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28 Putting It All Together: The Cost Structure of Personal Communications Services

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Executive Summary

This study examines the cost structure of proposed personal communications services (PCS) in order to assess the potential spectrum requirements of these new services. The cost model developed for this report estimates the costs of building and operating a new PCS network, as well as the costs of providing PCS using existing infrastructure such as the telephone, cable television, and cellular telephone networks. Based upon these estimates, this study finds 1) economies of scope between PCS and each of these services, 2) no justification based upon characteristics of the cost functions for limiting the number of licenses to the PCS market for license sizes of 20 MHz or more, and 3) that 20 MHz may be a sufficient spectrum allocation size to implement low-cost PCS systems. Because 20 MHz may not be enough spectrum for all PCS applications or in those areas where high densities of incumbent microwave users exist, the study recommends that PCS license holders should also be permitted to consolidate licenses up to a 40 MHz limit.

Because of the economies of scope which could be achieved, the study finds that consumers could benefit from allowing cellular and local telephone companies to hold at least some PCS spectrum if a sufficient number of PCS competitors exist. The study recommends that cellular operators be permitted to acquire up to 10 MHz of spectrum from new PCS licensees, an amount that was found to be sufficient for cellular providers to realize these economies of scope. With regard to local telephone companies, contingent upon the presence of adequate safeguards to insure non-discriminatory interconnection and to prevent cross-subsidization of PCS from the revenues of regulated services, the study similarly recommends these firms be allowed to acquire up to 10 MHz of spectrum in areas where they operate a cellular subsidiary, and be treated like any other PCS provider in the remaining service areas.

Estimating the Costs of New PCS Infrastructure

Much attention has been focused recently upon the prospects for PCS that would deliver a diverse set of wireless telecommunications services with an unprecedented degree of mobility and portability. This popularity has fueled optimism that PCS will grow and develop into major new markets over the next decade. Yet questions remain regarding who will be the suppliers of PCS. Local telephone, cable television, and cellular companies all claim their networks and service organizations are best suited to deliver PCS. Intuitively, the suppliers most likely to play major roles in PCS would seem to be those already owning infrastructure well suited for this purpose. Predicting future PCS providers, therefore, depends upon both the characteristics of the cost function for PCS and how well the network elements needed to deliver PCS match with the network elements of existing suppliers.

The extent to which synergies exist between PCS and existing network services can be described through the economic concepts of efficiency and economies of scale and scope. Economic efficiency strives to maximize the social benefits available from a limited allocation of resources. Efficiency can be improved by reducing costs, and potential means to lower costs are to capture economies of scale and scope in the production of multiple services. Economies of scale are present when unit costs decrease with higher levels of output. Economies of scope exist between services when the costs of providing these services over one network is less than the combined cost of separate networks. Determining whether the provision of PCS exhibits economies of scale and scope requires knowledge of the cost functions of PCS and the other services. The presence of these production economies has implications for a number of key public policy issues facing the Federal Communications Commission (FCC) which must be decided before deployment can proceed. These policy issues include deciding what is the appropriate service definition of PCS, the total amount of spectrum to be allocated to PCS, the size of the spectrum blocks assigned to each licensee, the number of PCS licenses in each service area, and who should be eligible to hold the new PCS licenses.

The purpose of this study is to estimate the costs of PCS systems in order to shed more light on these policy issues. The general methodology taken in this paper is to assume that a block of spectrum has been allocated for PCS near the 2 GHz band of frequencies as has been proposed by the FCC for PCS applications. This paper estimates the costs of building and operating a PCS network in a new residential housing development using an engineering cost model that assumes spectrum allocation sizes between 2 MHz to 40 MHz. The model assumes a PCS network consisting of fiber optic transmission network connecting radio cell sizes of less than 1.6 kilometers in radius, small lightweight handsets, and a five-year time horizon for technological options. Adding these figures to previously published cost estimates of telephone and cable television networks provides an estimate of the total costs of separate networks. The paper then estimates the costs of providing PCS on an integrated basis with telephone, cable television, and cellular services in order to predict whether economies of scope will be present.

A summary of the salient quantitative results of the cost model include:

- The capital costs of a PCS network, including the handset, in a new residential area would be $703 per subscriber assuming base case assumptions of 25 MHz allocation size and 10 percent household rate of penetration.
- The total annualized cost of operating this PCS network would be $546 per subscriber for these base case assumptions, with infrastructure costs accounting for 25 percent of the overall total.
- Economies of scale in the cost function of a new PCS network would be largely exhausted for subscription rates above 20 percent of households per provider. This result should be viewed as a high estimate of when scale economies would be exhausted, since the model assumes a network of small cells and therefore a high degree of fixed costs. This basic result held despite sensitivity analysis to the cost of electronic components, grade of service, levels of offered traffic, and spectrum efficiency of the radio system.

- PCS network costs vary substantially with the level of spectral efficiency of the radio system deployed in the PCS network. Radio systems with the lowest level of spectrum efficiency considered in this analysis are viable for PCS when the allocation size is greater than 20 MHz.

Estimating Economies of Scope Between PCS and Existing Communications Services

This paper finds that economies of scope exist between PCS and telephone, cable television, and cellular services for the network technologies assumed in this paper. Further, the economies of scope found between PCS and these services alter the characteristics of the cost function for PCS. Using these existing infrastructure exchanges fixed costs for variable costs in the cost function. As a result, the economies of scope not only lower the upfront investment initially necessary to provide PCS, they could reduce to 10 percent the level of subscription at which economies of scale are exhausted for a provider.

One implication of these findings is that an independent firm -- an entrepreneur or small company that obtains a PCS license but does not own any existing infrastructure in the subscriber loop -- probably would not choose to construct its own separate PCS network. Results indicate the fixed costs of a PCS network using very small radio cells are high in relation to the fixed costs of providing PCS using existing infrastructure. This cost differential is especially dramatic at the low levels of penetration which will expected during early deployment. Thus, independent providers are likely to pursue a strategy of negotiating alliances among the infrastructure alternatives available to deliver PCS.

The table below offers a broad, but not necessarily comprehensive, list of infrastructure alternatives which PCS licensees might use to deliver services. Each column represents a functional component of PCS. The table reports which infrastructure alternatives could serve as potential sources for these functional components based upon whether economies of scope might exist between PCS and the services already provided by the infrastructure. The table notes where the economies of scope have been verified by the cost model reported in this paper, and where the economies of scope are subjective assessments that have not been verified by the cost model. While this paper focuses upon the use of telephone, cable television, and cellular networks to deliver PCS, a number of other players or combinations of players are also likely to participate in these markets. This list includes interexchange carriers, competitive access providers (CAPs), and electric or gas utilities.

Subjective Assessment of Sources of PCS Functional Components Across Infrastructure Alternatives

Infrastructure Alternatives	OA&M*	Advanced Signalling Network & Intelligent Nodes	Switching	Transport	Cell Sites	Hand-sets
Telephone Network	•	Δ	•	•		
Cable Television Network	•			•		
Cellular Network	•	◊	•	◊	◊	•
Cable/Cellular Joint Venture	•	◊	•	•	◊	•
Interexchange Carrier	Δ	Δ	◊			
Competitive Access Provider	◊	◊	◊	◊		
Electric or Gas Utility				Δ		

* OA&M - Operations, Administration, and Maintenance Services
• Economies of scope found to exist in this component by cost model reported in this paper
Δ Strong economies of scope likely to exist in this component, although not verified by cost model
◊ Limited economies of scope likely to exist in this component, although not verified by cost model

Implications for Public Policy

What are the public policy implications of the preceding engineering and cost analysis that finds economies of scope between PCS and existing infrastructure, and that economies of scale are exhausted at low penetration levels?

Service Definition of PCS. The technical review of wireless technologies conducted in this paper shows that substantial uncertainties exist regarding future wireless services and the technologies that will be used to convey them. Given this uncertain environment, this study endorses a broad service definition of PCS, as the FCC already has proposed, which provides licensees substantial flexibility in how they are authorized to provide services under PCS licenses.

Number and Size of Spectrum Allocations. Modeling perhaps the worst case (*i.e.*, highest fixed cost) scenario, the results do not justify limiting the number of licenses in a market due to the characteristics of the cost function. With a total subscription rate of 30 percent of the households, the difference in total annualized costs between 1 supplier or 6 suppliers is about $125 per subscriber, or about $10 per month, using the telephone network to deliver PCS. The results support issuing the highest number of licenses possible if the spectrum block size is 20 MHz or more. Because the FCC has stated that it will allocate a minimum of 90 MHz, five or six 20 MHz licenses could be issued. As noted above, however, 20 MHz may not be enough spectrum to implement low-cost radio systems in areas where high densities of incumbent microwave users exist, or to provide other applications not considered in this analysis. Therefore, PCS suppliers should be permitted to consolidate licenses up to a 40 MHz limit.

Issuing five or six 20 MHz licenses has a number of desirable characteristics:

- A high number of licenses would establish a market structure with strong incentives for competition in the provision of PCS, and hence strong incentives for consumers to benefit through lower prices, higher quality services, and more choices among innovative service alternatives.

- If more spectrum than 20 MHz is necessary due to a high density of microwave users, or to provide other applications, consolidation would still result in the satisfactory outcome of three suppliers each with 40 MHz, with a market test of whether such an outcome were efficient.
- Numerous licenses offers more flexibility to resolve other licensing issues. For example, with 6 licenses available the FCC has more flexibility to offer a mix of nationwide, regional, and local licenses, or to permit telephone and cellular companies to have some form of eligibility to hold new PCS licenses.

Eligibility Requirements for PCS Licenses. The economies of scope found between PCS and both telephone and cellular services show that consumers could benefit from allowing these companies to hold PCS licenses. Moreover, the weak economies of scale in the cost function show that it is unlikely that one or two firms would dominate the market due to any cost characteristics of the market. As a result, the study recommends eligibility requirements that include a "spectrum cap" of 40 MHz for all firms and only slight additional eligibility restrictions on cellular firms. If five or six licenses are issued, then the benefits of permitting cellular companies not affiliated with the local telephone company to acquire some additional spectrum are likely to outweigh the costs. Therefore, this study recommends that these cellular operators be eligible to acquire an additional 10 MHz of spectrum, which model results show is sufficient to exploit economies of scope between PCS and cellular services.

Contingent upon adequate safeguards against discriminatory interconnection practices and cross-subsidy, the results of this analysis indicate that consumers could benefit from allowing local telephone companies to hold PCS licenses if a large number of PCS licenses are issued. If adequate safeguards are available to mediate the above concerns, telephone companies should be allowed to fully participate in PCS subject to the same restrictions placed on other entities. Telephone companies with cellular holdings, of course, should be subject to the same eligibility restrictions placed on unaffiliated cellular operators.

Putting It All Together:
The Cost Structure of Personal Communications Services

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Section I. Introduction

Much attention has been focused recently upon the prospects for personal communications services (PCS) that would deliver a diverse set of wireless telecommunications services with an unprecedented degree of mobility and portability. The rapid growth of cellular, cordless telephone, and paging services throughout the 1980s demonstrates the strong demand for wireless services. This popularity has fueled optimism that PCS will grow and develop into major new markets over the next decade. Before these markets can expand, however, changes in federal policies are needed to allocate more spectrum for PCS. Accordingly, the Federal Communications Commission (FCC) issued a *Notice of Inquiry* seeking comment on the appropriate regulatory model for allocating spectrum to PCS (FCC, 1990) followed by a *Notice of Proposed Rulemaking and Tentative Decision* with a proposed spectrum allocation and regulatory framework for these services (FCC, 1992a).

It is now widely accepted that PCS represent a family of service applications featuring wireless access to network-based services. Existing or enhanced versions of familiar wireless services that fall under this definition of PCS include cellular, paging, and cordless telephone, plus new services such as wireless private branch exchange (PBX), wireless local area network (LAN), and wireless replacement of portions of the telephone network in the subscriber loop.[2] As

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[1]The views expressed in this paper are solely those of the author and do not necessarily reflect those of the Federal Communications Commission, the Commissioners, or Commission staff. The author appreciates detailed manuscript comments given by James Gattuso, John Williams, Evan Kwerel, and Michael Marcus. The author, however, bears full responsibility for any errors of fact or interpretation in the paper.

[2]The PCS family could include wireless broadband services as well, although for the purposes of this study the definition of PCS will be confined to distribution of wireless narrowband services throughout the subscriber loop. The omission of broadband services from this study could alter some conclusions if there prove to be substantial economies present in the joint provision of narrowband and broadband wireless services. There has been some interest in including wireless broadband services within the PCS model in the early stages of development,

shown in Figure 1, the PCS model proposes a network infrastructure capable of delivering multiple wireless services to subscribers in both residential and business environments. Thus, an International Radio Consultative Committee (CCIR) study envisions five ways a personal radio handset can gain network access in the PCS model for voice services alone: accessing indoor or outdoor private and public base stations, accessing private indoor office base stations like a cordless phone, or communicating in a vehicular environment through a public mobile base station directly or via a vehicle mounted mobile station. (CCIR, 1990b). In this view, PCS represent the natural confluence of several existing and developing technologies and services using radio transmission as the access links to a network in the subscriber loop.

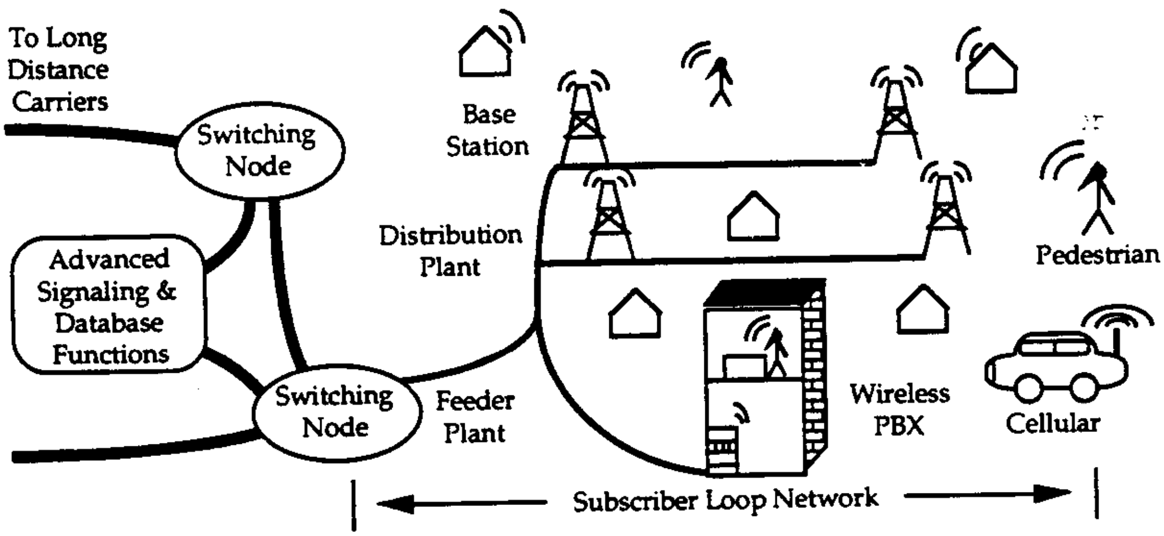

Figure 1. The Personal Communications Services Model

Given this model of PCS, who will be the service suppliers most likely to offer PCS to consumers? Telephone, cellular, and cable television companies all claim their networks and service organizations are best suited for PCS, and other independent service providers also seek to offer PCS. Intuitively, the suppliers most likely to play major roles in PCS would seem to be those already owning infrastructure and technologies well suited for this purpose. Predicting future PCS providers, therefore, depends upon both the characteristics of the cost function for PCS and how well the network elements needed to deliver PCS match with the network elements of existing suppliers. Figure 1 illustrates the principal functional elements of an infrastructure designed for wireless services, including network intelligence and switching nodes, and wireline transmission, base station, and handset equipment. Existing suppliers that can provide these

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particular at frequencies near 28 GHz. See, for example, *Hye Crest Management, Inc.*, 6 FCC Rcd 332 (1991); *Ex Parte Notice RM 7842*, Filed at FCC on March 20, 1992 by the Suite 12 Group, or *Telocator Bulletin*. Jan. 10, 1992. 8-9.

functional elements at low incremental cost could have an early advantage in developing PCS markets.

The extent to which synergies exist between PCS and existing network services can be described more formally through the economic concepts of efficiency and economies of scale and scope. Economic efficiency strives to maximize the social benefits available from a limited allocation of resources. Efficiency can be improved by reducing costs, and potential means to lower costs are to capture economies of scale and scope in the production of multiple services. Economies of scale are present when unit costs decrease with higher levels of output. Economies of scope exist between services when the costs of providing these services over one network is less than the combined cost of separate networks. Determining whether economies of scope exist between PCS and other services, or whether economies of scale are present, requires knowledge of the cost function for PCS, and how much it costs to offer these services on one integrated network and over separate networks.

The presence of economies of scale in PCS and economies of scope between PCS and existing services has implications for a number of key policy issues which must be decided before deployment can proceed. Among these are:

- *Service Definition of PCS*. The service definition of PCS describes the authorized uses for spectrum licenses allocated for PCS. This paper examines the cost implications of different service definitions of PCS.
- *Spectrum Allocation*.[3] The FCC must decide the amount of spectrum to be allocated to PCS and the size of the spectrum blocks assigned to each licensee. This paper analyzes how infrastructure costs may vary with total spectrum allocation and block size.
- *Number of PCS Licenses*. The FCC must also determine the number of PCS licenses it will issue. The form of the cost function for PCS can indicate the extent to which economies of scale and scope could naturally limit the number of suppliers in the market. While the scope of this study is insufficient to fully characterize the most efficient market structure for PCS, the model results do offer a measure of the economies of scale and scope present in the costs of providing PCS.
- *Eligibility for PCS Licenses*. The FCC has expressed concern regarding whether cellular providers should be barred from holding PCS licenses in their own service areas because of the threat they pose to competition.[4] Likewise, some believe telephone companies should be

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[3]If PCS providers could use market mechanisms to obtain the amount of spectrum they feel is necessary to deliver PCS, economies of scale and scope would have much less relevance to PCS policy since the competitive market would likely sort out the most efficient providers and number of players in the market.

[4]See *Notice* at ¶27: "To the extent that personal communications networks (PCN) and future generations of cellular would be similar, it could be argued that cellular licensees should not be permitted to apply for a PCN license in any market where they are licensed to provide cellular service. Such a policy would

ineligible for PCS licenses because they could use their control over switching and transmission facilities to discriminate against competing PCS providers. This study examines whether portions of the existing infrastructure are likely to be part of the future PCS network (*i.e.*, that economies of scope exist between PCS and existing services). This potential for economies of scope, in tandem with the anticipated market structure, is useful information in considering the merits of eligibility restrictions for PCS licenses.

The purpose of this study is to examine the costs of constructing PCS systems in order to shed more light on these policy issues. The general methodology taken here is to assume that a block of spectrum has been allocated for PCS near the 2 GHz band of frequencies, similar to what has already been proposed by the FCC (FCC, 1992b; FCC, 1992c).

This paper estimates the costs of building and operating a PCS network in a new residential housing development using an engineering cost model that assumes spectrum allocation sizes between 2 MHz to 40 MHz. The model assumes a PCS network consisting of fiber optic transmission network connecting radio cell sizes of less than 1.6 kilometers in radius, small lightweight handsets that can be used both indoors and outdoors and a five-year time horizon for technological options. Adding these figures to previously published cost estimates of telephone and cable television networks provides an estimate of the total costs of separate networks. The paper then estimates the costs of providing PCS on an integrated basis with telephone, cable television, and cellular services in order to predict whether economies of scope are present. Furthermore, by examining the distribution of costs across network components, the model identifies the network elements where economies of scope exist between PCS and existing services. This characterization of the cost structure of the market is useful in forecasting the potential evolution of PCS. The final step in this study is to apply the results of the engineering and economic analysis of PCS technologies to the policy issues listed above.

This study considers only a few of the potential alternatives for providing PCS. Considerable effort was expended to model generic network architectures likely to be representative of PCS systems five years in the future. The model results therefore are relevant only to the extent that the PCS alternatives modeled in this paper resemble the systems eventually deployed. The analytical framework and cost models reported in this paper, however, have been reported in sufficient detail to provide ample flexibility and opportunity for those who disagree with any assumptions or conclusions to insert their own assumptions into the model.

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appear to promote competition in the personal communications market and thus serve the public interest." (FCC, 1990)

Section II of this paper describes the network model, specific component cost assumptions, and the cost estimates of PCS networks included in the cost model.[5] Section III determines whether economies of scope exist between PCS and telephone, cable television, or cellular telephone services. Section IV examines several policy issues in light of the model results.

Section II. Estimating the Costs of Building a PCS Network

The objective is to forecast the costs of building and operating a PCS network and examine whether economies of scope exist in the provision of PCS and existing telephone, cable television, or cellular services. This section describes the network layout, salient assumptions, and results of the cost model which calculates the installation and operating costs of a PCS network in the subscriber loop.

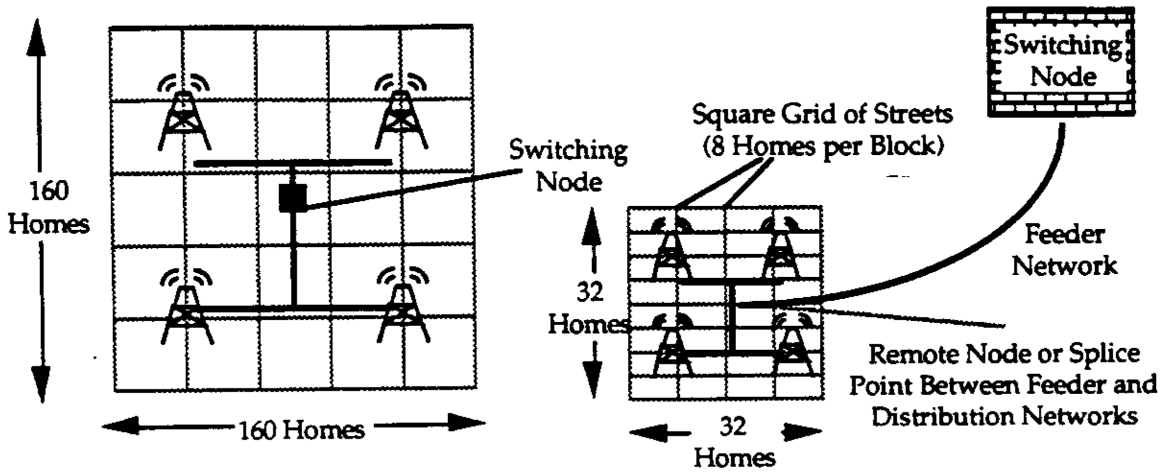
Network Layout

The network layout describes the geographic setting for estimating the costs of building a PCS network. The model assumes the same network layout used in (Reed, 1991; Sirbu, Reed, et al., 1989) to estimate the installation costs of telephone and cable television networks. Using the same network layout allows for economic comparisons between PCS systems and telephone or cable television systems under an equivalent set of assumptions.

Installation of the PCS network occurs in a hypothetical new residential development of 25,600 households, spread out over a square area with 160 homes to a side. As shown in Figure 2(a), the area consists of 25 square regions, each containing 1024 households uniformly distributed throughout a square grid of blocks with a mean housing density of 88 homes per street mile (Statistical Abstract of the United States, 1989). The uniform density of homes in this service area reduces the length of network segments relative to actual systems. With an average subscriber lot size of 37 square meters (one-third of an acre), all 25,600 households are concentrated in a 35 square kilometer area (13.5 square miles). To compensate, the model calculates installation costs for one region of 1024 homes -- including the equipment at the central switching node, and feeder costs attributable to that area -- and increases the length of the feeder network to reflect the presence of parks, businesses, and other undeveloped areas within the community (see Figure 2(b)). The mean length of the feeder network is 3072 meters; the mean of the distribution of residential loop lengths taken from a

[5]Because the engineering cost model is the key analytical tool which sets the foundation for the subsequent analysis, a technical appendix is included with this paper describing many of the technical and economic assumptions within the model. Readers unfamiliar with wireless technologies, proposed PCS radio systems, or network design issues posed by the implementation of PCS are referred to Appendix A for background material and model assumptions covering several important engineering and economic issues affecting the design of PCS networks.

survey of existing telephone networks (Bellcore, 1986). The model assumes all 1024 homes are part of a new residential housing development where the PCS network is installed alongside other essential infrastructure.



(a) PCS Model: 25,600 Households

(b) Close-up View : 1024 Households

Figure 2. Network Layout

The number of cells in the PCS network depends upon the spectrum allocation size and the level of network traffic. Today's cellular systems have a 25 MHz spectrum allocation. With each full-duplex channel occupying 60 KHz, a cellular system using the AMPS standard delivers a total of 395 channels plus another 1.25 MHz (5 percent of the total allocation) for control channels, guard bands, and other system overhead. The base case for this study assumes a duplex channel size of 25 KHz and a frequency reuse factor of N=7, which is almost a three-fold increase in capacity relative to the current cellular standard (see Appendix A). In the model, the channel size increases by a factor of 5 percent to 26.25 KHz to account for spectrum overhead. The model considers a range of PCS spectrum allocation sizes between 2 MHz and 40 MHz. This section reports costs assuming 25 MHz, 10 MHz, 5 MHz, and 2 MHz blocks (note that 1 MHz of the allocation is set aside for indoor cordless use, see Appendix A). Based upon these assumptions, Table 1 lists the maximum number of channels available per cell for these spectrum allocation sizes.

Size of Spectrum Allocation			
25 MHz	10 MHz	5 MHz	2 MHz
130	48	16	5

Table 1. Maximum Number of Radio-Based Channels Available Per Cell Site (N=7)

To simplify the model, all cells throughout the PCS network are assumed to be the same size, and enough cells are deployed to provide coverage over the entire service area. This emphasis upon coverage rather than capacity is consistent with the use of low-power handsets that must be in the near vicinity of a cell site to operate. The model considers five cell sizes: (1) a cell radius of 1.6 Km. (equivalent in area to 4096 homes), (2) a cell radius of 800-meters (covering 1024 homes), (3) a cell radius of 400-meters (covering 256 homes), (4) a cell radius of 200-meters (covering 64 homes); and (5) a cell radius of 100-meters (covering 16 homes).

Traditional traffic engineering techniques estimate the number of cells needed to provide service. The model calculates the number of channels needed to accommodate subscriber traffic using the Erlang B formula. The base case assumes a 1 percent grade of service, and that each subscriber offers an average of 0.03 erlangs during the busy-hour. Figure 3 illustrates how many cells are needed as a function of the percent penetration of PCS subscribers and the spectrum allocation size. For example, the number of cells in a PCS network with a 4 MHz block of spectrum increases with the level of service penetration, beginning with seven 1.6 Km. cells at a deployment rate of 2.5 percent, migrating to twenty-five 800-meters cells when deployment reaches 5 percent, and then migrating to one hundred 400-meters cells when deployment approaches 15 percent. The layout of the cable network can be found in Appendix B for each cell size. As shown in these diagrams, cable routes follow a square grid of streets and rights-of-way throughout the serving area.

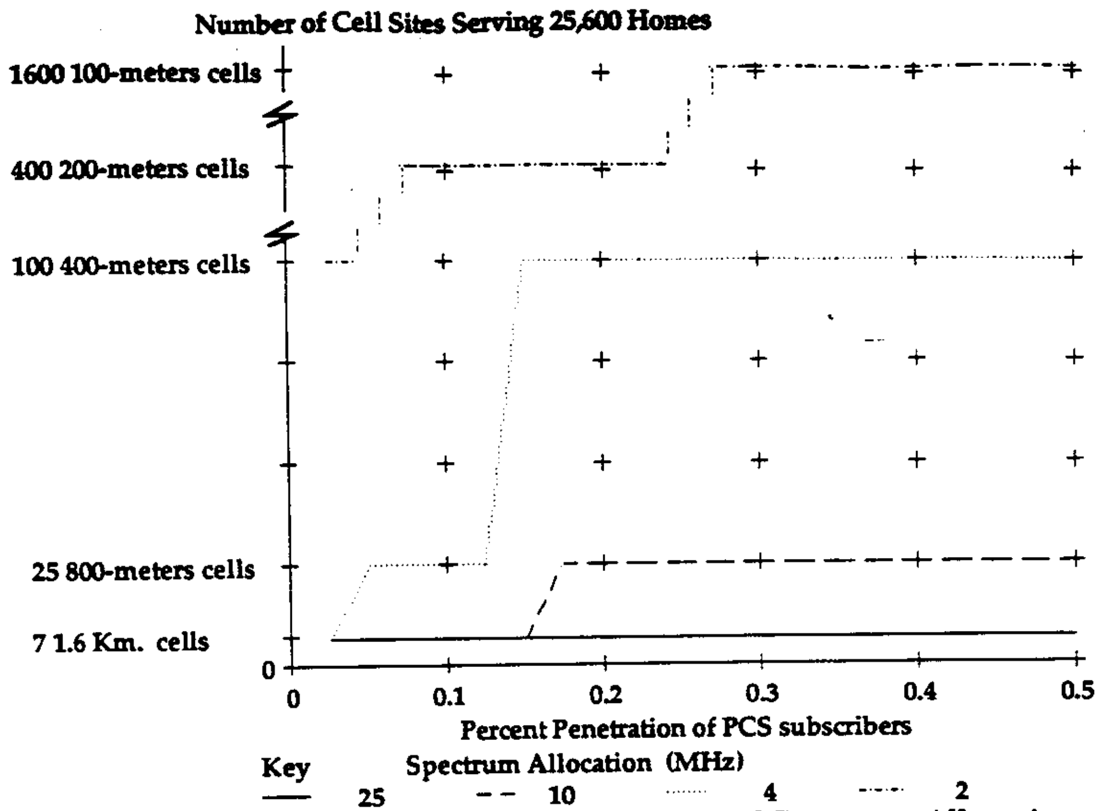


Figure 3. Number of Cell Sites as a Function of Spectrum Allocation and Level of Service Penetration

Estimating the Costs of a PCS Network

The model estimates the costs of building a network offering PCS as defined in Appendix A. Appendix C presents a summary of important base case assumptions within the cost model. PCS network costs can be decomposed into several components, each corresponding to a functional element of the service. Figure 4 illustrates a PCS network consisting of switching, wireline transport, cell site, and handset components. This section reports the estimated costs of each of these network elements, and the total system costs.

The rapid advances of microelectronic technologies have played an important role in the development of wireless electronic components. Cost estimates in this study assume that parts of key functional components, such as base station equipment and handsets, can be implemented as application specific integrated circuits (ASICs) using silicon semiconductor technology. Silicon integrated circuits (ICs) can be used if signal frequencies are below 2.3 gigahertz (GHz) (frequencies above this mark would require that baseband components use more expensive Gallium Arsenide (GaAs) technology (NCR, 1991)). As noted above, the model assumes the spectrum allocated for PCS will be near 2 GHz. Thus, cost estimates of RF equipment in the model assume custom-designed silicon ICs which can be manufactured in large quantities at low cost. All electronic devices are marked up 40 percent above the component cost to cover the costs of site engineering, field installation, and acceptance testing (Lu and Wolff, 1988).

The cost estimates reported below assume widespread introduction of wireless and optical components over the next five years. Some of the network components reported below are now available off-the-shelf, while others are still in the development stage. Allowances are made for technological advances which yield reductions in cost below today's levels and make deployment at these cost levels unlikely at this time. Large scale deployment implies that PCS and fiber networks have become the standard, and are routinely deployed into residential areas. This section reports the results of the model in dollars *per subscriber.* Unless otherwise specified, all results reflect the long-run average cost per subscriber assuming a household penetration rate of 10 percent, and two subscribers, or users, per home.

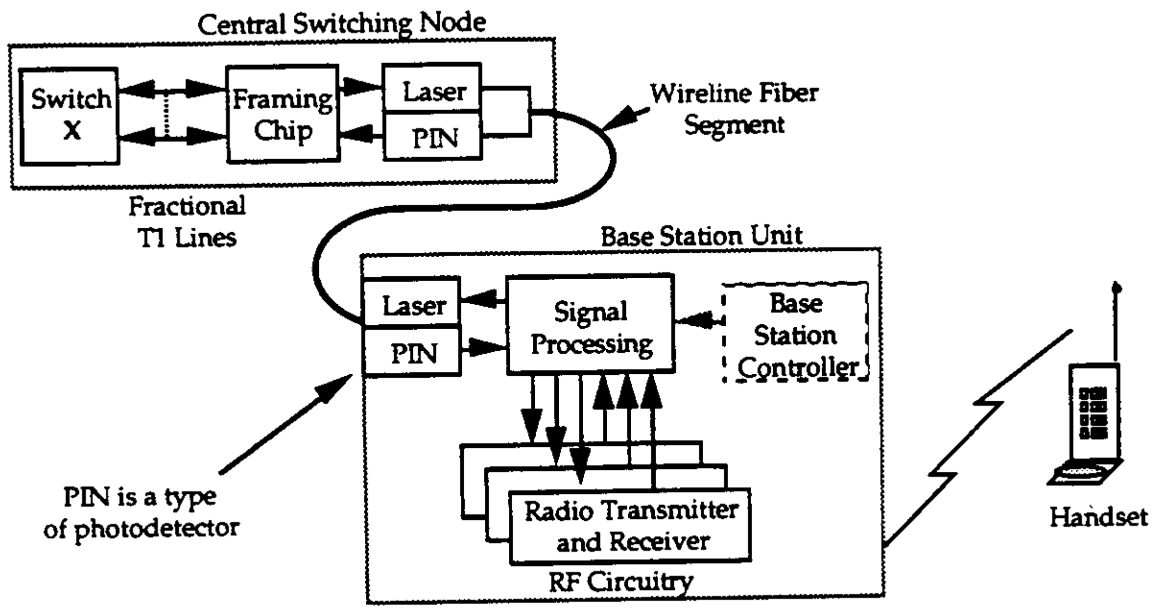


Figure 4. PCS Network Architecture

Network Switching

Estimates of the switching cost are based on a framework reported by Mitchell (Mitchell, 1990).[6] The switch costs reported in this section, unless noted, correspond to the upper bound of the cost data reported by Mitchell. These data appear to best match the description of the metropolitan area setting assumed in

[6]The data reported in Mitchell's study was obtained from local telephone companies in California and Bellcore's Switching Cost Information System, a planning tool commonly used by telephone network planners to evaluate the proprietary price profiles of switching equipment. See (Mitchell, 1990, Section III). Except where noted, it is assumed this cost data in 1988 dollars will be representative of switching costs over the next five years as well.

this study. Under this framework, switching costs are broken down into four categories: (1) fixed costs of "getting started", (2) cost per access line, (3) cost per trunk line, and (4) usage-based costs of the switch matrix and central processor.

"Getting Started" Costs

The start-up costs include the local engineering, power, emergency back-up power, and building costs associated with a central office switch. Mitchell reports these fixed costs are $400,000 in a metropolitan area. Using this figure, the fixed costs of the PCS switch are $78 per subscriber at a penetration rate of 10 percent.

Access and Trunk Line Termination Costs

The number of optical terminations at the switch will vary depending upon the number of subscribers, spectrum allocation, and peak hour traffic characteristics. In general, as subscriber demand increases and the network evolves to microcells, more optical terminations are necessary. For example, the model estimates a network with 800-meter microcells requires 10 fiber terminations, while a network with 400-meter microcells requires 16 terminations.

Calculations assume the cost of terminating a fiber feeder link (up to the T1 rate of 1.5 megabits per second (Mbps)) is $100 for the laser and photodetector circuitry and packaging, plus $150 for other call processing and line organization equipment. With a 40 percent markup for local engineering and testing, the access line card costs $350, equivalent to Mitchell's estimate of terminating a T1 trunk today. At this cost, the model calculates access line termination costs are less than $7 per subscriber for the range of spectrum allocations considered. Trunk line terminations -- where trunks are defined as T1 links spanning to other central office or tandem switches -- are an even smaller cost component. Costing $350 per line, the costs of T1 terminations are negligible at less than $1 per subscriber.[7]

Usage Sensitive Costs

The intensity and characteristics of call usage determine the size of the switching matrix and amount of processing power in the switch. The costs of these usage sensitive factors can be obtained through estimates of the number of call attempts and the originating usage per line during the busy-hour. Mitchell

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[7]Mitchell reports the fraction of originating traffic in the telephone network requiring an outgoing trunk during the busy-hour is 0.6--the product of the fraction of usage completely dialed and destined for the switching network (0.8) and the fraction of busy-hour usage requiring another switch (0.75). Because a number of alternative routes exist for most interoffice links, most T1 trunk lines are designed for a grade of service equal to 10 percent. Using Erlang B tables, this translates into a carrying capacity of 21.8 erlangs. See (Bellamy, 1982, p. 429). A PCS or cellular network, however, will have a much higher fraction of originating traffic requiring an outgoing trunk, since most calls will be to the existing telephone network. Assuming this fraction is 0.95, 7 T1 trunks are needed to carry the traffic of 10 percent of the households {(25600)(0.10)(2)(0.03)(0.95)/(21.8)}, at a cost of $0.48 per subscriber.

reports costs of $3 per busy-hour attempt and $936 per busy-hour erlang of originating traffic per line.

Mobile communications place additional requirements upon the switching and signalling systems relative to traditional telephone service. First, the tracking and signalling requirements of personal number service require a more powerful switch processor to manage network signalling and database retrieval. As described in Appendix A, the model assumes a 50 percent increase in processing power is needed to execute the more complicated call model associated with the intelligent network. Yet while the processing power of an intelligent network switch will have to be more powerful than today's switch, the cost of processing power has been falling rapidly over the past decade, and will continue to do so over the next five years. Given this tradeoff, the model assumes the usage sensitive costs of the more powerful PCS switch equal today's costs of switching (*i.e.*, $3 per busy-hour attempt and $936 per busy-hour erlang of originating traffic). This leads to a cost of $34 per subscriber for the usage sensitive switching costs of PCS assuming 2 busy-hour attempts and 0.03 erlang of traffic per subscriber (see Appendix A).

More processing capabilities also are needed in wireless networks to provide local mobility management. Base station controllers could take the form of an adjunct processor which directs system handoffs, monitors transmission power levels, and controls frequency assignments for groups of cells. An adjunct processor can be likened to a work station running customized software. Most high-end workstations today have a base cost between $10,000 to $20,000. In addition, the development of the software needed to operate the microprocessor can be costly (software accounts for as much as 70% of the total development costs of a telephone switch). As noted in Appendix A, local mobility management activities will increase dramatically with smaller cell sizes. This additional need for network processing power will arise as rapid advances in microprocessors will continue to lower computing costs. Within this context, the model assumes a cost of $600 per radio channel for mobility management, and that the increment of investment for this control equipment is 50 channels. Thus, a fully programmed adjunct processor costs $30,000 for every 50 radio channels under its control, and is assumed to be installed in 50 channel increments to meet new processing requirements as the number of users grow.

Table 2 lists the total estimated switching costs assuming 10 percent of the households subscribe to PCS. These estimates vary between $125 per subscriber for systems with more than 10 MHz of spectrum using 1.6 Km. cells, $155 per subscriber for a system with 5 MHz using 800-meters cells, and $307 per subscriber for a system with 2 MHz using 200-meters cells. The differences in costs reflect the additional costs of mobility management that arise with the deployment of smaller cell sizes.

Network Component	Estimated Future Cost	Cost Per Subscriber Versus Spectrum Allocation (MHz)				Derivation of Cost for 2 MHz Allocation
		25	10	5	2	
		Switching Node				
Starting Costs	400,000	78	78	78	78	1 node for city: 400K+5120
Access & Trunk Line Termination	350/access line	1	1	2	7	4 Duplex Access Line Terminations: 4 (350) + 205
Usage Sensitive (BH-Busy-Hour)	3/attempt; 936/erlang	34	34	34	34	2 attempts, 0.03 erlangs in BH per sub: 2(3)+ 03(936)
Handoff	600/line	12	12	41	188	1600 channels: 1600(600)+ 5120
Total		125	125	155	307	

Table 2. Estimated Switching Costs per Subscriber; 10% Penetration (in dollars)

To serve as a check on these estimates, this framework can be applied to telephone and cellular networks and compared with these known switching costs. Assuming 20 percent of the 25,600 households request a second line, the start-up costs for a telephone switch are $13 per line at 100 percent penetration. The switched-star architecture of the telephone network requires that every copper wire pair(s) dedicated to each household must be terminated at the central office with a line card. This card consists of an analog-to-digital converter and other call processing equipment at a cost of $125 per line. Assuming each telephone line originates 2.8 attempts and 0.10 erlang of traffic in the busy-hour, the usage sensitive costs of a telephone switch are $102 per line. Thus, the total switch costs for a telephone network are $241 per line, or $290 per household. This figure checks well with other estimates. For example, (Moondra, 1989) estimated an average cost of $211 per line (1987 dollars) for digital switch hardware, software, cable, and wire for a metropolitan area switch of 26,000 lines.

To estimate the cost of a cellular switch, the figures in Table 2 assuming a 25 MHz spectrum allocation can be used. The start-up and termination costs for the 25 MHz allocation are $263 per subscriber when adjusted to the current cellular penetration of roughly 3 percent of the population. Assuming the usage sensitive and handoff costs of a PCS network are similar to cellular, the model estimates a cellular switching cost of $307 per subscriber, which is consistent with current cellular costs.[8] The reason cellular switching costs are higher than the estimated PCS switching costs is the lower penetration rate assumed for cellular service.

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[8]Discussions with cellular service providers suggest that switching accounts for 15 - 25 percent of present cellular system costs, and that total system costs vary between $1000 - $1400 per subscriber. Thus, switching costs would appear to range from $150 - $350 per subscriber. As expected, the switching costs calculated by the model correspond to the upper bound of these cellular switching costs since they are based upon the upper bound of telephone network cost data. Note that the getting started costs account for over 70 percent of the switching cost. The significance of these fixed costs has given rise to "clustering" strategies in the cellular industry which seek to spread the fixed costs of cellular telephone switches over a larger service area, and capitalize upon apparent economies of scale. See "Report of the Bell Companies on Competition in Wireless

Wireline Transport

Another component of the PCS network is the wireline transmission or backhaul segment of the network which connects the switching node to the cell sites. Fiber optic, copper pairs, coaxial cable, and microwave links are different transmission media which could be used for this network. This section estimates the cost of the wireline portion of the PCS network assuming an optical transmission network. Fiber cable was selected because it appears to be the transmission medium of choice for new construction in the subscriber loop given the 5-year time frame. The wireline segment consists of a feeder portion lying between the switch and the remote node, and, when present, a distribution network lying between the remote node and the cell site. For larger cell sizes, the network architecture is a star with dedicated fiber running between the central switching node and each cell site. For smaller cell sizes requiring fiber in the distribution network, the network architecture is a logical star where optical couplers are used throughout the distribution network to save on fiber cable costs.

One approach to network evolution could be to install fiber cable only as additional demand for PCS warrants its deployment due to cell splitting. The drawback of this approach is that it can be costly to return frequently to the same area to install cable. Alternatively, one could pre-install enough fiber at the outset to handle future growth requirements for some period of time. Because of the considerable cost of cable installation, and the potential that PCS growth could be swift, the model assumes enough fiber is pre-installed in the feeder and distribution network to accommodate a 30 percent penetration rate.

All estimates of cable installation costs assume the cable is put below ground in coordination with other underground plant construction, such as gas or power lines, to reduce costs. Burying cable underground, or pulling it through conduit, can be costly depending upon local conditions. Underground construction in new residential areas will cost substantially less than existing neighborhoods where the repair of streets, lawns, and other developments can slow down the pace of installation.[9] PCS systems will eliminate a considerable portion of cable installation costs by using a radio link in the distribution network. The model assumes the installation cost of distribution cable in a new construction area is $4 per meter. Installation of the feeder cable, which runs deeper than distribution

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Telecommunications Services, 1991", filed for United States v. Western Electric Co. and AT&T, U.S District Court for District of Columbia, Civil Action No. 82-0192 (HHG).

[9]The assumption that construction takes place in a new neighborhood has little impact on this analysis of PCS systems. As will be shown below, almost all of the cable installation costs for the PCS network occur in the feeder network, where cost estimates assume cable is passing through existing areas. Moreover, the low cost of underground cable installation assumed above is roughly commensurate with the costs of installing an aerial cable system, as is the norm in most neighborhoods today.

cable and passes through existing neighborhoods, costs $12 per meter (Kerner, Lemberg, et al., 1986). Installation of feeder and distribution cable includes inner duct at a cost of $1.15 per meter and $0.75 per meter, respectively.

Larger cells (above 800-meters) only require fiber in the feeder network at a cost of $0.10 per meter and a cable sheath cost of $4 per 50-fiber cable-meter or $2 per 20-fiber cable-meter. As the number of users and traffic levels grow, the size of the cells decrease and fiber is extended deeper into the network and closer to the end user. To reduce network costs, the network includes optical couplers, at a cost of $25 per port, to form passive optical networks in the distribution network as smaller cells are deployed. Thus, up to 256 households are served by only 2 fibers (one for each direction) using 4-fiber cable in the distribution network with a sheath cost of $1 per cable-meter. A protection factor of 100 percent in the feeder and distribution network specifies the percentage of dark fiber installed to cover fiber failure and future growth needs.[10]

Table 3 lists the total costs of the wireline transmission segment as calculated by the cost model under these assumptions. Again cost estimates vary with the size of the spectrum allocation due to the number of cells required in the network to meet subscriber demand. As determined within the model, these costs reflect the use of 1.6 Km. cells for the 25 MHz and 10 MHz allocations, 800-meters cells for the 5 MHz allocation, and 200-meters cells for the 2 MHz allocation.

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[10]To assure adequate flexibility and organization, fiber pigtails attach the fiber to network equipment at the central office, remote nodes, and cell sites. The fiber pigtail is a segment of fiber several feet in length with a connector on one end that joins to a patch panel and bare fiber on the other end which splices to the fiber cable in the network. Fully installed pigtails and patch panels cost $50 and $25 per fiber, respectively, for a total cost of $75 per fiber. The model assumes low loss, multi-fiber fusion splices join the feeder cables, while higher loss mechanical splices join the distribution fiber. The cost of either splicing method, including installation, is $15 per splice. In the feeder loop, splices occur every 915 meters (3 Kft) corresponding to the manufactured length of the fiber.

Network Component	Estimated Future Cost	Cost Per Subscriber Versus Spectrum Allocation (MHz)				Derivation of Cost for 2 MHz Allocation
		25	10	5	2	
Feeder Network						
Single Mode Fiber	0.1/meter	12	12	30	30	One 20-fiber cable, 3072 m.: 0.1 (20) (3072) ÷ 205
Cable Sheath (Holding 20-fibers)	2/meter	18	18	30	30	One 20-fiber cable, 3072 meters: 2 (3072) ÷ 205
Inner Duct, Splice	1.15/meter, 15	19	19	22	22	(15(20)(3)+1.15(3072)) ÷ 205
Remote Enclosure, Patchcords	1000, 75	7	8	11	11	16 active fibers, 1 enclosure: (1000+(2)(8)(75)) ÷ 205
Cable Installation	12/meter	180	180	180	180	12 (3072) ÷ 205
Distribution Network						
Single Mode Fiber	0.1/meter	0	0	4	29	4-fiber cable: (.4)(14.74K) ÷ 205
Cable Sheath	1/meter	0	0	9	71	2 Km: 1 (14.74K) ÷ 205
Cable Installation	4/meter	0	0	24	243	1.2 Km Trench: 4(12.46K) ÷ 205
Inner Duct	0.75/meter	0	0	5	46	1.2 Km Duct: 0.75(12.46K) ÷ 205
Patchcords, Couplers, Splices	75, 25, 15	0	0	6	30	(75(68) + 25(24) + 15(32)) ÷ 205
Total		236	237	321	692	

Table 3. Cost per Subscriber of Wireline Transport (in dollars); 10 percent penetration rate of PCS

PCS Cell Sites

PCS cell sites provide the interface between the wireline transmission segment and the radio transmission channel. Figure 4 shows the network equipment necessary to perform this function, including the wireline network termination equipment, a system controller, and radio frequency (RF) transmitters and receivers.

Similar to the switching node, the cost of terminating an optical fiber link (usually at some fraction of the T1 rate) is $100 for the laser and photodetector circuitry and packaging. With a 40 percent markup for local engineering and testing, this remote line card costs $140. The cost of the antenna site varies with the size of the cell. In general, larger cells require higher antennas heights for signal coverage throughout the service area. For example, antenna heights for microcells may be above 20-meters for a cell radius of 1 - 2 Km., to streetlight level (10-meters) for 200-meters microcells. Today, a large cell site costs $300,000, and it is hoped that smaller cells serving between 80 and 250 households will cost less than $25,000 (Cox, 1989). Accordingly, the model assumes land and antenna costs are $100,000 for 1.6 Km cells, $20,000 for 800-meter cells, $5000 for 400-meter cells,

$1000 for 200-meter cells, and $100 for pole-mounted 100-meter cells.[11] The cost of the terminal casing which houses the cell site on a streetlight is $30 including installation.

Three important factors which determine the cost of cell site RF equipment are the carrier frequency, the allowed level of transmitted power, and the radio access technology. It appears that all frequencies between 500 MHz and 3 GHz are technically suitable for PCS (CCIR, 1990b). The suitability of frequencies above this band for PCS is under study.[12] Thus, preferences for certain frequency bands are likely to be driven more from economic concerns of equipment cost rather than concerns for propagation. As a general rule, service providers predict that the cost of RF equipment increases roughly 10 percent for every doubling in frequency (GTE, 1991). Thus, using 2 GHz frequencies for PCS suggests RF equipment will cost roughly 15 percent more than comparable cellular circuitry operating at 800 MHz.

The allowed levels of transmitted power between the cell site and base station is another cost factor. In general, equipment costs rise as the level of transmitted power increases. PCS might be a low-power technology with transmitted power levels below 50 mW versus the 600 mW - 5 W power levels used in cellular (CCIR, 1990b). Accordingly, RF equipment in the PCS base station could cost less than RF circuitry in a cellular base station, although the magnitude of these cost savings is highly uncertain and closely related to the complexity of the radio access technology.

In the past, the high-power RF circuitry in a cellular base station cost roughly $4000 per channel (Hatfield and Ax, 1988). Today, a microcell might cost $50,000 (Lynch, 1991), or $1250 per channel assuming a base station capacity of 40 channels. While the additional complexity of TDMA and CDMA radio access technologies might increase the cost per RF channel (or its equivalent with spread spectrum), the additional circuits per RF channel are likely to lead to lower RF equipment costs per subscriber (Calhoun, 1988). Thus, one study estimates that PCS base stations may cost $14,000 for a 44-channel base station with a radius of 200-meters, or $300 per channel (Lipoff, 1992). Given the trade-off between transmitted power and technological complexity, the model assumes the RF

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[11]Cell site costs will vary widely with local conditions. The cost assumptions above assume that citing costs will decrease significantly with the size of the microcell and that there are no restrictions on the placement of the cell sites throughout the residential area. In fact, a particular cell site may be unacceptable for unpredictable geographic or neighborhood concerns. The size and location of antennas has historically been a controversial issue for wireless services, particularly in residential areas. Modifications to the network to meet these concerns will add to the costs assumed above.

[12]For example AT&T is conducting field tests in the frequency range of 5.9 - 6.4 GHz. See *The Wall Street Journal*, "AT&T Seeks Pocket Phone Test Clearance," 6/25/91, B1. Also, the Suite 12 group is investigating the use of the 28 GHz band for PCS applications. See *footnote 2*.

equipment and any associated channel control circuitry costs $500 and $400 for microcells with a radius of 1.6 Km. and 800-meters, and $300 per circuit for microcells smaller than 400-meters.[13] This equipment is only installed in increments of 10 circuits.[14]

Finally, the cell sites will require a reliable source of electricity for operation. While metallic transmission media can generally carry enough electrical power to run network components, optical fiber cannot carry enough power to operate the cell site equipment. Arrangements are therefore needed to deliver power to the cell sites throughout the network, either by local means or through the installation of power distribution cable. Calculations assume the cost of powering cell sites is equivalent to the costs of powering fiber networks for telephone service (see Reed, 1991, Chapter 4). The capital cost of equipment to power the microcells is a variable cost of $50 per watt, which is analogous to the costs of powering fiber-to-the-curb and fiber-to-the-home architectures. Electronic equipment at the cell site is assumed to consume 10 Watts per channel, 4 - 5 times the amount required by an active telephone line at a remote node.

Table 4 lists the estimated cost per subscriber for cell sites assuming a 10 percent penetration. Note the high cost of powering a large number of microcells as is the case with the 2 MHz allocation. It is not surprising to find that PCS networks, like other fiber-based architectures proposed for narrowband and broadband services, incur high powering costs when substantial amounts of fiber are deployed in the distribution network.

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[13]For the lowest level of costs, the microcells may not have the functionality to provide high speed mobile service in a car, although they may be capable of slow speed handoffs for pedestrians.

[14]The high cost of radio channel equipment and antenna sites has given rise to proposals for distributed antenna systems. Under these approaches, the base station equipment is kept simple, consisting of only a receiver, transmitter, amplifier and antenna. Network controllers and signal processing equipment are kept in central locations, such as a switching node, to reduce site costs and provide opportunities for greater sharing of network equipment. See, for example, Chu, T. S., and M. J. Gans. *Fiber Optic Microcellular Radio*. 41st IEEE Vehicular Technology Conference. St. Louis. 1991. 339-344; Hart, George. *Cost Effective Cable Television Transport for PCN*. 1992 NCTA Technical Papers. 1992. The economics of these approaches, that is, any costs or savings arising from the placement of this equipment at a centralized locations, are not considered in this paper.

Network Component	Estimated Future Cost	Cost Per Subscriber Versus Spectrum Allocation (MHz)				Derivation of Cost for 2 MHz Allocation
		25	10	5	2	
Cell Site (Optical Network Interface)						
Optical Line Card, Housing	100/card, 30	-	-	1	13	16 cells per 1024 homes: 16 (1.4 (100) + 30) + 205
RF Circuitry and Control	200/channel; 5 channels/cell	38	38	54	164	16 (1.4 (5)(250)) + 205
Antenna Site Costs	1000/cell	122	122	98	78	16*1000+ 205
Power (cell only)	50/watt	22	22	34	157	50 (10)(16) (5)+205
Overall Total		182	182	187	412	

Table 4. Cost per Subscriber of PCS Cell Sites (in dollars); 10 percent penetration

Handsets

The final network component to consider is the portable radio unit. The portability and mobility requirements of PCS presume small, lightweight handsets with the capability to operate over long periods of time without recharging. Despite their small size, however, PCS handsets will be filled with advanced technology. New technologies incorporated into portable cellular handsets include microwave monolithic integrated circuit (MMIC) power amplifiers, large-scale integration (LSI) signal amplifier and modulation ICs, ASICs for logic and power control, and advanced battery design (Shimizu, Urabe, et al., 1991). This section offers a basis for estimating the costs of these devices.

Like the RF equipment at the cell site, the particular band of frequencies allocated to PCS will affect handset costs. Internal device components tend to interfere more with each other at higher frequencies, and therefore require additional design efforts as well as more materials to shield the components from these effects. This concern is part of the reason for estimating that RF equipment costs increase 10 percent with every doubling in baseband frequency. Also, the breadth of the spectrum allocation, and whether the allocation is entirely contiguous, are cost factors. In general, the greater the frequency agility, the more expensive the device. Handset costs will also increase if the spectrum allocation is divided into two bands of spectrum for each direction of transmission.[15]

The processing power of the handset will be derived from a set of semiconductor chips that implement the digital logic and control functions. As

[15]Allocations divided into paired bands of spectrum separated by guard bands require frequency division duplexing (FDD) methods where the transmit and receive directions use different frequencies. A contiguous allocation permits the use of time division duplexing (TDD) where both transmit and receive directions use the same frequency. As an indication of the relative costs of each approach, a private conversation with a manufacturer suggests that a FDD system could increase handset costs by roughly $30.

noted above, with a carrier frequency below 2.3 GHz, cost estimates can assume low-cost silicon ICs are used in the handset. Digital radio access techniques using silicon ICs are expected to consume much less power than their analog counterparts. Lower power requirements and large scale integration will extend the talk time and decrease the size of the handset despite the complexity of these approaches.[16] Current analog cellular phones hold up to 20 ICs. But a chip set for the proposed IS-54 TDMA standard consisting of 7 ICs has been developed by one manufacturer, and the next generation chip set consisting of only 5 ICs is under development (Perl and Bialik, 1991). Consequently, it appears reasonable to anticipate PCS handsets with less than five ICs at a cost of $10 - $20 per chip.[17]

Similar to a cordless telephone, a PCS handset will need batteries to operate. Battery storage capacity and the power consumed by signal processing and radio transmission determine the total "talk time" for the handset before recharging is necessary. Present cellular units usually transmit power at 3 W., and portables transmit at 600 mW (to keep the unit small and give more talk time). In contrast, PCS handsets might operate at transmit powers of less than 10 mW. An adaptive power control scheme could extend talk times even further by adjusting the level of transmitted power depending upon the proximity of the handset to the base station.

Cox argues that the additional complexity of advanced TDMA or CDMA circuitry, or large cell sizes, could preclude implementation of an acceptably small and portable handset due to the power requirements and the size of the battery needed to meet them (Cox, 1990). For example, under these schemes the PCS handset could require a digital signal processor (DSP) chip for coding speech between digital and analog forms at performance levels of 25 to 500 MIPs (Ericsson, 1992). Such a performance level translates into large power requirements -- each "MIP" usually consuming 20 - 50 mW of power in the receiving direction (Rockwell, 1992). Even so, the technological advance and falling costs of ICs suggests future devices are likely to meet these requirements at reasonable costs.

Thus, the prospects appear favorable that PCS handsets can be constructed with a small, powerful chip set at relatively low costs. A low-power, analog cordless telephone can be bought for $50 - $100 today, while the suggested retail of high-power mobile cellular phones, a less mature product manufactured in lower volumes, varies between $495 to $799 (the lightest portable cellular phones now retail for $945, with prices declining rapidly) (Mobile Phone News, 1992). One manufacturer estimates a digital PCS handset would cost a maximum of 1.5 times more than a digital cordless handset operating on the same frequency and having the same power output and production volumes (Ericsson, 1991). With the

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[16]For example, new dual mode phones provide 66 minutes of talk time in the analog AMPS mode and 120 minutes of talk time in the digital IS-54 TDMA mode. See *Telocator Bulletin*. Jan. 10, 1992. 9-10.

[17]NCR estimated the cost of the chip set in the handset could fall to $30 - $60 depending upon the complexity of the system. See (NCR, 1991, p. 4).

above considerations in mind, the model assumes the off-the-shelf price of a standardized PCS phone for the 2 GHz band, including the base station required for indoor cordless service, to be $160 per handset when manufactured in volumes comparable to cordless phones.[18]

Total Capital Costs of a PCS Network

The total cost of building a PCS network is found by summing the cost of each network element. Table 5 lists the average cost per subscriber of a PCS network for the range of spectrum allocation sizes assuming a penetration rate of 10 percent. The table also includes the model estimate of system costs assuming a 40 MHz allocation size. Figure 5 plots the total installation costs per subscriber versus the service subscription rate and spectrum allocation size. On this graph the estimated costs for the 25 MHz and 10 MHz allocations appear virtually identical for all subscription levels. Discontinuities or "steps" in the cost functions reflect the increased costs per subscriber arising due to the installation of smaller cell sizes.

These results suggest three notable observations. First, total system costs appear to increase rapidly when the size of the spectrum allocation falls below 5 MHz due to the additional switching, wireline, and cell site costs which accompany deployment of a large number of very small microcells. Conversely, for the set of base case assumptions, estimated costs are remarkably consistent for spectrum allocation sizes greater than 5 MHz, which suggests a large amount of spectrum is not necessary to deliver PCS using microcell sizes between 1.6 Km. and 400-meters.[19] Second, these results broadly imply that switching and handset elements each account for 20 percent of total costs, wireline transport accounts for 35 percent of total costs, and cell sites account for the remaining 25 percent of total costs. Third, most economies of scale arising from the fixed costs of a PCS system are exhausted once the penetration rate exceeds 20 percent of the population for spectrum allocations sizes above 5 MHz. This should be interpreted as a conservative result, since the model only considers microcell sizes below 1.6 Km. and assumes full signal coverage. As will be shown later, these assumptions lead to higher fixed costs than might otherwise result with larger cell sizes.

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[18]Assume a digital cordless handset designed to operate at roughly 50 MHz (near the current cordless spectrum allocation) costs $50. A PCS handset at the same frequency would cost $75 assuming a 50 percent markup for enhanced functions. Allowing a further markup of 15 percent (a high estimate) for every doubling in frequency leads to an estimate of about $160 for a 2 GHz handset (a total of 5.5 doublings).

[19]If the model were to consider cell sizes greater than 1.6 Km., then system costs would be likely to exhibit a greater sensitivity to variations in allocation size between 20 MHz and 40 MHz. Of course, PCS begin to look very similar to cellular services when larger cell sizes (and possibly higher power handsets) are considered. The next section considers the costs of this alternative.

Cost Category	PCS Spectrum Allocation				
	40 MHz	25 MHz	10 MHz	5 MHz	2 MHz
Switching	125	125	125	155	307
Wireline	236	236	237	321	692
Cell Site	182	182	182	187	412
Handset	160	160	160	160	160
Total Cost	703	703	704	823	1571

Table 5. Estimated Capital Costs per Subscriber of PCS System; 10% Penetration (in dollars)

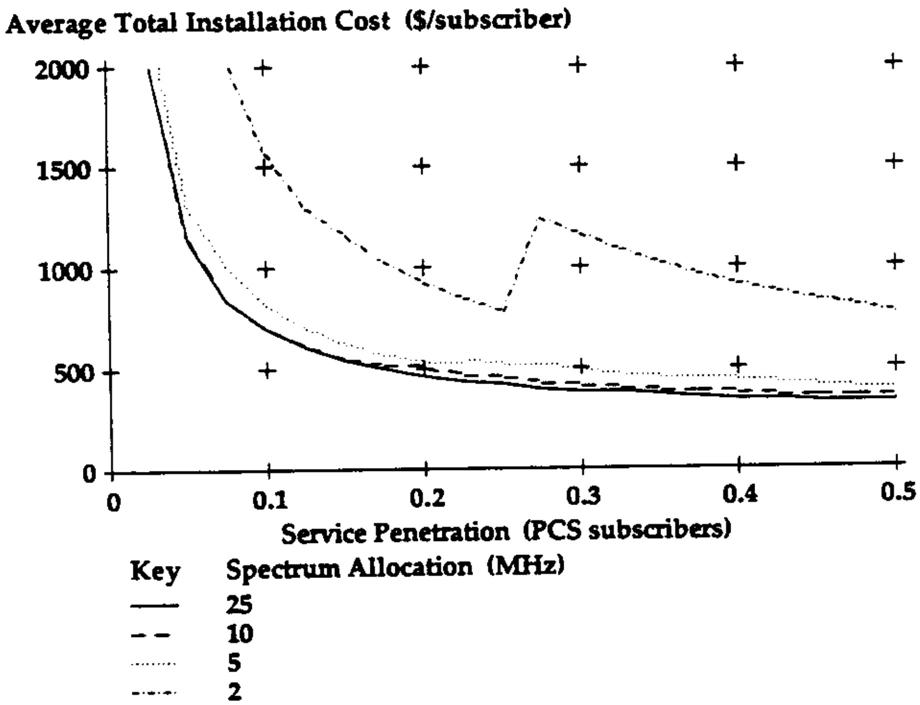


Figure 5. Total Estimated Capital Costs per Subscriber of PCS System (in dollars)

Sensitivity Analysis

The flexibility of the engineering cost model allows the opportunity to test how these results will vary with changes to a number of network parameters. This section examines the sensitivity of the results to assumptions concerning the estimated cost of network complexity, the grade of service, the average offered traffic per subscriber, and the degree of spectrum efficiency.

Network Complexity

The cost model incorporates a host of assumptions regarding the future costs of electronic components located at the switching node and base stations. Figure 6 illustrates the sensitivity of the total cost per subscriber to variations in the estimated cost of electronic equipment (including handsets) assuming a 25 MHz spectrum allocation size. The 'High' and 'Low' curves assume electronic components, including the handoff feature at the switching node, are 200 percent or 50 percent, respectively, of their base case costs. While the magnitude of system costs demonstrate considerable sensitivity to variations in the cost of network electronics, the basic form of the cost curve remains unchanged. This result suggests that electronic components primarily represent variable costs. Electronic components account for almost 30 percent of the total costs for spectrum allocation sizes above 10 MHz, or about $200 per subscriber, and $160 of this derives from the (variable) cost of the handset. Although not shown, this result remains unchanged for all other spectrum allocation sizes considered in the model.

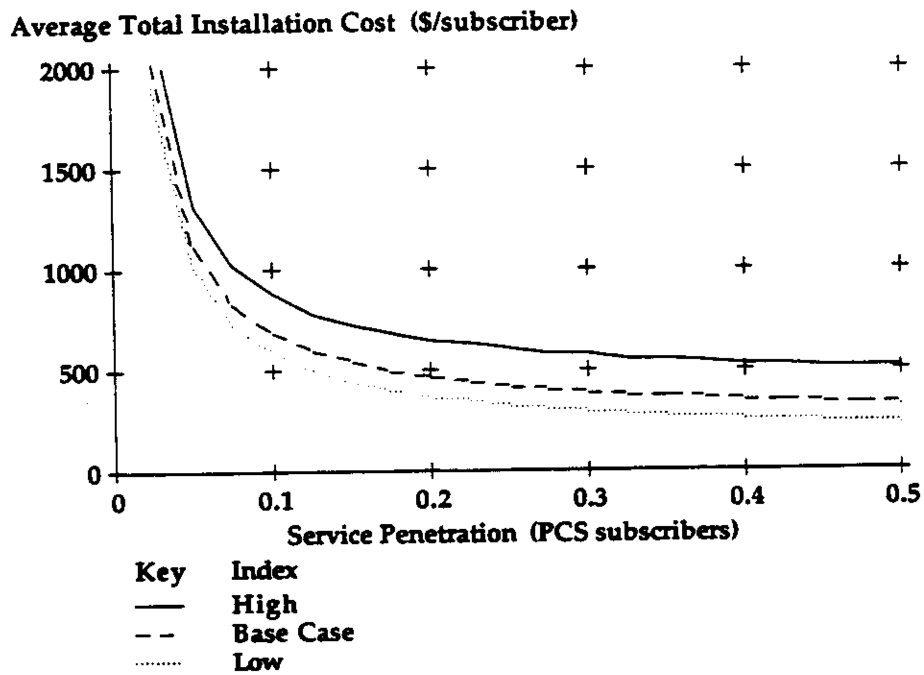


Figure 6. Variation of Total Estimated Costs per Subscriber to Electronics Costs; 25 MHz Spectrum Allocation Size (in dollars)

Grade of Service

The model can also measure the sensitivity of system costs to the grade of service. The base case assumes a 1 percent grade of service, which means the probability that a subscriber's call will be blocked because of a lack of network capacity during the average busy-hour is 1 percent. Table 6 illustrates how total costs vary for lower grades of service. Costs decrease with higher blocking probabilities because less network capacity is available for subscribers to use. These results indicate that systems costs are most sensitive to the grade of service when the spectrum allocation is small (*i.e.*, when the dedicated cost per channel of switching and base station equipment is high and the trunking efficiency in the system is low). For all spectrum allocation sizes considered greater than 2 MHz, variations in the grade of service did not change significantly the basic form of the cost curve.

Grade of Service	PCS Spectrum Allocation			
	25 MHz	10 MHz	5 MHz	2 MHz
1% (Base Case)	703	704	823	1571
2%	703	704	821	1485
5%	685	686	810	973
10%	683	684	775	951
50%	654	654	654	737

Table 6. Variation of Estimated Capital Costs per Subscriber to Grade of Service; 10% Penetration (in dollars)

Variations in Demand

While the base case assumes each subscriber generates 0.03 erlangs of traffic during the peak busy-hour -- a level of traffic comparable to today's cellular usage -- some believe PCS users will generate much higher levels of usage near 0.06 to 0.12 erlangs per subscriber (Cox, 1990). Clearly, the intensity of usage will depend upon the availability of substitutes for voice service and whether the system is designed for indoor use. Figure 7 plots the system costs over a range of average traffic levels between 0.01 to 0.12 erlangs per user in the busy-hour. The results indicate a consistent incremental cost of roughly $50 per subscriber for every 0.01 erlang increase in subscriber usage during the peak busy-hour. Although not shown in Figure 7, the model results indicate no substantial increase in economies of scale even under very heavy levels of demand.

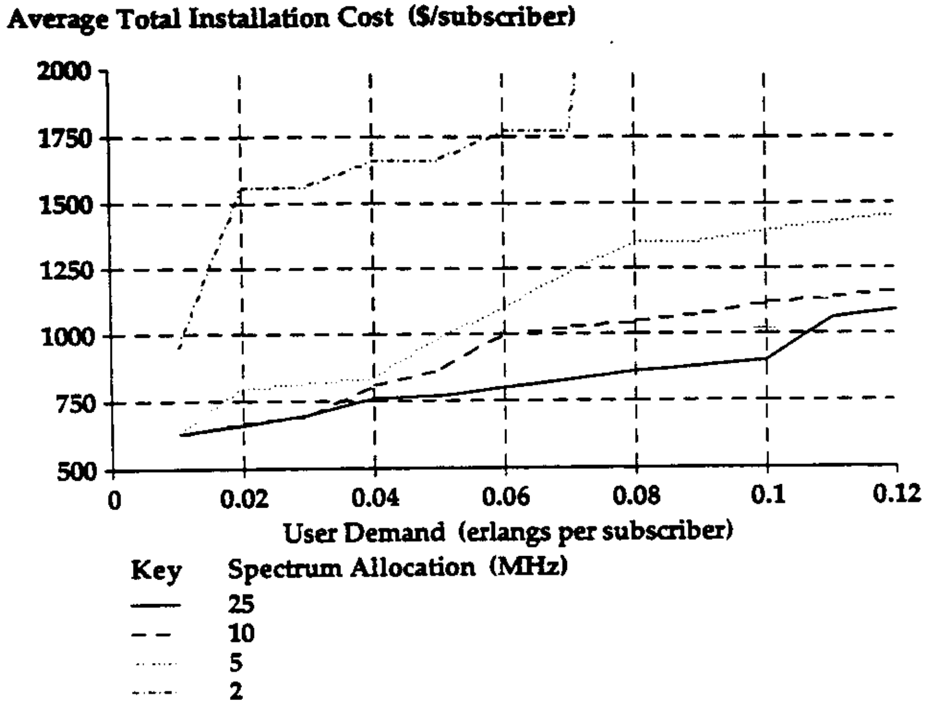


Figure 7. Variations in Total Estimated Costs per Subscriber to Usage; 10% Level of Penetration to PCS (in dollars)

Spectrum Efficiency

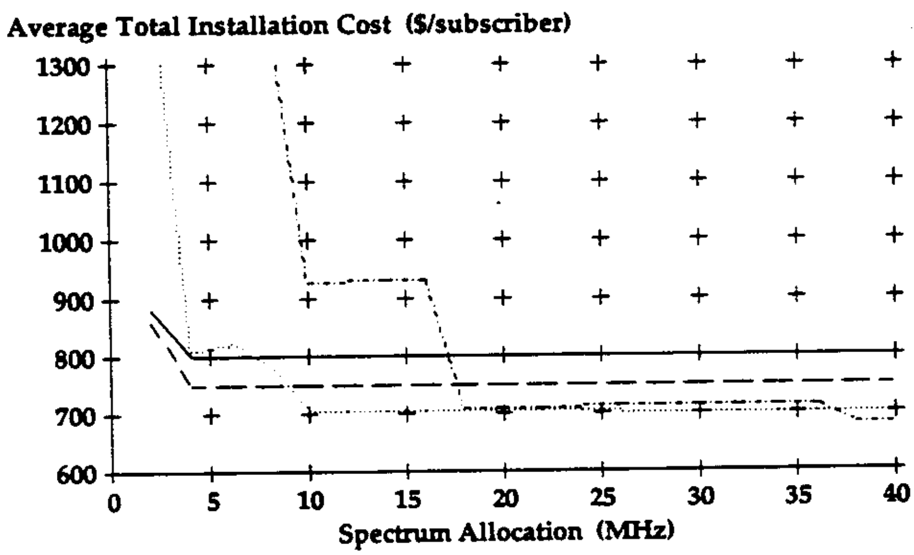
Spectrum efficiency is a measure of the amount of usage per unit area over a given band of frequencies. As a general rule, radio equipment with a higher level of spectrum efficiency is more expensive due to the additional complexity necessary to carry more information over the same amount of spectrum. While a number of elements in a PCS network determine the spectral efficiency of the system, the cell size, the frequency reuse factor, and the bandwidth of the voice channel are particularly important parameters.

This sensitivity test examines how total network costs will vary for a number of frequency reuse factors and voice channel sizes. Because the relationship between cost and complexity in RF equipment is highly uncertain at this stage of development, the sensitivity analysis reported below assumes upper and lower bounds (± 50 percent of the base case) for the savings or costs in device complexity. The base case assumes a system with a full-duplex bandwidth of 25 KHz for each voice channel and a cellular reuse factor of N=7. Three options are considered:

- A radio system with a reuse factor of N=1 with the equivalent of a 25 KHz voice channel bandwidth. Because this scenario presents the highest degree of spectrum efficiency, the costs of RF circuitry and control equipment are increased 50 percent above the base case.
- A radio system with a reuse factor of N=3 and 20 KHz full-duplex voice channels. Base station equipment and handset costs are 25 percent above the base case.

- The third alternative presents the lowest degree of spectrum efficiency. This system assumes a reuse factor of N=16 and a channel size of 70 KHz.[20] Base station equipment and handset costs are 50 percent below the base case.

Figure 8 plots the estimated costs for these three scenarios, along with the base case, versus the spectrum allocation size assuming 10 percent of household subscribe to PCS. These results illustrate the tradeoffs associated with spectrum efficiency. With a spectrum allocation size below 10 MHz, spectrum efficient systems reduce costs by reducing the number of cell sites necessary for coverage. (The cost of spectrum efficient alternatives are constant for allocation sizes above 5 MHz because the model does not consider cell sizes above 1.6 Km. that could lower system costs.) When the spectrum allocation size exceeds 18 MHz, the system with the lowest level of spectrum efficiency is the low-cost option since enough spectrum is available to offer service using the larger cell sizes considered in the model. This cross-over point at 18 MHz, however, is contingent upon the assumptions that less complex RF equipment offers a 50 percent savings in cost and that the penetration rate is 10 percent. Although not shown, the structure of the cost functions for these systems were unchanged from the base case.



Key — Channel Size
- —— 40KHz, N=1
- – – 20KHz, N=3
- ······ 25KHz, N=7 (Base Case)
- -·-·- 70KHz, N=16

Figure 8. Variations in Total Installation Costs per Subscriber to Radio Systems with Different Levels of Spectral Efficiency; 10% Penetration of Subscribers (in dollars)

[20]A system with similar parameters has been proposed in (Bellcore, 1991).

Annualized Capital and Operating Costs Estimates

The cost estimates can be annualized to reflect the cost of capital and the economic lifetimes of the network facilities. Annualized figures provide an estimate of the revenue requirements required to offset the upfront investment, and can be readily combined with other annual expenses such as operations, administration, and maintenance expenses.

To annualize the capital costs of the PCS network, the model assumes the necessary rate of return on new investment before taxes is roughly 17 percent.[21] Because the physical portions of the network will have longer useful economic lifetimes than the electronic components, the annualized figures assume a 10-year lifetime for electronics equipment and 20-year lifetime for physical plant. These assumptions lead to annuity factors of 0.21466 for electronics equipment with a 10-year lifetime, and 0.17769 for physical plant with a 20-year lifetime. The result is an annualized capital cost estimate of $135 per subscriber for the base case PCS network and a spectrum allocation size of 25 MHz.

Beyond the capital expenses, the other operating expenses of PCS fall under four major categories: network maintenance, interconnection, sales and marketing, and general administration.[22] To estimate these expenses, model calculations assume annual network maintenance expenses are 10 percent of the capital costs of the PCS network. Network interconnection charges to the public switched network are $0.03 per minute, with each subscriber offering an average of 140 minutes per month. Sales and marketing costs begin at $200 per subscriber for a penetration level of 2.5 percent, and decrease linearly to $75 per subscriber for penetration rates above 20 percent.[23] Annual general administrative costs

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[21]To calculate this tax and rate factor, the model assumes a debt ratio of 40 percent, an interest rate of 12.25 percent, an inflation rate of 3 percent, a return on equity of 16 percent, and a corporate tax rate of 40 percent. For more detail on annualizing cost figures, see Johnson, Leland L., and David P. Reed. *Residential Broadband Services by Telephone Companies? Technology, Economics, and Public Policy.* RAND Corporation, R-3906-MF/RL, Appendix I, (June, 1990).

[22]The estimates of the operating expenses provided below are similar to figures reported by the Pacific Telesis Group during a presentation to the Office of Plans and Policy, Federal Communications Commission, June 16, 1992.

[23]Cellular operators market their services through resellers, agents, or their own service organization. Agents receive a commission for each new subscriber, and attract new subscribers by selling discounted cellular handsets in exchange for a long-term service agreement. Cellular operators claim to pay as much as $500 - $800 to acquire a new subscriber due to commissions and marketing. These commissions, however, are not included in the sales and marketing estimate of PCS assumed above. This study focuses upon the *costs* of delivering PCS, not on the pricing strategy of the service. The current system of bundling service contracts and handsets to new subscribers represents a form a discriminatory pricing between new and existing subscribers, not a cost inherent to the production function. What is included in the sales and marketing figure

include $60 per subscriber for billing and $75 per subscriber for other administrative costs.

Figure 9 plots the annualized capital and operating expenses of PCS, and the total sum of these two cost functions assuming a 25 MHz spectrum allocation. At a 10 percent penetration level, total annualized costs are $546 per subscriber, or about $45 per month. The cost function for operating expenses exhibits some economies of scale, although the total cost function still shows most economies of scale are exhausted once subscriptions exceed 20 percent of households. The pie chart in Figure 10 illustrates the distribution of costs across this set of functions. Capital costs -- including all site engineering and testing required at the cell sites -- account for 25 percent of the total.

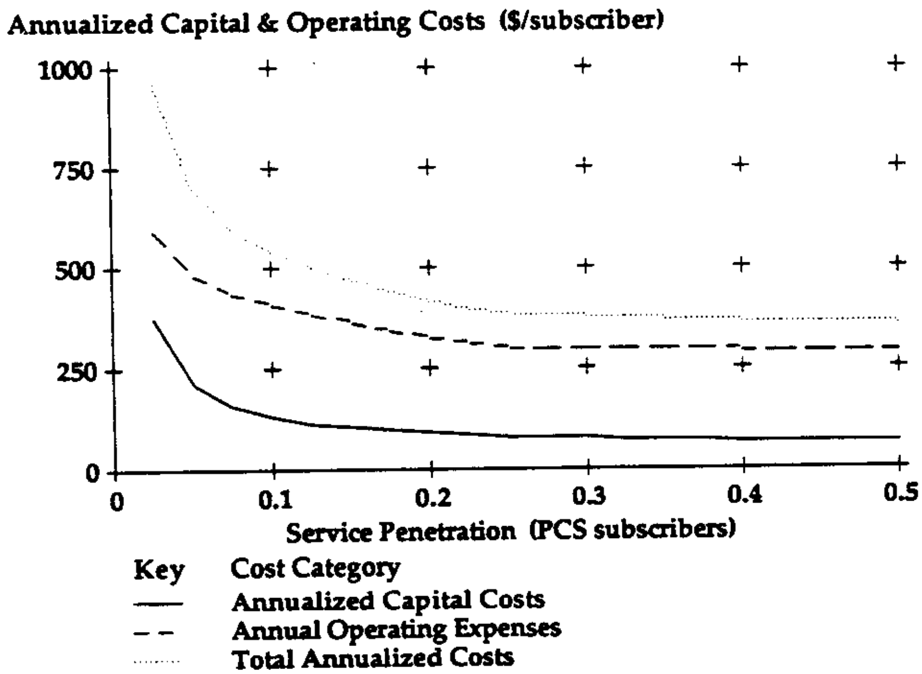

Figure 9. Total Annualized Expenses for PCS; 25 MHz Spectrum Allocation (in dollars)

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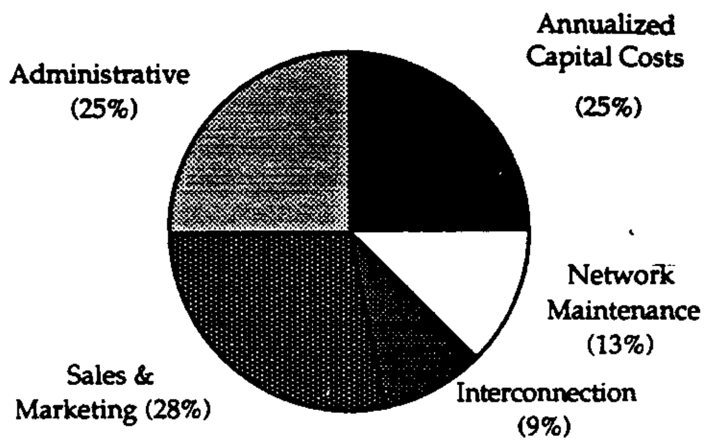
assumed above are the usual costs of advertising and customer service organizations. These costs are likely to reflect some economies of scale with the growth of new subscribers.

Distribution of PCS Expenses



(Total Cost of $546 Per Subscriber at 10% Penetration)

Figure 10. Categories of Annual PCS Costs

Summary of PCS Model Results

This section has described an engineering cost model developed to estimate the long-run average costs of building a PCS network. This "bottom-up" approach to forecasting the cost function of PCS describes how infrastructure costs are distributed across network components, and where uncertainty lies with regard to future costs and system alternatives. A sensitivity analysis examined the impact of a number of these uncertainties on the overall results.

To summarize the findings:

- The cost of the PCS network in a new residential area would be $703 per subscriber assuming base case assumptions of 25 MHz allocation size and 10 percent penetration of households.
- The total annualized cost of operating this PCS network would be $546 per subscriber for these base case assumptions, with infrastructure costs accounting for 25 percent of the overall total.
- Economies of scale in the cost function of a PCS network would be largely exhausted for subscription rates above 20 percent of households per provider. This result should be viewed as a high estimate of when scale economies would be exhausted, since the model assumes a network architecture of microcell sizes below 1.6 Km and therefore a high degree of fixed costs. This basic result held for spectrum allocation sizes above 5 MHz despite sensitivity analysis to the cost of electronic components, grade of service, levels of offered traffic, and spectrum efficiency of the radio system.

- PCS network costs would be sensitive to the price of RF equipment. The handset dominated the RF equipment cost category since there is no possibility for sharing this cost among several users.
- PCS network costs vary substantially with the level of spectral efficiency. The radio system with the lowest level of spectrum efficiency considered in this analysis would be viable when the allocation size was 20 MHz or more. Highly spectrum efficient radio systems would be better for allocation sizes below 10 MHz.

Section III. Economies of Scope Between PCS and Other Services

Section II focused on estimating the costs of providing PCS over a separate network. The next question is whether the economics of deploying a PCS system might change if existing infrastructure can be employed to deliver these new services. In the presence of economies of scope, initial costs of deployment could be reduced by utilizing existing resources to provide PCS. Savings through joint production could replace initial fixed costs investments with variable cost elements, thereby making it more attractive for a firm to enter the PCS market by reducing the upfront investment requirements. This section examines whether economies of scope exist between PCS and telephone, cable television, or cellular telephone services.

Providing PCS Over Telephone Networks

Current services and portions of the existing telephone network could be employed to offer PCS. Telephone companies could offer billing, administrative, and network maintenance services, or use network signalling, switching, and transmission components.[24]

The cost of building a new telephone network in the same residential setting described in Section II is $780 per home passed (Reed, 1991, Appendix B: Table B.3) for an annualized cost of $178 assuming annuity factors that have been lowered to reflect the lower competitive risk to the narrowband residential market. This cost estimate assumes a fiber-to-the-curb, passive double star architecture with fiber in the feeder and distribution segments of the network, including a percentage of dark fiber, and copper wire pairs in the drop. Each pedestal holds an optical network interface serving 8 households. This figure includes the cost of fiber termination at the switching node but does not account for all switching elements. Using the framework for estimating switching costs described in Section II, the "getting started" and usage sensitive costs for the switch are $110 per line, or roughly $130 per home passed assuming 20 percent of

[24]This discussion makes no distinction of whether the PCS provider is the telephone company or third party provider. Ideally, there should be little difference in costs between these two possibilities if tariffs reflect the true costs of the underlying switching and transport services. Due to the joint and common costs arising in the network, however, there will be some leeway in the pricing structure regarding how these costs are allocated among different services.

the homes request a second line. Thus, the total estimated cost of the new telephone infrastructure including switching is $910 per home passed, or an annualized cost of $202.[25]

To estimate the cost of an integrated network providing both PCS and telephone service, the model assumes the PCS network is an overlay network to the telephone network. That is, the PCS and telephone networks are physically distinct, but occupy the same buildings, remote terminal housings, cable sheath, and cable conduit in order to share equipment, installation, and other labor charges. The model also assumes the switching and transmission capacity of the integrated network equals the combined capacity of the separate networks. This assumption will underestimate the economies of scope present, since any cost savings in network integration of transmission or switching equipment -- in the form of potential trunking efficiencies which could be realized by aggregating this traffic together -- are not fully considered.

The model calculates the switching costs of the integrated network by adding the switching and fiber termination costs of the telephone network ($145 per home passed) to the PCS network ($125 per PCS subscriber at 10 percent penetration and a 25 MHz spectrum allocation) less the "getting started" costs of the PCS switch ($78 per PCS subscriber) for a total of $192 per PCS subscriber. The cost of the feeder portion of the telephone network ($88 per home passed) includes a 50-fiber cable, of which 16 fibers are active for telephone service. Thus, enough dark fiber is present in the feeder network to deliver PCS with only minor additional costs for fiber organization. There is no change in cell site and handset equipment costs as a result of integrating PCS with the telephone network.

The use of existing telephone company personnel and facilities to bill and administer PCS could reduce these annual operating expenses for the PCS supplier. In addition, PCS suppliers may hire telephone company personnel to maintain portions of the PCS network. Accordingly, model calculations arbitrarily estimate that the use of telephone company services for billing, administration, and network maintenance results in a 20 percent savings over stand-alone operating expenses.

Under these circumstances the model predicts economies of scope would be present between PCS and telephone services.[26] Figure 11 illustrates the

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[25]Note that these models predict the annualized cost of network infrastructure for a wireless network ($135) will be less than the a fully wired network ($202) in the subscriber loop. While these network architectures are not directly comparable (*e.g.*, the fiber-to-the-curb architecture could be upgraded to carry broadband services, while the wireless system probably could not due to a lack of spectrum), this result could have significant implications for future competition in the subscriber loop for telephone services.

[26]The mathematical approach to finding economies of scope is straightforward. If $C(x)$ and $C(y)$ represent the cost functions of providing two services (such as PCS and telephone service) on a separate basis, and $C(x,y)$ represents the cost function of providing these two services on an integrated basis,

magnitude of the savings that could be achieved in the joint provision of PCS and telephone service using an integrated network and a 25 MHz spectrum allocation. The highest cost function in the graph is the combined annualized costs of separate networks, which include the operating expenses for PCS but not for telephone service. The next lowest cost function is the cost of the integrated network (including only the operating expenses for PCS). The area between these two lines represents the economies of scope that can be realized by building an integrated network. Also notable is the form of the cost function showing the incremental costs of providing PCS with a telephone network. Because the switching and wireline transmission segments are fixed costs, the incremental cost function shows weaker economies of scale, particularly for penetration rates below 10 percent. This results confirms that use of existing telephone networks and services can replace fixed costs with variable costs. If the tariff structure of the leased telephone company facilities exhibits weaker economies of scale in comparison to the costs of building these facilities on a stand-alone basis, then the total cost function of a network providing PCS on an integrated basis with the telephone services would show fewer economies of scale.

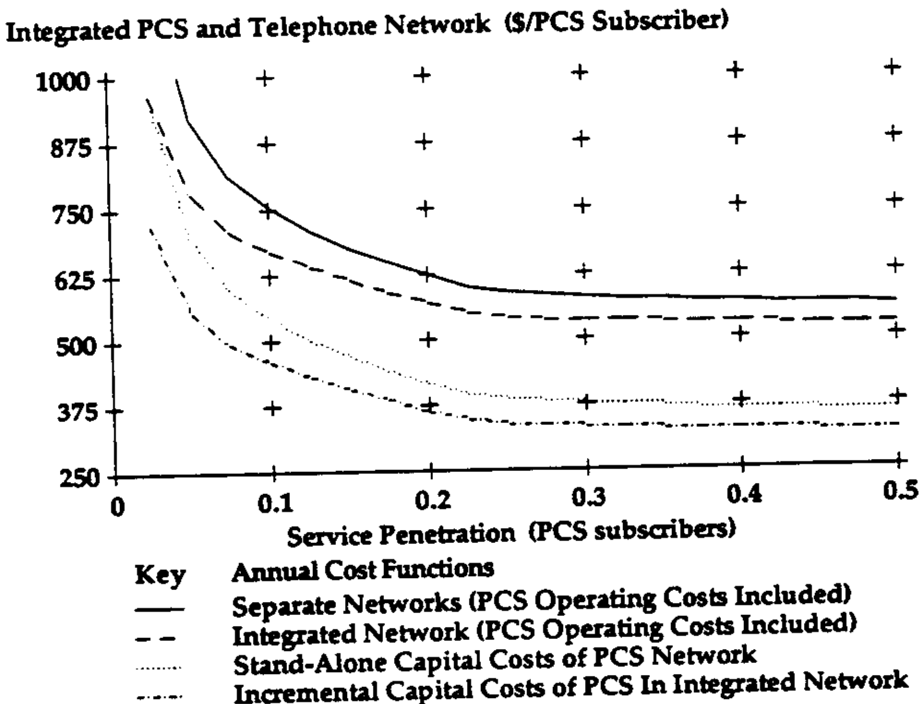

Figure 11. Measuring Economies of Scope Between PCS and Telephone Service (in dollars); 25 MHz Spectrum Allocation

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then economies of scope are present if $C(x) + C(y) \geq C(x, y)$ for the relevant range of output.

From a strategic planning perspective, having smaller fixed costs decreases the average cost per subscriber significantly at low penetration levels when the service is first being introduced. Consequently, telephone networks have an opportunity at the outset to offer crucial elements of the PCS infrastructure to suppliers. While the model finds economies of scope between PCS and telephone service assuming a fiber-based network, the results should hold for most copper-based loops used today. Copper wire pairs can carry a half-duplex T1 signal in the local loop at least two kilometers without the need for a repeater.[27] Assuming enough spares are present in the telephone network, copper pairs could serve as the backhaul for microcells in most circumstances. In those areas where there is not a sufficient number of spare copper wire pairs available, and no plans for immediate deployment of fiber in the feeder, then any economies of scope in transport between PCS and telephone service would be unavailable.

In short, the telephone network offers the key strategic advantages of ubiquitous network presence for transport and switching facilities, in addition to an advanced signalling network and intelligence nodes. These synergies between PCS and telephone services raise several policy questions regarding interconnection and access to the public network. A key element of the PCS regulatory model will be the incentives it extends to telephone companies to provide components of the PCS infrastructure to licensees. Policy issues regarding whether telephone companies should be eligible for PCS licenses are discussed in Section IV.

Providing PCS Over Cable Television Networks

Portions of the existing cable television network may also be used to deliver PCS. The fiber- or copper-based transmission links of a cable television network could be used to deliver PCS on an integrated basis with cable television service, as could be billing, administrative, and network maintenance services from cable companies. This section estimates whether economies of scope exist between PCS and cable television service.

Most cable television networks today are a tree-and-branch architecture using coaxial cable (see Figure 12(a)). Recently cable companies have begun to replace the coaxial cable in the trunk portion of the network with fiber backbones as shown in Figure 12(b) to increase network capacity, and improve the quality and

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[27]Alternatively, High-speed Digital Subscriber Lines (HDSL) technology might be considered using copper wire pairs in the subscriber loop. HDSL techniques transmit a full-duplex 1.544 Mbps data rate over two twisted pairs without requiring any conditioning of copper plant and allowing repeaterless operation for all loop lengths under 4 Km. HDSL would be attractive if the costs of the HDSL electronic equipment at each end of the link are less than the costs of traditional T1 carrier equipment plus repeaters (if necessary). In general, see *IEEE Journal of Selected Areas in Communications* issue on High-Speed Digital Subscriber Lines, August 1991.

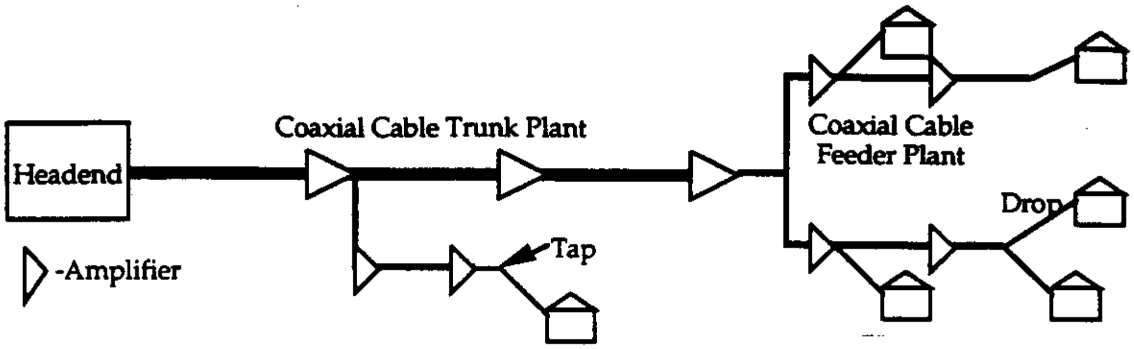
reliability of cable television service.[28] Cable companies are now looking at how PCS could be offered on a cable network with a fiber backbone architecture (Dukes, 1992).

Most cable companies envision using their dark fiber to transmit PCS traffic between the headend and the optical network interface, or fiber node. For this reason, an important design factor in integrating PCS and cable television transport services is the coverage area of the fiber node versus the coverage area of the microcell. Ideally, the size of the fiber nodes and microcells would coincide so that no modifications to the coaxial cable below the fiber node would be necessary. Such a result is highly unlikely, however, since the characteristics of PCS and cable television service are very different. Typically the coverage area of a single fiber backbone deployed today is between 5000 to 2000 subscribers per fiber node, which would correspond to cell sizes of roughly 1.6 Km. to 800 Km. using the network model reported in this paper. In the future, the number of subscribers per fiber node could fall to 200 (a cell size of 400-meters) as the cost of broadband optical systems decline.

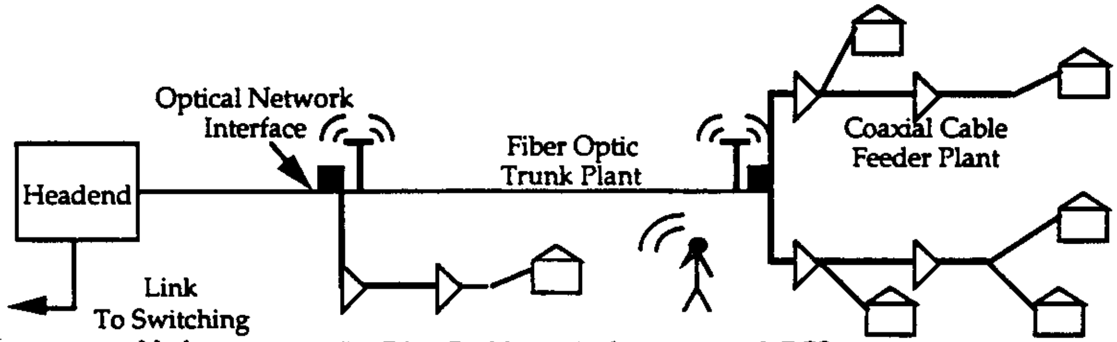
When the coverage area of the fiber node exceeds the cell size, then a connection between the fiber node and the cell site is necessary. The operator can either dedicate some portion of the transmission spectrum on the coaxial cable to deliver PCS or install a overlay a parallel network alongside the cable television network.[29] To simplify the analysis, all estimates reported below assume the fiber node and cell site are placed at the same location (or have identical coverage areas).

28By 1992, only 22 systems (out of the roughly 10,700 cable systems in the U.S.) have planned or built fiber backbone systems into the subscriber loop. The cable industry expects the number of fiber backbone systems to grow rapidly over the next few years. See *Multichannel News*, June 15, 1992, p. 1.

29To transmit PCS signals over the cable network, operators could use frequencies bands on their coaxial cable between 5 MHz and 30 MHz, or between 550 MHz and 1 GHz if the lower band is insufficient due to technical or capacity limitations. Because cable networks are only equipped to transmit information in the downstream direction, two-way amplifiers will have to be installed over any portions of the coaxial cable network used to transmit two-way PCS signals.



(a) Tree-and-Branch Architecture using Coaxial Cable



(b) Fiber Backbone Architecture with PCS

Figure 12. Cable Television Network Architecture to Deliver PCS

The cost of building a new, fiber-based cable television network is $424 per home passed, or an annualized cost of $137, when the penetration of cable television is 60 percent (Reed, 1991, Appendix B: Table B.17). This estimate assumes a fiber backbone architecture with fiber in the feeder segment of the network, and coaxial cable in the distribution and drop segments. The fiber node housing the optical network interface serves 1024 households. This estimate includes the cost of a video headend to provide 64 channels of distributed video and addressable converters at 60 percent of the households.

The cost of the fiber backbone in the cable network is $26 per home passed. When additional fibers are added to the fiber backbone for PCS, the costs of the feeder network can increase by an increment of up to $6 per home passed. Thus, the costs of adding more fiber to the backbone feeder cable are small. To calculate the cost of an integrated network, the model assumes billing, administrative, and network maintenance expenses decrease by 20 percent, and that PCS and cable television service use separate feeder fibers within the fiber backbone cable. There is no change in the switching, cell site and handset costs as a result of integrating PCS with the cable television network.

Given these assumptions, the cost functions indicate economies of scope exist between PCS and cable television service. Figure 13 plots the relevant cost functions assuming a 25 MHz spectrum allocation. The most expensive cost function in the graph is the combined costs of separate cable television and PCS networks. The next lowest cost function is the costs of the integrated network, with the area in between these two lines representing the economies of scope that can be realized by building an integrated network. Like the previous case with the use of the telephone network, the incremental cost function shows fewer economies of scale than does the PCS cost function because the cost of the wireline network includes a large portion of the fixed costs of delivering PCS.

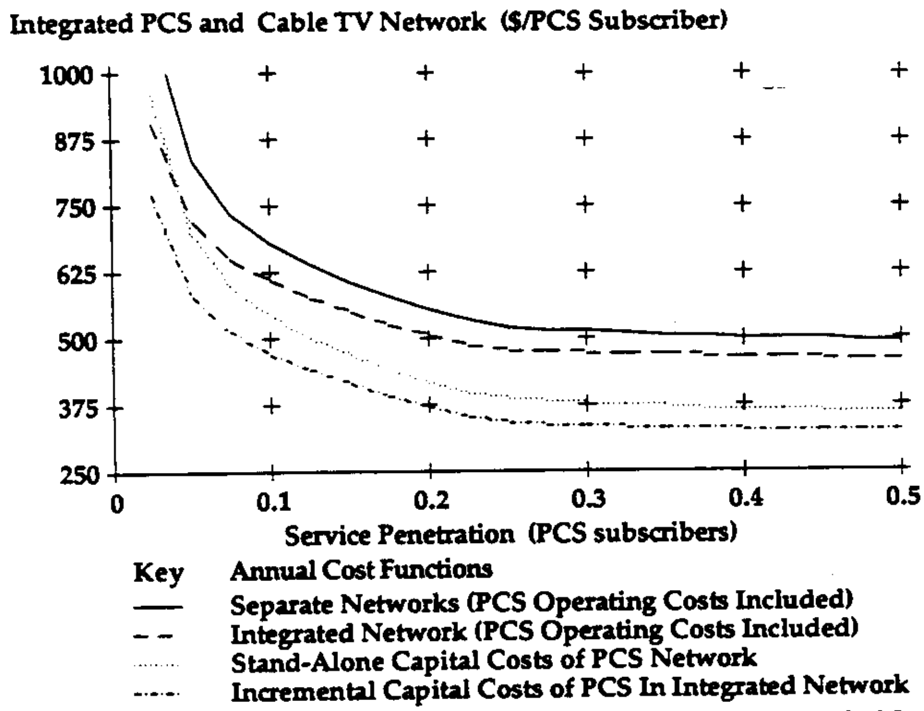


Figure 13. Measuring Economies of Scope Between PCS and Cable Television Service (in dollars); 25 MHz Spectrum Allocation

The strategic advantage of the cable television infrastructure is that it offers a ubiquitous, alternative medium of transport for PCS in residential areas. Through a fortuitous coincidence, the upgrade of the existing cable networks to a fiber backbone architecture to improve cable television service also provides cable operators an opportunity to deploy dark fiber that can be used to distribute PCS. Model results demonstrate that upfront fixed costs are reduced by using the cable network to distribute PCS.

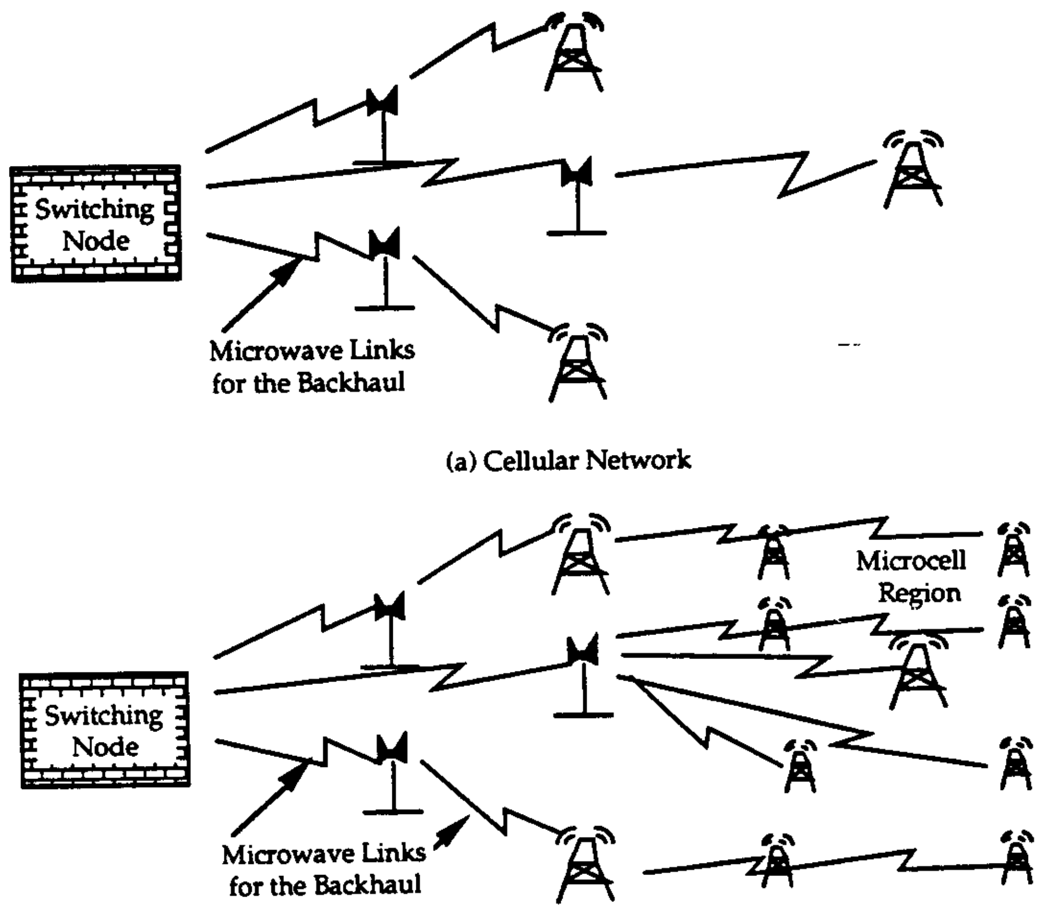
Whereas the existing copper telephone network could be used as backhaul for the PCS network, the existing cable television networks without fiber backbones probably would not be suitable to offer backhaul for PCS. The main problem is not capacity, since the coaxial cable offers a sufficient bandwidth to deliver PCS signals and video on the same cable, but that the tree-and-branch architecture of the existing coaxial cable network would require a complex multiplexing system, or large information bus, for concentrating traffic as well as the installation of two-way amplifiers along all trunk lines. Such an expensive modification to the coaxial cable system would seem unwise given the attractive economics of fiber backbone systems in the immediate future. Once fiber backbones are deployed, use of the remaining coaxial cable in the feeder and drop segments of the network can be used with much fewer technical constraints.

In sum, this study finds that cable companies that have upgraded their systems with fiber backbones present a competitive PCS transport alternative to the telephone network. Because cable companies generally have experience in transport services, plus shared network maintenance, administrative, and billing functions, they are logical candidates for commercial relationships with PCS licensees lacking sufficient network presence throughout the service area.

Providing PCS Over Cellular Networks

Because of the substantial similarities to today's cellular service, PCS are often described as second or third generation cellular services. Throughout this study, PCS have been differentiated from cellular services by describing PCS as portable mobile services featuring low-power, lightweight handsets that may not operate in vehicles travelling at a high velocity. Cellular services have been characterized as less portable services due to the high-power handsets required to maintain a connection over large areas. Clearly, these points of distinction are vague, and technological progress promises to further push the convergence of these two services in the future. Given this caveat, this section estimates whether economies of scope exist between PCS and cellular telephone services defined in this fashion.

The network architecture of a typical cellular system is shown in Figure 14(a). This architecture is similar to the PCS architecture with the exception that microwave links are usually employed for backhaul rather than fiber cable. Cellular operators favor microwave links over other alternatives because they are low cost, although this situation may change due to increasing traffic levels and the declining costs of fiber optic transmission systems. Figure 14(b) shows one possible approach for delivering cellular and PCS over an integrated network. A layer of macrocells provides high-power cellular service while another layer of microcells provides low-power PCS. Traffic gathered by the group of microcells is concentrated at macrocell sites for transmission to the switching node.



(a) Cellular Network

(b) Network Delivering PCS and Cellular Services Using Macrocells and Microcells

Figure 14. Cellular Telephone Architecture to Deliver PCS

Modifications to the cost model necessary to obtain a cost estimate of a cellular system include assuming a 25 MHz spectrum allocation, a frequency reuse factor N=7, and a duplex channel bandwidth of 20 KHz. Like the PCS model, each subscriber offers 0.03 erlangs of traffic during the peak hour and two subscribers per household. The model considers three macrocell sizes ranging from a radius of 8 Km. (a size which covers all 25,600 households in the model), to 4 Km. (covering 12,800 households), and 2 Km. (covering 6400 households). The antenna site costs for these macrocells are $300,000, $200,000, and $150,000 respectively, and the base station RF equipment costs $850 per channel. Calculations assume the backhaul network consists of fiber optic cable instead of microwave links.

Table 7 lists the estimated cost per subscriber of a cellular network at 10 percent penetration and shows the distribution of costs across network components, as well as the cost calculations used to arrive at this estimate. Assuming the cost of a portable cellular handset is $300, the model estimates a total cost of $593 per subscriber. At today's level of penetration of cellular service (about 3 percent), this translates into a cost of $1000 per subscriber, or $700 per subscriber not including the cost of the handset. As should be expected, this estimate is lower than the current costs of cellular infrastructure -- which is often cited in the range of $1000 to $1400 per subscriber (not including the handset) -- because it reflects the use of digital techniques and other new technologies.

Figure 15 plots the annualized cost function for cellular telephone service versus the level of service subscription. Note that the larger cell sizes of the cellular model have significantly weakened the economies of scale of the capital cost function at lower penetration levels relative to the PCS estimates. This confirms the earlier observation that the PCS cost function overestimates the presence of economies of scale by assuming cell sizes less than 1.6 Km. in radius.

Network Component	Future Cost	Cost Per Sub	Derivation of Cost for 25 MHz Allocation
		Switching Node	
Getting Started	400,000	78	1 node for city: 400K+5120
Access & Trunk Line Termination	350/access line	1	8 Access Line Terminations, 7 Trunk Line Terminations: (8 + 7)(350) +5120
Usage Sensitive (BH-Busy-Hour)	3/attempt; 936/erlang	34	2 attempts, 0.03 erlangs in BH per sub: 2(3)+.03(936)
Handoff	600/line	23	200 channels: 200(600) +5120
Total		136	
		Feeder Network	
Single Mode Fiber	0.1/meter	3	50-fiber cables, 2.9 Km.: 0.1(50)(2.9K) + 5120
Cable Sheath	4/meter	2	50-fiber cables, 2.9 Km.: 4 (2.9K) + 5120
Inner Duct, Splice	1.15/meter, 15	1	(15(50)(1) + 1.15 (2.9K)) + 5120
Remote Enclosure, Patchcords	1000, 75	1	16 active fibers, 2 enclosures: (2(1000) + (2)(16)(75)) + 5120
Cable Installation	12/meter	7	12 (2.9K) + 5120
Total		14	
		Cell Site (Optical Network Interface)	
Optical Line Card	100/card, 30	1	2 cells for region: 8 (1.4 (100)) + 5120
RF Circuitry and Control	850/channel	46	100 channels per cell: 850 (1.4 (2)(100)) + 5120
Antenna Site Costs	200,000/cell	78	2 cells for region: 2 (200K) + 5120
Power (cell only)	50/watt	18	93 active channels: 50 (10) (2) (93) + 5120
Total		143	
Handset	300	300	
Overall Total		593	

Table 7. Cost per Subscriber of Cellular Network (in dollars); 10 percent penetration of PCS

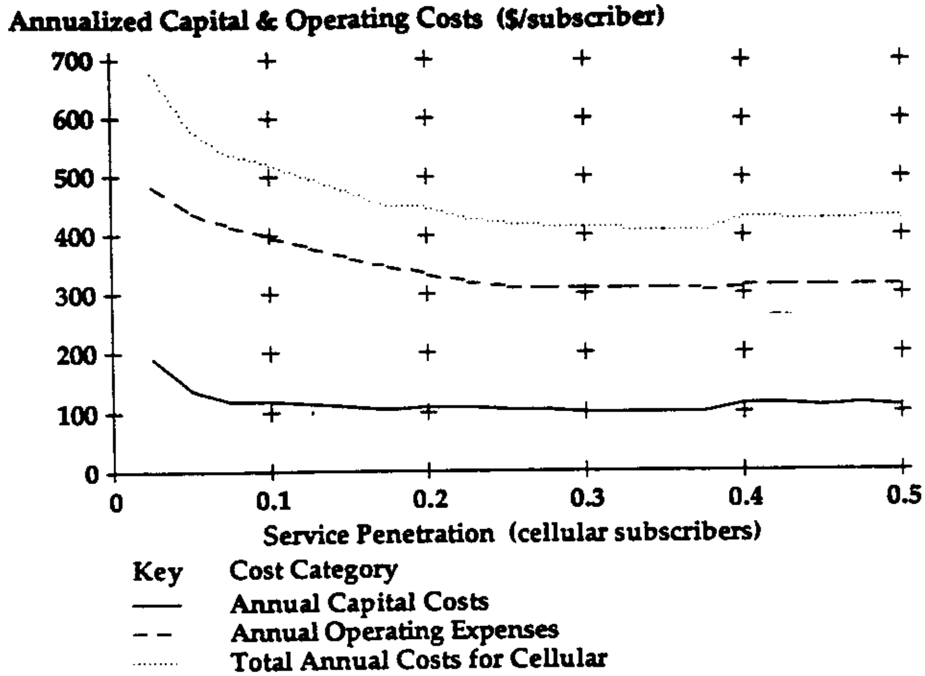


Figure 15. Annual Cost Function for Cellular Telephone Service (in dollars)

A PCS network of microcells and a cellular network of macrocells could share portions of the switching, backhaul, and cell site, and handset costs (see Figure 14(b)). To estimate the magnitude of the economies of scope between these services, however, the model only assumes that the start-up costs of the switch and handset costs can be shared. This assumption ignores potential economies of scope between switching, portions of the backhaul, and antenna site locations. In order for the same handset to be used for both services, the model assumes a power booster module for use in cars at a cost of $50.[30]

As was the case with telephone and cable television networks, model calculations assume combined operations of cellular and PCS billing and administrative functions reduces annual costs by 20 percent. Network maintenance costs of PCS facilities that are part of the cellular network are also 20 percent less.

Figure 16 plots the costs functions given these assumptions. Most of the economies of scope calculated between these two services stem from savings in shared use of handsets. Because handset costs are variable costs, the economies of scope shown in this graph do not significantly reduce the fixed costs of the PCS network. Recall that these calculations do not reflect the extent to which backhaul and antenna cite costs could be shared between PCS and cellular service.

[30]This cost estimate assumes the power module could simply snap on the handset and operate much like current cellular portable phones. This cost would be much higher if the power booster saddle and antenna must be installed in the car.

Economies of scope in these components would serve to reduce the fixed costs of a PCS system integrated with a cellular network to a degree not shown in this graph.

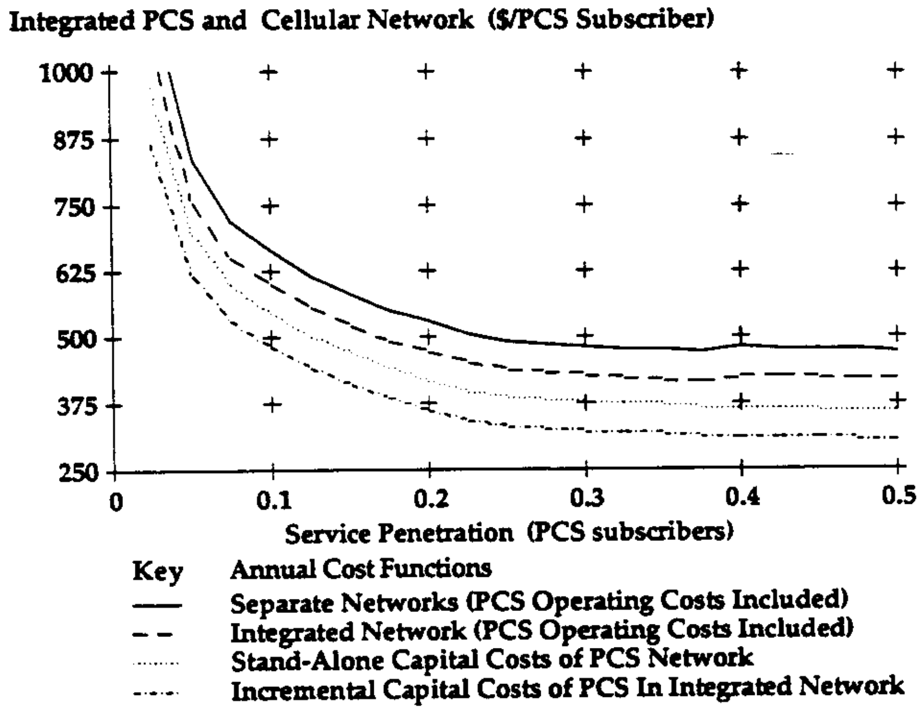


Figure 16. Measuring Economies of Scope Between Cellular and PCS (in dollars); Two Separate 25 MHz Spectrum Allocations For Each Service

These results suggest that cellular companies have some of the service components in place to deliver PCS. Because of the similarity between cellular and PCS, cellular operators clearly cannot afford to be complacent regarding the development of PCS markets. The competitive threat of PCS will spur cellular carriers to reasonably match the services and features offered by PCS providers. Cellular companies can meet this challenge by taking advantage of the similarity of these services and fully utilizing their infrastructure to provide elements of PCS

The likelihood of competition between PCS and cellular services leads to the interesting question of how much it might cost a PCS or cellular licensee to offer both PCS and cellular services over its existing spectrum assignment. The integrated network would consist of a microcell network to distribute PCS and a macrocell network to distribute cellular services. Figure 17 plots the estimated annualized capital costs of this integrated network versus the amount of spectrum dedicated for PCS out of the total allocation (assuming a 10 percent penetration rate) assuming a 20 MHz, 25 MHz, 30 MHz, 35 MHz, or 40 MHz block of spectrum. The calculations assume shared handset costs and start-up switching costs between PCS and cellular services. The "u-shaped" curve reflects the high costs of a network when only a small amount of spectrum is available for

PCS (the left-hand side of the graph) or cellular services (the right-hand side of the graph) for these spectrum block sizes.

For the technology considered in the base case, this graph shows that 20 MHz is enough spectrum to offer both PCS using microcells and cellular services using macrocells at competitive unit costs. The benefits (in the form of savings in capital costs) of a spectrum block size greater than 20 MHz are small (roughly an annual cost of less than $25 per subscriber). As long as each service has roughly 10 MHz of spectrum dedicated for its use, there does not appear to be substantial economies to be obtained from a larger block size. A 20 MHz spectrum allocation size, however, could make it too costly for a network operator to deliver both cellular services and PCS using low-cost, low-spectrum efficiency radio systems (*i.e.*, a radio system with a channel size of 70 KHz and N=16) for PCS. Figure 18 plots the estimated annualized capital costs of an integrated network providing PCS and cellular services using this technology versus the amount of spectrum used for PCS out of the total allocation (assuming a 10 percent penetration rate) for the same range of spectrum block sizes.

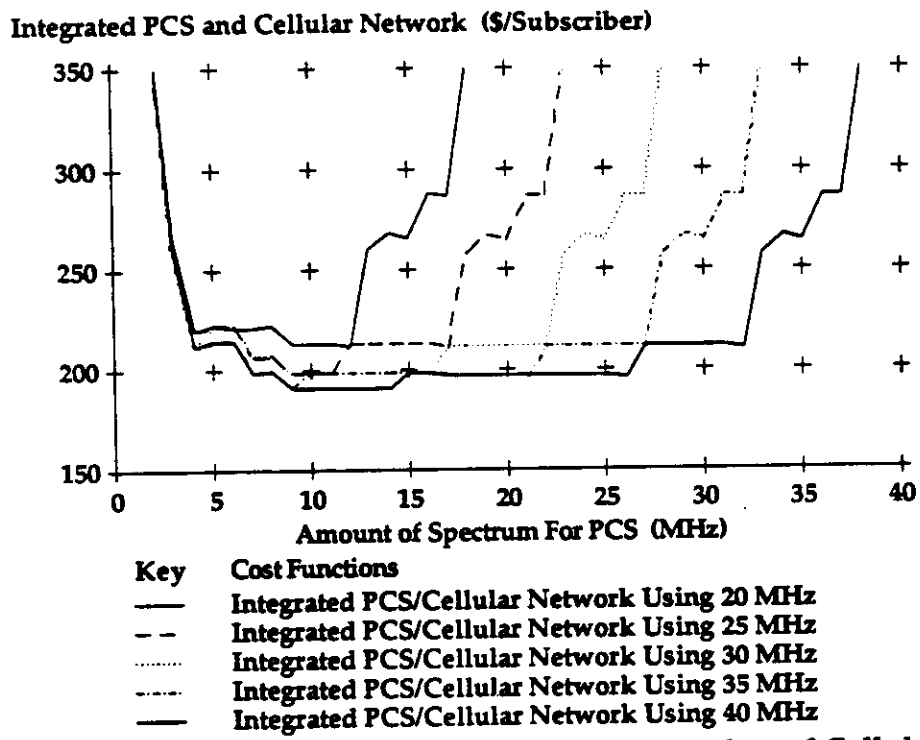


Figure 17. Average Annual Capital Cost Per Subscriber of Cellular System and Base Case PCS System Assuming Varying Amounts of Spectrum Dedicated for PCS; 10% Penetration (in dollars)

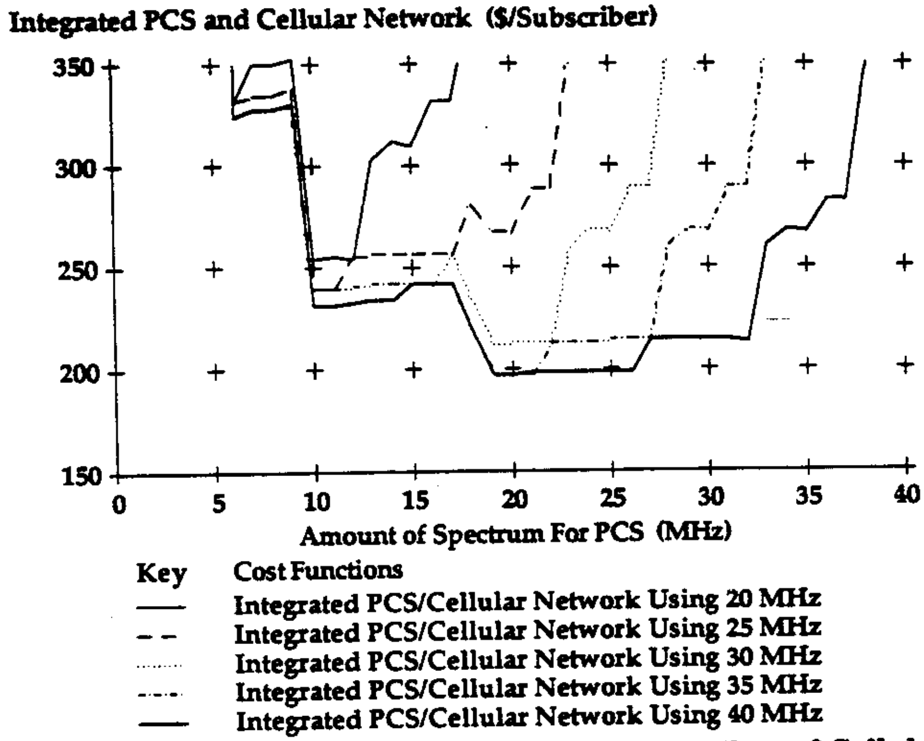


Figure 18. Average Annual Capital Cost Per Subscriber of Cellular System and PCS System (N=16, Channel Size=70 KHz) Assuming Varying Amounts of Spectrum for PCS; 10% Penetration (in dollars)

Figure 18 demonstrates that the benefits of a spectrum allocation size greater than 20 MHz are larger when a technology with lower spectrum efficiency is considered. In this case, the benefits of a radio system (with a channel size of 70 KHz and frequency reuse factor of N=16) increase to about $50 per subscriber for a block size of 35 MHz or 40 MHz. The reason for this increase is that an allocation size below 35 MHz is insufficient to deliver both cellular services and this PCS system at the same level of costs (recall the earlier result in Figure 8 that showed at least 20 MHz is required to viably implement this system).

The results in Figures 17 and 18 also illustrate the benefits that current cellular operators could realize with up to 15 MHz in addition to their 25 MHz allocation.[31] For the base case assumptions, the marginal benefit of additional spectrum appears to be relatively small. When the case of a system with lower spectrum efficiency system is considered, however, results show more substantial benefits for a spectrum allocation size of 35 MHz or more.

[31]These cost estimates do not consider the additional costs in network equipment and handsets that could arise if this additional spectrum lies in the 2 GHz band given the 25 MHz cellular allocation is located near 800 MHz. The additional frequency agility required in the network equipment under these circumstances is likely to increase radio system costs.

Overall, the important point is that an operator could provide both PCS using a microcell network and cellular services using a macrocell network at reasonable costs with a modest amount of spectrum. Consequently, cellular companies will have strong incentives to respond by competing in PCS markets, and strategic advantages in entering these markets. The similarity between cellular and PCS will allow cellular operators to use their existing switching, transport, and cell sites to deliver PCS and lower the incremental costs of entering the market. This similarity, however, also has led to suggestions that cellular operators be barred from holding new PCS licensees in order to prevent them from dominating emerging PCS markets. See Section IV for a discussion of whether cellular carriers ought to be eligible for PCS licenses.

Summary and Discussion

The analysis of this section discovers two important results. First, model results indicate that economies of scope do exist between PCS and telephone, cable television, and cellular telephone services using the network technologies described in Appendix A and Section II. Table 8 summarizes the magnitude of the economies of scope measured between PCS and these services, and shows the distribution of savings across network components for these infrastructure alternatives. Given the conservative nature of these estimates -- recall that in all alternatives potential trunking efficiencies in switching and transport were not considered -- little emphasis should be placed on the relative magnitudes of these savings across infrastructure alternatives. Second, the economies of scope found between PCS and both telephone and cable television services (and potentially cellular services as well) change the form of the cost structure for PCS. Using existing infrastructure exchanges fixed costs for variable costs in the cost function. As a result, the economies of scope not only lower the investment initially necessary to provide PCS, they could reduce the level of subscription where economies of scale are exhausted to 10 percent of the household depending upon the tariff structure of the leased switching and transport facilities.

Existing Infrastructure	Switching	Wireline	Handset	Other Operating Costs	Total Savings
Telephone Network	14	41	0	28	83
Cable Television Network	0	46	0	28	74
Cellular Network	14	0	24	27	65

Table 8. Estimated Annual Savings For PCS Using Existing Infrastructure; 10 Percent Penetration of PCS, 25 MHz Spectrum Allocation for PCS (in dollars)

While this section has focused upon the use of telephone, cable television, and cellular networks to deliver PCS, a number of alternative players or combinations of players are also likely to participate in the development of these markets. For example, strong economies of scope appear likely to exist between PCS and a joint venture of cable television and cellular companies. Such a venture may be attractive as cable operators seek to offer more services over their new fiber backbone networks and cellular operators attempt to expand the functionality and portability of their switched wireless services.[32] For example, this venture could pursue a strategy of continuing to use the cellular infrastructure for premium cellular service and using the cable infrastructure to link together the microcells designed to serve the mass market with PCS.

In contrast, an independent firm -- an entrepreneur or small company that obtains a PCS license but does not own any existing infrastructure in the subscriber loop -- probably would not choose to construct a stand-alone PCS network. Results indicate the fixed costs of a PCS network using microcells are high in relation to the fixed costs of providing PCS using existing infrastructure. This cost differential is especially dramatic at the low levels of penetration which are to be expected during the first few years of deployment. Instead, the independent provider is likely to pursue a strategy of negotiating alliances or commercial relationships among the infrastructure alternatives available to deliver PCS.

Table 9 offers a broad, but not necessarily comprehensive, list of infrastructure alternatives with which PCS licensees are likely to seek strategic alliances or lease resources. Each table column represents a large functional component of PCS, including the advanced signaling and intelligent nodes component of these services which have not been considered in the cost model. The table reports which infrastructure alternatives could serve as potential sources for these functional components based upon whether economies of scope might exist between PCS and the services already provided by the infrastructure. The table notes where the economies of scope have been verified by the cost model reported in this paper, and where the economies of scope are subjective assessments that have not been verified by the cost model.

Beyond the infrastructure alternatives considered above, Table 9 also includes several other existing telecommunications companies which may have an interest in using their infrastructure to provide PCS. This list includes interexchange carriers, competitive access providers (CAPs), and electric or gas utilities. Two players of particular interest are the interexchange carriers and CAPs. Interexchange carriers have substantial experience in network operations, administration, and maintenance, as well as intelligent network services, and a limited network switching presence. CAPs will also be developing similar expertise as regulatory barriers to competition in the local telephone exchange market are removed. Both of these players would also seem to be logical candidates for commercial relationships with players who hold a stronger presence in the subscriber loop, such as cable companies, cellular companies, or

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[32]Market trials are under way which explore the synergies to provide PCS between cable and cellular operators. In Ashland, Oregon McCaw and TCI have deployed four low-power microcells interconnected with McCaw's existing cellular switching facilities via TCI's fiber optic cables. See *Telecommunications Reports*, March 23, 1992, p. 37-38. In Trenton, New Jersey, Comcast is conducting a market test to use Comcast's cable network to route calls from microcells into their cellular network. See *Multichannel News*, September 30, 1991, p. 50.

independent PCS providers. Finally, electric or gas utility companies might be interested players since they enjoy pole attachment rights and right-of-way throughout service areas.

Infrastructure Alternatives	OA&M*	Advanced Signalling Network & Intelligent Nodes	Switchin g	Transpor t	Cell Sites	Hand -sets
Telephone Network	•	Δ	•	•		
Cable Television Network	•			•		
Cellular Network	•	◊	•	◊	◊	•
Cable/Cellular Joint Venture	•	◊	•	•	◊	•
Interexchange Carrier	Δ	Δ	◊			
Competitive Access Provider	◊	◊	◊	◊		
Electric or Gas Utility				Δ		

* OA&M - Operations, Administration, and Maintenance Services

• Economies of scope found to exist in this component by cost model reported in this paper

Δ Strong economies of scope likely to exist in this component, although not verified by cost model

◊ Limited economies of scope likely to exist in this component, although not verified by cost model

Table 9. Subjective Assessment of Potential Sources of PCS Functional Components Between Infrastructure Alternatives

Section IV. Public Policy Implications

A primary policy objective of the PCS regulatory model proposed by the FCC is to expand the availability of wireless services to both business and consumer markets by increasing the amount of spectrum and suppliers delivering these services (FCC, 1992a, ¶25-28). More spectrum would lower the costs of providing wireless services to consumers by lowering spectrum efficiency requirements. More wireless service providers would allow competition to develop between PCS providers and lead to lower prices, more innovative services, and better service quality.[33] In addition, consumers would be likely to benefit from PCS providers competing directly with cellular services due to the similarities of these services. Thus, the most important aspects of the regulatory model could be the amount of spectrum allocated for PCS and the number of new licenses to be issued for any given service area.

[33]The loss of consumers benefits through monopoly rents is well documented in the economics literature. Recent studies of the cellular duopoly suggest the two carrier market structure provides insufficient incentives for suppliers to price services near costs (*i.e.*, the benefits to consumers from competition between the two carriers are limited). See "Concerns About Competition in the Cellular Telephone Service Industry," U. S. General Accounting Office, July 1992. The long distance telephone market offers an example of a telecommunications market with open entry and three large carriers, and the additional benefits arising to consumers of suppliers pricing services closer to costs.

Beyond the benefits of competition to consumers, there are two other policy objectives which are relevant to this analysis.

- *Minimizing Unnecessary Delays.* The regulatory model should eliminate unnecessary regulatory delays and establish a market structure which fosters the rapid development of PCS markets.
- *Facilitating Development of an Efficient Infrastructure.* Components of the PCS network may be drawn from a number of existing infrastructure. The regulatory model should facilitate the development of new infrastructure, or use of existing network resources, that represent an economically efficient means to deliver PCS.

This section examines the implications of the engineering and economic analysis reported in this paper on four policy questions raised by PCS: the service definition of PCS, the size of the spectrum allocation and number of PCS licenses in any given market, and whether eligibility restrictions are necessary for PCS licenses. The discussion of these policy issues follows a simple framework. First, how are results of this study relevant to the particular policy issue? And second, in light of these results, what are the best policy options using the three policy objectives as a means for evaluation.

Service Definition of PCS

The service definition of PCS will determine the authorized uses for spectrum in a PCS license. The definition of PCS has two important elements: the type of services that are permitted with a PCS license, and the technical standards for the radio systems operating under a PCS license. A narrow service definition of PCS could limit the services that can be offered with a PCS license, or mandate the technical parameters of a particular radio system standard. Alternatively, a broad service definition of PCS would not restrict the types of services permitted under the license, and would limit the scope of technical standards to managing interference concerns. In light of the substantial uncertainties regarding PCS, this analysis concludes that substantial flexibility should be afforded licensees in how they are authorized to provide services under the PCS licenses.[34]

One conclusion that can be drawn from the technical and economic review of wireless technologies conducted in Appendix A and Section II is that substantial uncertainties continue to exist regarding future wireless services and the technologies that will be used to convey them. PCS have the potential to encompass a broad family of existing voice and data services, both indoor and outdoor, as well as unknown future applications. Service providers remain uncertain regarding the group of features that consumers will value the greatest. Indeed, aspiring PCS providers are just beginning to conduct serious market

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[34]This finding is generally consistent with the service definition proposed by the Commission. The *NPRM* defines PCS broadly as any mobile or portable services, not to include broadcasting service, or fixed point-to-point service unless it is ancillary to the provision of PCS (FCC, 1992a, ¶29-30).

trials to assess consumer demand by learning, for example, the importance that consumers place upon features such as the degree of mobility, service quality, and handset size. (Over the past three years, the FCC has granted almost 150 experimental licenses to conduct technology and market trials of PCS.) These uncertainties in consumer demand make it difficult to forecast what are the best services and technologies for PCS. Thus it is not surprising to find that a myriad of different definitions of PCS have been offered, along with a variety of network architecture proposals.

These uncertainties favor a broad definition of PCS so as not to eliminate the consideration of any promising new technologies or service concepts. Similarly, under a broad definition, PCS providers would have the flexibility to develop an efficient infrastructure to deliver services. A narrow definition of PCS would inevitably favor particular applications, technologies or network infrastructure. Different wireless network services require starkly different operating requirements for network parameters such as transmitted power levels, handset features, and system coverage. These differences translate into a variety of network architectures (*e.g.*, macrocell versus microcell) which are optimized for different applications. A PCS definition that mandates the provision of a large number of services also could be inappropriate since there is no guarantee that a single network designed to carry the greatest common denominator of wireless services would be more efficient than separate networks optimized for smaller groups of services.

Moreover, a broad definition would permit innovative approaches to spectrum use. A PCS licensee, for example, may find it cost-effective to use a part of its spectrum for fixed point-to-point wireless links for backhaul. Technical standards which specify channelization requirements for PCS spectrum could limit this flexibility.

Some have pointed to the need for common technical standards as a reason to not adopt a flexible service definition. Under a service definition of PCS that includes a detailed standard, consumers could benefit from PCS systems that are interoperable and permit users to subscribe to any PCS providers' services without having to switch handsets. Interoperability would allow users to roam between PCS systems in different geographical regions with technical compatibility virtually guaranteed. In addition, a common air interface standard for PCS could lower handset costs by making this device a commodity widely produced by a large number of manufacturers, and would prevent consumers from being "locked in" to a certain provider because the costs of changing to new suppliers are very high.[35] Finally, proponents of requiring adherence to detailed

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[35]In written testimony to the FCC, Donald C. Cox calls for a minimum set of standards which enable the interoperability of customer handsets among the offering of different PCS providers. He cites Bellcore's experience with the development of industry consensus on generic requirements for the public switched telephone network as evidence that industry forums can achieve a common standard. In particular, he cites the successful development of the Synchronous Optical Network (SONET) standards which first began in 1984, and

technical standards argue that a voluntary standard may not appear if left to market forces.[36]

Nevertheless, a broad service definition without detailed technical standards would minimize regulatory delay, which could be significant in light of the uncertainties noted above. A broad definition avoids the delays of waiting for technical standards to emerge from a standards body. With no mandatory technical standards, PCS providers could respond rapidly to changes in consumer preferences instead of having to go to a standards body and achieve consensus before any changes can be implemented.[37] Given the breadth of PCS applications and technological options, and the diversity of interests likely to be present in an industry standards group, the prospects for a quick agreement to a technical standard would seem remote.[38]

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is now going into service across the country. See Written Statement of Dr. Donald C. Cox before the FCC's *En Banc* Hearing on December 5, 1991.

[36]The issue of what factors contribute to the formation of voluntary standards is complex. Sirbu and Stewart link the emergence of standards to the market structure. They argue that incentives are largest for a single standard to emerge in the presence of decentralized providers and unrelated buyers. Thus, given PCS is targeted for the mass-market (or unrelated buyers), incentives for a single standard increase with an increasing number of PCS licenses. See Sirbu, M., and S. Stewart, "Market Structure and the Emergence of Standards," Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, 1986. This relationship also has implications for the size of the service area for each PCS license. Nationwide PCS licenses could decrease incentives for interoperability and common standards because of the smaller number of centralized providers, each of which would attempt to implement its own standard. In contrast, smaller service areas would increase the number of PCS licensees and create more incentives for the decentralized providers to agree upon common standards.

[37]Even with flexible licenses, some technical standards are necessary to constrain interference levels below a designated threshold. Interference limits of PCS systems will be necessary between adjacent frequencies and geographically adjacent areas. In the 2 GHz band it is likely that PCS licenses will occupy the same spectrum as existing microwave users, in which case technical restrictions limiting the interference between these incumbents and PCS users will be necessary as well.

[38]Even though cellular licenses included a detailed technical standard for cellular radio systems, these requirements probably did not contribute significantly to the long regulatory delay experienced in the roll-out of cellular services because there were not any significant competing alternatives to the FDMA analog technology. In the cellular case, most of the regulatory delays resulted from the overall rule making and licensing process. In written testimony to the FCC, Charles L. Jackson estimates that the regulatory delays in implementing cellular between 1973 and 1984 resulted in a loss of $86-billion to the

For these reasons, the benefits of broad service definition appear at this time to exceed the costs of attaching detailed technical standards to PCS licenses.

Number and Size of Spectrum Allocations

The total amount of spectrum allocated for PCS limits the number of licenses and spectrum block size.[39] While the amount of spectrum that the FCC will allocate to PCS has yet to be decided, the total amount could range between the 220 MHz that has been proposed as part of the emerging technologies band near 2 GHz (FCC, 1992b) and the minimum of 90 MHz proposed by the FCC for licensed operation (FCC, 1992a, ¶37). In addition, the *NPRM* proposes between 3 to 5 new licenses in each market (FCC, 1992a, ¶38-40).

Number of Licenses

Based on the estimated cost function of a stand-alone PCS network reported in Section III, the economies of scale for a PCS network appear to be largely exhausted above a 20 percent penetration rate for all spectrum block sizes above 5 MHz. When the economies of scope between PCS and existing services are considered, the economies of scale for a PCS network are mostly exhausted above penetration rates of 10 percent. Note that these results should be viewed as overstating the penetration levels at which economies of scale are exhausted because the model assumes a network architecture with microcells smaller than 1.6 Km. The model has shown that the costs of a microcell network incur much higher fixed costs than a macrocell system. Consequently, the economies of scale of a macrocell PCS network would be expected to be mostly exhausted for penetration levels less than 10 percent.

Given this presence of economies of scale at low penetration rates, some might argue that a large number of suppliers could prevent the industry from capturing economies of scale when the total industry penetration rate is low. To investigate this question, Figure 19 plots the total annualized costs per subscriber of a PCS network assuming there are between one to six suppliers who evenly split the market and each supplier possesses a 20 MHz block of spectrum. This graph shows that if the *total* rate of penetration for PCS is 20 percent, annualized costs

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American economy. See Written Statement of Dr. Charles L. Jackson before the FCC's *En Banc* Hearing on December 5, 1991.

[39]This total will likely include spectrum for PCS licenses analogous to current cellular licenses and spectrum for unlicensed applications. This discussion focuses upon the amount of spectrum needed for licensed applications. Any spectrum required for unlicensed applications is spectrum required in addition to the total allocation amounts discussed below. Unlicensed applications that could be used over this band of frequencies include the transmission of high or low speed data between computers, cordless telephones, and wireless PBXs. See, for example, *Petition for Rulemaking*, RM-7618, filed at the FCC by Apple Computer, Inc. on January 28, 1992.

would be roughly $400 per subscriber with one supplier, and up to $725 per subscriber with six firms splitting the market.

The economies of scope found in this analysis between PCS and existing services, however, would reduce the effect on infrastructure costs of having a large number of firms in the market. Figure 20 shows how annualized costs vary with the number of suppliers assuming PCS are offered using the telephone network for switching and transport. (Note these figures include the costs of the telephone network and are therefore not directly comparable to the stand-alone PCS network costs shown in Figure 19). In this case the cost differential between one firm and six firms in the market becomes only $200 per subscriber at 20 percent penetration, and $125 per subscriber at 30 percent penetration.

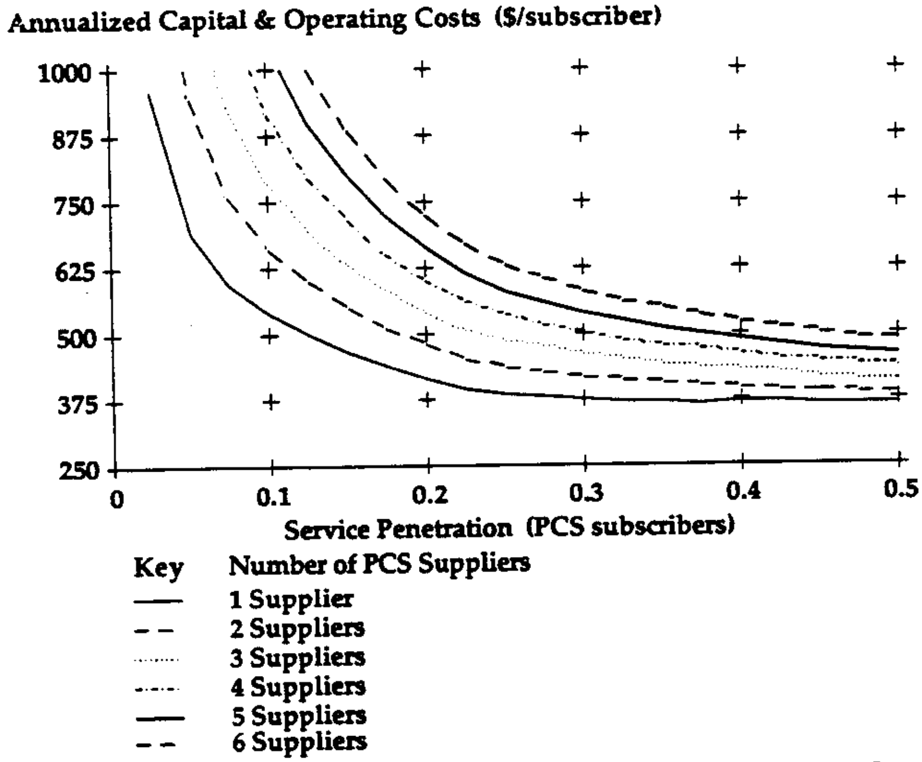

Figure 19. Variation in Total Annual Costs to Varying Numbers of Firms in the PCS Market; 20 MHz Spectrum Block (in dollars)

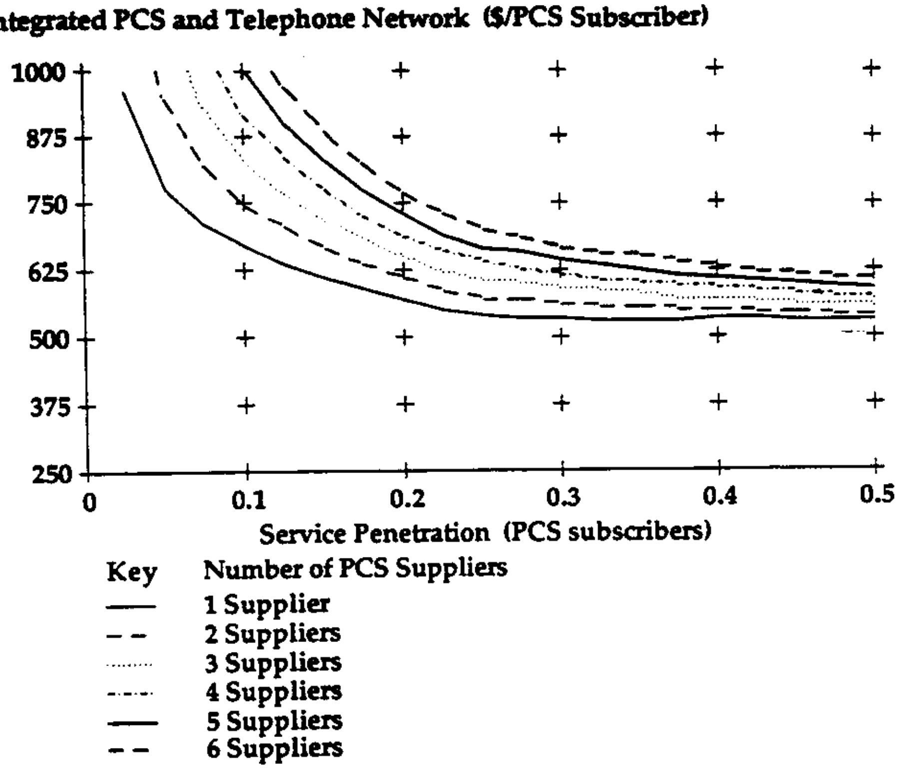

Figure 20. Variation in the Annual Costs of an Integrated PCS and Telephone Network (Including Capital and Operating Expenses for PCS Only) to Varying Numbers of Firms in the PCS Market; 20 MHz Spectrum Block (in dollars)

These results provide no justification for limiting the number of licenses to the market due to the characteristics of the cost function. A truly mass-market wireless service can be expected to obtain penetration levels well above 30 percent over a period of several years. At this level, the study results suggest several firms could compete with only minimal losses in efficiency. At an industry penetration level of 30 percent, the difference in total annualized costs between one supplier or six suppliers would be about $125 per subscriber, or only $10 per month.[40] This figure represents the additional costs of duplicate wireless facilities (but not necessarily duplicate switching and transport facilities if such

[40]Compare this figure to the $300 to $800 per subscriber marketing costs common to the cellular industry. Because of the limited opportunity for facilities-based competition in the cellular duopoly market, cellular carriers can afford to spend large amounts on signing up new subscribers, and then recover these costs with subsequent usage.

facilities would be provided by existing network operators) that would arise if each PCS supplier chose to construct its own system.[41]

These results also demonstrate that the marginal cost of introducing another supplier decreases with each successive entrant. Consequently, allowing up to six suppliers would be reasonable given the small incremental costs of adding a fourth, fifth, and sixth supplier at penetration levels above 20 percent. This finding would be even stronger if PCS providers chose to deploy systems with larger cell sizes than were assumed in the cost model because of the smaller fixed costs incurred by systems using large cells.

Of course, the most efficient number of suppliers surely will vary with local conditions. If service penetration levels turn out to be much lower than expected, then a more concentrated market might be the outcome given the economies of scale present at low penetration rates. Even in this outcome, however, the policy objective of extending the benefits of competition is still best served by having more licenses than actual suppliers given that spectrum constraints have been met. First, it is far better for several licenses to be issued, and only one or two new systems constructed, then for only one or two licenses to be authorized and economic forces never given the chance to determine the appropriate number of competitors. Second, the threat of competitive entry by the other licensees will serve as a market check upon the prices, service quality, and service options offered by PCS providers. Third, if PCS is defined broadly as suggested above, then licensees will still have the flexibility and incentives for innovation to find a niche market for wireless services and otherwise use the spectrum in productive fashion. Fourth, a smaller number of licenses (which implies a larger license size) could increase the acquisition costs beyond the reach of smaller firms, even though the additional spectrum may not be essential to deliver service.

Some have argued that issuing a small number of licenses is a more efficient since the FCC can always issue more licenses at a later date if it appears more are needed (APC, 1992). This strategy is not likely to be efficient for a number of reasons. First, the preceding cost study suggests that up to six licenses could be issued while still satisfying constraints on spectrum requirements. A small number of licenses could be justified if the cost function for PCS exhibits strong economies of scale for the relevant spectrum allocation sizes; the results of this study suggest this is not the case. Second, there could be significant delays in issuing subsequent PCS licenses, especially given that incumbent PCS licensees will find it in their interests to delay the entry of potential competitors. Third, allowing all PCS licensees entry into the market at the same time would allow each licensee equal access and opportunity to develop the market. Limiting entry

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[41]Whether the entry of up to six firms is efficient is a complex modeling problem which depends upon the characteristics of demand curve for PCS and the pricing strategies of the suppliers. Such an effort to find the optimal market structure for PCS according to these parameters is beyond the scope of this study. The importance of the results reported above is that they do not preclude, or cast serious doubts, upon the prospects of having three or more suppliers in the PCS market due to any inherent properties of the cost function.

at the outset of the PCS market could deny some operators from participating in a phase of high growth at the initial stages of market development.

The policy objectives of minimizing delay and infrastructure development can also be well served by increasing the number of PCS licenses. The competitive market formed by issuing several licenses engenders strong incentives for suppliers to develop the market quickly in advance of other competitors. Some have made the argument that offering more than one or two PCS licenses will actually delay the construction of new systems due to the increased investment uncertainties created by the competitive market. While there is certainly no guarantee that investment in a PCS system will be profitable, a policy that seeks to minimize investment uncertainty by artificially constraining the availability of PCS licenses is not certain to speed up the rollout of PCS. Indeed, limiting the number of PCS licenses could delay or limit service provision as suppliers restrict output to increase prices and are less responsive to service requests. With regard to the availability of investment capital, a more efficient alternative is to let the capital markets determine how many networks should be built than to have the FCC reduce the number of licenses in an effort to promote investment by managing market entry.

In addition, results of the engineering cost model demonstrate that using portions of the existing telephone, cable television, and cellular networks to deliver PCS could reduce upfront investment costs. Limiting the number of licenses would reduce the number of switching and transport alternatives delivering PCS, and thus not fully exploit potential economies of scope available through these alternatives.

Lastly, it should be noted that numerous licenses would offer more flexibility to resolve other licensing issues. For example, with six licenses available the FCC would have much more flexibility to offer a mix of nationwide, regional, and local licenses, or to permit telephone and cellular companies to have some form of eligibility to hold new PCS licenses.

Amount of Spectrum Per License

The model also provides insight on how much spectrum should be allocated for each PCS license based upon infrastructure costs. Parametric analysis of the cost function has demonstrated how costs decrease as the size of the spectrum allocation increases and less spectrally efficient systems can be deployed. For the base case assumptions, model results show little variation in the system costs for spectrum block sizes above 5 MHz. For a system with a lower level of spectral efficiency than the base case, the model indicates little variation in system costs once the allocation exceeds 20 MHz (see Figure 8). Thus, so as not to preclude this lower cost technology, a spectrum allocation size of at least 20 MHz would appear to be a reasonable lower bound on the spectrum allocation size for any PCS provider.

While this study has assumed that all the spectrum in the allocation is available to the licensee, in reality PCS applications will have to coexist with existing fixed point-to-point microwave users in the 2 GHz band. Barring alternative means for compensating these users to move to other frequencies, PCS providers will not be able to utilize the full amount of the spectrum in the allocation due to these microwave users for several years. The severity of this problem hinges upon the number of microwave links within a service area, and the location of the links relative to PCS usage patterns. Microwave users are not uniformly distributed within the U.S., but concentrated in a few regions of heavy use (Marrangoni, Campbell, et al., 1992). In short, while the model results show that the benefits of additional spectrum above 20 MHz of clear spectrum are minimal, the increased interference requirements due to incumbent microwave users could be a reason for a larger spectrum allocation size, particularly in regions of dense microwave use.[42]

One side-effect of having the 2 GHz band populated with incumbent microwave users is that spectrum allocation sizes that are multiples of 20 MHz are attractive. The existing channelization plan for microwave users in this region generally allocates spectrum in 10 MHz channels. The FCC has proposed a plan of negotiated reallocation which would allow PCS providers to negotiate with microwave users and compensate them for any costs incurred for moving to another frequency band (FCC, 1992a). Consequently, relocation negotiations are likely to be more difficult when the spectrum allocation of the microwave user overlaps two separate PCS licenses because one licensee could attempt to gain a "free ride" at the expense of another licensee trying to move the microwave incumbent. A PCS license size that is a multiple of 20 MHz should eliminate most cases in which this situation could occur. A 30 MHz spectrum allocation size is likely to encounter this situation to some extent since the allocation is separated into two 15 MHz allocations, one for each direction of transmission, which will have to overlap onto more than one 10 MHz microwave channel.

A 20 MHz allocation also might not provide enough spectrum to deliver wireless applications that have not been considered in this analysis. The engineering cost model assumes a network architecture consisting of microcells delivering symmetric, narrowband, interactive channels to small, lightweight handsets. While this architecture has enough flexibility to deliver a large family of wireless services, there could be other applications, perhaps not even conceived of at this point in time, with characteristics that require wider channels and a larger spectrum block size than 20 MHz (*e.g.*, new radio access techniques or wireless data services).

This analysis shows that all three policy objectives are best satisfied by the licensing option that provides the highest number of suppliers while still

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[42]To put the problem into perspective, Telesis Technologies Laboratory has developed a model to estimate the amount of spectrum available in the 1850 to 1990 MHz frequency band given the presence of microwave users. Using low power PCS transmitters, their model predicts that about 120 MHz out of this band could be used throughout 90 percent of the San Francisco or Dallas areas, and 100 MHz could be used throughout 90 percent of the Los Angeles area. See Telesis Technologies Laboratory, *Experimental License Progress Report to the FCC*. February, 1992.

providing at least 20 MHz to each provider. Thus, given that the FCC has indicated that it will allocate a minimum of 90 MHz, licensing options that include five or six 20 MHz PCS licenses would appear to be the most attractive. There could be concern, however, that the 20 MHz licenses may not be sufficiently large to allow suppliers to implement low-cost radio systems in areas where high densities of microwave users exist, or to provide additional complementary services beyond the microcell services considered in this analysis.

There are at least two possible solutions to this problem. The first would be simply to assign licenses of 30 MHz each, thereby providing a 10 MHz "cushion" to address these concerns. This option, however, could result in licenses which are too large in those instances where 20 MHz is sufficient. A 30 MHz allocation would also not fit as well with the existing 2 GHz channelization plan.

A better option would be to assign 20 MHz licenses, but allow licensees to acquire additional spectrum up to a 40 MHz limit.[43] Results of the model indicate that 40 MHz would be a reasonable limit in this regard (*i.e.*, the marginal benefits of additional spectrum above 40 MHz likely would be to be very small, and the market would appear to support at least three suppliers after consolidation). If six licenses are initially granted, this option would still guarantee that at least three independent suppliers exist, with a market test to determine the size of licenses and number of competitors.

While allowing licensees to obtain only complete licenses would be the most administratively simple solution, the market could be made more efficient if licensees are allowed to lease or sell portions of their allocation, instead of having to face an all-or-nothing proposition. Some restrictions that would be necessary to govern this market for PCS spectrum are discussed below in the discussion of eligibility restrictions.

Eligibility Requirements for PCS Licenses

Until more spectrum becomes available, there is likely to be a need for eligibility restrictions to safeguard against one or two firms exploiting the scarcity of spectrum to dominate a market. These eligibility restrictions would contain two elements. One element would specify the total amount of spectrum that any single firm can hold in a service area. For example, the FCC could limit any firm from holding more than 40 MHz for the purposes of providing PCS (FCC, 1992a,

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[43]Only a few of the radio systems that have been proposed for PCS would actually require at least 40 MHz for operation. One system in this category is the CDMA spread spectrum standard proposed by Rockwell (Rockwell, 1992). One reason for a 40 MHz allocation, in their view, is that the 10 MHz wide notch filter necessary to avoid interference with microwave users would destroy too much of any remaining signal more narrow than 40 MHz.

¶81).[44] The second element would restrict particular industries from the spectrum licenses because of the possibility these industries could exploit market power in their current markets to dominate or suppress competition in the second market. For example, the FCC in the *NPRM* sought comment on whether incumbent cellular licensees or local telephone companies ought to be barred from holding PCS licenses within their own service areas (FCC, 1992a, ¶63-81).

Within this context, two results of the model are relevant. First, the strong economies of scope found between PCS and both telephone and cellular services demonstrate that consumers could benefit from allowing these companies to hold PCS licenses. Conversely, the explicit cost of eligibility requirements would be the loss of these production efficiencies. Second, the weak economies of scale in the cost function indicate that it is highly unlikely that one or two firms would dominate the market due to any cost characteristics of the market.

Based upon these findings, and assuming a licensing option which provides for a high number of PCS licenses, this study recommends eligibility requirements that include a "spectrum cap" for all firms and only slight additional restrictions for cellular companies not affiliated with telephone companies. With regard to telephone companies, this analysis shows that substantial benefits could be realized by allowing them to offer PCS on an integrated basis with telephone services. While this result favors telephone company eligibility for PCS licenses, other factors which are beyond the scope of this study -- such as interconnection and cross-subsidy questions -- also need to be considered before proceeding in this fashion.

The following discussion examines which eligibility restrictions are consistent with the findings of this study. The organization of this discussion falls along three categories of firms: new PCS providers, cellular operators not affiliated with local telephone companies, and local telephone companies.

New PCS Providers

For the purposes of this discussion, "new PCS providers" are any firms providing wireless services with a PCS license that are not financially affiliated with the local telephone or cellular companies operating in the same service area. Thus, new PCS providers could be the cable television company, interexchange carriers, local utilities, a CAP, out-of-region telephone or cellular companies, or an independent firm.

Eligibility restrictions are necessary for this category of firms due to the scarcity of spectrum allocated for PCS. Allowing any one PCS supplier the opportunity to acquire a significant share of spectrum in a service area would be counter to the policy objective of extending the benefits of competition to consumers. To prevent this outcome, a limit on the total amount of spectrum that any one PCS provider may own is necessary.

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[44]Spectrum licenses held in current cellular frequencies, specialized mobile radio frequencies, and proposed PCS frequencies could be counted as part of the spectrum cap.

If six 20 MHz PCS licenses were issued, a reasonable upper limit on the amount of spectrum allocated to any one new PCS supplier could be 40 MHz. As discussed in the previous section, a 20 MHz license, or even a 30 MHz license, might be too small in regions with a high density of microwave users or if the supplier wants to offer some wireless applications that have not been considered in this analysis. A 30 MHz license also might create small inefficiencies due to the channelization plan that would overlap two PCS licenses over a microwave license and thus possibly complicate relocation negotiations. Anything larger than 40 MHz would appear to be inefficient since the model results show that the marginal benefits of spectrum above 40 MHz are very small. In addition, a 40 MHz cap would allow a firm to acquire up to two licenses, enough additional spectrum to offer a wide variety of applications or maneuver around regions with a high density of incumbent microwave users, while still insuring a minimum of three new suppliers to the PCS market (assuming more than 80 MHz is allocated).

Cellular Operators Not Affiliated With Telephone Companies

By definition a cellular company holds one of the 25 MHz licenses issued between 824 MHz and 894 MHz to provide cellular telephone service. For analytical purposes, this paper has distinguished PCS from cellular services based upon the levels of transmitted power of the handsets and the degree of mobility offered by the service, although it was noted that technical advances will likely reduce these differences in the near future. The larger similarities between PCS and cellular foretell direct competition in price, features, and quality between these close substitutes. Consequently, cellular operators rightly can be viewed as already being PCS providers with 25 MHz spectrum allocations.[45]

Several reasons exist for precluding cellular operators from acquiring additional spectrum in the 2 GHz band. First, model results indicate 25 MHz of spectrum is sufficient to deliver PCS using microcells and cellular services using macrocells at competitive unit costs. In particular, the marginal benefits of additional spectrum appear to be relatively small for the base case assumptions. Second, cellular operators already have a significant first mover advantage on PCS markets. Allowing them to gain the benefits from additional spectrum would make it more difficult for new entrants to establish themselves in the marketplace. Third, allowing cellular operators to obtain 2 GHz spectrum would reduce the number of competitors in the PCS market.

On the other hand, there would be benefits to giving cellular operators permission to acquire a small amount of additional spectrum. First, when the case of a system with lower spectrum efficiency system is considered, model results show cellular operators could benefit from acquiring an additional 10 MHz. Without this additional spectrum, cellular operators could be precluded from implementing these technologies. Second, to the extent that they could not be realized with a 25 MHz allocation, some economies of scope between PCS and

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[45]The *NPRM* specifically proposes to amend the FCC's rules to insure that cellular licensees can provide all forms of PCS. See (FCC, 1992a, ¶70).

cellular services could be more fully exploited with the additional spectrum. In particular, cellular operators could take advantage of natural propagation characteristics by using 2 GHz spectrum to deliver PCS using microcells, while continuing to use their 800 MHz frequencies for mobile services. This arrangement might be particularly attractive for a joint merger between cellular and cable television companies where the cable television network provides backhaul for a microcell PCS network at 2 GHz.

Third, cellular operators could reduce network costs by using additional spectrum to manage the transition to new digital technologies from their existing base of analog equipment. One problem facing cellular operators seeking to enter PCS markets will be the evolution of their existing networks, which employ analog radio systems, to the new digital technologies of PCS networks. Analog base stations and handsets will have to be replaced by digital equipment. Because this transition would be too costly to accomplish in a single flash-cut, the amount of spectrum allocated for use by analog equipment must be phased-out over time. In this regard new PCS suppliers will be at an advantage relative to cellular operators because they can deploy state-of-the-art digital radio systems over the full spectrum allocation without having to manage a transition of technologies.

In the final analysis, the need for eligibility restrictions against cellular operators will depend strongly upon the number of PCS licenses and the total spectrum contained in the regulatory model. If five or six 20 MHz licenses are issued, then the benefits of allowing cellular operators to acquire a small amount of additional spectrum would appear to outweigh the costs, although a quantitative analysis of the precise number of licenses that need to be issued for this finding to be true falls beyond the scope of this analysis. With six licenses, both cellular operators acquiring some portion of one or two 20 MHz licenses would still leave at least 2 - 4 unaffiliated suppliers in the market depending upon the degree of consolidation in the market. Thus, acquisitions of PCS spectrum by cellular operators likely would be based more on the benefits this spectrum could bring to the operator, and not an attempt to suppress competition since it would have a small impact on the overall market structure.

If these competitive concerns are met, how much additional spectrum should a cellular operator be permitted to acquire? Out of concerns for fairness -- in the sense that competitors should be allocated equal amounts of spectrum -- cellular operators should not be allowed to exceed the spectrum cap set for new PCS suppliers. This constraint would limit cellular operators from acquiring licenses more than 15 MHz of 2 GHz frequencies.

Results of the model, as well as concerns about the first mover advantage of cellular operators and the channelization plan, however, suggest limiting cellular operators to 10 MHz of additional spectrum. Model results indicate that 10 MHz is a sufficient amount of spectrum to deliver PCS and for cellular operators to realize the economies of scope between these services for a wide range of technologies. Also, cellular operators undeniably enjoy a first mover advantage to PCS markets. As PCS licenses come closer to being issued, cellular operators will vigorously evolve their existing networks to provide a wide range of PCS.

Limiting cellular operators to a total of 5 MHz less than the total amount of spectrum that new PCS suppliers can hold slightly reduces this first-move advantage. Finally, a 10 MHz limit meshes well with a channelization plan for 20 MHz licenses and does not lead to small blocks of "left-over" spectrum that cannot be put to productive use. For example, the 5 MHz left over when a cellular operator acquires 15 MHz out of a 20 MHz license could be unproductive because it may be too small to serve any useful purpose for delivering PCS.

In sum, if a high number (*e.g.*, six) of licenses are issued, then the benefits of permitting cellular operators not affiliated with the local telephone company to acquire portions of a PCS license are likely to outweigh the costs. Accordingly, this study recommends that these cellular operators be eligible to acquire an additional 10 MHz of spectrum, which model results show is a large enough block of spectrum to fully exploit economies of scope between PCS and cellular services. Even though this would result in cellular operators being limited to a total of 35 MHz, while new PCS providers would have the option to acquire up to 40 MHz, this difference is justified because of the fact that cellular spectrum in unencumbered by the presence of other users, and because of the first mover advantage currently enjoyed by cellular operators.

Local Telephone Companies

This category refers to all local telephone companies, regardless of whether they have a cellular subsidiary in their service area or not. When cellular licenses were issued in the 1980s, most local telephone companies received one of the two licenses, and were required to operate the cellular company through a separate subsidiary. Because of the virtual monopoly that telephone companies hold on transport in the subscriber loop, and the competitive opportunity posed by PCS, the FCC has asked for comment on whether these firms should be eligible to hold PCS licenses (FCC, 1992a, ¶71-80). This analysis indicates that considerable benefits could be achieved by allowing telephone companies to be eligible to some degree for new PCS licenses. The potential costs of this eligibility in the form of anti-competitive interconnection or cross subsidies practices, however, are beyond the scope of this analysis.

The rationale for barring telephone companies from holding new PCS licenses is that it would create incentives for them to discriminate against those requesting interconnection to the local telephone network and to cross-subsidize the provision of PCS with revenues from regulated telephone services. Interconnection issues, in particular, raise a number of serious policy concerns since many PCS are not likely to succeed without interconnection to public telephone network at reasonable rates. Because telephone companies could view PCS as a competitive threat to their own PCS offerings, to their own wireline cellular subsidiary, or even to basic telephone service, they may try to disadvantage competitors with inferior interconnection. While the potential costs of telephone company entry cannot be satisfactorily quantified by the model, the results do demonstrate the importance of interconnection by showing that viable alternatives to the telephone network could exist for PCS switching and transport. The presence of economies of scope between PCS and telephone, cable television, and cellular services indicates that multiple networks could develop in the subscriber loop if interconnection rules are adopted. This point is not surprising, since there already appears to be agreement that PCS suppliers, at a minimum, should be able interconnect with the public switched telephone network at the same terms extended to current cellular operators (FCC, 1992a, ¶99-103).

The core issue that must be decided is whether telephone companies will be limited through eligibility restrictions to the role of a "carrier's carrier" for other PCS suppliers. Regardless of the eligibility restrictions placed upon telephone companies, it is clear that portions of their infrastructure are likely to be used to deliver PCS. Eligibility restrictions are likely to influence how fast the telephone companies will move to meet these requests, and how they modify their infrastructure to support PCS (*i.e.*, telephone companies would seem to be more likely to develop their infrastructure to efficiently support PCS if they are one of the PCS providers using the network).[46]

Contingent upon adequate safeguards against discriminatory interconnection practices and cross-subsidy, the results of this analysis indicate that consumers could benefit from allowing local telephone companies to hold PCS licenses if a large number of PCS licenses are issued. If adequate safeguards are available to mediate the above concerns, telephone companies should be allowed to fully participate in PCS subject to the same restrictions placed on other entities. Telephone companies with cellular holdings, of course, should be subject to the same restrictions placed on other cellular operators.

[46]In the *NPRM*, the FCC tentatively concludes that the benefits of allowing telephone company eligibility could outweigh the potential costs given adequate safeguards (FCC, 1992, ¶75) and proposes two options for allowing them to hold new PCS licenses (FCC, 1992, ¶76-80). One option would apply the same eligibility restrictions to telephone companies that are applied to non-affiliated cellular operators. (This option also seeks comment on whether Bell Operating Companies should be required to continue to provide cellular services through a separate subsidiary.) The other option would allow telephone companies to acquire up to 10 MHz of 2 GHz spectrum for PCS -- a limit that would apply regardless of whether the telephone company operated a cellular subsidiary in the service area.

Appendix A. Wireless Technologies

This appendix reviews the fundamental technologies and engineering tradeoffs arising in the design of wireless networks, and the nature of the demands for mobility and portability which shape these systems. The discussion begins by describing the basic principles of network design in the wireless environment, and how these principles might apply to PCS systems Next, this appendix examines the radio access technologies which define the network architecture for wireless services. Ultimately, it is the demand for mobile and portable communications capability which will drive the functionalities and implementation strategies for wireless services. The last part of this appendix looks at how the demand for different wireless applications could influence network design and evolution.

Design of Wireless Communications Systems

The obvious distinction of PCS technology is the radio transmission channel between the network base station and handset as shown in Figure 1. Preserving the integrity of the wireless channel can be a difficult task depending upon the local conditions. The design of a PCS network will be strongly influenced by the characteristics of the radio transmission link, and the cellular approach to network design is an important concept of the network architecture in this environment. The following discussion briefly reports the basic principles of cellular design relevant to this analysis. More thorough treatments of this subject can be found in (Bellcore, 1991; Calhoun, 1988; Lee, 1989).

The Wireless Channel

As a radio signal propogates through the atmosphere toward its destination, it both becomes weaker and accumulates noise from other sources. The extent to which the transmitted signal loses power relative to its initial strength is called the propagation *path loss*. The magnitude of the path loss can be estimated by the general relationship:

$$C \sim R^{-\gamma}$$

where C is the power of the carrier signal, R is the distance measured between the transmitter and receiver, and γ is the propagation path loss slope which varies between a minimum of 2 (perfect free space) and 5.5 (a dense, urban environment such as Manhattan with a very high path loss) (Gilhousen, Jacobs, et al., 1991; Lee, 1989). Due to reflected waves,[1] there is a high degree of variation in the magnitude of the path loss at any given time and location. This variation, known as multipath, requires a received signal sufficiently strong to offset the effects of fading. In addition, the frequency of the carrier signal changes the value of the

[1]If the wavelength of the carrier frequency is much less than the size of surrounding structures, the signal bounces back and forth between these structures. The reflected signals reinforce or cancel themselves with the direct signal at various points in space causing wide variations in signal strength.

path loss. As the carrier frequency increases, the path loss caused by the absorption of the signal by the atmosphere and other things (*e.g.*, foliage) increases.[2]

From the user perspective, the quality of a wireless service is set by the clarity of connections, the size of the service area, and the frequency of blocked calls. Using a *power link budget* -- a budget calculation which determines the sufficient level of transmitted power to offset all system losses -- network planners design a network architecture according to these criteria. An important measure of radio channel quality is the ratio of the carrier and noise power levels at the receiver, called the *carrier-to-interference (C/I) ratio*.[3] The radio link fails when the information impressed upon the carrier cannot be recognized from the interference and noise (*e.g.*, when the C/I ratio drops below a threshold set by the characteristic of the radio receiver). Because of the variability of path loss, the level of received power changes with time and location. One way to design for constant high quality is to continuously transmit sufficient power to overcome the worst case levels of fading. This approach, however, increases interference levels in the system. A dynamic power control scheme, in contrast, could constantly adjust transmitted power to maintain the maximum required C/I ratio at each receiver and minimize interference.

For a PCS network, a key factor in the link budget calculation is the power of the transmitter in the handset, which must be small and lightweight, yet strong enough to offset the path loss to the base station. To minimize power requirements in the handset, PCS systems may use shorter radio transmission paths (smaller cells) and dynamic power control techniques (which places more processing requirements into the handset) (Cox, 1990).

The Cellular Concept

Prior to cellular, the general approach to providing wireless mobile services was to build one tower equipped with a high-power transmitter capable of covering the entire service area with the full range of frequencies available to the service provider. Such a simple design, however, has a number of deficiencies. If

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[2]For example, a CCIR study reported experimental data showing that received power is about 6 dB less at 1.5 GHz that at 900 MHz, and 5 dB less at 2.2 GHz versus 1.5 GHz. See (CCIR, 1990b, p. 215). The different propagation characteristics of 2 GHz versus 800 MHz will be particularly important if PCS are competitive with cellular services offered at 800 MHz. In some circumstances, increased path loss at 2 GHz may actually affect frequency reuse favorably by increasing signal isolation and reducing interference from other signals between small cells.

[3]The C/I ratio is measured in decibels (dB). A decibel is a relative measure defined as the logarithmic ratio of power signal levels:

$$dB = 10 \log_{10}(C/I)$$

where C and I are the received power levels of the carrier signal and noise component, respectively.

the service requires a return link from the user, then the user also needs a relatively high-power transmitter to reach the tower from the edge of the service area. Consequently, the portability of the subscriber unit was limited because of the larger and heavier batteries needed to supply the operating power. Also, because each frequency was used only once in the system, the overall capacity of the system was strictly limited. Thus, while this system architecture may still be attractive to deliver paging services, for example, where only small amounts of information are transmitted in one direction, it is no longer used for high capacity, two-way service applications, where handsets must be conveniently small and lightweight.

Because the amount of spectrum allotted to a particular service is unlikely to change often, the large bandwidth requirements of two-way services suggest the need for a network architecture that can accommodate service growth in a cost-effective and spectrum efficient fashion. The *cellular* network architecture was developed to increase capacity in a cost-effective manner by reusing the same spectrum many times within the same service area.

A cellular network breaks the service area into a large number of geographic regions, or cells, that can be served by low-power transmitters. Users in different cells, although not usually adjacent, can simultaneously be engaged in telephone calls over the same frequency channel. The extent to which frequencies can be reused depends upon the amount of interference arising due to the common use of the spectrum and the pattern of frequency reuse. The maximum acceptable *co-channel interference* (as specified by a minimum C/I ratio) is therefore a critical design parameter for cellular systems. The quality of service criteria of the system and the radio technology define the acceptable threshold value for the C/I ratio. For example, the normal practice in the cellular industry today is to specify a C/I ratio of 18 dB or higher for its analog frequency modulation systems (Lee, 1989, p. 18). With this specification, the network planner can then determine the size of cells and necessary pattern of cell reuse based upon the link budget.[4]

[4]The required co-channel cell spacing, D (the distance between the center of cells), and cell radius, R, are related to the carrier-to-interference ratio as:

$$C/I = \frac{1}{\sum_{k=1}^{N} (\frac{D_k}{R})^{-\gamma}}$$

where γ is the propagation path-loss slope and N is the "reuse factor" or the number of cells in the frequency reuse pattern. The relationship between the reuse ratio and N is defined as:

$$(\frac{D}{R}) \equiv \sqrt{3N}$$

A typical value of this ratio is 4.6 corresponding to the N=7 cell reuse pattern and 18 dB C/I ratio common to the cellular industry. See (Lee, 1989, Chapter 2; CCIR, 1990c).

The pattern of cell reuse for any particular system is based upon signal coverage and traffic requirements. For example, a cellular network could be designed initially to provide signal coverage over the entire service area using large cells. Then, as traffic increases in particular areas over time, more cells can be inserted into the network by subdividing the existing cells into smaller cells through a process known as *cell splitting*. These smaller cells are called *microcells*. As a first-order approximation, system capacity increases by a factor of 4 every time the cell radius throughout the system is halved (Lee, 1991). For example, network capacity could increase by a factor of about 250 by reducing cell size from a radius of 6.4 Km to 400-meters without the need for any more spectrum. Another way to increase capacity is to install directional antennas which transmit and receive with a "sector" channel assignment pattern. For example, a seven cell reuse pattern would become a 21 sector reuse pattern by dividing each cell into three 120° sectors. A sector plan allows co-channel cells to be placed closer together, thus increasing overall system capacity.

PCS networks are likely to include small cells, however, for more reasons than just an increase in network capacity. The weight and size of the radio handset is proportional to the level of transmitted power. Today's cellular networks use high-power -- from 600 milliwatts (mW) up to 5 Watts (W) -- handsets to communicate in large cells, while a PCS network might use microcells to better accommodate pocket-sized, low-power (less than 50 mW) handsets. Low-power handsets will generally dictate a smaller maximum cell size in order to maintain adequate signal strength at the base station receiver.

A cellular network has the capability to maintain connections as users roam through coverage areas by handing off calls from one cell to another. Whenever this happens, the system must detect, locate, and register the user in the new cell (CCIR, 1990c). To execute a handoff, cellular networks currently transmit network control messages using a "blank and burst" signalling technique that interrupts speech transmission with audible clicks. This centralized signalling approach relies upon a system controller to monitor the strength of calls in progress and to decide when and where handoffs are necessary. The controller also directs which mobile units are tuned to a particular base station and assigns the appropriate frequency. The cell radii of current systems are usually not greater than 20 Km due to power and propagation loss constraints, and not less than 1.5 Km due to the difficulties in procuring cell sites (communities often object to the 30 - 45 meters antennas and radiated power associated with cellular towers) (CCIR, 1990a; Chu and Gans, 1991).

With microcells, however, the number of simultaneous handoffs will increase significantly, which could dramatically increase the complexity of the network architecture. Widespread deployment of microcells will mean that each call in progress is more likely to require a handoff because of the smaller cell size. For example, at least 256 400-meters microcells are needed to cover the area of one 6.4 Km cell. Moreover, not only must the network process more handoff requests, it must also execute each request much faster. For example, the time it takes a car travelling 40 - 100 kilometers per hour to cross a cell of radius 6 Km. is 7.2 - 18 minutes, but only 28.8- 72 seconds to traverse 400-meters microcells. While not insurmountable, these requirements illustrate why mobility management will be a critical component of PCS systems employing very small cells.

To compensate, PCS networks are likely to capitalize upon two trends emerging in second generation cellular systems (Goodman, 1991): 1) dedicated control channels for network signalling purposes, and 2) decentralization of network control capability from the switch to base stations and handsets. Dedicated control channels can provide more signalling capacity in the network, and enhance the functionality of the wireless network analogous to the use of the D-channel in the integrated services digital network (ISDN).[5] By placing more functionalities in handsets and base station equipment, decentralized network control allows handsets and adjacent base stations to monitor calls in progress and direct the system controller where the handoff should occur. These *mobile assisted* handoffs can speed up the handoff process and reduce the processing load on the central controller at the expense of introducing more complexity in base station and handset equipment.

The tradeoffs associated with the network handoff capabilities and equipment complexity may not be trivial. Some network planners believe that the network requirements of a high-speed mobile service differ sufficiently from pedestrian service to justify construction of two separate cellular networks (Cox, 1990). In this view, the additional complexity of a network architecture featuring mobile assisted handoffs, radio access technologies with a high degree of spectral efficiency, or handsets with dynamic power control may drive up the power requirements of the handsets to such a degree that they are no longer conveniently portable. If true, then two types of networks would be expected to emerge in the future, networks that offer high-speed mobile services using large cells and high-power handsets analogous to today's cellular telephone networks, and networks that deliver low-speed pedestrian services using microcells and low-power handsets.

In summary, the reason for cellular design is to markedly increase network capacity through frequency reuse. The overall objective is to build a network with the smallest number of cells while still meeting the system performance requirements of quality, capacity, and coverage. In a highly evolved cellular system with high-power handsets, one would expect a dense infrastructure of microcells for areas of high traffic and less dense pattern of large cells in lower traffic areas for signal coverage. In a PCS network featuring low-power handsets, such variability in cell sizes may not be possible because of service quality requirements or the limitations of the handset. Instead, a PCS system may consist of a uniform distribution of microells which are capable of providing coverage to simple, low-power handsets. The extent to which the limit on cell size

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[5]ISDN is a set of standards that define the interfaces for a fully digital network. The CCITT standards body has recommended a "2B + D" narrowband interface for the subscriber loop consisting of two B channels, each representing a 64 Kbps data signal, and a 16 Kbps D channel that serves as a dedicated signaling channel for control functions.

adds to investment costs of a PCS system remains unclear, and is a key question addressed in this cost study.

Radio Access Technologies

A key component of the network architecture is the radio access technology, which determines network capacity and potential for future growth. This section reviews the radio access technologies under consideration for PCS networks, and notable engineering tradeoffs inherent to each approach.

As with most other future telecommunications applications, the radio access technology implemented to deliver PCS is certain to include increasing amounts of digital technology (CCIR, 1990a). The advantages of this technology include: 1) digital speech coding, channel coding, and signal processing techniques can improve spectral efficiency; 2) digital signal modulation can reduce the C/I threshold necessary for signal reception; and 3) digital signals can be easily combined together, which allows more flexibility in service provision. First generation cellular and cordless services mainly use analog frequency division multiple access (FDMA) schemes for transmission of the voice signal (Kucar, 1991). The trend in second generation radio systems is to digital techniques employing time division multiple access (TDMA) technology or spread spectrum technology using code division multiple access (CDMA). These approaches can carry more voice channels over the same amount of spectrum as today's networks using more complex network equipment. All access techniques are under serious consideration for future PCS applications.

The TDMA approach compresses the information signal in time so that multiple voice or data channels can transmit over the same radio channel. Placing more voice channels on each radio frequency (RF) carrier permits greater sharing of the spectrum and RF equipment. CDMA using spread spectrum techniques takes each voice or data signal and transmits it over a wide range of frequencies -- a process known as "spreading" -- to a receiver which knows in advance the code which has been assigned to its signal. Because the power broadcast over any one frequency is very small, the mutual interference between spread signals is limited. Proposed CDMA systems rely upon dynamic power control schemes to keep the amount of mutual interference to a minimum, which will add some complexity to base station and handset equipment (Beach, Hammer, et al., 1991).

An attractive advantage of CDMA systems is that spectrum can be reused in every cell. Today's cellular systems typically employ a 7-cell frequency reuse pattern, meaning that any particular frequency cannot be reused within each group of seven cells (a frequency reuse pattern which could be carried over with TDMA systems as well). A CDMA system allows for $N=1$, where each cell can use all the spectrum in the allocation with isolation among the cells provided by the path loss. Techniques for decreasing the frequency reuse factor of TDMA systems from $N=7$ to as low as $N=3$ have also been proposed (Lee, 1991).

Table A-1 shows a small sample of the technical parameters of nine systems based upon FDMA, TDMA or CDMA radio system technologies.[6] The variance in technical parameters between the cellular and cordless standards stems from the different characteristics of these services. Cordless handsets transmit over short distances, ranging from 30-meters indoors to 150-meters outdoors, at very low-power levels on the order of 10 mW. In addition, speech voice coders in the handset operate at much higher rates -- 32 kilobits per second (Kbps) versus 8 or 13 Kbps -- to improve service quality, lower equipment costs, and keep handset power requirements to a minimum (a lower speech rate requires more signal processing to reconstruct or transmit a voice channel in real-time). Thus, the duplex channel size for a cordless system is much larger at over 100 kilohertz (KHz) than the cellular standard.

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[6]The cellular and cordless technologies listed in Table A-1 are:

1) Advanced mobile phone service (AMPS) is the current analog cellular standard in the United States. A Narrowband AMPS (N-AMPS) standard has been proposed which would expand network capacity by a factor of 3 by decreasing the duplex RF channel size to 20 KHz.
2) United States cellular interim standard (IS) 54 is set by the Telecommunications Industry Association (TIA) and uses the same carrier spacing as AMPS. IS-54 systems are being deployed this year in a few major cities.
3) The Groupe Special Mobile (GSM) standard for cellular service has been initiated by 15 European countries. Begun in 1987, the ambitious GSM standard was due to be introduced across Europe by July of 1991 but has encountered serious implementation delays. Many operators remain hopeful that they can start up GSM systems within the next two years. See Taylor, Jack T. "PCS in the U.S. and Europe." *IEEE Communications Magazine* June, 1992. 48-50.
4) QCDMA represents a spread spectrum system developed by Qualcomm, Inc. for PCS and cellular applications. See (Gilhousen, 1991).
5) RCMA represents a spread spectrum system developed by Rockwell International for PCS applications. See (Rockwell, 1992).
6) First generation Cordless Telephones (CT) are generally interoperable only with the type of base station bought with the telephone. United States systems employ narrowband frequency modulation (N-FM) with 10 channels.
7) CT2Plus is a second generation cordless telephone developed by Northern Telecom and Motorola that uses digital voice coding but the same FDMA techniques as CT. A CT-2 handset can initiate, but not receive, calls -- a service also called telepoint. CT2Plus would allow call handoff between cells at low speeds and includes a common air interface (CAI) standard which would allow all handsets and base stations to interoperate.
8) The Universal digital PCS (UD-PCS) system proposed by Bellcore enables a handset to operate with a network of base stations connected to the public switched network. See Bellcore (1990).
9) The digital European cordless telephone (DECT) standard is a third generation cordless system developed by Ericsson in Europe, mainly designed for in building uses, where handsets can both initiate and receive calls.

Parameter	AMPS	IS-54	GSM	QCDMA	RCDMA	CT	CT2Plus	UD-PCS	DECT
Radio Access Method	FDMA	TDMA /FDMA	TDMA /FDMA	CDMA/ FDMA	CDMA	N-FM	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA
RF Chan. Size	30KHz	30 KHz	200KHz	1.25MHz	40 MHz	20K	100	700 KHz	1.7 MHz
Chan. Rate	-	48 Kbps	270.8 K	10 or 32K	20 or 40K	-	72 Kbps	514 Kbps	1.1Mbps
Voice Chan. per RF Chan.	1	3	8	20-60 per sector	126	1	1	10	12
Duplex Voice Channel Size	60KHz	20 KHz	50 KHz	-	-	40K	100KHz	70 KHz	144KHz
Voice Bit Rate	-	8 Kbps	13 Kbps	8 - 32 K	16 Kbps	-	32 Kbps	32 Kbps	32 Kbps
Handset XMIT Power: Max/ Avg (mW)	600 /600	3000 /200	1000 /125	200 /6	100 /1	≤ 10	10 /5	100 /10	250 /10
Max. Cell Radius	> 32 Km	> 32 Km	32 Km	2.5 Km	450 meters	100 m.	100 meters	500 meters	500 meters

Sources: (Bellcore, 1990; Gilhousen, Jacobs, et al., 1991; Kucar, 1991; Rockwell, 1992). Both IS-54 and GSM standards anticipate twice the capacity within 5 years by halving the rate of each voice channel.

Table A-1. Comparison of Cellular and Cordless Radio System Parameters

At this early point in the development process, it is difficult to evaluate between TDMA and CDMA technologies. The complexity of equipment appears roughly comparable. The most significant difference is that users of a CDMA system all share the same channel, but are assigned a unique spreading code to minimize mutual interference, whereas a TDMA system designates a separate frequency and time slot to avoid interference.[7] Thus, mutual interference places a "soft" limit on the capacity of CDMA system -- whenever the number of users exceeds some ceiling, all the connections are maintained albeit at a lower quality level -- whereas the time slot size relative to the overall bandwidth places a "hard" limit on the capacity of a TDMA system which cannot be exceeded under any

[7]This property raises the possibility that a CDMA system could operate over the same range of frequencies as other spectrum users without causing significant harmful interference. Field tests have demonstrated that a CDMA system can operate in the same spectrum as microwave users, although precautions need to be exercised to minimize disruptive interference. See Schilling, Donald L. et al. "Broadband CDMA for Personal Communications Systems." *IEEE Communications Magazine* November 1991, p. 86-93; and Telesis Technologies Laboratory. *Experimental License Progress Report to the FCC.* February, 1992.

circumstances.[8] The improvement in cochannel interference tolerance of proposed digital systems reduces *C/I* objectives from current analog FM ratios of 18 dB to 9-13 dB for TDMA systems (Calhoun, 1988), and 5-8 dB for CDMA systems.

Equally uncertain is the extent to which TDMA and CDMA approaches could increase network capacity relative to current cellular systems. Compared to cellular networks using AMPS, the IS-54 TDMA standard would increase the number of available channels by 3 to 6 times; CDMA systems are predicted to increase the available channels by 18 times (Gilhousen, Jacobs, et al., 1991), although this number must be treated only as an estimate until further field experience can be obtained.[9]

Because the uncertainty surrounding the costs of TDMA and CDMA equipment is sufficient to make any cost differentials between these two technolgies indistinguishable, cost estimates in the engineering cost model do not assume explicitly either a TDMA or CDMA radio access technology. Instead, given the 5-year time horizon of this study, the base case model assumes a radio access technology that offers more than twice the capacity relative to current cellular networks (*i.e.*, a duplex traffic channel size of 25 KHz and the same frequency reuse factor of N=7). By keeping the reuse factor unchanged, and the channel size relatively large, this base case allows the improvements made available by digital technology, such as lower *C/I* and power requirements, to be applied to improve service coverage and service quality.[10] The sensitivity analysis, however, does explore the impact of decreasing the frequency reuse

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[8]Of course, the network requires capacity and equipment for each subscriber connected to the network. Thus, the "hard" limit for a CDMA network may no longer be set by the spectrum available in the wireless link, but the capacity of the network switching and transmission equipment.

[9]The two factors which make the capacity of a CDMA system much larger than a AMPS system are an assumed frequency reuse pattern of N=1, which provides a seven-fold increase, and the use of digital speech interpolation (because speakers are active only 37.5 percent of the time during a call, these gaps in the call can be filled with blocks from another call). Making similar assumptions regarding the amount of time a speaker is active, Hughes claims their *extended* TDMA system provides 15 times the capacity of AMPS. See *Telecommunications Reports*, p. 23-24, May 25, 1992.

[10]Even though it is stated throughout this study that the PCS network offers "ubiquitous" coverage throughout the service area, a 100 percent level of service coverage is not practical due to propagation variations. Service coverage can be characterized as a probability distribution function based upon a particular link budget. For example, today's cellular systems usually try to cover 90 percent of an area in flat terrain and 75 percent of an area in hilly terrain assuming a *C/I* ratio of 18 dB (Lee, 1989). Thus, improved service coverage could be obtained by either increasing the link budget to illuminate weak spots in the coverage pattern or, alternatively, by choosing a dynamic power control scheme to compensate for some percentage of the variations in the power budget.

factor to N=1 consistent with the use of a CDMA radio access technology, and use of different channel sizes, and the impact on total costs due to variations in the cost of radio system components.

Network Signalling and Database Requirements

Beyond the hardware necessary to deliver PCS on a large scale, there are significant logical or network operations capabilities essential to the provision of PCS as well. A highly touted feature of PCS is "personal number" service where a telephone number would no longer be associated with the location of a telephone line or a mobile telephone, but instead with an individual subscriber.[11] To manage this mobility, a PCS network must be capable of routing incoming calls to the correct location, charge on the basis of the personal number, interconnect calls among different networks, and authenticate the user by personal number on a real time basis (CCIR, 1990b). It is anticipated that an important network management tool in this regard will be the user profile, a database record associated with each personal telephone number that profiles the subscriber's individual preferences and current location (Nguyen, Tam, et al., 1991).

Switch manufacturers and telephone companies have already started to develop the network intelligence required to manage mobile services. The vehicle for this functionality is the advanced intelligent network (AIN). PCS has been touted as one of the lead service drivers of this new technology (Homa and Harris, 1992). When a call is placed on the current telephone network, the switch establishes the connection according to the *call model* (embedded in the switching software) that defines what steps, or check points, are executed during the call. The AIN specifies a new call model with a new set of steps, or check points which depend upon external processors in the intelligent network to operate.

The network intelligence to interact with the call model can be located either locally, in the form of adjunct processors, or centrally in large intelligent network nodes. While it is premature to know how the network intelligence will be distributed throughout the network to offer PCS, preliminary studies suggest hierarchical approaches to mobility management are the most promising (Northern Telecom, 1992). In any event, the AIN will increase network signalling traffic, and personal number service -- whether offered in conjunction with PCS

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[11]Early versions of personal number service are now available to cellular and long distance subscribers. Currently, these services allow subscribers to automatically forward their calls to predetermined locations, or receive a lifetime number. See, for example, "Bell Atlantic Plans Service That Links Phone Numbers," *New York Times*, D7, March 17, 1992; see also AT&T News Release, April 28, 1992. Future personal number services anticipate a network capable of automatically tracking subscribers' locations through their handset and forwarding calls to any location, if desired.

or otherwise -- will engender even more signalling traffic.[12] The price for adding these enhanced features into the PCS network is a more complex call model, which will consume a commensurate increase in the real-time processing power of the switch (Homa and Harris, 1992). Without an advanced signalling network platform, however, the call set-up times for roamers throughout the PCS network will suffer greatly (Jabbari, 1992).

In calculating switching costs, the engineering cost model assumes a 50 percent increase in processing power at the switch relative to today's telephone switch is necessary to execute the AIN call model required for PCS. The model does not consider the costs of interoffice transport facilities and centralized intelligent nodes. Except at very low-penetration levels, the costs of these facilities are not likely to be significant on a per subscriber basis because this equipment can be shared among many users. For example, even if an intelligent node costs several million dollars, it is expected to support roughly 1-million subscribers at a cost of several dollars per subscriber.

Link Between Service Demand and Network Architecture

A clear understanding of PCS can only emerge from detailed knowledge of how consumers really want to use these new technologies. It is difficult to define or describe PCS because a clear description of these markets has yet to emerge. While it is obvious that the nature of the demand for mobility and portability will strongly influence network design, uncertainty regarding the characteristics of this demand make it difficult to select the network architecture best suited to deliver PCS.[13] This discussion examines how the characteristics of the demand for PCS could influence the design of the network infrastructure, and the relevant assumptions incorporated into the engineering cost model.

So far, this paper has advanced the notion that virtually all wireless applications fall into a broadly defined category of PCS. Indeed, potential wireless

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[12]One way the network can track users' locations is by monitoring handset locations and storing this information in a large database. This approach has been applied in the development of the TIA IS-41 standard which is derived from the GSM standard. This approach maintains two network registers. The home location register (HLR) holds billing validation and subscriber profiles; the visitor location register (VLR) holds the local records of roaming subscribers. If a subscriber moves to a "visited" location, the "visited" location updates the "home" location database through signalling between the handset and network. When a call is placed to the roaming subscriber, the network queries the HLR for the current customer location, which routes the call to the appropriate VLR for completion. See (Jabbari, 1992; Nguyen, 1991).

[13]A number of the experimental PCS licenses granted by the FCC are marketing trials which seek to learn the strength of consumer preferences for different service functionalities such as mobility and handset portability. For example, see "GTE launches nation's largest PCS customer trial," GTE Press Release on August 25, 1992.

services span a diverse set of applications including voice, voice messaging, electronic mail, facsimile, data transmission, paging, dispatch, archive and inventory information, to name but a few. Yet each application generates different signalling and network capacity requirements. Mobile voice service requires a two-way circuit of sufficient bandwidth, and constant network management throughout the call. In contrast, a paging service only needs a one-way connection of very brief duration, and data services can tolerate substantial delay in transmissions. Consequently, a network optimized to deliver voice service will be very different than one optimized for paging, data, or other wireless applications. This connection between network architecture and network services underscores the importance of clearly defining the network services incorporated into the engineering cost model, since costs can be expected to vary widely with different sets of services.

This study assumes the primary objective of the PCS network is to deliver voice services (*i.e.*, establish two-way interactive channels) using small portable handsets. Three observations suggest this level of functionality is appropriate:

- The demand for wireless voice service is already well-founded as demonstrated by current cellular and cordless markets. In contrast, the mass-market appeal for other wireless services, with the exception of paging, remains speculative.
- The lack of wide-spread, small, lightweight handsets with a large coverage area in today's market suggests a market opportunity for this service. To be sure, this window is a temporary one, in recognition of the rapid progress made by manufacturers in producing lighter and smaller cellular portables.
- A digital network providing voice service has the capability to carry the great majority of other wireless services (although whether it is the most efficient means of distribution is an another question).

Where economies of scope prove to exist between different wireless services will determine the eventual mix of PCS offered over a single network. Again, this paper makes no assumptions regarding what this mix of services may evolve to be, only that voice services using low-power handsets will be driving the deployment of PCS networks in the subscriber loop.[14] Indeed, PCS providers

[14]Because digital signals are more easily combined than their analog counterparts, high expectations of service integration often accompany deployments of digital technology. Thus it is not surprising to find that GSM has been described as a "mobile ISDN" standard because of its digital format, the large number of services it can provide (e.g. facsimile, paging), and the dedicated signalling channel. Historically, many of these expectations have proved to be premature, mainly because the broadest common denominator is often not the most efficient means of distribution. For example, even though the concept is nearly a decade old, the roll-out of a narrowband ISDN has yet to reach most consumers in the United States. Likewise, deployment of broadband ISDN has been slowed by the lack of economies of scope between narrowband and broadband services (Reed, 1991, Chapter 5).

probably will try to integrate other complementary applications with their voice service. The presumption, however, is that the demand for these complementary services will not be great enough to change the network architecture in a manner more suited to the particular characteristics of these services.

Subscriber Location and Velocity

A key question is the immediate circumstances under which consumers are likely to use wireless services. Two important service attributes in this regard are the subscriber location -- whether the call takes place indoors or outdoors -- and the velocity of the subscriber during the call.

Subscriber Location

Whether a PCS network will be designed to offer services to subscribers located both inside homes, apartments, or offices and outdoors is a question with major implications for network design. PCS providers may view the portable indoor communications as an attractive market to enter.[15] Moreover, if the cost is reasonable, consumers are likely to have a strong preference for one handset that can be used in all these environments.

To operate indoors through an outdoor base station, however, PCS handsets would need sufficient power to overcome path loss through the walls of homes. The penetration losses that occur as radio signals travel through ceilings and walls average 20 dB for large buildings (Cox, Arnold, et al., 1987). Thus, a PCS network optimized for outdoor calls will provide much lower circuit quality for most indoor calls.[16] Designing a PCS system to offer both indoor and outdoor coverage will therefore increase system costs. For instance, a system for indoor and outdoor coverage would require smaller cell sizes, higher radiated power levels, larger antennas, or more efficient radio access and modulation techniques.

The question, then, is whether PCS systems which provide coverage over a wide area can viably offer indoor services in light of the alternative wireless services available. In particular, a PCS system offering indoor coverage from outdoor microcells will be competing with cordless telephones using the existing telephone network. The profusion of cordless telephones -- over 30 percent of U.S. households now own one -- demonstrates the popularity of the inexpensive low-

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[15]One study estimates that cordless residential telephony will account for 33 percent of the PCS market share in 1995, while high-speed hand-off and walking hand-off services will account for 13 percent and 8 percent of the market share, respectively. See Clifford Bean, "Outlook for Wireless Personal Communications in the United States," Eastern Communications Forum, Rye Brook, NY, 1992.

[16]Cox, et al. offer a simple model to demonstrate that "if indoor users are served on a system originally designed to give good service to 90 percent of the outdoor users at some chosen radius, then only 16 percent of the in-building users will receive that same service. (In practice, many of the call attempts from in-building units will fail, so that the probability of good service (given that it was possible to start the call at all) will be higher.)" See Appendix in (Cox, et al., 1987).

power handsets in households. Even supposing that a PCS system could provide an equivalent quality of indoor coverage, an advantage of cordless service could be the apparent lack of "air-time" charges for use of the spectrum. Today, consumers enjoy the benefits of cordless service at no incremental costs above their regular telephone rates. Against this benchmark, PCS systems will need to offer an indoor cordless service at a cost comparable to normal telephone rates plus "free" air-time charges.[17] These formidable technical and economic factors will influence how PCS providers will introduce their services. Within these constraints, two strategies for providing indoor and outdoor service over one handset can be imagined.

Setting Aside Spectrum for Indoor Cordless Applications. The PCS operator could set aside a portion of its spectrum for indoor cordless services. When indoors, the handset automatically senses the presence of a private base station and acts like a cordless telephone. The cost of indoor calls would be reflected in the monthly bill for telephone service. When outdoors, the subscriber is linked using the same handset to a network of macrocells or microcells optimized for outdoor coverage. A PCS provider could coordinate these services by distributing its own private cordless base stations for residential use in conjunction with its outdoor wireless services. One advantage of this approach is that it allows the PCS provider to integrate indoor and outdoor service features into a seamless package that is completely transparent to the user. A PCS provider could also assure the quality of its indoor service because it has full control to manage the interference within its exclusive spectrum assignment.

Using a Common Allocation for Cordless Applications. Instead of setting aside a portion of its spectrum allocation, the PCS provider could use a spectrum allocation available for unlicensed cordless telephone applications, such as the allocations near 49 MHz or 915 MHz in the United States. In addition, the FCC has proposed allocating 20 MHz out of the 2 GHz emerging technologies band for unlicensed applications such as indoor cordless telephone (FCC, 1992a). The PCS provider would still be able to offer customers indoor and outdoor coverage over a single handset, although it would forfeit the ability to manage the quality of the indoor service over the unlicensed spectrum allocation. The PCS provider also might be constrained by a more limited set of features available in the cordless phone mode.

Whether these two options or other approaches eventually gain the most acceptance cannot be predicted at this time. In this paper, all cost calculations assume PCS providers set aside 1 MHz of their spectrum allocation for indoor cordless service. This approach appears to minimize infrastructure costs while

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[17]There is a cost to the use of the spectrum for cordless service -- measured by the highest amount that would be paid by another application for the use of this spectrum. Because the spectrum used for cordless services is not licensed to one supplier, there is no charge for using the spectrum in spite of the opportunity costs for using these frequencies in this fashion. Conversely, subscribers may opt to pay more for indoor services from a PCS network to avoid crowded conditions on the cordless frequencies.

still providing ubiquitous, easy-to-use service on one handset. While technology advances and more innovative approaches to spectrum management will increase the availability of spectrum, the overriding objective at the outset of deployment will be to minimize infrastructure costs, and designing a wide area microcell network to provide toll quality indoor service does not serve this goal.

Subscriber Velocity

The degree of mobility most frequently requested by subscribers also could hold substantial implications for the design of the PCS network. Whether walking down the street or driving on a highway, subscribers need the same network functionalities but at different speeds. Specifically, the processing speed and volume of network signalling and control functions increase directly with the velocity of the subscriber and inversely with the average cell size. As noted earlier, the extent to which these factors will determine the network architecture remains highly uncertain, and depends in large part upon the costs of network complexity and the power requirements of the handsets.

The model incorporates estimates which assume aggressive reductions in the costs of network handoff, power control, and signalling using microcells. Within this environment of significant uncertainty, however, these assumptions might be overly optimistic for the smaller-sized microcells considered in the model. As a result, the sensitivity analysis examines the sensitivity of network costs to this factor.

Usage Characteristics

Another highly uncertain factor is the rate at which consumers might opt to sign-up for new PCS. Fueled by the explosive growth of cellular and cordless services, a number of marketing studies forecast large markets for PCS featuring lightweight handsets. For example, a US West marketing study predicts 21 percent of the population would subscribe to PCS assuming a low-cost handset with adequate capabilities (US West, 1991). The model in this paper estimates network costs under static assumptions regarding subscriber penetration and usage levels. The analysis makes no assumptions regarding the price elasticity of PCS, or cross-price elasticities between PCS and other wireless services that could ultimately influence the strategy of network evolution.

The same traffic engineering principles applied to calculate the size of cellular or telephone networks can be used to determine the necessary capacity of a PCS network. The expected level of subscriber traffic during the peak usage hour determines system capacity. But unlike traditional telephony, high usage of PCS during the peak hour also translates into a need for more spectrum, or more efficient radio transmission links. Additional capacity to accommodate growth is acquired by lowering the spectrum reuse factor, cell splitting, or by improving the radio access technology. Thus, as usage increases, either the number of cells or the complexity of equipment, or both, must also increase.

The expected number of customers and the average offered traffic per subscriber in the peak usage hour are key parameters in the engineering cost model. Telephone networks enjoy near universal penetration of households with a typical residence generating 0.1 erlangs per line during an average busy-hour.[18] In 1991, cellular telephone services had roughly 9-million subscribers who offer an average of 0.02 - 0.03 erlangs of traffic during the average peak hour. Because the diffusion rate of PCS will be highly uncertain, this value is treated as a parameter in the cost models. The model assumes as a base case that each PCS subscriber generates 0.03 erlangs of mobile traffic on average during the peak hour and that there are an average of two subscribers per household. The sensitivity analysis examines how costs vary with levels of offered traffic by subscribers.

Planning for Network Evolution

Over time the demand for wireless services will vary depending upon new growth, introduction of new services, or other changes in patterns of consumer choices. The dynamic nature of demand translates into the need for a network infrastructure which can be flexibly modified to efficiently accommodate new patterns of usage. *Network evolution* is the process through which planners change the network architecture in order to satisfy new patterns of demand or incorporate new technologies into the network. To remain commercially viable, PCS network architectures should have the capability to evolve to reflect the growth in wireless service demands and technological innovations.

One attractive aspect of cellular design is that the network can evolve to accommodate new traffic demands through the process of cell splitting. Cell splitting permits a strategy of network evolution which begins with a few, large-sized cells when there are a small number of subscribers and progresses to a large number of microcells in those areas where traffic growth warrants the additional investment in network capacity. Service quality will place a lower bound on the number of large cells initially deployed in the network. In particular, low-power handsets could constrain the maximum cell size available for a given level of service quality. Once an acceptable service coverage region is achieved, the amount of spectrum available and the rate of growth will determine the number of new cells created by cell splitting.

The cost model assumes a system that is initially designed to provide coverage throughout the entire service area. As noted above, the penetration level of PCS subscribers is a model parameter. This usage level and the size of the spectrum allocation determine both the network capacity and number of cells needed in the network. For a given spectrum allocation size, the model calculates the largest microcell size possible for a given level of usage. Thus, the model calculates the long-run average costs of building the PCS network assuming smaller cell sizes are needed as the subscription levels rise. The output is a matrix of values with the spectrum allocation size and subscriber penetration parameters as indexes.

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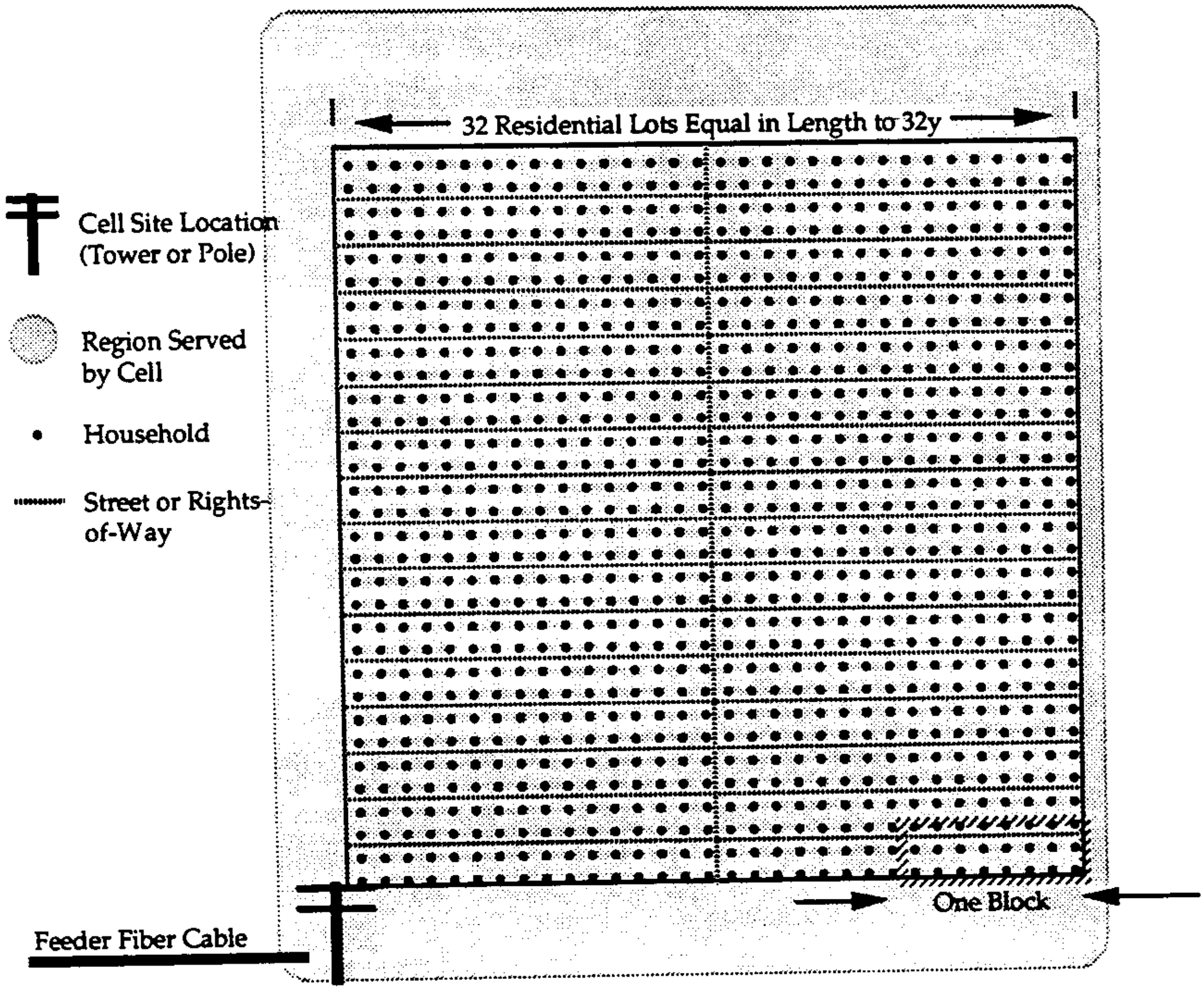
[18]Erlangs are the unit used to measure the traffic load on telecommunications systems. Erlangs can be viewed as the ratio of the time that an individual circuit is busy.

Appendix B. Cable Layouts of PCS Networks



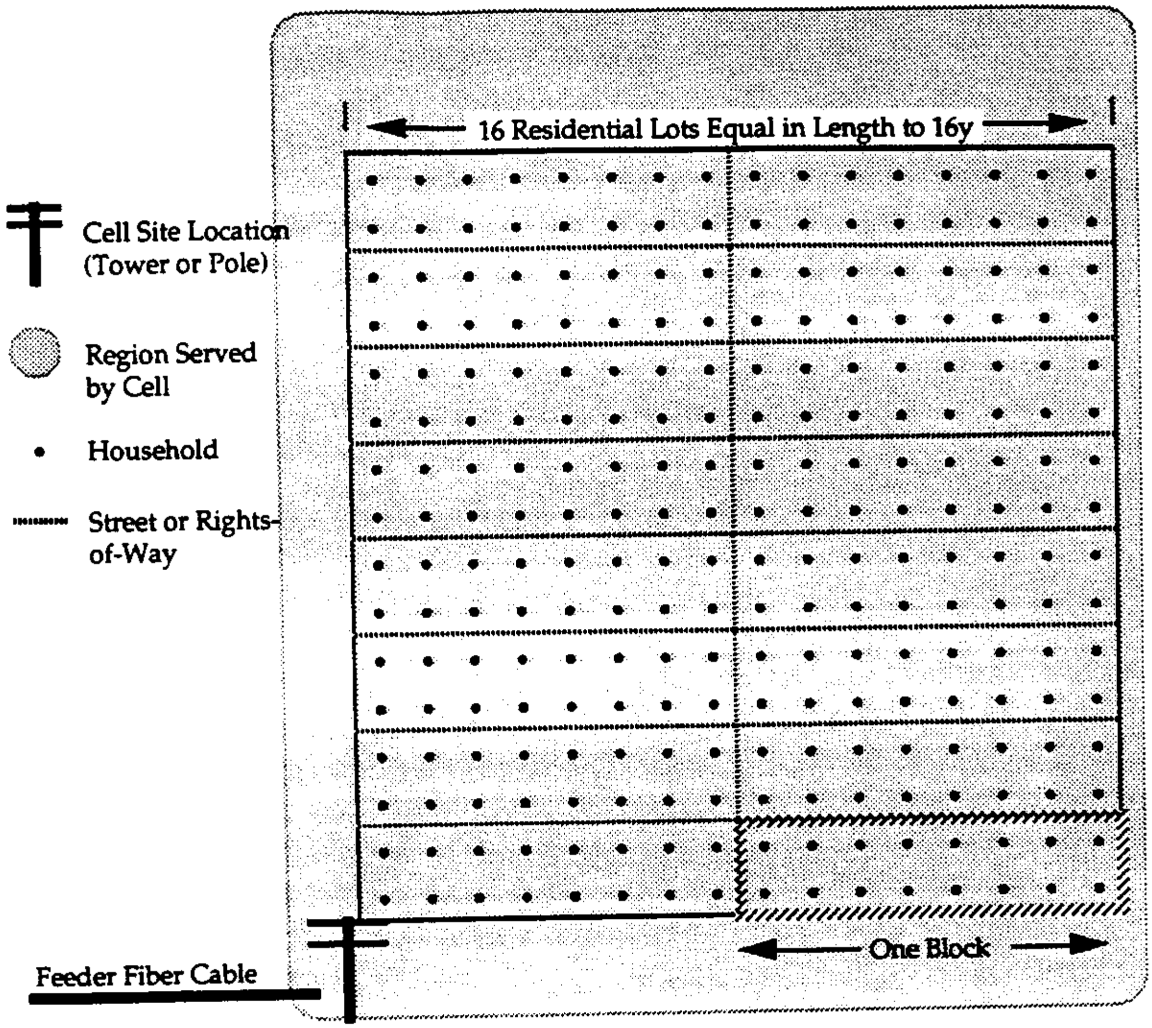
Calculations of Cable Length and Path Distance for PUS Network Using 1600-meters Microcells Throughout the Serving Area of 1024 Households

Number of Cell Sites = 1 per 4096 Households

Length of Distribution Cable and Path = 0

Radius of Cell = $32(\sqrt{2})y$

Figure B-1. PCS Architecture with 1600-meters Microcell



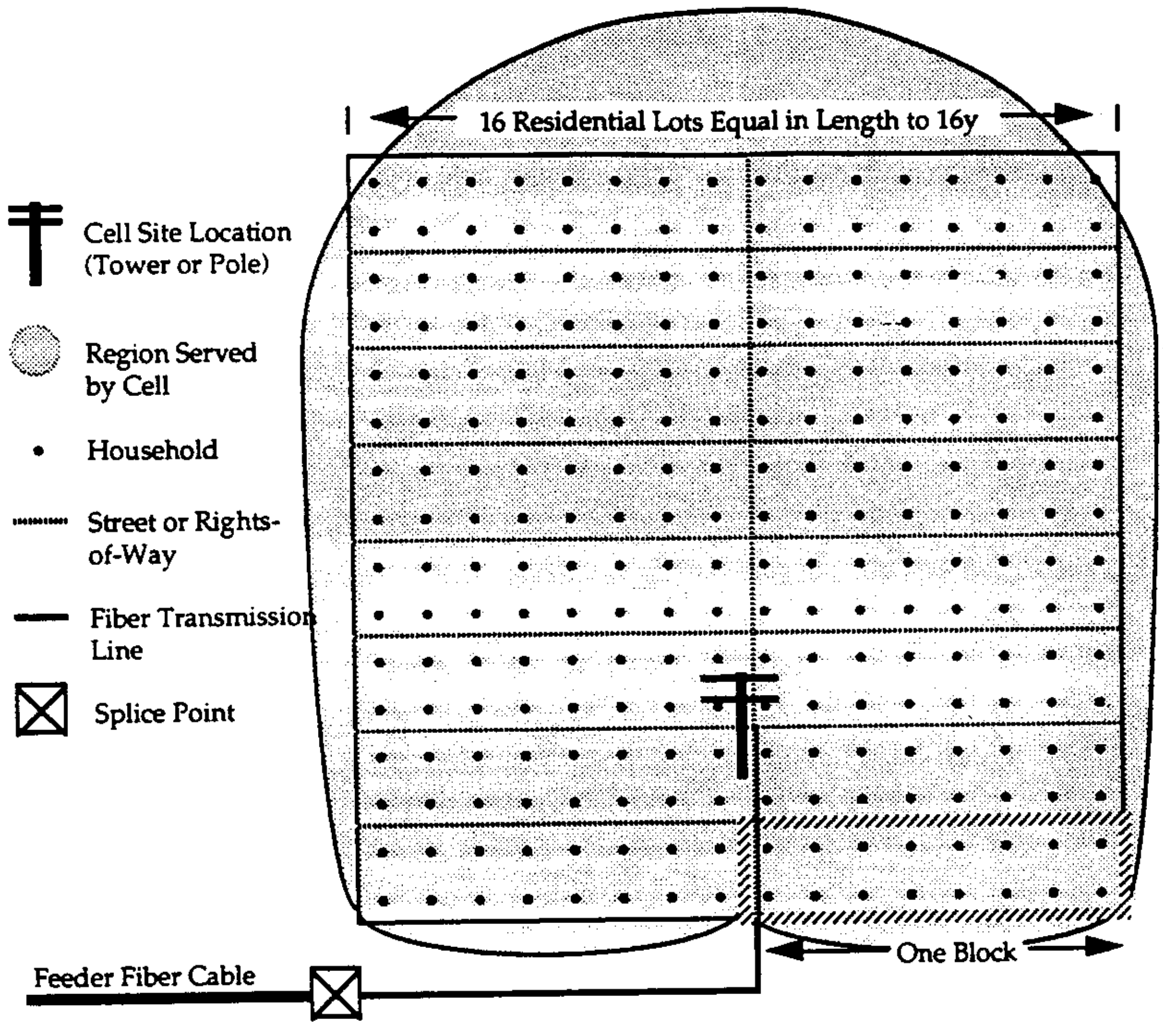
Calculations of Cable Length and Path Distance PCS Network Using 800-meters Microcells Throughout the Serving Area of 1024 Households

Number of Cell Sites = 1

Length of Distribution Cable and Path = 0

Cell Radius = $16(\sqrt{2})y$

Figure B-2. PCS Architecture with 800-meters Microcells



Calculations of Cable Length and Path Distance for PCS Network Using 400-meters Microcells Throughout the Serving Area of 1024 Households

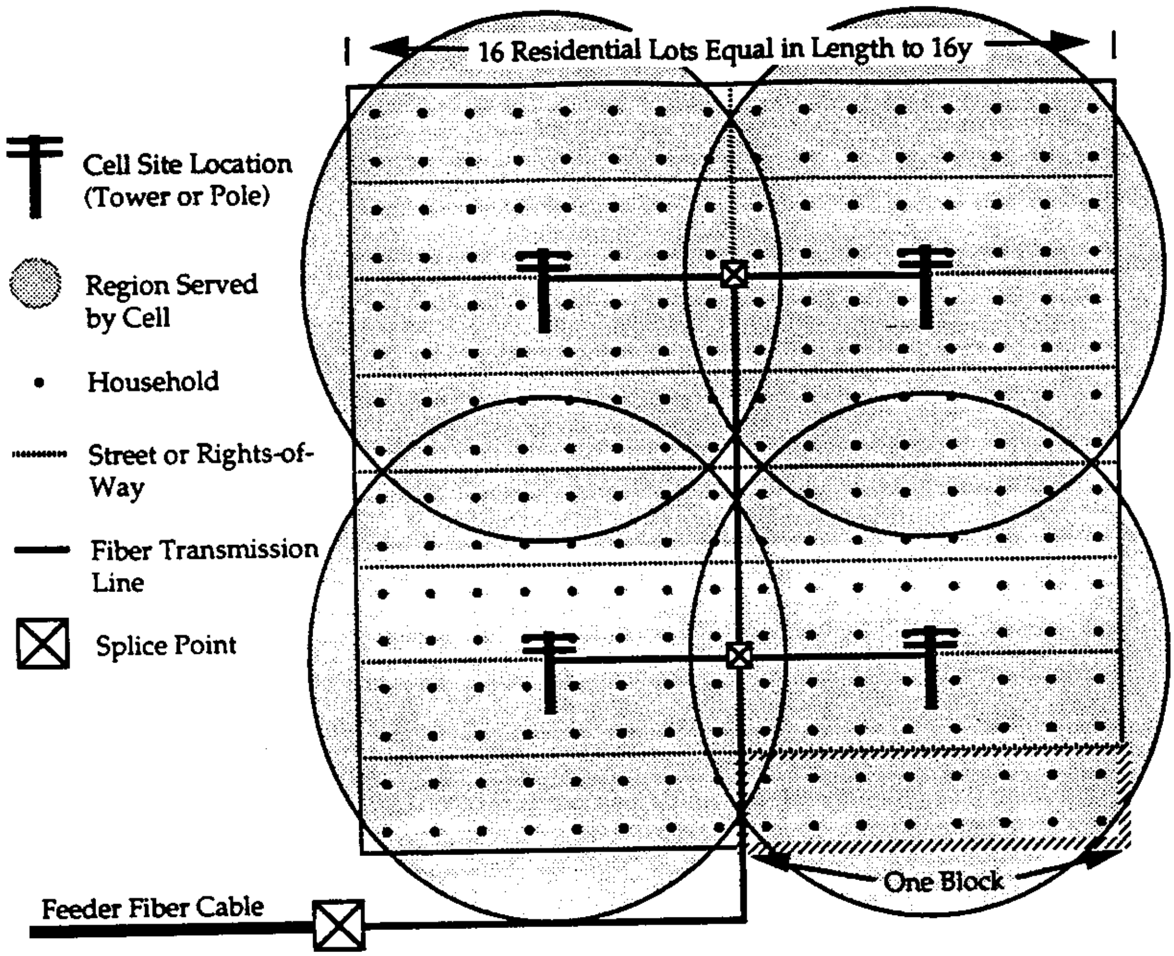
Number of Cell Sites = 4

Length of Fiber Cable = 4*(4y+8y) = 48y (plus 12 streetwidths and 5% overhead)

Length of Path = 4*4y + 2*8y = 32y (plus 10 streetwidths)

Cell Radius = 8(√2)y

Figure B-3. PCS Architecture with 400-meters Microcells



Calculations of Cable Length and Path Distance for a PCS Network Using 200-meters Microcells Throughout the Serving Area of 1024 Households

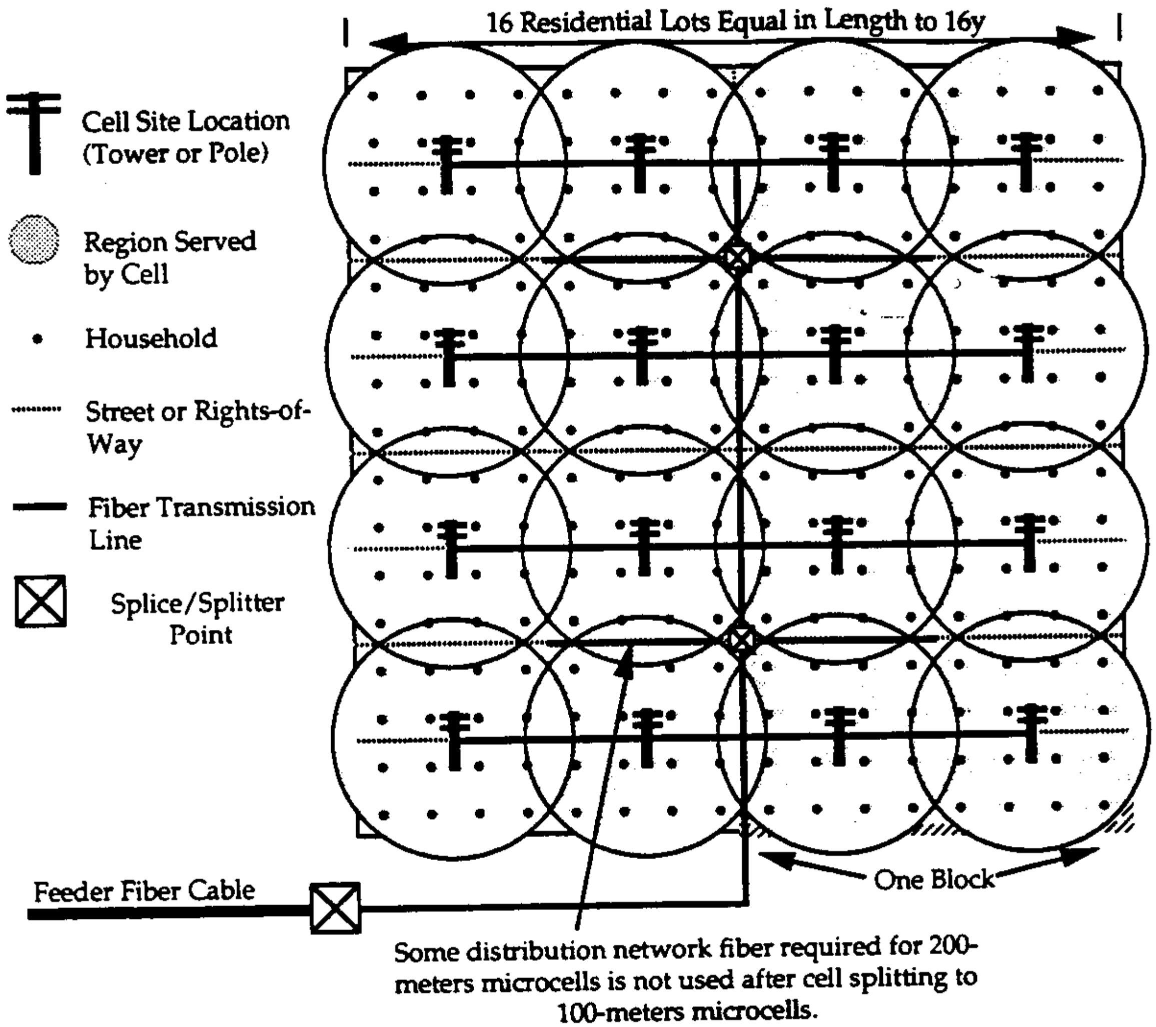
Number of Cell Sites = 4*4 = 16

Length of 4-Fiber Cable = 4*(12y+8y+2*8y) = 144y (plus 36 streetwidths and 5% overhead)

Length of Fiber Path = 2*8y+4*(12y+2*8y) = 128y (plus 34 streetwidths)

Cell Radius = $4(\sqrt{2})y$

Figure B-4. PCS Architecture with 200-meters Microcells



Calculations of Cable Length and Path Distance for PCS Network Using 100-meters Microcells Throughout the Serving Area of 1024 Households

Number of Cell Sites = 4*16 = 64

Length of 4-Fiber Cable = 4*{12y+8y+2*8y+4*12y+2*4y} = 368y (plus 60 streetwidths and 5% overhead factor)

Length of Fiber Path = 2*8y+4*{14y+2*8y+4*12y} = 328y (plus 54 streetwidths)

Cell Radius = 2($\sqrt{2}$)y

Figure B-5. PCS Architecture with 100-meters Microcells

Appendix C. Summary of Cost Model Base Case Assumptions

Parameter	Base Case Assumption	Comments
Average Offered Traffic	0.03 Erlangs/Subscriber	Assumes 2 call attempts per busy-hour; sensitivity analysis considers range between 0.01 - 0.12 erlangs per subscriber.
Subscribers per Household	2	
Radio Channel Size	25 KHz	Full-Duplex. Sensitivity analysis considers a range between 20 - 70 KHz.
Spectrum Reuse Factor	7	Sensitivity analysis considers a range between 1 -16.
Indoor Cordless Set-Aside	1 MHz	Amount of spectrum out of block size dedicated for indoor cordless applications.
Cell Sizes	100-meters to 1.6 Km.	Cell size depends upon amount of offered traffic.
Allocation Size	25 MHz	Model considers range between 1 - 40 MHz.
Grade of Service	1 percent	Network design assumes a 1 percent blocking probability using Erlang B formula.
Housing Density	88 homes per mile	

Table C-1. Base Case Assumptions for Cost Model

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