ($x1000) |
| 10 | Cell site service life (years) |
| 60 | Subscriber equipment annualized cost ($) |
| 10 | Subscriber equipment service life (years) |
| 0.025 | EDCT retail per minute charge for local calling ($) |
| 0.0025 | taxes (local, state, federal sales and excise) ($/minute) (~10%) |
| 0.01 | EDCT congestion toll, per minute ($) |

Notes:

1. EDCT cell site capacity can be expanded in small increments to serve all in county, at a negligible incremental cost (a T / R module and DSP card as needed).
2. Local EDCT air time pricing for 721 minutes of use is shown for reference only.
3. Trunk and Port charges are included in service provider expenses.

EDCTcos1.wb2 A1:H70 14 APR 99

Table 5.4. EDCT cost of service estimate summary.

**Discussion of EDCT cost of service models.**

One can compare the county-wide average cost of service predictions of the second EDCT cost model to the ILEC weighted average cost of service (WACS) predictions of the Hatfield Model discussed in chapter three. In table 5.5 below, I list the EDCT cost model results for the three rural Wisconsin counties, together with the incumbent local service providers for those areas.[11] In addition I show what local voice service would cost those residents using the existing cellular technology (airtime only) at the national average per minute rate and at ten cents per minute. I list the nationwide

[11] GTE and Tri-County service much of these three counties.

average billing for local service, as reported in the SOCC for 1997 (FCC, 1999).

The technology underlying EDCT is able to provide high quality local voice and data service to rural areas at a cost slightly above the nationwide average for local service, and well below the Hatfield Model prediction for rural Wisconsin. EDCT cost of service would in fact be about equal to the Hatfield Model prediction for the urban Wisconsin customers of Ameritech.

In terms of the cost sensitivity of the EDCT models, one can see that the traditional problem of the capital intensity of the public utilities has been overcome by the trajectory of costs associated with silicon and EHF wavelengths. The EDCT model is now mostly contingent on the labor costs of operating this new class of service. Organizing clusters of EDCT cell sites for efficiency in the utilization of technical support and office staff can significantly improve costs over the conservative estimations made here.

The cost breakdown for a prototypical EDCT service provider contained in the first model shows the relation between fixed and variable costs. I have based the costs shown on my expert knowledge of the costs of the nearest equivalent hardware, their time evolution (in terms of cost and service features over generations of EDCT product offerings), and my experience with the operations of small technology based craft-like organizational structures.

| | | |
|---|---|---|
| **EDCT model predictions.** | | |
| Buffalo County | $ 29.7 | |
| Jackson County | 26.7 | |
| Trempealeau County | 24.6 | |
| | | |
| **Hatfield Model predictions.** | **WACS** | **No.of lines** |
| Cochrane Cooperative Tel. Co. | $ 87 | 1,178 |
| Frontier Comm. Of Mondovi | 60 | 2,423 |
| Tri-County Tel. Coop. (Strum) | 71 | 3,684 |
| GTE Wisconsin | 35 | 456,000 |
| All Wisconsin. | 31.1 | 3,426,000 |
| All non-RBOC companies | 40 | 1,028,000 |
| Firms with <10,000 lines only | 45 | 340,000 |
| Wisconsin Bell (urban) | 26.8 | 2,397,000 |
| | | |
| **U.S. Wireline** average local billing | $19.92 | |
| | | |
| **Existing cellular.**[1] | | |
| At average $0.336 per minute | $242.26 | |
| At a possible $0.10 per min. | 72.10 | |
| | | |
| **Existing cellular cost of service.** | | |
| Airtime only.[2] | $ 21.63 | |

**Notes:**

1. The prices shown are for airtime only. The monthly estimate is based on the nationwide wireline monthly local usage of 721 minutes (sure to display elasticity of demand at these prices). Figures cited are prices, not costs.

2. This figure comes from my earlier accounting estimate of the cost of service of cellular telephony, which excluded certain business expenses. Thus this figure approximates the shut down price of a cellular provider.

Table 5.5. Monthly residential cost of service comparisons for rural Wisconsin customers, using EDCT, wireline (Hatfield Model) and existing cellular technologies.

With the EDCT business, instead of sending out a site acquisition specialist to incentivize people into permitting use of their hilltops in the rent-seeking scheme of another, the people themselves can be sold the equipment and services they need to become their own service providers.[12] The property owners will optimally estimate the value of their own capital asset (real estate for antennas) in their individual service pricing plans.

**3. The EDCT spectral congestion toll: Optimal toll and an estimate of the resulting federal revenue stream.**

We would not imagine (or a free people tolerate) a government grant of a few licenses to hunt deer, given their abundance. On the other hand, when elk are scarce, advance applications are gladly made for a limited number of permits to hunt them. Scarcity was understandable in the analog realm. Pseudonoise spreading codes are as abundant as deer. Thus everyone should be enabled to enter into the business of EDCT.

Just as for a living resource, some management of the

---

12 I envision a sales approach similar to that used to introduce analog television into rural areas: A station wagon with a TV set in it, towed a crank-up folding Rohn™ tower (about 30 feet high). The salesman would drive from one farm to the next giving demonstrations. I am told the method was highly effective.

overall utilization of the spectral resource is needed. A spectral congestion toll primarily serves the purpose of bringing about the best level of utilization (i.e., efficiency) of the resource. A secondary objective is to recover fees that may be used for some public purpose, be it operating the agency that manages the resource or increasing the treasury.

Oddly, the advent of the digital era of telecommunications is bringing an imposition of scarcity, as exclusiveness is cultivated to a perfection without foundation. Exactly two winning bids were accepted for all of digital audio broadcasting (FCC, 1999a). There were two digital direct broadcast television providers, but they have since merged. When flags were raised about the merger of two baby Bells (Ameritech and SBC Communications), FCC Chair Kennard called for “discussions,” so that the merger might ultimately proceed (FCC, 1999b). As was seen in the study of the U.S. cellular industry by McKenzie & Small (1997), all but one of the providers appear to experience diseconomies of scale. Why should a regulator of industry intentionally sanction the operation of service providers at a scale far above the minimum efficient scale?[13]

I will comment briefly on certain practical implications of the operation of spectral auctions and the services they empower, so that the distributive implications of auctions may be compared with the distributive implications of a spectral congestion toll. (I risk being more than a little blunt, but please bear with me.) In a spectral auction the wealthy buy rights to operate markets with highly restricted competition.[14]

---

[13] Minimum efficient scale is known to microeconomists as $Q_{MES}$, the point on a producer unit cost vs output curve where the curve flattens out and then remains flat, until diseconomies of scale set in at large output quantities. Diseconomies of scale are usually due to increasing costs of attaining strategic coordination in a large firm. Sometimes we need large firms, sometimes we do not.

[14] Apparently the FCC has not been cured of its mindset that because two firms provide competition, that duopolies adequately serve the public interest. I have heard such a view expressed by an FCC official in the Common Carrier Bureau.

In turn the players accumulate rents.[15] The rents have over time corrupted not only the regulatory agency, but the enabling government. The end result is a culture of domination.[16]

A spectral congestion toll instead arises from an ongoing productive activity, not contrived scarcity. Thus the logical end result is a culture that enriches many. A toll is compensation for the use of a natural resource, a resource which no individual should imagine they own,[17] but which all hold in common as stewards. Both spectral auctions and a spectral congestion toll are ways of bringing about efficiency in the utilization of a resource. Both approaches raise money for the treasury. But the distributive and moral outcomes are very different.

A congestion toll is needed with pseudonoise modulation and uncoordinated assignment, to ensure efficient use of the spectral resource. It is envisioned that a spectral

---

[15] “The wealthiest people demand higher than normal profits!” (Here the context was the clients of an attorney practicing communications law.) (Smith, 1995).

[16] See Wink (1993) for a discussion of the essence of organizational cultures.

[17] Even in a spectral auction no actual property right is conveyed (Smith, 1995), except perhaps in the expectations of the purchasers. Thus I propose no change in policy concerning ownership of the radio spectrum.

congestion toll will create a possible alternative to auction fees for that portion of the spectrum allocated to EDCT. The task at hand is first to discuss the various considerations at work in setting an EDCT toll price, then to estimate the present value (PV) of the toll, so that policy makers can compare the worth of the proposed EDCT toll revenue stream to PCS auction license fees.

**The optimal choice of a toll: Considerations.**

The principal purpose of the congestion toll is to bring about market efficiency. A second purpose is to substitute for the revenue generating function that spectral auctions perform in the PCS mechanism design. In addition there is a social implication of the presence of a congestion toll: Some who can’t afford the toll may get tolled-off the information highway. From a purely economic perspective the optimal toll is equal to the marginal cost of spectrum usage. However, setting the toll rate is clearly a matter of more than economics or communications system engineering, though the process must account for both streams of thought. The optimal toll is ultimately a political and moral decision.

In the previous section, we learned that the marginal cost of an EDCT voice call was about two cents a minute, exclusive of the effects of spectral congestion. The cost structure of the EDCT business is one source of guidance in setting a corresponding toll, sufficient if efficiency were the only goal. The implication is that the toll should not be larger than a major fraction of the other costs of EDCT calls. This first approach is useful in setting a toll rate that makes business sense to the proposed EDCT industry.

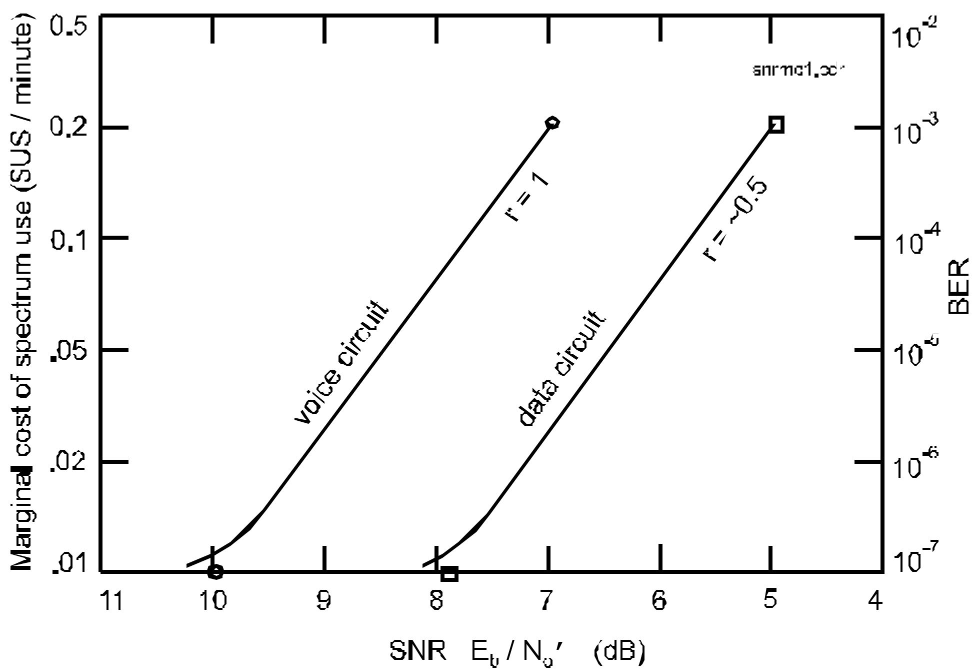



Figure 2.3 (reproduced). Marginal cost curves for spectrum use in an uncoordinated pseudonoise radio network (priced on a competitive basis).

To the extent that competitiveness with the pricing practices of the existing wireless choices is a consideration, then the congestion toll can be set in a way that matches the price of an analog cellular call, when EDCT circuit quality has been degraded to the point that it offers the same level of service. That approach was taken in the construction of figure 2.3, reproduced above. As spectral congestion declines to a negligible amount, the toll would decline to about one cent per minute.[18] This second approach is useful in setting an absolute upper bound on the range of toll charges to consider.

Finally, let us say the objective is to set a toll that is sufficient to influence behavior, but not impose such a burden that it conflicts with the EDCT social objective of providing universal service in rural areas. Then a practical minimum toll would be perhaps ten percent of the marginal cost of EDCT service, or about 0.2 cents per minute. An upper bound would be no more than about the marginal cost of EDCT.

In any case long run spectral noise density surveys of service areas, conducted by the FCC, would then be used to ascertain that the toll set is sufficient to ensure efficiency.

---

[18] Note that because prices, and not costs, are the basis of this toll price level, that the approach is not properly one of economics, but of competitive analysis.

**An estimate of the revenue stream resulting from a spectral congestion toll.**

The key statistics for the U.S. wireline telephone industry, developed in the previous section, provide the information needed to estimate EDCT congestion toll revenue to the treasury. The estimate will be in terms of annual revenue per one percent of U.S. market share of existing wireline telephony, for a hypothetical toll price of one cent per minute.

Local call dial equipment minutes (DEMs) for the nation for 1997 are estimated to be 2,807 billion ($2.8 \times 10^{12}$). For one percent of that total market, and at $0.01 per minute, the annual toll revenue is:

$$2.8 \times 10^{12} \text{ minute} \times \frac{\$0.01}{\text{Minute}} \times 1\,\% = \$280 \text{ million}$$

**Present value of the revenue stream.** Assuming that DEMs continue to grow at a rate greater than inflation, as they have in the late 1990s, the present value of the congestion toll under these assumptions would be an unbounded function -- a delight to any tax collector. The reason can be seen by examining the equation for PV:

$$PV = N + \frac{N}{(1+I-G)^1} + \frac{N}{(1+I-G)^2} + \frac{N}{(1+I-G)^3} + \ldots$$

Whenever the inflation factor (I) is less than the growth factor (G), the denominator of the term for each successive year is less than one. Under such conditions, a direct comparison with a spectral auction lump sum payment is clearly not fair: The auction would lose every time. Just for purposes of illustration, though, let us estimate PV for a finite term, for various years and combinations of I and G. Then the PV of the $280 million stream of payments would be:

| Term (years): | 10 | 20 | 25 |
|---|---|---|---|
| I = 4%, G = 0% | $2.4 billion | $4.0 billion | $4.5 billion |
| 4 3 | 2.7 | 5.1 | 6.2 |
| 4 4 | 2.8 | 5.6 | 7.0 |
| 4 8 | 3.4 | 8.5 | 12.0 |
| 6 4 | 2.6 | 4.7 | 5.6 |
| 6 8 | 3.1 | 6.8 | 9.0 |

Table 5.6. Present value of EDCT congestion tolls, based on one percent market share of U.S. wireline DEMs and a one cent per minute toll.

**Market potential for EDCT.** Between two and three percent of the U.S. population is presently employed in agriculture.

However, direct agricultural employment represents but a fraction of the total rural economy, generally about 25 percent of total rural employment (NERA, 1990). In addition there are others living in the rural environment, but working in urban or ex-urban settings. I estimate that the market for which EDCT would be an appropriate choice is somewhere between two and ten percent, with five percent being a reasonable mean estimate.

## 4. A cost and feature comparison of the different institutional choices.

I summarize the key features of EDCT and the existing analog and digital classes of telephony in table 5.7 below:

| | | **Class of Service:**[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Specification:** | Wireline (POTS) | EDCT | AMPS | IS-54 | IS-95 | DCS-1800/ GSM | DECT | CT-2 |
| **Technology:** | | | | | | | | |
| Frequency (GHz) | (Baseband) | 60 | 0.8 | 0.8 | 0.8 | 1, 1.8 | 1.9 | 0.86 |
| Handoff? | No | no | yes | yes | yes | yes | indoor | no |
| Target market | All | Several | U.S. | U.S. | U.S. | Eur. | Eur. | Britain |
| Multiple access | circuit sw. | PN | FDMA | TDMA | CDMA | TDMA | TDMA | FDMA |
| speech rate (Kbps) | 4 KHz | 64/32 | 4 KHz | 7.95 | 8 | 8 | 32 | 32 |
| Modulation | - | BPSK | FM | (3) | BPSK | GMSK | GFSK | GFSK |
| **Internet Connectivity:** | | | | | | | | |
| Bit rate (Kbps) | 53 | 64/768 | 9.6 | | | 9.6 | | |
| Throughput (Kbps) | 115 | 32& up | 9.6 | | | 14.4 | | |
| Cost per megabyte transferred ($ / MB)[4] | 0.14 | 0.35 | 17 | | | 13.50 | | |
| **Cost of local service:**[2] | | | | | | | | |
| Per minute of use (¢) | 2.8 (in UK) | 2.5 | 10-34 | | | 30-39 | | |
| Average monthly bill ($) | 20.00 (U.S.) | - | 29.84 | | | 30-50 | | |
| Weighted average cost of service (est) ($) | 31.10 (Wisc) | 25-30 | - | | | - | | |
| **Resource allocation choice:** | | | | | | | | |
| | Intensive regulation | Congestion toll | Lottery | | | Spectral auction | | |

**Notes:**

1. AMPS is traditional analog cellular; IS-54 and IS-95 are competing upgrades to AMPS. AMPS, IS-54, and IS-95 have indistinguishable pricing. GSM is a European Union mobile standard, adopted by some U.S. PCS system operators. DECT is a cordless phone standard intended as an add-on to PBXs. CT-2 is a European and Asian microcell system.
2. Average monthly billing and per minute charge for cellular are based on an average of 80 minutes per month usage of airtime, less handset, and with no roaming.
3. IS-54 uses B/4 DQPSK.
4. Data transfer costs are estimated, based on $0.34/ minute airtime and listed throughput. POTS transfer cost is based on 115 Kbps throughput and $0.028 estimated variable cost of local calling.

Table 5.7. Key characteristics of the available choices in comparison with EDCT. (See Cox, 1996.)

As Cox (1996) explains, among the PCS services, there is a split between higher performance choices, like GSM or DCS-1800, and low-tier choices like the digital European cordless telecommunications standard (DECT)[19] or cordless telephone 2 (CT-2). The tradeoff in PCS standards centers around digital signal processing complexity and transmitter power, and the implications for handset weight, cost, and battery life. The high-tier systems are tailored to the demands of urban mobile users.[20] The low-tier PCS solutions make for the most compact handsets, while offering little to no call handoff capability.

DECT has been proposed as an urban fixed wireless architecture (Asghar, 1996, 479). EDCT is chosen to offer very similar subscriber equipment signal processing requirements and cost. But EDCT is intended to offer higher Internet data rates, a feature-rich cell site architecture, the likelihood of multiple uncoordinated service providers, and the capacity advantages of EHF spectrum use.

The IS-54 and IS-95 (and soon to be IS-136) standards are second generation retrofits to the existing AMPS frequency allocation. The goal is to increase channel capacity.

---

[19] See Asghar (1996) for an overview of the DECT system.

[20] I explain more of what the urban environment implies about demands on speech coding rates and spectral efficiency in the next section.

I will be making comparisons in greater depth in the next section on technology choices for urban and rural customers.

**5. Crossover between technology choices for urban and rural service.**

The EDCT system architecture contains aspects of the other existing classes of service, to leverage existing engineering paradigms and technical standards, while best meeting the needs of rural fixed wireless customers. For example, 32 Kbps ADPCM speech coding and BPSK modulation with no FEC have intentionally been chosen to lower signal processing requirements in the subscriber equipment, thus minimizing costs. Pseudonoise (PN) direct sequence transmission has been chosen over channelized TDMA, to avoid the cochannel interference and network synchronization challenges that would effectively preclude the competitive provision of wireless service in rural areas.

All of these engineering choices are a good fit to the requirements of fixed customers removed from the urban core. These same engineering choices facilitate the adoption of spectral congestion pricing, because they provide for a communication link that gradually degrades in the presence of increasing congestion from other PN transmitters.

On the other hand, urban mobile customers experience a very different set of engineering considerations. The result is that while spectral congestion pricing is a natural institutional choice for providing rural universal service, the existing channelized architectures are a better fit for most urban customers. Specifically, there are several factors affecting the desirability of the proposed new class of service, compared to other existing wireless choices:

1. Spectral utilization efficiency.
2. Differences between radio propagation in a dense urban mobile environment and open terrain for fixed wireless subscribers, particularly in regard to delay spreading.
3. Increasing importance of Internet connectivity to rural users.
4. Costs of the various alternatives for local telephony.

I discuss each of these aspects below.

Finally I have a bit of good news for those EDCT customers who want to move between worlds: Emerging software-defined-radio technology can serve the role of a technology converter. Though imperfect, customers would gain the ability to use a single handset at home, in the car, or at work.

**Spectral utilization efficiency.** The first factor is the spectral utilization efficiency of the pseudonoise modulation scheme and decentralized system architecture to be employed, compared to a channelized modulation scheme and centrally administered architecture, such as analog (FM) cellular telephony or its second generation digital successors employ. The engineering literature quantifies the small but meaningful efficiency disadvantage of the pseudonoise approach (Rowe (1982) and Viterbi (1982), as cited in Yue, 1983). The implication is that in the most population dense areas a channelized architecture is to be preferred, for reasons of the traditional doctrine of spectral resource scarcity alone.

Compared to a reference system using narrowband FM modulation and fully occupied channels, Yue calculates a spectral utilization efficiency of 72 percent. But just how significant is this tradeoff? With the combination of digital speech coding and digital modulation standards, it is possible to design links with a wide range of bandwidth requirements, in factor of two increments. As the bandwidth of a digital link is reduced, two effects occur: First, the recovered speech progressively loses its human qualities. Second, the increasing costs of signal processing trade against the costs of spectrum usage. The bandwidth to assign a digital link takes on a level of subjectivity, but with coarser increments than the partial loss Yue has calculated.

I conclude that Yue’s efficiency tradeoff is less significant than the tradeoffs that occur all the time in the digital channelized design approaches. Therefore, the competitive and distributive implications, as well as the various costs of spectrum and telephony regulation ought to be most on our minds when comparing spectral congestion pricing to spectral auctions or lotteries. In other words the social costs dominate over the engineering considerations.

**Implications of radio propagation environment.** The issue of greatly increased delay spreading in the urban core, that I discussed earlier, has profound implications for practical link bandwidth. A system architecture that is intended to serve mobile urban subscribers will have to tolerate delay spreading of three to as much as 25 microseconds, along with rapid deep fading (“picket fencing”). The result is that modulation bit rates are highly constrained, to a maximum of perhaps 32 Kbps. A link intended for a fixed rural customer has almost two orders of magnitude less delay spreading and a greatly improved fading scenario, making several Mbps readily attainable. Therefore a mobile solution for urban customers cannot provide useful Internet connectivity for fixed subscribers, for engineering reasons alone.

**Need for Internet connectivity.** While the existing cellular choices provide data rates not exceeding 19.2 Kbps,[21] urban wireline customers are over the next year going to be routinely offered Internet connectivity at 768 Kbps and above. In a very short while Internet content will reshape itself to utilize a fatter "last mile," leaving rural customers cut-off like never before. A rural universal service alternative must offer data rates comparable to the urban setting to be a total solution for the rural economy. The alternative could be a reversing of decades of effort to develop and diversify rural areas.

**Cost characteristics of the alternatives.** The third major consideration is the comparative costs of the various alternative classes of service that might present themselves as consumer options. Here we are aided by the cost studies that were performed in chapter three and the EDCT system design example of chapter four. We are now in a position to compare and contrast costs and make recommendations.

It is immediately apparent that the EDCT system architecture yields a cost of voice service that is nearly identical to urban wireline service, and without the use of a universal service cross-subsidy. The pleasant surprise is

[21] The 19.2 Kbps data rate cited is for Cellular CDPD service, a dedicated packet data service that overlays AMPS networks.

that for data connectivity, an EDCT voice channel offers a far lower cost per megabyte transferred than does analog cellular or a high-tier PCS solution. The reason for the much higher data service costs of the existing cellular choices is that their data rates are so constrained by the engineering realities of urban mobile service.

EDCT data service, while much faster than an EDCT voice channel pressed into data service, will cost more on a per megabyte basis. First, the greater bandwidth required will cause a correspondingly higher spectral congestion toll. Second, the use of FEC will halve the spectral efficiency in favor of a lower BER. Third, it is after all an optional service.

British wireline customers are presently billed by the minute for local calling, with a weekday / weekend price differential, that is in itself a crude congestion toll. The monthly service charge is effectively divided about equally between a fixed charge and a variable charge. For an average 750 minutes of local usage, the effective per minute rate is about on a par with the projected EDCT per minute rate. British Telecom has already put into effect a local service pricing approach quite similar to what I advocate here for EDCT.

**EDCT and mobile service.**

Call handoff capability is not intended to be a feature of EDCT, and as one can see, the limited mobility solutions of DECT and CT-2 have greatly restricted handoff capability. Various authors (Cox, 1996 and Ricci, 1997) have stated that a key reason for the rapid growth of mobile telephony is that users cherish their mobility, as well as the ability to use a single handset for all calls.  For a rural residential customer, handoff in itself is of no value, but many users may wish to possess a handset that would function both at home and when mobile.

Over the past two years considerable effort has been expended by the cellular industry to develop architectural approaches and technical standards for a software-defined-radio (SDR) handset (Womack & Braun, 1999).[22]  The approach is to have a hardware T / R section that can operate on a range of service frequency allocations, connected to a digital signal processor (DSP) section that can handle one or more modulation and speech coding schemes.  A DSP is software programmable.  Changing from AMPS, to IS-95, to GSM, or anything else, would be simply a matter of preselection, or of detecting the protocol in use by the cellular service

---

[22] The intention is apparently to develop a consumer equivalent of the Speakeasy multiprotocol radio used by the military.

provider.  There would be only a small incremental cost associated with the T / R electronics.

There is no reason why an SDR handset could not be built that would operate on AMPS or GSM and an advanced cordless phone standard, like CT-2.[23]  Then rural customers could have a cordless base unit at home (with range sufficient to reach out buildings), drive the freeway using AMPS, and enjoy wireless PBX connectivity at work.  Could handoff of ongoing calls be achieved in a competitive environment of disparate technologies?  That is not likely.  But cell site switches could easily be programmed to locate a customer, by calling a list of numbers provided by that customer.

---

[23] See Hanzo (1996) for a very complete description of the service characteristics and technology of the CT-2 system.

# CHAPTER 6. CONCLUSION AND AREAS FOR ONGOING RESEARCH.

First I summarize what has been accomplished to date in this work. Frankly, there is much more that needs to be done, in order that what has begun as a simple investigation of the possibilities for the future of rural local telecommunications might in the end be of actual benefit to people. The work needed to make EDCT a reality needs to occur in a number of settings: There is much applied research to be done on the infratechnology of EDCT, most of it well suited to university engineering departments. There is work remaining on the development of policy relating to the proposed EDCT industry, some of it suited to the academic environment. I discuss some of the opportunities in a second part of this chapter.

Finally, my analyses have pointed to some areas of potential interest to those who regulate and shape policy concerning the existing kinds of telecommunications service. I mention a few of those issues in a final section of this chapter.

## 1. Conclusions.

I have described and analyzed a new institutional choice for rural voice telephony and data service. The new class of service, EDCT, has distinct cost of service and service feature advantages, compared to existing technologies. EDCT has a unique network architecture tailored to the varied topography frequently encountered when planning network buildouts for rural customers.

A new approach to radio frequency spectral resource allocation has been developed, which when combined with the use of EHF frequencies, offers several structural advantages. Among these advantages are an ending of the need for a universal service cross-subsidy for rural local service, the opening up of low population density regions to competitive local access, and Internet connectivity rates rivaling those promised for urban households. Making full use of the trajectory of cost and performance of semiconductor technology alters the traditionally high fixed cost-to-revenue business ratio of wireline telephony, potentially transforming the business of providing connectivity in rural areas.

Finally, the studies of the existing telecommunications infrastructure, carried out in chapter three, contribute unique views of the cost / service feature vectors of the incumbent service providers in Wisconsin. The PCA analysis of Wisconsin LECs is almost certainly the first of its kind made for the benefit of the public. I discuss one implication shortly.

**2. Areas for ongoing research.**

The policy for a new industry to provide EDCT has been explored. Implications and the many benefits for the existing telecommunications industry have been discussed. What remains is to carry out the applied research and to create an enabling social environment that will bring about EDCT industry formation and the promised benefits for rural residents. I next touch on several areas of needed research and action.

**Understanding the role of concentration of ownership in EDCT.** Big isn't necessarily bad, and economists are eager to point this out. Still, the EDCT market itself is only several percent of the U.S. market for universal telephone service. Are technology choices that make $Q_{MES}$ quite small sufficient in themselves to prevent the emergence of a defacto monopoly? I have suggested that local ownership and a stakeholder management model would be a best fit to the needs of EDCT customers. Other researchers may have additional perspectives on industry structures and administrative law that would be beneficial. There is an opportunity to perfect an enveloping institution for EDCT in parallel with the effort to move from infratechnology to product realizations. That is a rare opportunity that should involve many.

**Creating an enabling legal environment.** In order for the private sector to be willing to make investments in the development of products for EDCT, they must be assured of an allocation of radio spectrum for their proposed activity. Allocation is a step distinct from and prior to the specific assignment of spectrum to individual license holders, but is sufficient for industry formation. As touched upon earlier, the World Radio Conference 2000 will be occurring in one year, to consider allocation for fixed wireless through 67 GHz. I would like the U.S. government to propose that EDCT be allocated spectrum for first generation product designs, including an allocation for a network backbone.

Apart from international coordination, the domestic regulatory environment needs to be shaped. This year Congress will be reauthorizing the FCC. There is an opportunity to authorize the FCC to use spectral congestion pricing for a new class of service. At a latter time, as the EDCT industry gets underway, the FCC can then go ahead and create the administrative rules needed. All that is needed now are the "hooks."

**Perfecting the fit between spectral congestion price levels, the air interface, and the public good.** The air interface is the connection between the processed baseband signal and the imperfection of radio wave propagation. The engineering choices of the degree of forward error correction, the speech coding algorithm, and the minimum acceptable signal-to-noise ratio affect the economics of congestion: They determine the uncongested speech quality and the rapidity of deterioration of circuit quality with mounting congestion. With pseudonoise modulation the air interface chosen further interacts with the excess noise generated by other simultaneous users to determine the circuit quality and economics of usage. EDCT and the proposed third generation cellular (3G CDMA) under development (see CDMA Development Group, 1999) treat the degrading effects of excess noise very differently. Is the stage set for a “technology shootout” between spectral congestion pricing and the legacy channelized assignment approach of CDMA? Are the two approaches really best suited to distinct regimes of customer classes? Time will tell, if EDCT will be allowed to operate in a market.

Let us compare the EDCT approach to treating the effects of excess noise as congestion, to the system approach of third generation cellular, which foregoes the potential of the concept of congestion in favor of a brute force method. In the 3G CDMA standards currently under development for urban mobile subscribers, excess noise from other transmitters is handled differently. North American 3G CDMA uses 1.25 MHz exclusively assigned “channels,” with dozens of pseudonoise conversations occurring simultaneously in each channel. CDMA transmitters are to have their output power under the control of the cell site: Close to the cell site, transmitter power is to be reduced to maintain the minimum acceptable signal-to-noise ratio of 3 to 9 dB. As a mobile user moves away from the cell site, its transmitter power is increased under central control. The maximum working distance of a cell site is reached as the transmitter power tries to become infinite. The consequence for 3G CDMA is that voice quality is nearly always going to be brought down to the minimum level acceptable, as the channel will nearly always be fully congested.

**Congestion toll and the public good.** As I discussed earlier, the level at which the EDCT congestion toll is set (in the limit of no congestion) is not simply a matter of engineering, but also of public policy. The EDCT congestion price level in the presence of substitute goods determines the competitive outcome, as the marginal cost of EDCT less toll appears to be below the shutdown price of existing cellular providers. A non-zero congestion toll forces efficient use of the spectral resource. But the congestion toll also takes on the form of a tax, with all the attendant social implications of taxes.

**Researching the market for EDCT products and services from a consumer perspective.** EDCT is to employ a packet switched, rather than a circuit switched, network. Services not presently available even to urban wireline customers could be offered. For example, opportunities exist for virtual private networks involving growers and seller cooperatives. What kinds of services rural customers might want, and their offering bundles, might be a fertile area of research for master programs in telecommunications-related areas.

**Exploring the relation between the existing players and an emergent EDCT industry.** The stakeholder analysis for the proposed EDCT industry was developed to the extent of a first cut in chapter five. These industry relationships need to be more developed, with a view toward making EDCT a reality. A key aspect of making EDCT happen is to make everyone a winner to the extent possible, especially the telephone companies currently providing rural service.

**Prototyping the equipment required for EDCT using UHF.** Just above 2 GHz is a band set aside for experimental services. A special licensing procedure exists, with a renewable license term of about one year. It should be within the ability of an electrical engineering graduate student to assemble a prototype of a cell and a set of subscriber T / R units. One could then conduct field trials to determine the suitability of the EDCT concept.

Prior to building hardware, a software simulation of an EDCT cell might be undertaken. Such a simulation could have an economic module simulating spectral congestion pricing running on top of an engineering model of the radio channel. In addition the simulation would have modules that generate simulated voice and data traffic. One could then experiment with various coding algorithms, degrees of FEC, simulated fading models, congestion toll price levels, and the like. One ought to be able to fairly thoroughly compare the EDCT system concept to existing and proposed 3G cellular radio. Field trials would serve to validate the simulations.

### 3. Areas of potential further interest to regulators and policy types.

**EDCT and urban telephony.** To what extent might a spectral congestion toll and uncoordinated assignment of cellular providers be a suitable paradigm for the delivery of competitive local access to residences? Is there a potential to design a low cost, cooperatively owned fixed wireless service for low income urban residents?

**EDCT and bandwidth markets.** The emergence of financial markets for telecommunications bandwidth, limited though they are at present, promise to supplant the need for the inefficient and sometimes abusive bilateral interconnection agreements that are a hallmark of the 1996 Act (see Blau, 1999). Open trading in access to network bandwidth portends a bright future for the independent local service provider, as long as the markets are run better than the cheese market.

**Paying for spectrum by instituting a user fee.** It has been suggested that wireless service providers might pay a "user fee" for access to the spectral resource. A user fee paid, say, on a monthly basis, might serve as an administrative convenience for the agency overseeing collection. There are, however, at least three considerations that come into play in assessing the fit of such a proposal to the needs of spectrum users and managers.

First, in the nationwide trend to move the public switched telephone network from a circuit switched architecture to a packet switched network of a type more suited to the convergence of voice, video and data, it becomes more natural to meter packets than usage time. In the emerging commodity markets for bandwidth, it seems likely that packets will be mostly on the table (Blau, 1999). A congestion toll is traffic-based, like packets, whereas a user fee seems a better fit to a circuit switched network environment.

Second, the political and administrative law realities of setting user fees might bring about a fee schedule that artificially restricts competition or keeps EDCT providers out of some service territories. With a traffic-based approach to spectral resource pricing, the opportunities for regulatory capture are greatly reduced. The rate making process, which otherwise might carry forward some of the administrative structure of the public utility rate design process, is reduced to setting a price level that brings about efficient use of the spectrum. EDCT system architecture choices become the principal means of attaining universal service goals.

Third, a congestion toll is a better fit to a distinctive reality of the radio spectrum -- it cannot be owned by the nations. With the exception of but one minor nation (a nation where one percent of the population owns 90 percent of everything), property rights are never conveyed with licensure. In the first several pages of chapter two I discussed the highly developed nature of the international law of radio communications, in comparison to the bilateralism dominant in the law of physical communications. This advancement mirrors the expansiveness of a propagating electromagnetic wave.

Paying a user free, which is essentially renting the right to use a good, implies that the property used has an owner. Property rights and respect for the rule of law are key foundations to our prosperity and the advancement of other kinds of rights and liberties. Yet the radio spectrum compels us to think beyond property, so that we might best enable markets.

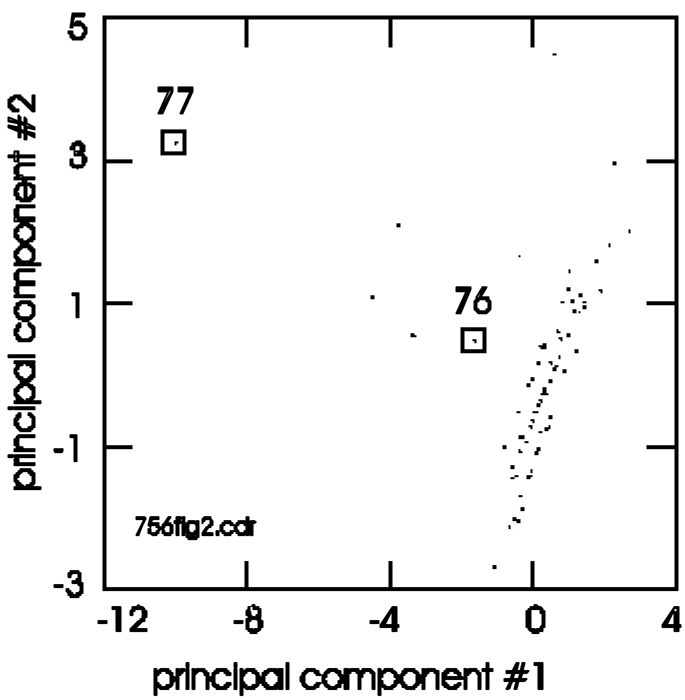



Figure 3.5 (Reproduced at left.)
Plot of the first two principal components of the PCA analysis of the Wisconsin telephone local exchange carriers. Ameritech is (77).

**Revisiting Ameritech and Airadigm.** Might it be that Ameritech has been cross-subsidizing the construction of a private digital wide area network for its cellular subsidiary with investments made for the public switched telephone network? (If so, perhaps it is an accident.)

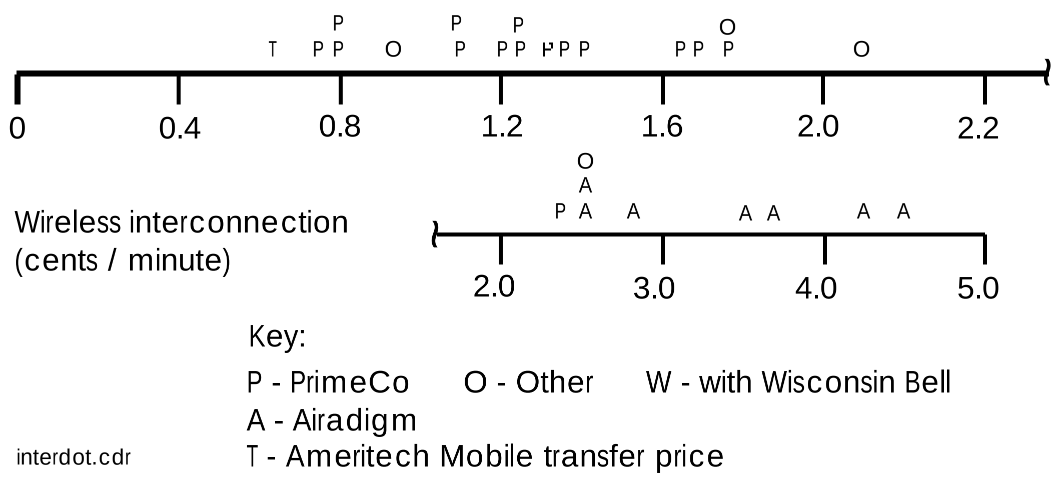



Figure 3.16. (Reproduced.) Bilateral interconnection agreements reached in 1997 or 1998 involving a Wisconsin wireless service provider.

The tool of principal components analysis, applied to Wisconsin’s intensively regulated telephone industry, affords a view of the effectiveness of regulation that goes beyond the rate-of-return equation. Consider simultaneously the plot of the first two principal components of the LEC survey (figure 3.5) and the univariate analysis of Wisconsin wireless interconnection agreements (figure 3.16).

The first principal component loaded heavily on access lines (business and residential) served by a digital switch, fraction of ISDN lines available to businesses, fraction of switches that are digital, and average subscriber distance to a switch. The second principal component loaded heavily on five year average switching and transmission investments. How can an LEC score so extraordinarily high on investment, and yet unusually low for delivering the benefits of digital switching and outside plant to customers? (Component three is also large and positive, a four component model describes the same behavior, and the four component outlier plot looks ok.) Ameritech’s transfer price for wireless call termination is unusually low. Who is paying for transporting calls over Ameritech’s statewide cellular local calling area?

Airadigm, whose negotiated wireless call termination rates are nearly two standard deviations above the mean, has a very different situation. Is the bilateralism of the 1996 Act failing, by freezing in a structural disadvantage for smaller service providers?

# APPENDICES.

## APPENDIX A. Variable definitions for the multivariate PCA model.

**WSTA SURVEY VARIABLE DESCRIPTIONS.** (File WSTAVAR4)

| POS. | NAME | DESCRIPTION |
|---|---|---|
| 1 | Reply | Sequential case number, 1-75, small TELCO summary, plus 2 big TELCOs (GTE, WI Bell), summary. (numeric) |
| 2 | Firm name | (label) |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | PSCWfirm | PSCW- four digit firm identifier code used by PSCW. |

**-Question 1: Residential subscriber access lines.**

| POS. | NAME | DESCRIPTION |
|---|---|---|
| 7 | Rtotal | 1.1- total number of line pairs providing residential service. |
| 8 | Rcrossba | 1.2- fraction served by an electro-mechanical switch. |
| 9 | RanaSPC | 1.3- ... by an analog stored program control (SPC) switch. |
| 10 | RdigSPC | 1.4- ... by a digital SPC switch. |
| 11 | RnarISDN | 1.5- lines that are narrow band (T0) ISDN, rather than analog. |
| 12 | RwidISDN | 1.6- lines that are wide band ISDN (T1 or better). |
| 13 | ReqAcc | 1.7- lines that allow customer choice of long distance co. |

**-Question 2: Business access subscriber lines.**

14 Btotal 2.1- total number of line pairs providing residential service.

15 Bcrossba 2.2- fraction served by an electro-mechanical switch.

16 BanaSPC 2.3- ... by an analog stored program control switch.

17 BdigSPC 2.4- ... by a digital stored program control switch.

18 BnarISDN 2.5- lines that are narrow band (T0) ISDN, rather than analog.

19 BwidISDN 2.6- lines that are wide band ISDN (T1 or better).

20 BeqAcc 2.7- lines that allow customer choice of long distance co.

**-Question 3: Advanced service features.**

21 FrRelay 3.1- frame relay protocol for high speed digital transmission.

22 SMDS 3.2- another protcol for high speed digital transmission.

23 BroadTV 3.3- broadcast (NTSC or equiv.) quality real-time video.

24 otherVid 3.4- video, but not in real-time.

**-Question 4: Number of switches.**

25 Switches 4.1- total number of firm-owned switches, of all types.

**-Question 5: Switch features.**

26 SanaSPC 5.1- number of switches that are analog SPC.

27 SdigSPC 5.2- number of switches that are digital SPC.

28 STP 5.3- ATT Signal System 7 (SS7) installed, is an STP (host).

29 SP_SSP 5.4- ATT Signal System 7 (SS7) installed, SS7 only (tandem).

30 EqAccess 5.5- switches allowing customer choice of long distance co.

31 DTMF 5.6- switches providing Touch Tone (tm) dialing.

32 NE911 5.7- switches having non-enhanced 911 calling installed.

33 E911 5.8- switches having enhanced 911 calling installed.

34 ATM 5.9- asynchronous transfer mode (ATM) protocol capable.

**-Question 6: Miles of local loop (phone lines).**

35 LoopMi 6.1- miles of subscriber wiring, in cable sheath miles.

**-Question 7: Miles of fiber optic cable (generally not subscriber).**

36 FiberMi 7.1- route miles of fiber optic cable presently installed.

**-Question 8: Other digital transmission (microwave or coaxial).**

37 DigitMi 8.1- route miles of other digital transmission line.

**-Question 9: Fiber installation planned over next three years, total.**

38 FOplanMi 9.1- route miles of fiber optic cable the

company plans to install in total, over the next three years.

**-Financial measures:**

| | | | |
|---|---|---|---|
| 39 | totTrans | PSCW- | total 1992 investment in transmission facilities. |
| 40 | totSwtch | PSCW- | total 1992 investment in switching equipment. |
| 41 | aveTrans | PSCW- | five year average (88-92) annual transmission investment, |
| 42 | aveSwtch | PSCW- | five year average (88-92) annual switching investment, |

**Other Notes:**

**Cases:**

1. Case 76 is GTE North (WI operations only).
2. Case 77 is WI Bell (i.e., Ameritech- WI operations only).
3. Case 78 (last case) is total for all WI firms, large and small.

**Data points:**

4. 40 of GTE North switches are crossbar, and are not broken out in data.
5. GTE-owned analog switches are not SPC.
6. Century telephone has a significant number of crossbar switches in use.

**Variables:**

7. SS7 reduces call set-up time.
8. NE911 does not have caller ID or keep open features.
9. E911 does have caller ID and keep open features.

10. Other digital serves same function as fiber, but has roughly 1/10 the capacity (bandwidth).
11. totTrans is the sum of PSCW accounts 2231, 2232, 2411, 2421-2425, 2431, 2441; summed over the five year period 1988-1992. Source: reports to PSCW.
12. totSwtch is the sum of PSCW accounts 2211, 2212, 2215, 2220; summed over the five year period 1988-1992. Source: reports to PSCW.
13. aveTrans is in dollars per subscriber line. It is the sum of PSCW accounts 2231, 2232, 2411, 2421-2425, 2431, 2441; averaged over the five year period 1988-1992. Source: reports to PSCW.
14. aveSwtch is in dollars per subscriber line. It is the sum of PSCW accounts 2211, 2212, 2215, 2220; averaged over the five year period 1988-1992. Source: reports to PSCW.

## APPENDIX B. Variables used in the Multivariate PCA model.

| PCA Variable | How calculated from survey var. | Meaning |
|---|---|---|
| FBus | 14 / 7+14 | Fraction of lines business. |
| FrdigSPC | 10 / 7 | Fraction of residential lines. served by a digital switch. |
| FbdigSPC | 17 / 14 | Fraction of business lines served by a digital switch. |
| FsdigSPC | 27 / 25 | Fraction of switches that are digital. |
| FbnISDN | 18 / 14 | Fraction of business lines which are narrow band ISDN. |
| Fsystem7 | 28+29 / 25 | Fraction of switches which are AT&T Signalling System 7 compatible (host or tandem). |
| FE911 | 33 / 25 | Fraction of switches having enhanced 911 dialing. |
| aveLmi | 35 / 7+14 | Average subscriber distance to switch in miles. |
| aveDtran | [36+38+0.1(37)] / 7+14 | Average digital transmission (mi) owned by firm on a per-subscriber basis. |
| avTrans | 41 / 7+14 | Five-year average investment in transmission facilities on a per-subscriber basis. |
| avSwtch | 42 / 7+14 | Five-year average investment in switching facilities on a per-subscriber basis. |

**Notes**:

1. aveLmi is the average local loop length. It is a surrogate measure of customer density and indicates the degree to which economies of density are present in the firm's service territory.
2. aveDtran is a per-subscriber measure of miles of digital transmission line owned by the firm to interconnect switches or to link switches to inter-exchange carriers (IXCs).
3. aveTrans and aveSwtch are measures of firm investment in plant and equipment on a per-subscriber basis. Together they represent total firm investment per line. Each is a sum over the five-year period from 1988-1992, to provide for some smoothing.
4. aveDtran is the sum of existing fiber-optic cable, fiber-optic cable planned for installation over the next three years, and one-tenth the non-fiber digital transmission (to approximately correct for differences in information bandwidth), divided by the total number of firm subscribers.
5. Rtotal and Btotal are used to correct for firm size (see text), and are not used directly as variables in the PCA model.

**Definitions**:

1. A switch is used to complete a call to the desired party and is generally located at the firm's central office.
2. Narrow band ISDN is a new type of subscriber line which is digital and permits the comingling of voice and data.
3. Signalling System 7 is at independent, supervisory network link between switches that greatly reduces the time to complete a call.
4. Enhanced 911 permits identification of the caller's number and address, which non-enhanced 911 dialing does not.

## APPENDIX C. Cases used in the Multivariate PCA model.

| Case No. | Firm Name | Case No. | Firm Name |
|---|---|---|---|
| 1 | Amery Telcom | 41 | Midway Tel |
| 2 | Amherst Tel | 42 | Milltown Mutual |
| 3 | Badger Telcom | 43 | Monroe Co Tel |
| 4 | Baldwin Telcom | 44 | Mount Horeb Tel |
| 5 | Bayland Tel | 45 | Mt Vernon Tel |
| 6 | Black Earth Tel | 46 | Mozanie |
| 7 | Bloomer Tel | 47 | Nelson Tel |
| 8 | Belmont | 48 | Niagra |
| 9 | Bondwell Tel | 49 | Northeast Tel |
| 10 | Bruce | 50 | Price Co Tel |
| 11 | B.B.&W. Tel | 51 | PTI Communic |
| 12 | Central State | 52 | Pecoco (Peo&FBA) |
| 13 | Chequamegon Tel | 53 | Rib Lake Tel |
| 14 | Chibardun Tel | 54 | Riverside Telcom |
| 15 | Citizens Coop | 55 | Rhinelander |
| 16 | Clear lake Tel | 56 | Richland-Grant Tel |
| 17 | Crandon Tel | 57 | St Croix Tel |
| 18 | Cochaave Tel | 58 | State Long Dist |
| 19 | Century reg III | 59 | Scandinavia Tel |
| 20 | Coon Valley | 60 | Siren Tel |

| Case No. | Firm Name | Case No. | Firm Name |
|---|---|---|---|
| 21 | Cuba City | 61 | Somerset Tel |
| 22 | Dickeyville Tel | 62 | Southeast Tel |
| 23 | East Coast Tel | 63 | Spring Valley Te |
| 24 | Farmers Ind | 64 | Stockbridge&Sher |
| 25 | Farmers Tel | 65 | Tenney Tel |
| 26 | Grantland Telcom | 66 | Tri-County Tel |
| 27 | Hager Telcom | 67 | Union Tel |
| 28 | Hillsboro Tel | 68 | Urban Tel |
| 29 | Indianhead Tel | 69 | UTELCO |
| 30 | Kendall | 70 | Viroqua Tel |
| 31 | Lakefield Tel | 71 | Vernon |
| 32 | Lakeshore | 72 | Waunakee Tel |
| 33 | LaValle Tel Coop | 73 | Wittenberg Tel. |
| 34 | Lemonweir Valley | 74 | West Wi Telcom |
| 35 | Luck Tel | 75 | Wood Co Tel |
| 36 | Maple Tel Coop | | |
| 37 | Mid-Plains Tel | 76 | GTE North |
| 38 | Mondovi Tel | 77 | WI Bell (Ameritech) |
| 39 | Manawa Tel | 78 | Total (all firms) |
| 40 | Marq-Adams Tel | | |

**BIBLIOGRAPHY**


05-MA-0108. 1998. Application for Approval of an Interconnection Agreement Between New-Cell, Inc. And Frontier Communications, Inc. Before the Public Service Commission of Wisconsin. Docket 05-MA-0108.

05-TD-0100. 1998. Complaint before the Wisconsin Public Service Commission: CTC Communications, Inc vs. GTE North, Inc.

05-TI-0138. 1995. Investigation of the Appropriate Standards to Promote Effective Competition in the Local Exchange Telecommunications Market in Wisconsin. Before the Public Service Commission of Wisconsin. Docket 05-TI-0138.

05-TI-0140. 1997. Interim Procedures for Negotiations, Mediation, Arbitration and Approval of Agreements. Wisconsin Public Service Commission staff report in Docket 05-TI-0140.

05-TI-0149. 1998. Application for Approval of an Interconnection Agreement Between Wisconsin Bell, Inc. (d/b/a Ameritech Wisconsin) and Wisconsin Entities of Ameritech Mobile Communications, Inc. Before the Public Service Commission of Wisconsin. Docket 05-TI-0149.

95-C-0657. 1997. Re AT&T Communications of New York, Inc. 177 PUR 4th. Public Utilities Reports.

97-1912. 1998. Guidance to proponents of cost models in universal service proceeding: Switching, interoffice trunking, signaling, and local tandem investment. FCC DA 97-1912 in CC Docket Nos. 96-45 and 97-160.

1996 Act. 1996. Telecommunications Act of 1996. 110 STAT 56. (S652).

1994 Act [Act 496]. 1994. 1993 Wisconsin Act 496.

1934 Act [USC 47]. 1934, as amended. Communications Act of 1934. 47 USC 151-1001. (September, 1995.)

Alexandrowicz, Charles Henry. 1971. <u>The Law of Global Communications</u>. New York: Columbia University Press.

Anonymous. 1997. Private conversation with a state IT employee in the Wisconsin Department of Administration.

Arellano, Michael. 1998. AT&T: Who needs ILECs? Tele.Com, 3:9, p. 44. August.

Asghar, Saf. 1996. Digital European cordless telephone. In The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press.

Barbour, I. G. 1974. Myths, Models, and Paradigms: A comparative study in Science and religion. New York: Harper & Row. ISBN 0-06-060388-7 (paperback).

Baumol, William. 1982. Contestable markets: An uprising in the theory of industry structure. American Economic Review, 72. Pp. 1-15. March.

Baumol, W.; Panzer, J.; and Willig, R. 1982. Contestable Markets and the Theory of Industry Structure. San Diego, CA: Harcourt, Brace, and Jovanovich.

BCPM. 1997. Benchmark Cost Proxy Model. Universal service cost studies for selected states. 913-624-2460. Contact: Dunbar, Jim.

Berg, S. V. 1988. Duopoly compatibility standards with partial cooperation and standards leadership. Information Economics and Policy, 3, pp. 35-53.

Bhagava, V. K. & Fair, I. J. 1996. Forward error correction coding. The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press. pp. 209-241. ISBN 0-8493-8573-3.

Blau, John. 1999. Dealing time: A hot young market for telecom bandwidth takes the floor. Tele.Com, 4:8, pp. 51-54.

Bromley, D. 1998. Private communication.

Brown, Patricia. 1999. Headers: German cable industry’s fear of flying. Tele.Com Magazine, 4:9, pp. 13-14.

Buber, Martin. 1970. I and Thou. New York: Charles Scribner’s Sons.

Buber, Martin. 1956. The Eclipse of God. New York: Harper & Brothers, Publishers.

Bush, E. E. 1985. Radioman 1 & C. NAVEDTRA 10229-H (unclassified). Washington, D.C.: U.S. Government Printing

Office. Stock order number 0502-LP-051-1475.

Calhoun, George. 1988. Digital Cellular Radio. Norwood, MA: Artech House, Inc.

Carter, N. M., Stearns, T. M., Reynolds, P. D., and Miller, B. A. 1994. New venture strategies: Theory development with an empirical base. Strategic Management Journal, 15, pp. 21-41.

CDMA Development Group. 1999. The CDMA revolution. Microwave Product Digest. April. Pp. 38, 46, 71.

Cerrina, F. 1998. Private communication.

Chandler, A. 1962. Strategy and Structure: Chapters in the History of the American Industrial Enterprise. Boston: MIT Press.

Cleary, J. F. 1964. General Electric Transistor Manual, Seventh Ed. (Out of print.) Especially chapter 2.

Connectix. 1995. Advertisement for the Connectix VideoPhone™. San Mateo, CA 415-571-5100 or 800-930-5880.

Cordone, S.; Gunderson, J.; Piccirillo, L.; Timbie, P.; Chen, T.; Cheng, E.; Cottingham, D.; Fixsen, D.; Silverberg, R.; Wilson, G.; Knox, L.; Meyer, S.; Norgaard-Nielson, H. U.; Hermit, S.; and Puchalla, J. Unpublished. NASM2: An observation of cosmic background anisotrophy at medium angular scales. A poster. Timbie is at the University of Wisconsin-Madison, Wilson is at NASA/GSFC.

Cox, Donald C. 1996. Wireless personal communications: A perspective. In The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press.

Danner, Carl. 1991. The oligopoly paradox: Cellular telephones and a difficult regulatory problem. Journal of Policy Analysis and Management, 10:4, 671-675.

DARPA. 1997. Defense Advanced Research Projects Agency and Office of Naval Research program review of X-ray lithography-related research funded under DARPA / ONR grant number N00014-96-1-0558. Madison, Wisconsin. July 21-22, 1997. (Unfortunately the authors of the SCREAM and COMBAT processes didn’t leave printed works for attendees.)

Drucker, P. F. 1985. Innovation and Entrepreneurship:

Practice and Principles (1st Ed). New York: Harper and Row.

Economics and Technology, Inc. & Hatfield Associates, Inc. 1994. The Enduring Local Bottleneck: Monopoly Power and the Local Exchange Carriers. February, 1994. $$ (617) 227-0900 or (303) 442-5395 (UW-Madison Public Utility Institute has a copy to read.)

Economides, N. S. 1996. The economics of networks. International Journal of Industrial Organization, 14:6, 673-700.

Eliason, A. 1998. A letter to the editor: DTV. Desktop Journal, Madison Ed. December. P. 26. Andye8@mailcity.com

Fantle, Will. 1999. Watching the utilities. Isthmus, 24:13, pp. 9-11. March 26.

FCC. 1996. Spectrum Inventory Table, 137 MHz to 100 GHz. Washington, D.C.: Federal Communications Commission, Office of Engineering and Technology. DA96-1704.

FCC. 1997. Millimeter wave propagation: Spectrum management implications. Washington, D.C.: Federal Communications Commission, Office of Engineering and Technology. Bulletin Number 70. July.

FCC. 1998. Concerning the “tragedy of the commons”, from e-mail.

FCC. 1999. Statistics of Communications Common Carriers (SOCC). Available from the FCC Internet site in PDF format.

FCC. 1999a. Completed auctions Web page. Http://www.fcc.gov/auctions/.

FCC. 1999b. Letter regarding SBC Ameritech merger sent today. CC Docket No. 98-141. (Letter from William E. Kennard.) Http://www.fcc.gov/Bureaus/Common_C...er/News_Releases/1999/nrcc9024.html. April 1.

Ferguson, C. H. 1985. American microelectronics in decline: Evidence, analysis, and alternatives. Cambridge: Massachusetts Institute of Technology VLSI Publications. VLSI Memo No. 85-284 (November) Microsystems Research Center Room 39-321 (617) 253-8138. (Draft of 1986 Ph.D. thesis.)

Flippo, Hyde. 1998. Hedy Lamarr (1913 - ): Beauty and Brains. An online supplement to The German Way, by the same author. Http://www.german-way.com/cinema/lamarr.html

Freeman, R. E. 1984. Strategic Management: A Stakeholder Approach. Marshfield, MA: Pitman (out of print).

Garg, Vijay K. & Wilkes, Joseph E. 1996. Wireless and Personal Communications Systems. Upper Saddle River, NJ: Prentice Hall PTR.

Gargini, P.; Glaze, J.; and Williams, O. 1998. The SIA's 1997 national technology roadmap for semiconductors. Solid State Technology, January, pp. 73-76.

Gearhart, S. S. 1998. Private communication.

Glassner, Joanna. 1999. The western wireless showdown. Wired News. February 24, 2:15 P.M. PST. Http://www.wired.com/news/print_version/business/story/ 18066.html?wnpg=all.

Goldsmith, John E. M.; Barr, P. K.; Berger, K. W.; Bernardez, L. J. II; Cardinale, G. F.; Darnold, J. R.; Folk, D. R.; Haney, S. J.; Henderson, C. C.; Jefferson, K. L.; Krenz, K. D.; Kubiak, G. D.; Nissen, R. P.; O'Connell, D. J.; Perras, Y. E.; Ray-Chaudhuri, A. K.; Smith, T. G.; Stulen. R. H.; Tichenor, D. A.; Ver Berkmoes, A. A.; and Wronosky, J. B. 1998. Recent advances in the Sandia EUV 10x microstepper. SPIE Proceedings (in press).

Griffiths, Brian. 1984. Morality and the Market Place: Christian Alternatives to Capitalism and Socialism. Britain: Hodder & Stoughton 1982 edition. Pp. 71-99. (Reproduced for the U.S. market as an essay in Atherton, John. 1994. Christian Social Ethics: A Reader. Cleveland, OH: The Pilgrim Press. Pp. 353-371.)

Guckel, H. 1990. Private communication.

Hanz, Lajos. 1996. The British cordless telephone standard: CT-2. In The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press.

Harmatuck, D. 1994. Based in part on a class lecture, apparently derived in turn from Sharp (1966). (See also St. Clair, 1964, 67-70, esp. Figure 3.)

Hatfield. 1997. Hatfield Model Release 4.0. Hatfield Associates, Inc.; AT&T Corporation; and MCI Telecommunications Corporation.

Hatfield. 1997a. Hatfield Model Release 4.0: Model Description. Boulder, CO: Hatfield Associates, Inc.

Hatfield. 1997b. Hatfield Model Release 4.0: Inputs Portfolio. Boulder, CO: Hatfield Associates, Inc.

HDS. 1999. DirecPC home: How it works and Pricing. Hughes Data Services. Http://www.direcpc.com/about/a36f.html & /a34f.html

Heaton, John L. Unpublished. As cited in: The future of x-ray lithography. Presentation 15 Jan 1998 at UW-Madison Physical Sciences Laboratory by Prof. James W. Taylor.

Hobica, George. 1998. The best way to phone home. Travel Holiday, 181:3, p. 21. April.

I-00940035. 1995. Universal Service Standards. Before the Pennsylvania Public Utilities Commission. Docket I-00940035.

Jainschigg, John. 1999. Build your own IP gateway. IP Telephony Supplement to Miller Freeman’s Computer Telephony Magazine 7:4. Supplement pp. 6-11. April. Sidebar on p. 7 concerning Brooktrout’s TR2001 DSP board.

Katz, M. & Shapiro, C. 1985. Network externalities, competition and compatibility. American Economic Review, 75:3, pp. 424-440.

Kane, M. 1998. Digital unveils Alpha plans. ZDNet News. http://127.0.0.1:15841/v1?catid=16646147&md5=67636fbb81b307902d2b10ea3f478593

King, Rachael. 1998. To have and have not: The digital divide between rich and poor runs deep -- particularly in America’s cities. Tele.Com, 3:9, pp. 53-58. August.

Kreps, D. M. 1990. A Course in Microeconomic Theory. Princeton: Princeton University Press.

Krzanowski, W. J. 1988. Principles of Multivariate Analysis: A User's Perspective. New York: Oxford University Press (1993 printing).

Kucar, Andy D. 1996. Mobile radio: An overview. In The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press.

Last, Susan. 1998. Hedy Lamarr -- A woman before her time. Wisconsin Engineer magazine. April. Http://www.cae.wisc.edu/~wiscengr/issues/current_issue/hedy.html

Locicero, Nick. 1996. Up front in QST: Photos of a cellular antenna disguised as a tree. QST Magazine. October. P. 21.

McGinity, Meg. 1999. IP in the sky. Tele.Com, 4:6. Pp. 25, 30.

McKenzie, David J. & Small, John P. 1997. Econometric cost structure estimates for cellular telephony in the United States. Journal of Regulatory Economics, 12:2, 147-157.

Mansfield, S. 1999. Prospects still murky for the 106th congress. QST, 83:1, p. 15. January.

Milstein, L. B. & Simon, M. K. 1996. Spread spectrum communications. In The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press.

Mohring, H. & Harwitz, M. 1962. Highway Benefits: An Analytical Framework. Northwestern University Press.

Moore, F.; Mickelson, B.; Lee, S.; and Topper, J. Pending. A Multivariate Analysis of Wisconsin Telephone Incumbent Local Exchange Carriers: Infrastructure Deployment and Implications for Business Strategy. Submission pending.

Moore, F.; Brown, M.; and Reilly, M. 1997. X-ray mask process guidebook. University of Wisconsin Center for X-ray Lithography. +1-608-877-2400.

Moore, F. 1995. Economics, technology and public policy: Advice to policy makers concerning institutional choice in the provision of telecommunications infrastructure. Unpublished (PA 974 class paper).

Moore, J. 1996. Private communication.

Moss, Mitchell L. 1998. Technology and cities. Cityscape: A journal of policy development and research, 3:3, 107-127.

Moto. 1999. CyberSURFR™ Cable Modem Specifications.

Http://www.mot.com/MIMS/Multimedia/prod/specs/modemSpec.html March.

NAVPERS 92676. 1958. Radio Receiving Set AN/URR-35C. (Also published as Department of the Army Technical Manual TM 11-527-15.)

NERA. 1990. Telecommunications infrastructure, productivity, and economic development. Prepared for the United States
OTA. 1991. Rural America at the Crossroads: Networking for the Future. US Congress, Office of Technology Assessment, OTA-TCT-471. Washington, DC: US Government Printing Office.

NTIA. 1996. U.S. radio frequency spectrum allocation table. United States Department of Commerce, National Telecommunications and Information Administration, Office of Spectrum Management. March.

Olson, Duane. 1976. Private communication.

Orsak, G. C. 1996. Optimum receivers. The Mobile Communications Handbook, Jerry D. Gibson, Ed. Boca Raton, FL: CRC Press. pp. 123-136.

Parker, Phillip M. & Roller, Lars-Hendrik. 1994. Collusive conduct in duopolies: Multimarket contact and cross-ownership in the mobile telephone industry. London: Centre for Economic Policy Research. Discussion Paper No. 989. July.
Note: Also published under the same title in the Rand Journal of Economics, 28:2, 304-322.

Pessar, P. 1998. A tribute to Hedy Lamarr: 1997 Associated Press interview of an early spread spectrum military communications system designer. ppessar@aol.com Http://www.wp.com/rism/atribute.htm

PL 103-337. 1994. Section 216: Advanced Lithography Program. Defense Appropriations Act. 108 Stat. 2693 (old).

PL 104-106. 1996. Section 271: Advanced Lithography Program. Defense Appropriations Act. 108 Stat. 2693.

Pocock, Emil. 1999. The world above 50 MHz. QST Magazine. 83:3, p. 85. March.

Pocock, Emil. 1999a. The world above 50 MHz: Microwave news. QST Magazine. 83:4, Pp. 90-92. April.

Porter, Michael E. 1985. Competitive Advantage. New York: The Free Press.

Prakash, Mysore N. 1997. Private communication concerning cell site equipment prices. December 10.

Price, L. E. & Rinaldo, P. L. 1998. WRC 97: An amateur radio perspective. QST. February. Pp. 31.

PSCW. 1993. Wisconsin Public Service Commission. Private communication. The PSCW regulates communications carriers and services in-state.

PSCW. 1997. Wisconsin Public Service Commission. Private communication.

Rappaport, T. S. 1996. Wireless Communications: Principles & Practice. Upper Saddle River, NJ: Prentice Hall PTR.

Raynovich, R. Scott. 1999. Speed traps: Warning lights are flashing in the market for DSL. Tele.Com, 4:6. Pp. 38-44.

Ricci, Fred J. 1997. Personal Communications Systems Applications. Upper Saddle River, NJ: Prentice Hall PTR.

Riordan, M. & Hoddeson, L. 1997. The Moses of silicon valley. Physics Today 50:12 (December), pp. 42-47.

Ross, I. M. 1997. The foundation of the silicon age. Physics Today 50:12 (December), pp. 34-39.

Rowe, H. E. 1982. Bounds on the number of signals with restricted cross-correlation. IEEE Transactions on Communications, vol. COMM-30 (May), pp. 966-974.

Rubin, Paul. 1996. Local loops, without the messy wires. Tele.Com. July. Http://www.teledotcom.com/0796/headend/tdc0796headend_wireless.html

Samuelson, L. 1999. Private conversation.

Sandberg, Jared. 1999. She’s baaack! Newsweek. February 15. Pp. 44-46.

Sands, Leo G. & Tellet, G. Geoffrey. 1986. VHF-FM Mobile Radio. West Chester, PA: Chilton Books.

Schetgen, R. 1994. The ARRL handbook. Newington, CT: The

American Radio Relay League. ISBN 0-87259-171-9. Especially chapter 12.

Scott. 1999. Telephone discussion of GSM data service characteristics of a local service provider.

Service, R. F. 1996. Can chip devices keep shrinking? Science, Vol. 274, 13 Dec 96, pp. 1834-1836.

Sharda, R. 1998. Private communication.

Sharp, Clifford H. 1966. Congestion and welfare -- An examination of the case for a congestion tax. Economic Journal [of the Royal Society], 76, pp. 806-817. December.

Shivashankar, G. V. & Libchaber, A. 1997. Applied physics letters, 71:3727. As cited in Physics today, Feb 1998, p. 9.

Shockley, W. 1957. On the statistics of individual variations of productivity in research laboratories. Proceedings of the Institute of Radio Engineers (IRE), 45:3, pp. 279.

Sklar, B. 1988. Digital Communications: Fundamentals and Applications. Englewood Cliffs, NJ: Prentice-Hall. P. 300.

Smeed, R. & staff. 1964. Road pricing: The economic and technical possibilities. London, England: Report of the Ministry of Transport Panel.

Smith, Adam. 1817. The Theory of Moral Sentiment, or, An essay towards an analysis of the principles, by which men naturally judge concerning the conduct and character, first of their neighbors, and afterwards of themselves. Boston: Wells and Lilly.

Smith, Linda. 1995. Class discussion.

St. Clair, G. P. 1964. Congestion tolls - An engineer's viewpoint. Highway Research Record, 47, pp. 66-112.

Staff. 1999. Amateur radio world: Gearing up for WRC-2000. QST Magazine. 83:3, p. 89. March.

Staff. 1993a. Convergence, Competition, Cooperation: The Report of the Governor's Blue Ribbon Telecommunications Infrastructure Task Force. Volume II: Assessment of User Needs and Existing Environment. # 1914, Document Sales Unit, Wisconsin Department of Administration.

Stockwell, N. 1998. Community radio in a changing El Salvador. The Radio Pilot. Autumn issue. P. 3.

Stone, Norman. 1994. Cellular radio and the modern amateur. QST. March. Pp. 50-55.

Task Force. 1993a. Convergence, Competition, Cooperation: The report of the Governor's Blue Ribbon Telecommunications Infrastructure Task Force. Volume One: Report. Stock No. 1913. (Available at no charge for single copies.) Madison, WI: Wisconsin Department of Administration. Document Sales Unit. 608-264-9419.

Task Force. 1993b. Convergence, Competition, Cooperation: The report of the Governor's Blue Ribbon Telecommunications Infrastructure Task Force. Volume Two: Task force staff reports. Especially Chapter 9: Wisconsin's existing infrastructure. Stock No. 1914. ($3.10 per copy.) Madison, WI: Wisconsin Department of Administration. Document Sales Unit. 608-264-9419.

Taylor, James W. 1998. The future of x-ray lithography. Presentation 15 Jan 1998 at UW-Madison Physical Sciences Laboratory.

TEK 82. 1963. <u>Tektronix Type 82 Plug-in Instruction Manual</u>. Beaverton, OR: Tektronix, Inc. (Out of print.)

Tenenbaum, D. 1998. Darwin rules. Isthmus 23:10, pp. 10-12.

Thibault, L. & Le, Minh Thien. 1997. Performance evaluation of COFDM for digital audio broadcasting Part I: Parametric study. IEEE Transactions on Broadcasting, 43:1 (March), pp. 64-.

Tyne, G. F. J. 1977. Saga of the Vacuum Tube, 1st Ed. Indianapolis, IN: Howard W. Sams & Company 1-800-428-7267.

U.S. Census. 1998. County population estimates for July 1, 1998. Statistical Information Staff, Population Division, U.S. Bureau of the Census. (301) 457-2422. Http://www.census .gov/population/estimates/county/co-98-1/98C1_55.txt.

U.S. Census. 1995. Model-based income and poverty estimates for various Wisconsin counties. Statistical Information Staff, U.S. Bureau of the Census. Http://www.census.gov/

hhes/www/saipe/estimate/cty/cty55025.htm

U.S. Census. 1992. 1992 economic census -- area profile. U.S. Bureau of the Census. Http://www.census.gov/epcd/www/92profiles/county/55025.txt

U.S. Census. 1990. Census data for three Wisconsin counties. GO System CD-ROM and Census Tract/Block Numbering Area Outline Map Set. Statistical Information Staff, Population Division, U.S. Bureau of the Census.

Van der Ziel, Aldert. 1979. Private communication.

Van der Ziel, A. 1954. Noise. New York: Prentice Hall.

Varian, H. R. 1992. Microeconomic Analysis, Third Ed. New York: W. W. Norton & Company.

Various. 1998. Wireless wonders: The phones are getting better -- and the deals are getting sneaker. (A special report with several sidebars appears in this issue.) Consumer Reports. September.

Vedro, Steve. 1995. Class discussion.

Viterbi, A. J. 1979. Spread spectrum communications - Myths and realities. IEEE Communications Magazine (May), pp. 11-18.

Viterbi, A. J. 1982. Bandwidth efficiency in coded networks of fixed and mobile users. Presented at the IEEE Communications Theory Workshop (April).

Viterbi, A. J. 1985. When not to spread spectrum - A sequel. IEEE Communications Magazine (April), pp. 12-17.

VLSI Research, Inc. Unpublished. As cited in: Service, R. F. 1996. Can chip devices keep shrinking? Science, Vol. 274, 13 Dec 96, pp. 1834-1836. Contact VLSI Research, Inc. (408) 453-8844.

Walsh, Jeff. 1999. InterNIC putsch? New site disputed. InfoWorld, 21:13, p. 22. March 29.

Weinschenk, Carl. 1999. The modem march continues. Tele.Com, 4:6. Pp. 34-37.

Wiecki, A. 1998. Private communication.

Wink, Walter. 1993. Engaging the Powers. Minneapolis: Fortress Press.

Womack, Steven & Braun, Carl. 1999. Key issues remain for designing multiband, multiprotocol phones. Wireless Systems Design, 4:4, pp. 25-28.

WSJ. 1999. Eistein Personal Communications, Inc. advertisement. Wisconsin State Journal. February 27. P. 12A.

WSTA. 1993. Wisconsin State Telephone Association. Private communication. The WSTA is an organization whose members include all LECs in the state, and which represents the interests of its members in a variety of ways.

Yue, On-Ching. 1983. Spread spectrum mobile radio, 1977-1982. IEEE Transactions on Vehicular Technology, VT-32:1 (February), pp. 98-105.

Zita, Ken. 1999. For richer and for poorer. Tele.Com, 4:6. P. 54.