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)

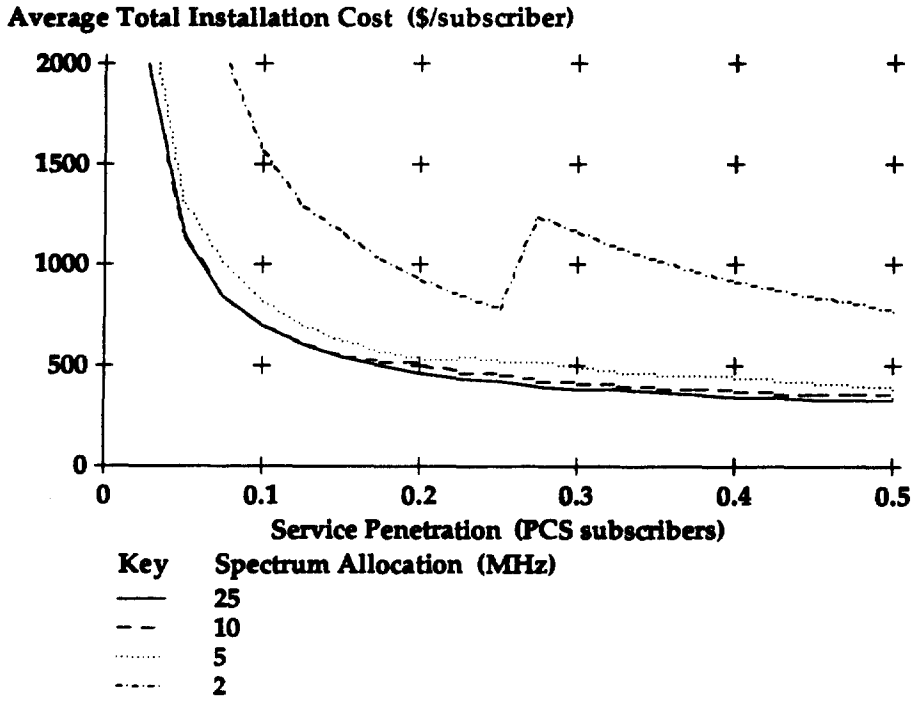


Figure 5. Total Estimated Capital Costs per Subscriber of PCS System (in dollars)

## 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.

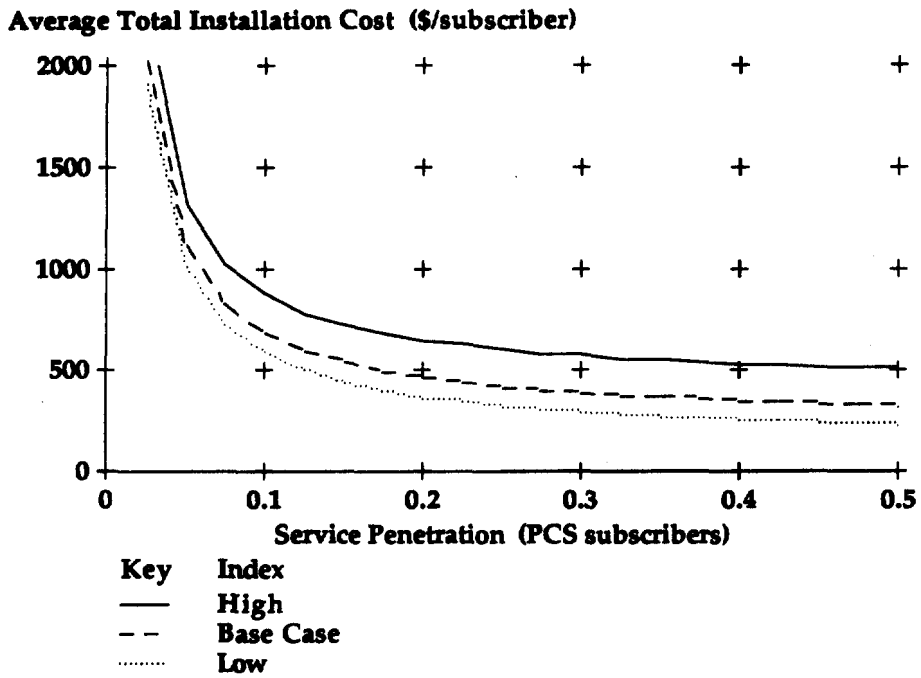


Figure 6. Variation of Total Estimated Costs per Subscriber to Electronics Costs; 25 MHz Spectrum Allocation Size (in dollars)

***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.

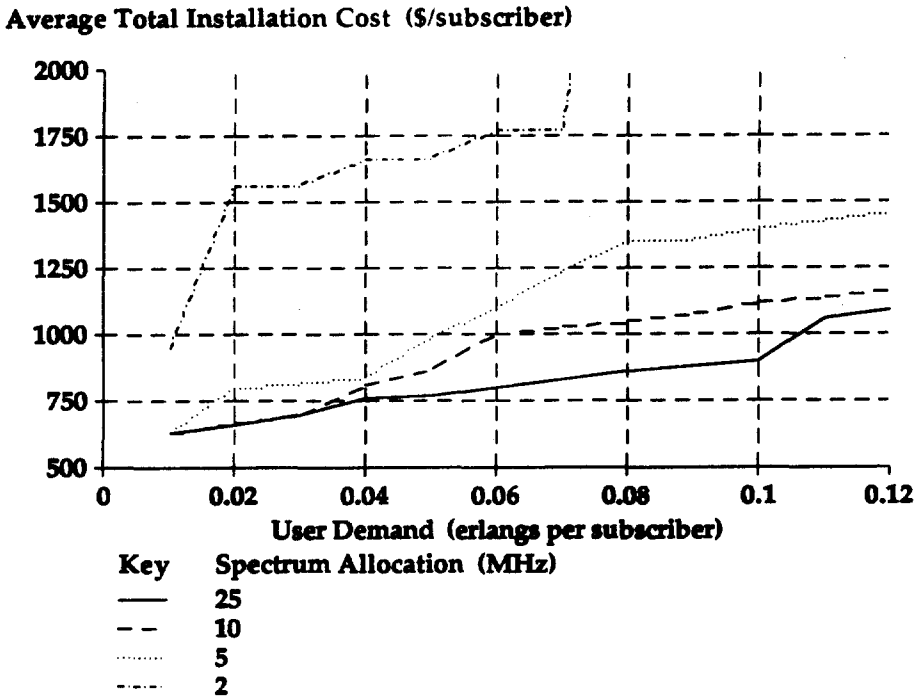


Figure 7. Variations in Total Estimated Costs per Subscriber to Usage; 10% Level of Penetration to PCS (in dollars)

***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.

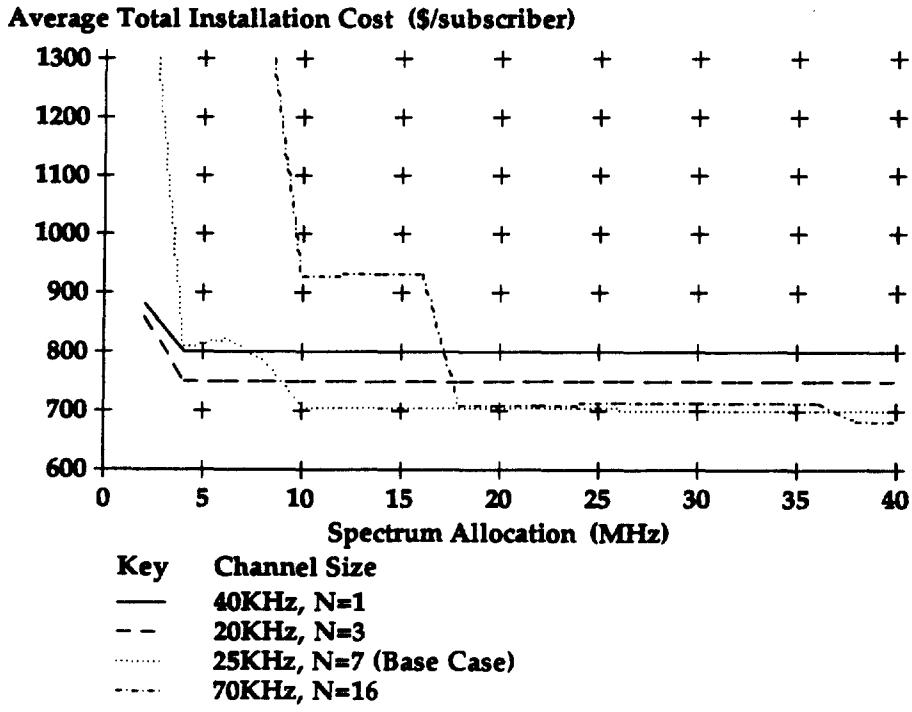


Figure 8. Variations in Total Installation Costs per Subscriber to Radio Systems with Different Levels of Spectral Efficiency; 10% Penetration of Subscribers (in dollars)

[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 assumed above are the usual costs of advertising and customer service

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.

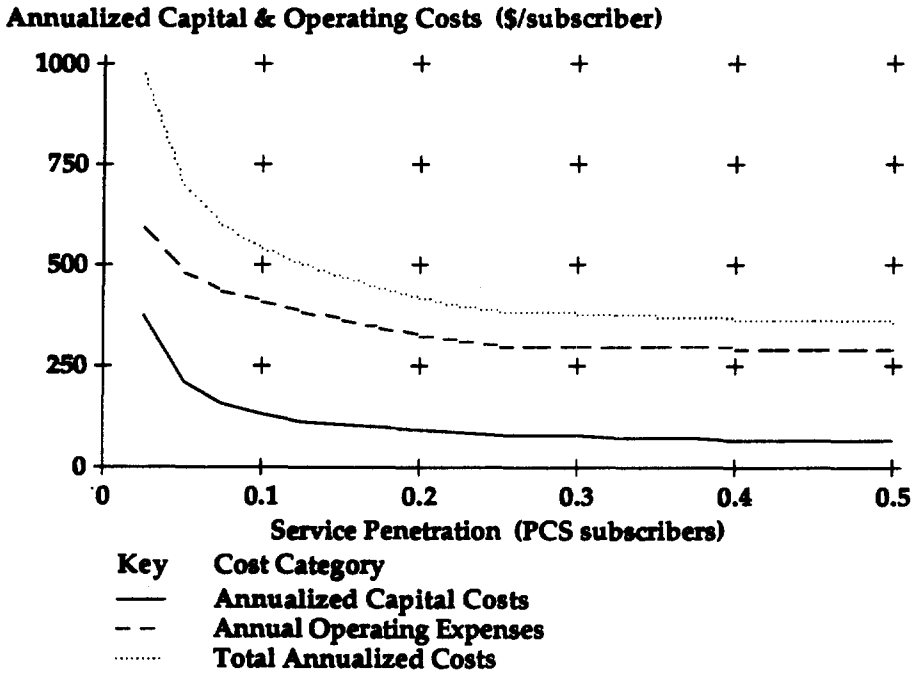


Figure 9. Total Annualized Expenses for PCS; 25 MHz Spectrum Allocation (in dollars)

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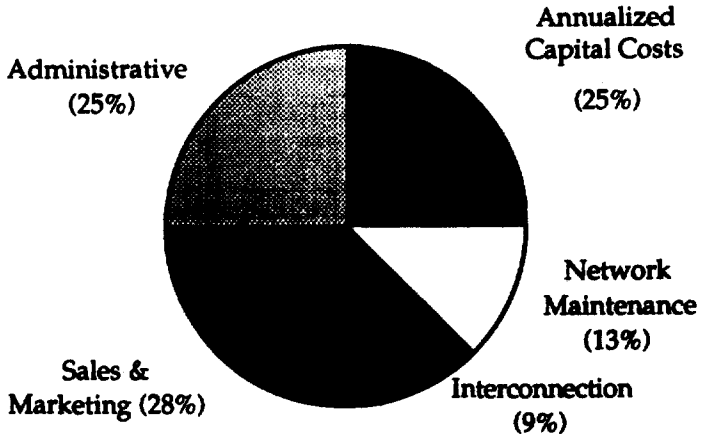
organizations. These costs are likely to reflect some economies of scale with the growth of new subscribers.

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.

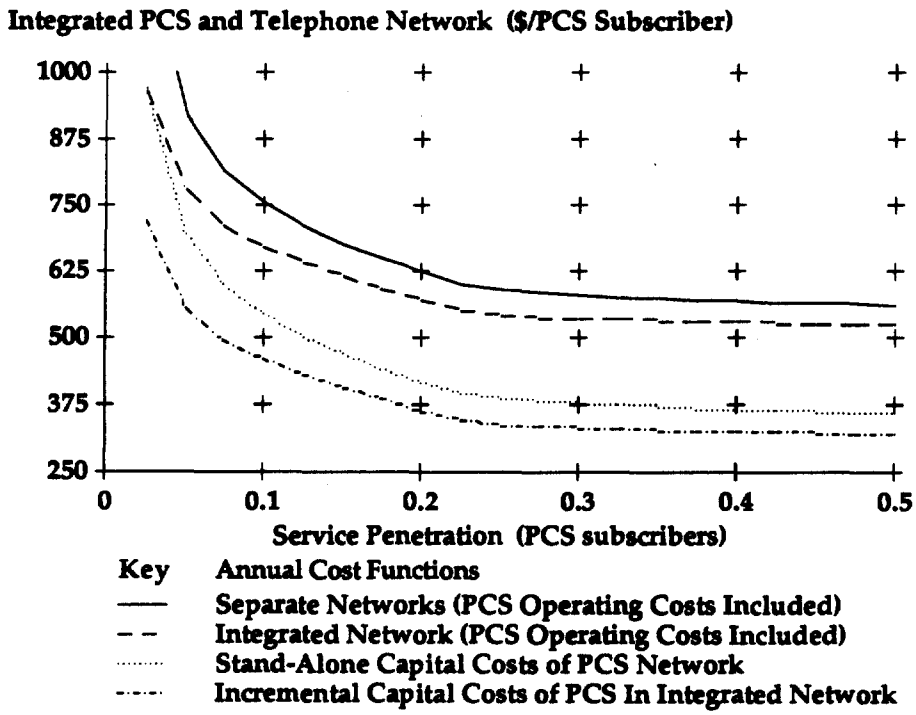


Figure 11. Measuring Economies of Scope Between PCS and Telephone Service (in dollars); 25 MHz Spectrum Allocation

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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).

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[28]By 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.

[29]To 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.

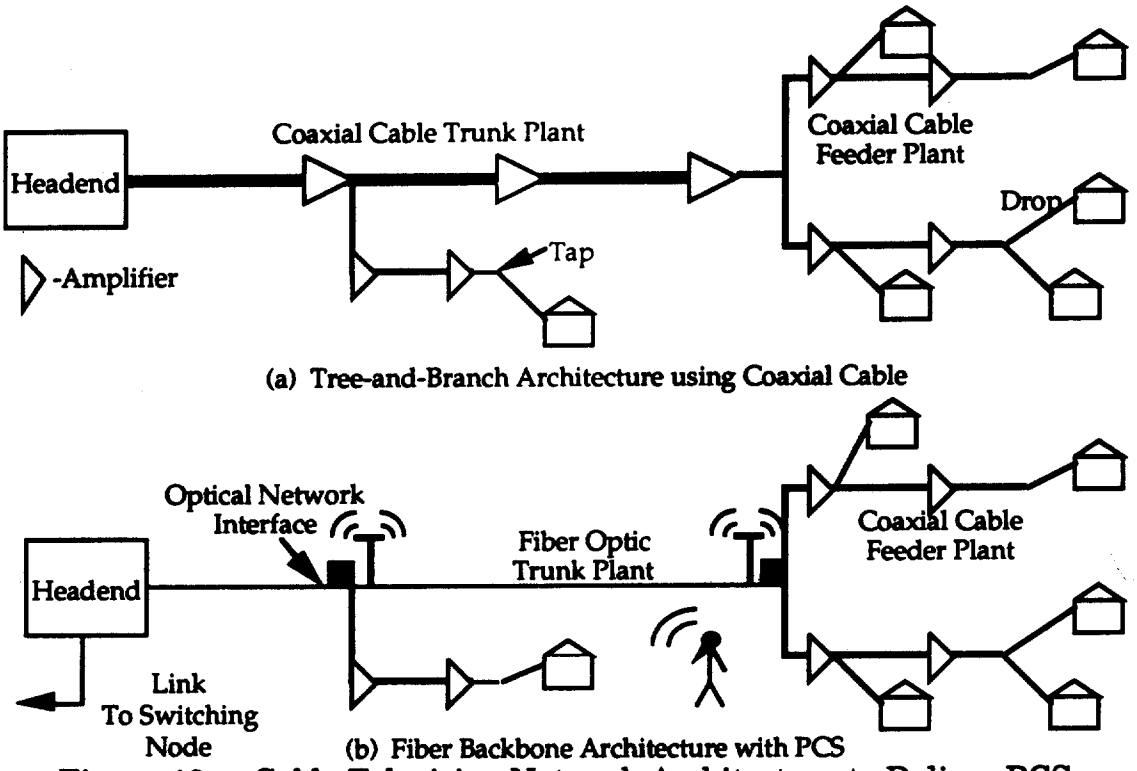



Figure 12. Cable Television Network Architecture to Deliver PCS

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.

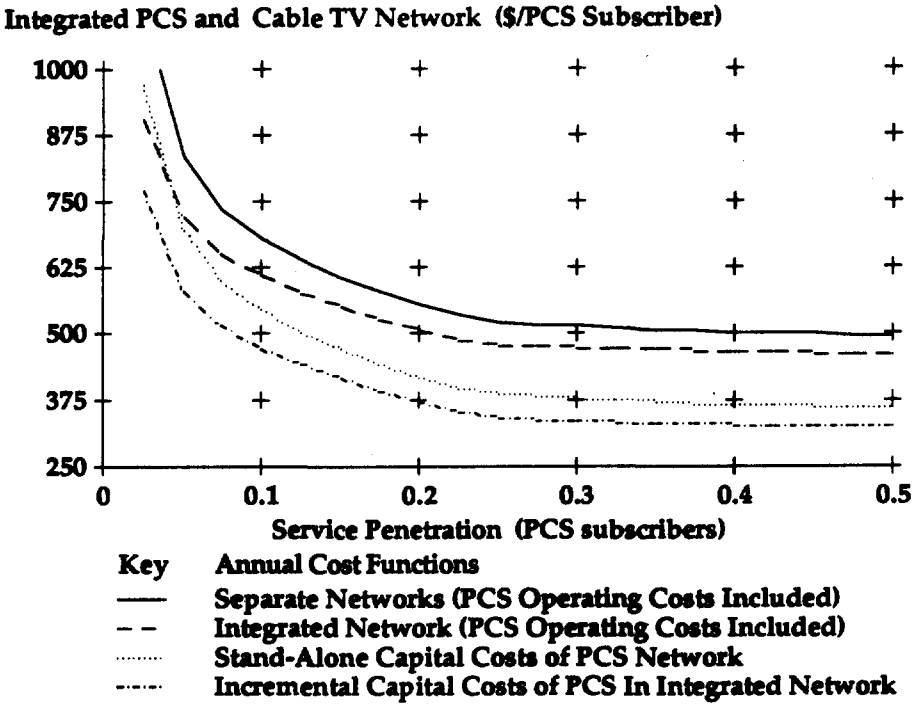



Figure 13. Measuring Economies of Scope Between PCS and Cable Television Service (in dollars); 25 MHz Spectrum Allocation

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

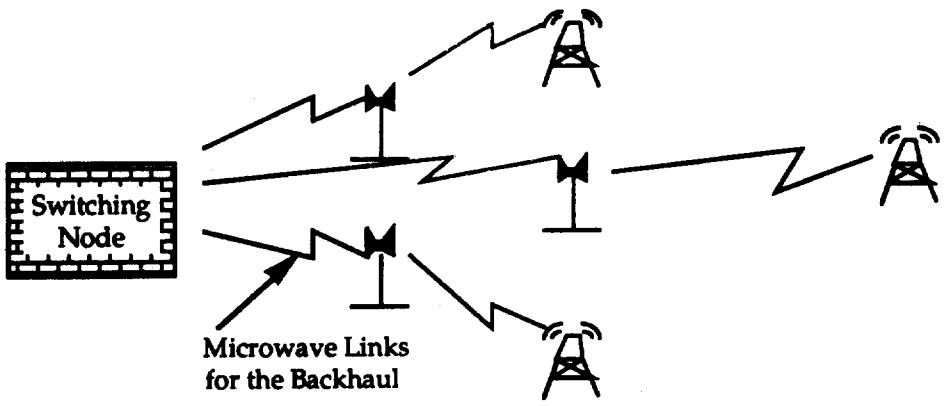
backbone systems in the immediate future. Once fiber backbones are deployed, use of the remaining coaxial cable in the feeder and drop segments of the network can be used with much fewer technical constraints.

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.

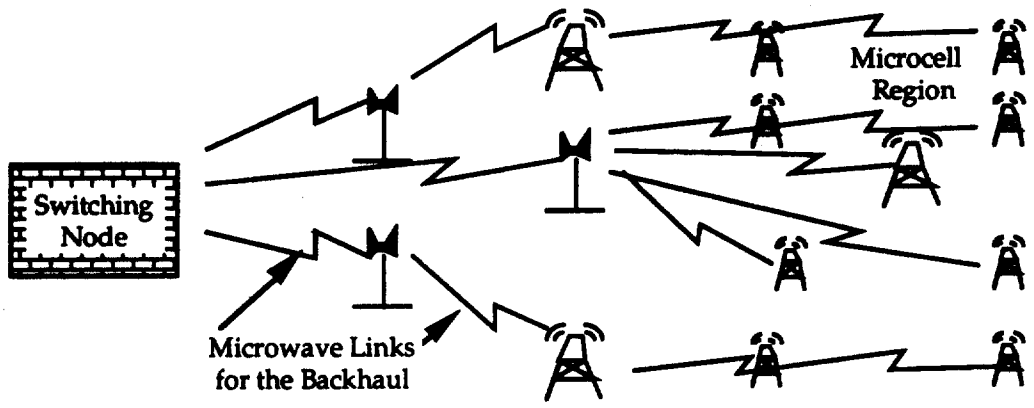
**Providing PCS Over Cellular Networks**

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

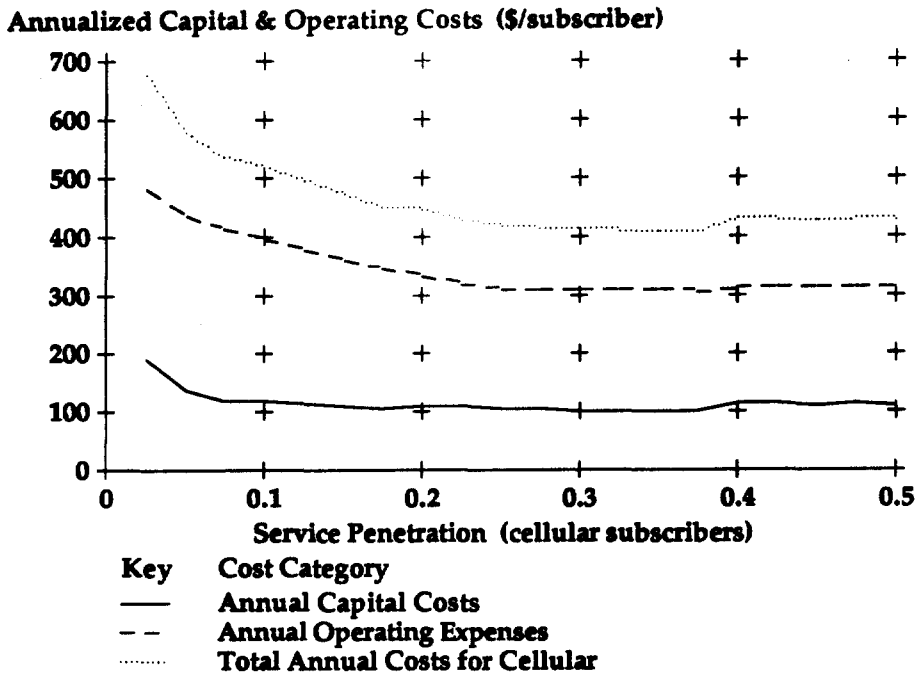



Figure 15. Annual Cost Function for Cellular Telephone Service (in dollars)

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.

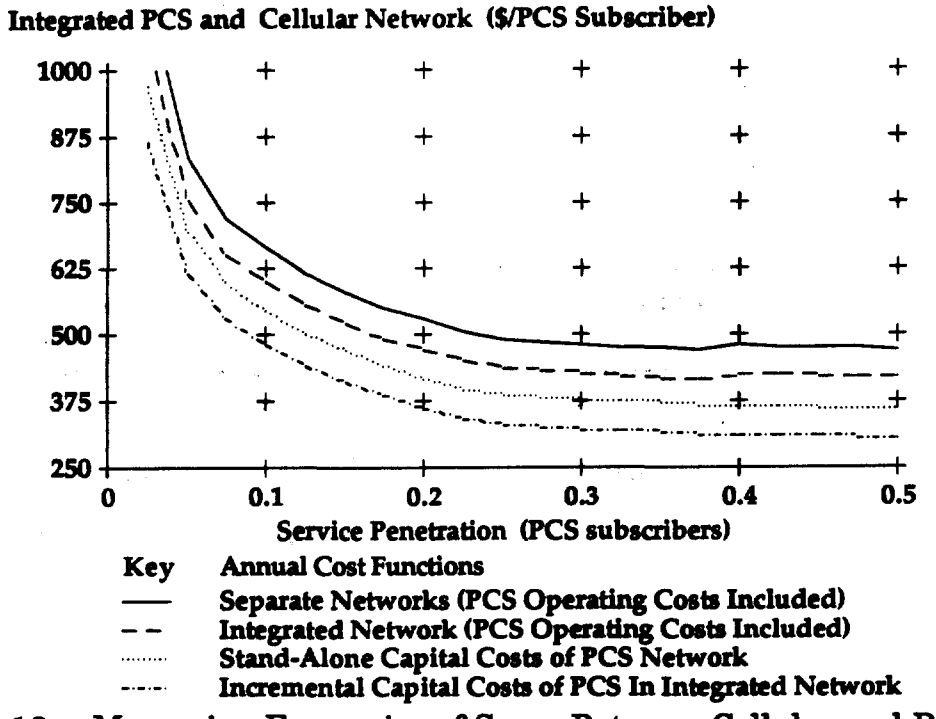



Figure 16. Measuring Economies of Scope Between Cellular and PCS (in dollars); Two Separate 25 MHz Spectrum Allocations For Each Service

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.

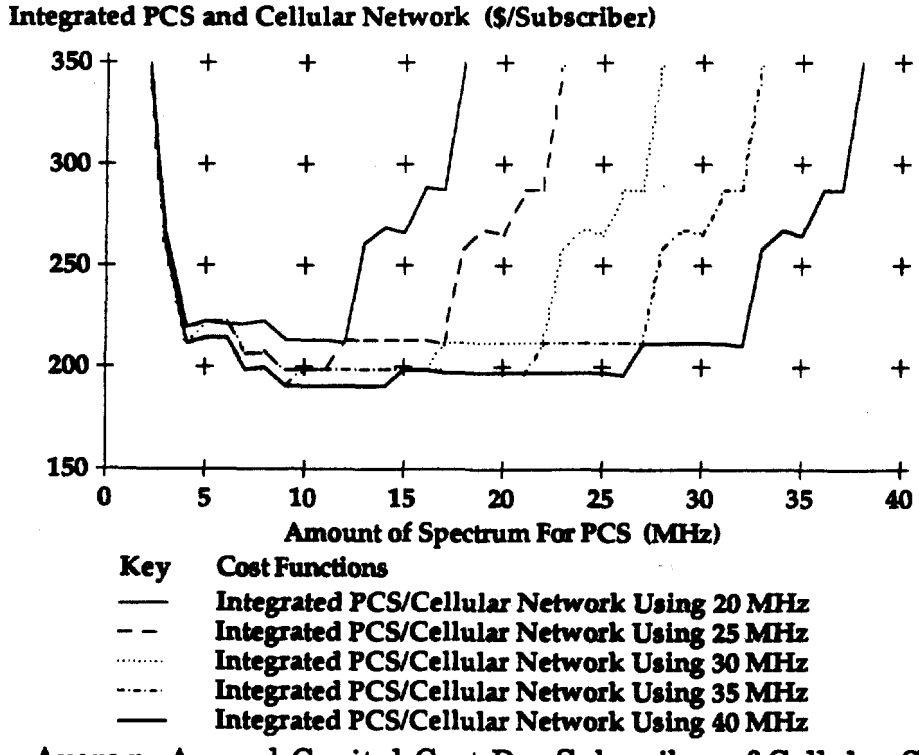



Figure 17. Average Annual Capital Cost Per Subscriber of Cellular System and Base Case PCS System Assuming Varying Amounts of Spectrum Dedicated for PCS; 10% Penetration (in dollars)