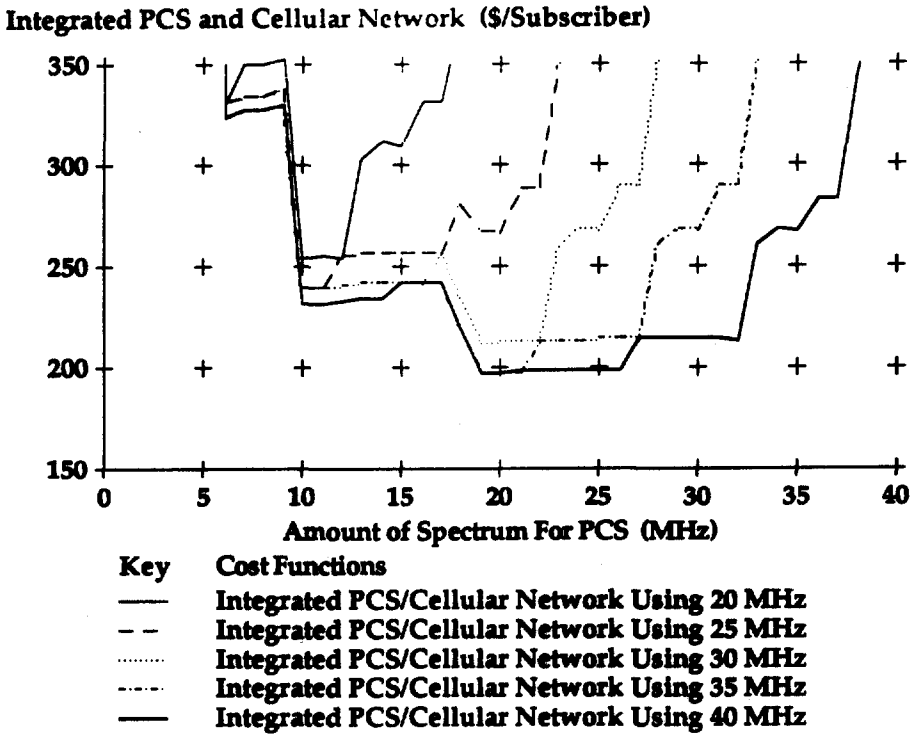

Figure 18. Average Annual Capital Cost Per Subscriber of Cellular System and PCS System (N=16, Channel Size=70 KHz) Assuming Varying Amounts of Spectrum for PCS; 10% Penetration (in dollars)

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

---

[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	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

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

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

[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

---

[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]

---

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

---

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.

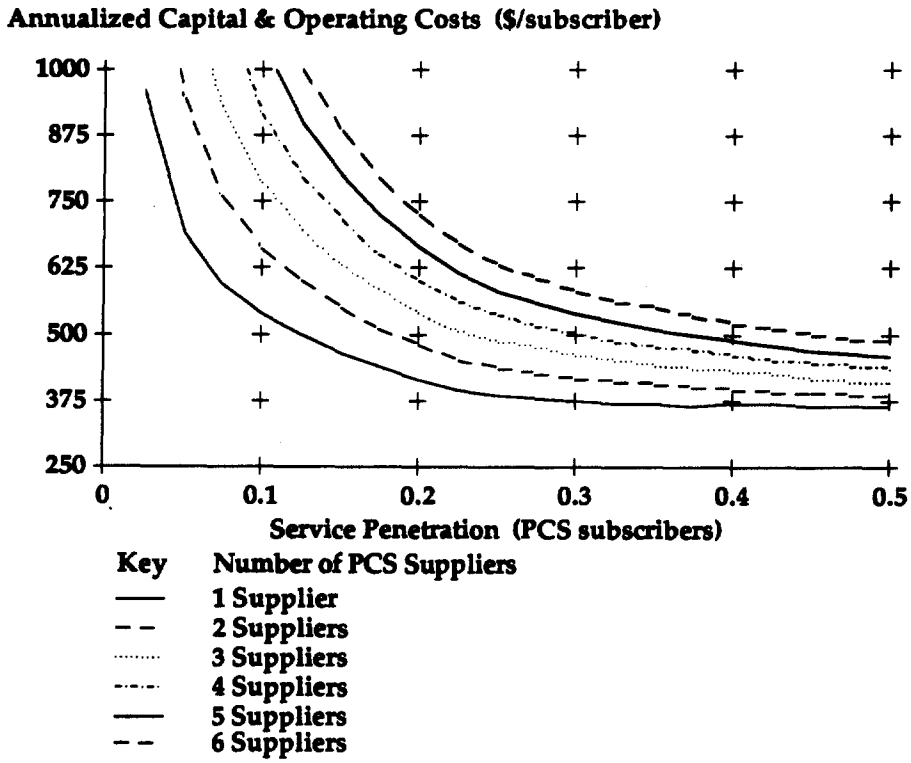

Figure 19. Variation in Total Annual Costs to Varying Numbers of Firms in the PCS Market; 20 MHz Spectrum Block (in dollars)

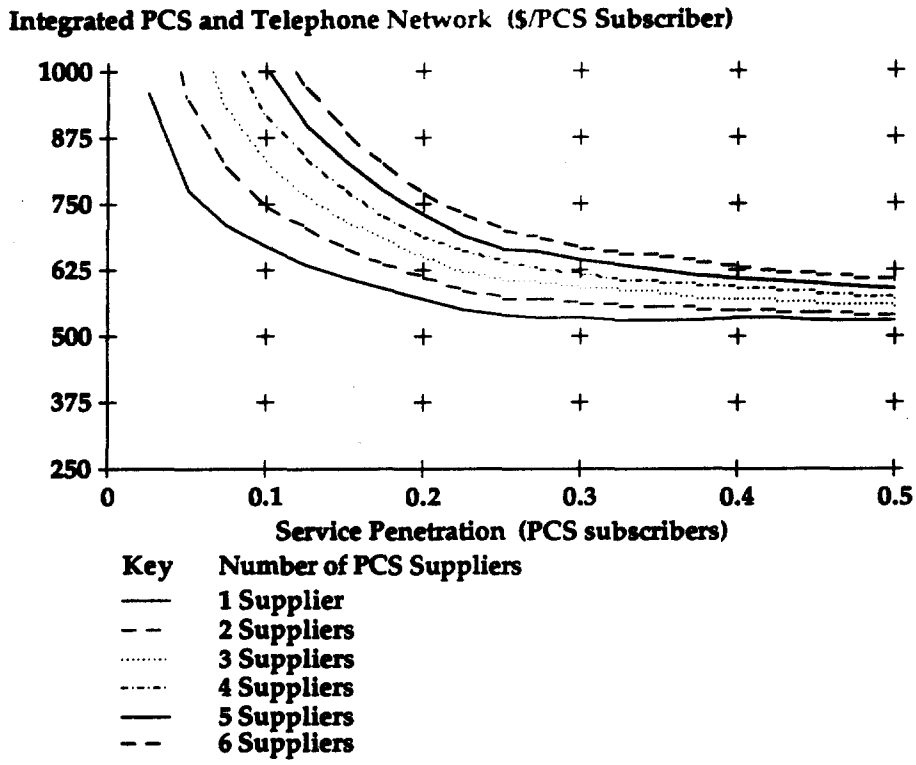

Figure 20. Variation in the Annual Costs of an Integrated PCS and Telephone Network (Including Capital and Operating Expenses for PCS Only) to Varying Numbers of Firms in the PCS Market; 20 MHz Spectrum Block (in dollars)

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

---

[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

---

[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,

[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.

---

[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

[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

---

[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:

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

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:

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

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:

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

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

---

[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).