Auctioning the Airwaves: The Contest for Broadband PCS Spectrum

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The House and Senate of the United States Congress recently passed legislation that directs the FCC to establish a system for using auctions to allocate the use of radio spectrum for personal communications services. There is a unique and unprecedented set of issues that arise in this context, which are of interest to economists, industry analysts, regulators, and policymakers. We discuss these issues and evaluate their likely impact on the outcome of the spectrum auctions. In addition, we argue that there may be pitfalls in the auction procedure adopted by the FCC, and we discuss possible alternative procedures.

1. Introduction

A recently enacted amendment to the Communication Act of 1934 directs the FCC to establish a system for using auctions to allocate the use of radio spectrum for a new generation of wireless communications called personal communications services (PCS).[1] The legislation is revolutionary in its proposed use of auctions as a mechanism to allocate more efficiently the use of this scarce national resource and

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1. The amendment was enacted on August 10, 1993, as part of the Omnibus Budget Reconciliation Act of 1993, which added a new section 309(j) to the Communication Act of 1934 (as amended, 47 U.S.C. ¶151-713, Communication Act).

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for raising funds to reduce the national deficit.[2] The auctioning of radio spectrum raises a unique and unprecedented set of economic and public policy issues that are key to achieving the goals set forth in the legislation. Many of these issues concern policy makers not only in the United States, but also in other countries, such as Canada and New Zealand, that plan to allocate spectrum in the near future. The purpose of this paper is to discuss these issues and to evaluate the likely impact of the auction design on the outcome of the spectrum auctions.[3]

There are two types of PCS: "narrowband PCS" and "broadband PCS." The former will use small slices of spectrum (12.5–50 KHz) in the 900 MHz band for services such as two-way paging and interactive television. The latter will use much larger 10–30 MHz slices of spectrum in the 2 GHz band. These services will permit access to a variety of voice, data, and video communications services such as lightweight wireless telephone handsets, wireless computer networks, portable fax machines, and other graphic devices.[4] The narrowband PCS auctions began in July 1994, and an extensive analysis from an insider's viewpoint is presented in Cramton (1995). In this paper we will focus on the broadband PCS auction. Although many of the issues are similar, additional economic issues are raised as broadband PCS is also a potential substitute for cellular and traditional "wireline" telephony. Hence, the deployment of broadband PCS, and the identity of the auction winners spectrum, may have a significant impact on the cellular and wireline local telephony market, which is roughly a $100 billion per year industry. Additionally, the broadband auction may be more complex because of the much larger number of licenses being auctioned and the technological issues involved in building a broadband PCS network.

The use of auctions represents a dramatic change in the manner in which spectrum is being allocated. In the past, the right to use radio spectrum had been allocated by comparative hearings or lotteries. These procedures have been criticized for creating windfall profits to speculators, delaying the deployment of new services, and for distorting the allocation of a valuable public resource. The new section

2. The Congressional Budget Office (CBO) estimates that the auction could raise $1.3 billion to $5.7 billion, see *Auctioning Radio Spectrum Licenses*, CBO study, released on March 1992. The Office of Management and Budget estimates revenues of $12.6 billion, see *Budget of the United States, Analytical Perspectives, Fiscal Year, 1995.*

3. Many of these issues are also discussed in McMillan (1994).

4. PCS is distinguished from the currently available cellular services by its use of digital technology, low-powered handsets, and smaller cell sites, thereby making the PCS handset more portable.

309(j) of the Communication Act directs the FCC to select an auction procedure that:

1. encourages rapid deployment of new technologies and services to benefit all the public, including rural areas, without administrative or judicial delays.
2. promotes economic opportunity and competition and ensures that new and innovative technologies are readily available to the public.
3. recovers for the public a portion of the value of the spectrum.
4. promotes efficient use of the spectrum, that is, the allocation is made to those who value it the most.

One critical issue that needs to be considered to ensure that the legislative objectives are accomplished is the design of the auction format. Auctions can be conducted on a sealed-bid basis or on an open-outcry basis in either Dutch format (i.e., descending-price auction that is used in Holland to sell tulips) or English format (i.e., ascending-price auction). The FCC could use a first-price auction (the winner pays the highest bid), or a second-price auction (the winner pays the second highest bid), or possibly as a more complicated function of all bids. Licenses could be auctioned sequentially or simultaneously, individually or in bundles, or possibly as a combination of both, that is, a combinatorial auction. The FCC could prespecify certain bundles that could be bid on, or leave it to the bidders to select their preferred bundles. The differing auction formats present bidders with different optimal bidding strategies and with differing abilities to influence the outcome of the auction. From a public policy perspective, a well-designed auction format should award the spectrum to the most qualified bidder(s), and bidders should be deterred from engaging in socially wasteful attempts at market manipulation. At the same time, a key argument in favor of auctions is their ability to raise significant revenues. Hence, the revenue generating capabilities of different auction formats are also an important consideration.

A second issue to be considered is the number of licenses to be granted in each area, and the size of the geographical area (i.e., local, regional, or national) to be covered by each license. The FCC plans to allocate a total of 120 MHz across the United States for broadband PCS, which is three times the spectrum originally allocated for cellular telephony. The licensed allocation in each geographical service area has been split into six blocks: three 30 MHz channel blocks, and three 10 MHz channel blocks. The license service areas adopted have been designated as Major Trading Areas (MTAs) for two of the three 30 MHz channel blocks, and Basic Trading Areas (BTAs) for the remaining channel blocks.[5] There are 51 MTAs and 493 BTAs under the FCC's plan. As three of the 30 MHz MTA licenses have been awarded under the "pioneer preference" clause, the total is 2071 licenses to be auctioned. Given the large number of licenses, two questions arise: Should the licenses be auctioned simultaneously, sequentially, or should the FCC hold a sequence of simultaneous auctions? In the case of sequential auctions, what should be the appropriate sequence in which licenses are being auctioned? These questions are important because of the likely impact of the auction format on the eventual number of licensees, which will affect both the structure of the emerging PCS market and the government's revenue from the auction.

Further policy issues that arise in the broadband case include whether current providers of cellular service should be able to participate in the spectrum auctions. Also, since some of the allocated spectrum is currently being used for purposes that are incompatible with PCS, should the incumbents be relocated or allowed to bargain with the auction winners? Finally, how should the FCC's desire to promote the ability of small businesses, minority-owned firms, and entrepreneurs to compete for a share of the market be addressed?

In this paper we summarize some of the relevant insights to be gained from auction theory. We show how these insights combined with a simple economic-engineering model about the probable structure of the PCS market help answer the policy issues outlined above. In particular we argue that the cost structure of broadband PCS is likely to exhibit significant economies of scale and that these economies in turn suggest the use of combinatorial auctions.

The remainder of the paper is organized as follows: Section 2 presents the general auction framework used to evaluate the auction procedures. In Section 3, we discuss a number of PCS-specific economic and public policy issues that need to be taken into account in designing the auction procedure. In Section 4, we present the FCC's chosen mechanism and argue that it may lead to an inefficient geographical aggregation of licenses. We then make a case for the use of combinatorial auctions to mitigate this inefficiency. Finally, in Section 5 we offer concluding remarks.

2. Auctions in Economic Theory

In this section, we review the economic literature on auctions and bidding strategies. We focus attention on results that provide insights

5. The MTAs and BTAs are generally defined by the *Rand McNally 1992 Commercial Atlas and Marketing Guide,* 123rd Edition.

regarding the impact of alternative auction formats on the feasibility of achieving the legislative objectives cited in the introduction. The reader interested in basic auction theory or a broader perspective may wish to consult the excellent surveys by McAfee and McMillan (1987), Milgrom (1987, 1989), Chari and Weber (1992), and Wilson (1993).

2.1 The Game-Theoretic Framework

In practice there are a variety of auction formats, including, first- and second-price, sealed-bid auctions, Dutch, and English auctions. To evaluate which auction format best meets the legislation's objectives, the FCC needs to predict how bidders will act. The approach used in auction theory is to model each type of auction as a noncooperative game and to use the resulting equilibrium outcomes as a basis for making recommendations about the most appropriate auction format.

We begin by briefly presenting a benchmark case. Under certain assumptions, a remarkable result, first proved by Vickrey (1961), holds: All of the above auction formats are efficient in the sense that the item being auctioned is awarded to the bidder who values it the most, and, moreover, they all yield the same expected revenue. We first review this result and then consider how relaxing the assumptions, to incorporate features of the case at hand, alters this conclusion.

To review Vickrey's result, consider the following canonical model of an auction: A seller plans to auction a single object to a number of potential bidders. Each bidder knows how valuable this object is to himself but is uncertain about its value to other bidders. The seller is also uncertain about its value to the bidders. Each bidder cares about other bidders' valuations only insofar as it affects his bid. Given these conditions, bidders are said to have *independent private values*. Assume that the seller and the other bidders believe that the value of bidder i, v_i, is a random variable drawn from a known distribution function that is common to all bidders. That is, bidders are *symmetric*. Assume that the payoff to a bidder who loses is zero; we refer to this as the *normalization assumption*. The payoff of bidder i, if he wins the auction and pays m dollars, is $v_i - m$. The assumption that payoffs are measured in dollars implies that the bidders are *risk neutral*. We can now state the following result:

The Revenue Equivalence Theorem: *(Vickrey, 1961) When a single object is auctioned, if bidders are symmetric, risk-neutral, have independent private values, and the normalization assumption holds, then, provided that the auction format is efficient, the expected revenue of the seller is the same regardless of the auction format used.*

It is easy to show that all of the auction formats mentioned above are efficient under the above assumptions, and so, by the theorem, they all produce the same expected revenue. In the remainder of this section, we examine the relevance of the canonical model to the case of the broadband PCS auction and explore the implications of dropping the more restrictive assumptions.

2.2 Determining Valuations

In order to bid successfully in the spectrum auction, each bidder must base his bid on his "valuation" of spectrum. An implicit assumption of the canonical model is that each bidder knows his own valuation of the object. In practice, just computing this valuation can be a complicated task. This is due to the inherent uncertainties associated with predicting the demand for PCS, the radio technologies and network architectures involved, and the cost of providing services.[6] In addition, there are at least four other factors that complicate this task further. First, it matters who the other license winners are. Do they currently offer local exchange, cellular telephone, or cable TV services in the geographical area that the license covers? Second, future alliances, mergers, re-sale of licenses, and regulation must be anticipated. Third, bidders should be aware of the possibility that future administrations may auction additional spectrum. In fact, even if the government could commit not to issue additional licenses, emerging digital technology may result in new competitors offering close substitutes for PCS.[7] Fourth, the value of a license is also affected by the presence of incumbents in the parts of the spectrum that the license encompasses. The winner's projection about the negotiation process with the incumbent must also be factored in.

2.3 Correlated Values

One of the less appropriate assumptions in the case of broadband PCS is probably the assumption that values are completely independent. We turn, therefore, to a model where bidders have correlated values.

Consider, again, a single-object auction and assume that the "true" present discounted value of a license is v dollars. However, bidders do not really know v when the auction takes place. Each bid-

6. For a description of a valuation model for the narrowband case, see Cramton (1995).

7. A case in point is the cellular communications market, in which Nextel Communication, Inc. has purchased spectrum from taxi operators and, by using digital technology, has constructed a third cellular network in the major U.S. markets.

der, *i*, makes an unbiased estimation of v based on demand analyses, its knowledge of the state of PCS technology, projections about the industry structure, etc. Bidder *i*'s value estimate, describing that bidder's maximum willingness to pay given his information, is denoted $v_i = v + e_i$, where the e_i's are white noise. Thus, bidder's values are now correlated because they are the sum of a common term v and white noise.[8]

When values are correlated, a phenomenon known as the winner's curse can emerge. Consider, for example, a first-price, sealed-bid auction. In such an auction, winning is not necessarily good news for the winner, because it implies that his bid was higher than everybody else's. Thus, the winner has on average overestimated the value of the object and bid too much[9]; hence, the "curse" on the winner. The source of the curse is that while each value estimate is unbiased, the highest value estimate is necessarily biased upward. In other words, since the expected value of each e_i is zero, the highest e_i must have a positive expected value.

A crucial implication of the winner's curse is that each bidder should optimally shade his bid, recognizing that, if he wins, his bid would be the highest and may therefore be based on an overestimation of v. Failure to recognize this may prove to be costly. Capen, Clapp, and Campbell (1971) suggest that bidders' ignorance of the winner's curse caused enormous overbidding in offshore oil tract auctions during 1967–1969.[10]

Two important factors reinforce the winner's curse. First, as the number of bidders increases, the highest e_i is likely to be higher, and so the likelihood of overbidding increases as well. Second, an increase in the uncertainty regarding the value of v also raises the expected value of the highest e_i. Since these two factors make the winner's curse more problematic, one should expect them to lead to increased bid shading.

Due to the winner's curse, the revenue equivalence theorem does not hold when values are correlated. Milgrom and Weber (1982a)

8. Values may also be correlated when the object can be bought and then resold to others. In the spectrum auction, this is likely to be the case, since some of the initial winners may fail to profitably provide the new service, while others may be pure arbitrageurs. As a result, a bidder's willingness to pay will be affected not only by his own valuation but also by what the license would fetch if it were resold in a secondary market. Since the resale price will depend on the willingness of others to pay, each bidder must take into account all the bidder's values in determining his own bid.

9. Or, if values are correlated because of a resale market, winning would indicate that, on average, others value the license less than the winner does, so if he ever wanted to resell it, he would probably lose money.

10. Additional evidence (both from experiments and from field data) is surveyed in Thaler (1988).

proved that the seller earns the highest expected revenue from selling a single object in an English auction, followed by the second-price, sealed-bid auction, with the first-price, sealed-bid auction, and the Dutch auction generating the least expected revenues.[11]

The explicit ranking of the different auction formats suggests that for broadband PCS, where values are likely to be correlated, the FCC should prefer an English auction. Indeed, from the FCC's Fifth Report and Order (PP Docket No. 93-253), the FCC has chosen this type of auction process.[12]

2.4 Asymmetric Bidders

Bidders in the spectrum auctions are expected to have asymmetric information regarding the value of licenses across geographical areas. This is because bidders who currently operate in the geographical area covered by a license, either as local exchange carriers, or as cellular services providers, may have better information about the demand for PCS, or very different costs of providing PCS in that particular area.

In general, the theory is ambiguous if bidders are asymmetric in the sense that their valuations are drawn from different distributions.[13] The source of this ambiguity is that it is no longer true that all auction formats are efficient. Hence, the revenue equivalence breaks down. To see why, note first that in an English auction it is still optimal for each bidder to remain in the auction until the price exceeds his own valuation. Consequently, the English auction remains efficient even if bidders are asymmetric. This, however, is not necessarily the case for other auction formats. For example, an optimal strategy for

11. The intuition for this ranking is the following: A first-price, sealed-bid auction awards the object to the highest bidder at the bid price. But, since values are correlated, a winner's curse may emerge, so all bidders end up shading their bids below their own value estimates. In contrast, in a second-price auction, the winner pays the price bid by the next highest bidder, so bidders will raise their bids above their first-price auction bids. In an English auction, revenues are higher than in the second-price auction, because the fact that some bidders do not drop out as the auction progresses conveys information to the remaining bidders, thus ameliorating the winner's curse and inducing bidders to bid more aggressively.

12. In practice, first-price, sealed-bid auctions are often used. There could be several explanations for using this format, which from the seller's point of view is apparently inferior. First, open-outcry auctions are more susceptible to "principal–agent" problems than sealed-bid auctions, because bidders are typically represented by agents, who may be operating with a limited set of instructions and be under enormous pressure. Moreover, communication between the principal and agent is limited; hence, mistakes can be made, which could work against the efficiency objective of the FCC.

13. In fact, even computing the equilibrium strategies in this case may be very hard. Marshal et al. (1994) propose numerical algorithms for solving bidding strategies in first-price auctions for specific kinds of distributional asymmetry of bidders.

a bidder in a first-price, sealed-bid auction is to shade his bid by his estimated gap between his own valuation and the second highest valuation, conditional on his own valuation being the highest. But, when valuations are drawn from different distributions, this estimated gap will be different across distributions, so the bidder with the highest valuation need not win the auction. Since the major bidders have very different cost structures and existing revenue streams from cellular and wireline telephony, it seems likely that their valuations will be drawn from different distributions. Thus, although auction theory is ambiguous about the revenues raised in the different formats, the theory suggests that an ascending-bid auction would appear better than a descending-bid, or a one-shot, sealed-bid auction on efficiency grounds.

2.5 Auction of Multiple Objects

The FCC plans to auction 2,071 licenses to use radio spectrum for PCS: two 30 MHz channel blocks in each one of 51 MTAs (less the three Pioneer Preference awards), a further 30 MHz block, and three of 10 MHz each in each one of 493 BTAs. Therefore, we now consider issues related to auctions of multiple objects.

The multiple-price analog of a first-price auction is a discriminatory auction, where the M licenses are awarded to the M highest bidders at their bid prices. The analog of a second-price auction is a uniform-price auction, where each bidder pays the price bid by the highest rejected bidder. The theory can be extended to cover these situations and the ranking of different auction formats when values are correlated is similar: the multiple-unit English auction yields higher expected revenues than the uniform-price (second-price) auction, which in turn yields higher expected revenues than the discriminatory (first-price) auction (Milgrom and Weber, 1982b).

An additional issue to consider is whether licenses should be auctioned simultaneously or sequentially. Krishna (1993) shows that sequential auctions need not be efficient and may raise less revenue than simultaneous auctions. For example, consider an auction of two identical units of some object with only two bidders. Bidder 1 assigns a value of 10 to having one unit and a value of 20 to having both. The corresponding valuations of bidder 2 are 9 and 10, respectively. When the auction of the two units is simultaneous, or when the two units are sold as a bundle, the outcome of the auction is such that bidder 1 bids 10 and wins both units. Note that the outcome is efficient.

Next, suppose that the two units are auctioned sequentially. If bidder 1 won the first unit, he will have to bid 9 to win the second unit; otherwise bidder 2 will outbid him. Since bidder 2 is willing to pay 9 to have at least one unit, bidder 1 will also have to bid 9 in the first round in order to win. Therefore, in order to win both objects, bidder 1 has to pay a total of 18, leaving him with a payoff of $20 - 18 = 2$. However, if bidder 1 loses the first unit, then he can win in the second round by bidding 1, the most that bidder 2 will pay for a second unit. The payoff of bidder 1 in this case is $10 - 1 = 9$. Bidder 1 is therefore better off losing in the first round, since this enables him to win in the second round with a very low bid. In order to win in the first round, bidder 2 has to bid 2, which is the maximum that bidder 1 is willing to bid in this round.[14] The outcome of the auction is that bidder 2 wins in the first round by bidding 2, and bidder 1 wins in the second round by bidding 1. Thus, the sequential auction yields an inefficient outcome, and it raises a revenue of 3 instead of 10 raised in the simultaneous auction.

Sequential auctions may be inefficient for additional reasons. Hausch (1986) considers a sequential first-price, sealed-bid auction in which the outcome is revealed after each round. He shows that when values are correlated, a high valuation bidder may wish to underbid in the early rounds in order to deceive its rivals into believing that the value of the objects being auctioned is low. This softens competition in late rounds and so the deceiver can buy for a low price late in the auction. However, since the high valuation bidder may lose in the early rounds, the outcome of the auction need not be efficient. This inefficiency can also be avoided by conducting the auction simultaneously.

A related problem with sequential auctions arises when bidders have constraints on their total budgets. Then, as Pitchik and Schotter (1988) show, some bidders (presumably, those with deeper pockets) may be tempted to bid aggressively in the early rounds in the hope of depleting the resources of their rivals, thereby facing less competition in later rounds. Moreover, if the objects are not homogeneous, then the sequence in which they are sold affects both the expected selling price of each object and the seller's expected revenue (Pitchik, 1989). In addition, the outcome may or may not be efficient, depending on the particular sequence of the auction.

A feature common to the above papers is that they exhibit a decreasing sequence of prices, despite the fact that all objects being auctioned are identical. As Ashenfelter (1989) and McAfee and Vin-

14. Let p denote the maximum bid of bidder 1 in the first round. Anticipating a payoff of 9 by losing the first round, and a payment of 9 in the second round if he wins in the first round, bidder 1 will set p such that $20 - 9 - p = 9$. Thus, $p = 2$, so bidder 2 can win the first round by bidding slightly over 2.

cent (1993) report, such a phenomenon is common in wine auctions and is known among wine dealers as the "afternoon effect."[15] A similar decline in prices in sequential auctions of identical items has also been recorded in the 1981 sale at Sotheby's, New York, of seven leases on RCA satellite-based telecommunications transponders (Milgrom and Weber, 1982b) and in experiments with Australian wool traders (Burns, 1985).

An alternative explanation for the afternoon effect suggested by Ashenfelter (1989) and formalized by McAfee and Vincent (1993) is along the following lines: Losing the auction in a given round and hoping to win in a future round is essentially a gamble. Thus, if bidders have an aversion to risk, they would be willing to pay a premium to avoid it. Hence, such bidders will bid higher in the early rounds. The afternoon effect can therefore be thought of as reflecting the willingness of risk-averse bidders to pay a risk premium.[16] As a consequence, the equilibrium could be inefficient.

Thus, auction theory suggests that a simultaneous auctioning of like licenses would be better than a sequential auctioning of the licenses, on both efficiency and revenue grounds.

2.6 Risk-Averse Bidders

The discussion in the previous paragraph leads us to the next issue: risk aversion. It has often been argued that large corporate entities are virtually risk-neutral with respect to any single transaction because their size allows them to spread their risks. However, the stakes at the radio spectrum auction are likely to be high even for large corporations because of their potential impact on the evolution of the markets for PCS and the resulting effects on the local exchange and cellular telephone markets. Moreover, it must be kept in mind that the bidders in the auction are not the corporations themselves but individuals representing them. Success or failure at the auction could have a significant impact on the compensation and career prospects of these individuals. Therefore, it be could argued that the bidders at the spectrum auction are risk-averse.

When value estimates are correlated, a comparison of the seller's revenue across different auction formats yields ambiguous results (Milgrom and Weber, 1982a). In the independent private-values con-

15. Ashenfelter finds that the price of identical wines in identical lot sizes are twice as likely to decline as to increase. This pattern has been found to hold in every auction house in London and the U.S.

16. For an alternative explanation for the afternoon effect observed by Ashenfelter, see Black and De Meza (1993).

text, however, risk aversion implies that the seller's expected revenues are higher in a first-price (discriminatory) auction than in a second-price (uniform-price) auction (Harris and Raviv, 1981; Riley and Samuelson, 1981; Maskin and Riley, 1984). The reason is that submitting one's true valuation remains a dominant strategy in the second-price (uniform-price) auction. In contrast, in a first-price (discriminatory) auction, risk-average bidders are willing to pay more than risk-neutral bidders to avoid the loss from failing to win the object. With regard to revenues, this result favors a sealed-bid auction. However, as we argued above, the bidders' values are likely to be correlated, and so this result is unlikely to be applicable to the spectrum auctions.

2.7 Information Acquisition

In the correlated values case, each bidder shades his bid. The optimal amount of bid shading depends on the bidder's information, so each bidder will have an incentive to devote resources to acquiring information about the other bidders' valuations. Since this activity merely redistributes payments from uninformed to informed bidders, it has no value to society as a whole. Even worse, the existence of informed bidders drives relatively uninformed bidders away from the auction, and consequently, the seller's revenues tend to be lower. Moreover, as Matthews (1984) and Hausch and Li (1993) show, the cost of acquiring information also reduces the expected revenues of the seller, who indirectly pays this cost. In this regard, an English auction has a significant advantage over Dutch and sealed-bid formats because it allows information to be transmitted through the auction process as each bidder can observe the decisions of the other bidders to stay in or drop out.

3. Auctioning Radio Spectrum

Apart from the design of the auction format, a number of economic and public policy issues need to be taken into account in designing the auction procedures if the legislative objectives of the Communication Act are to be accomplished. In this section, we discuss some of these issues ands evaluate their likely impact on the outcome of the spectrum auctions.

3.1 Spectrum Segmentation and Efficient Bundling of Licenses

As noted in the introduction, the FCC plans to allocate in each geographical area a total of 120 MHz of spectrum, partitioned into six blocks: three large blocks of 30 MHz each and three smaller blocks of

10 MHz each. The revenue raised by the auction is negatively correlated with the number of eventual licensees, since the presence of fewer licensees will tend to soften the competition for providing PCS, thereby raising the expected value of obtaining a license. This consideration presents the FCC with a trade-off between promoting competition in the market for PCS and generating more revenue in the spectrum auctions.

A second, related trade-off arises since a decrease in the number of eventual licensees means that each licensee will receive, on average, more spectrum and will therefore be able to use equipment and introduce services that require more frequency. In addition, from a technological standpoint, fewer licensees mean that the likelihood for radio interference is lower. Given the conflict between competing standards, the latter is likely to be a key issue. These factors in turn may both increase the market opportunities of eventual licensees, as well as cut their costs. Again, these benefits should be traded off against the potentially negative effect of having fewer licensees in competition in the market for PCS. Consistent with this trade-off, the FCC permits most licensees to aggregate spectrum only up to a total of 40 MHz, thus ensuring that in each geographical area, there will be at least three providers of PCS.

A further consideration that affects the value of each license, as well as the market for PCS as a whole, is the geographical segmentation of the spectrum. This consideration is complex because in general it is impossible to determine which type of licensing system, national or regional, would lead to a more efficient market for PCS and would generate more revenues. The answer depends on the presence of economies of scale, scope, and density; on whether issues of technical standardization and compatibility are at stake; and on whether bidders have preferences for particular regions. For instance, a national licensee would have more customers than regional or local licensees and would therefore be able to lower the per customer costs of establishing the network, developing databases and billing systems, and advertising. Salant (1994) argues, "The technology indicates that PCS architecture exhibits economies of density, that is, the greater the density, the lower the cost per subscriber. Additionally, there are likely to be economies of scope between video-to-the-home services and PCS as well as between them and regular telephone services." Gandal (1994) examines data from the recent sequential auction of area cable television licenses in Israel and finds evidence that competition for licenses was greater in later rounds of the auction. He attributes this finding mainly to the interdependence among licenses (due to economies of scale and scope), which induces early winners to bid aggressively in later rounds. As we shall argue in Section 4.2, the cost structure of delivering broadband PCS is likely to cause strong interdependencies among licenses across geographical areas.

Similarly, a national licensee would be able to adopt a single set of standards and generic requirements, thus enhancing the value of the service to users and lowering the costs of its equipment. Achieving the same objectives when there are many local or regional licensees would require mutual agreements that may be difficult and costly to obtain.

An auction for a national license might also generate more revenue than an auction for regional licenses if bidders have preferences for particular regions. To illustrate this point, consider a simple example with two bidders, each of whom values only one region. If the auction offers the rights to each region separately, then each bidder, realizing that the other bidder is not interested in "his" region, will bid the minimum acceptable amount. But, if the rights to serve the two regions are bundled into a national license, then the two bidders are forced to compete with one another, so the auction will raise more revenues for the government. At the same time, however, a national license will lead in this situation to a less efficient market for PCS, since the winner would not value one of the regions, in which case he may not deploy PCS technology in the most efficient manner. Alternatively, the winner may sell the license to someone else, but such a sale may lead to a delay in the deployment of PCS that the FCC wishes to avoid.

3.2 Eligibility of Cellular Providers

The FCC's plan allows cellular companies to compete for only one of the three small 10 MHz PCS blocks in their existing service areas. In addition, cellular companies are permitted to compete for licenses outside their existing service areas and in areas where they serve less than 20% of the population, provided that they will divest their cellular interests after winning. These limitations are based on the premise that PCS and cellular services are substitutes and are intended to promote competition between them. But an argument could be made that the two technologies are in fact complements: As PCS is more portable and less expansive, but uses smaller cell sites than cellular services, customers may use it for ordinary mobile communications, and use cellular services for fast-moving vehicles. This complementarity suggests that permitting cellular providers to enter the PCS market may not necessarily be anticompetitive. We explore the issue further in Section 4.2.

However, even if cellular companies are not be allowed to own more than one 10 MHz block for PCS, then as Nalebuff and Bulow (1993) argue, there is still a good reason to allow them to participate in the auctions and resolve their ownership conflicts later. This arrangement will allow cellular providers to avoid the high risks associated with the strategy of divesting their cellular operations in the hope of winning licenses for PCS at the auction. In addition, the participation of cellular companies in the auction may play a key role in mitigating the winner's curse because their bidding may reveal, at least partially, their superior knowledge about the market for wireless communications.

3.3 Small Firm and Entrepreneur Financing

There has been considerable discussion on the need to design the radio spectrum auctions in a way that will be fair to "designated entities," that is, minority- or female-owned firms, entrepreneurs, and small firms. The case for assisting small participants goes beyond the issue of equity and providing a "level playing field." It is asserted that small firms may have an advantage over large firms in providing new services due to their greater flexibility and the fact that they have more at stake. Thus, small firms are expected to be more responsive to customer needs. Moreover, it has been argued that the experience in the computer industry has shown that "out-of-the-garage" operations are often the fount of novel ideas and inventions that eventually grow to become industry leaders.

While the fairness argument—that small-firm participants should be encouraged as a matter of equity to small investors—clearly has its merits, one should bear in mind that the stocks of large telecommunication companies are publicly traded, so these firms are actually owned by a wide set of relatively small investors.[17] Small firms, on the other hand, are typically owned by a handful of investors and privately held. Therefore, they do not share their gains with the public. Thus, favoring small entrepreneurs and firms would tend to create windfall profits to a small group of individuals, much in the same way that comparative hearings and lotteries created in the past. This would defeat one of the main reasons for using auctions to allocate the radio spectrum.

The efficiency arguments for small-firm participation—that such firms are more innovative and more responsive to customer

17. In fact, the stocks of the seven RBOCs, together with stocks of AT&T and GTE, appear regularly in the *New York Times'* list of the favorite stocks (i.e., stocks with the largest number of investors). Moreover, these stocks are often referred to as "widows and orphans" stocks, indicating that they are widely held by relatively small investors.

needs—are also questionable, especially as small firms are often start-ups with little or no experience. Moreover, even if these firms are currently successful, providing services on a large scale may be a very different story. Relying on small firms to provide new services is a gamble, which if unsuccessful, may hurt consumers.

Advocates of entrepreneurs and small firms have noted that if special financing provisions are not made for small firms, or if some degree of consolidation of small firms is not allowed, the emerging market for PCS will be swamped by large established companies with deep pockets. There is a variety of financing schemes that may be offered to small participants to ensure that they are not at a disadvantage in the bidding process. The payment can either be made via installments, or by means of a loan made by the government to the participant, which will be repaid over time. Typically, the interest rate to be applied to such payments is kept artificially low so as to provide the firm an incentive to participate.[18] From an economic point of view, such schemes have the following drawback: Winning a license is risky, because providing a new service may either turn out to be profitable or may turn out to be a losing proposition. But any scheme that defers the payment of the license fee shifts the downside risk from the bidder to the government, since the bidder can default on its promised payment to the government if the license turns out to generate losses. Thus, it effectively insures the bidder against losses at the government's expense. In the case of the radio spectrum auctions, this could manifest itself in the form of overly aggressive bidding. Consequently, small firms may win licenses even if they are not among the most efficient in providing PCS, and even if their likelihood of success is small. This exposes the government and consumers to excessive and potentially costly risks.

3.4 Coalitions

One novel policy issue in the broadband PCS auction was the proposal that coalitions of firms should be allowed to bid collectively for licen-

18. The FCC decided to set aside two license blocks of broadband spectrum for designated entities. In the auctions for these blocks, designated entities will receive a bidding credit of 10% to 40%, depending on the type of designated entity. Thus, winning a license with a bid of $100 million means that a minority- or female-owned firm would only have to pay $60 million. Additionally, designated entities received a favorable payment schedule. Upon winning a license, designated entities only have to make a 5% down payment, and pay the outstanding balance over 9 years. The interest rate charged is the rate on a ten-year treasury bill plus 2.5%. Furthermore, the deposit was reduced from 2 cents per MHz pop to 1.5 cents per MHz pop. See the FCC *Fifth Report and Order* at ¶130, ¶139, and ¶154. In the regional narrowband auctions, designated entities won all of the licenses in the two bands where these conditions applied, but the 40% credit was entirely competed away.

ses. The formation of coalitions reduces the number of bidders and so raises the same issues as collusion. Studies on how collusion affects the auction design problem include Cassady (1967), Robinson (1985), and Porter and Zona (1993). These studies suggest that collusion lowers auction revenue and could lead to inefficiencies. Thus, initially, allowing coalition formation seems inconsistent with the FCC's stated policy goals.

However, in the case of broadband PCS, there are several countervailing factors. As mentioned above, there are several competing PCS technologies that are mutually incompatible. If different standards were adopted, customers using PCS under one technology would not be served in regions that have adopted another technology (as is currently the case with cellular services). Allowing bidders to form coalitions may promote the adoption of a single standard and may therefore be socially beneficial. In addition, there may be synergies that could be exploited by firms forming a coalition to deploy PCS, for example, by linking existing networks or by sharing advertising, billing, and product development costs. Allowing coalitions to form and bid for licenses at the outset may help to exploit these synergies. Furthermore, coalition formation would help in "internalizing" any economies of scale that may exist across geographic regions and so promote the efficient aggregation of licenses. Thus, allowing coalition formation may improve the efficiency of the auction outcome, thereby promoting the legislative goals.

4. The FCC Proposal

In this section, we review the FCC's proposal regarding the implementation of Section 309(j) of the Communication Act. We then claim that the FCC could have improved on its proposal by using combinatorial auctions.

4.1 The Chosen Procedure

In its *Fifth Report and Order* (PP Docket No. 93-253), and subsequent modifications, the FCC decided to use a sequence of *simultaneous, multiple-round, ascending-bid auctions.*[19] That is, the FCC divided the

19. The simultaneous format selected by the FCC was first proposed by Robert Weber and Jerry Hausman in a paper submitted to the FCC before the NPRM. Independently Milgrom and Wilson (1993) and McAfee (1993) proposed the idea of multiple round sealed bids to make a simultaneous auction practical. Milgrom and Wilson also suggested the use of "activity rules," while McAfee suggested closing individual auctions, to ensure that the auction will end in a timely fashion. Nalebuff and Bulow (1993) proposed an overlapping sequence of auctions, while both Milgrom and Wilson and McAfee proposed a single auction for all 2,071 licenses. In the end, the FCC decided to use a sequence of large simultaneous auctions.

total of 2,071 licenses into three groups: 99 MTA licenses, 986 BTA licenses reserved for designated entities, and 986 BTA licenses that can be awarded to all bidders. All the licenses within a given group are put up for sale simultaneously. To ensure bona fide bidding, bidders must deposit a 2 cents per MHz per person (per pop) to become eligible to bid on a given license. This deposit is forfeited if the winner fails to meet his payment. Given their deposits, bidders can bid in each round on any number of licenses that they wish, up to their eligibility. At the end of each round, the current high bids on each license are publicly announced. In subsequent rounds, each bidder must remain "active" or else he loses part of his eligibility to bid in subsequent rounds. That is, a bidder must either be the highest valuation bidder from the previous round or submit a new higher bid on a number of licenses. If not, the bidder's eligibility to bid in subsequent rounds is permanently reduced. (Each bidder, however, can pass on a limited number of rounds without losing his eligibility.) All licenses are awarded simultaneously when no bidder increases the high bid on any licenses. To ensure that the auction ends in a timely fashion, minimum bid increments are imposed.[20]

The proposed mechanism is cleverly designed to maximize the amount of information about the value of licenses that is transmitted through the bidding process, thus ameliorating the winner's curse. Furthermore, the multiplicity of rounds allows bidders time to digest the revealed information and adjust their plans accordingly. Since the stopping rules are designed to ensure that the auction will not be needlessly prolonged, it appears that the proposed procedure will enable the FCC to meet the goals of the legislation. Nonetheless, to the extent that there are significant economies of scale in the geographic aggregation of licenses, the question still remains whether the selected auction procedure will yield an efficient outcome. In the following discussion, we suggest that the answer to this question may be negative.

4.2 The Case for a Combinatorial Auction

In its initial Notice of Proposed Rule Making, the FCC proposed using "combinatorial auctions," according to which two auctions would be held for each of the two 30 MHz blocks of spectrum: an English auction

20. The minimum bid increments are set as the greater of, a percentage of the previous high bid, or an amount per MHz pop. At the end of the auction the amounts are 5%, or 1 cent per pop, respectively. For further details on the activity and stopping rules, which are quite complex, see the FCC's *Fifth Report*, at Paragraphs 42–57.

for each MTA license and a sealed-bid, second-price auction for a national license (i.e., the bundle of 51 MTA licenses). The FCC proposed to award the licenses on a national basis if the high bid for the national license exceeds the sum of the high bids on the 51 MTA individual licenses, and award licenses on an MTA basis otherwise. The objective of this procedure was to determine if there are economies of scale and scope in the provision of broadband PCS and to facilitate the aggregation of licenses when such economies are present.[21]

The FCC's suggestion drew criticism from many commentators who claimed that the proposed mechanism might be biased toward a national license and, hence, lead to too much aggregation of licenses. To illustrate this argument, consider the following example that appears in McMillan (1994) and is due to Preston McAfee: There are two regions, East and West, and three bidders, B1, B2, and B3. B1's valuations are 2 for East, 1 for West, and 3 for a bundle that contains East and West. B2's respective valuations are, 1, 2, and 3, and B3's valuations are 1.6, 1.6, and 3.3. Efficiency requires that B1 wins East and B2 wins West. Indeed, this is the outcome when both licenses are auctioned separately in an English auction, with the price of each being 1.6. If we add an auction for the bundle East–West, then B3 would win this auction by bidding 3. Anticipating this outcome, B3 should abstain from bidding on the individual licenses. Now, the high bids on East and West at the separate auctions will each be 1. Thus, the bundle East–West would raise the most revenues, and B3 would win both licenses. This problem has been labeled a "free-riding" problem because B1 and B2 refrain from raising their bids in order to top the high bid on the bundle East–West, since both are hoping that the other bidder would raise his bid. This label, however, seems a misnomer, since it is really an equilibrium coordination problem: Together, B1 and B2 are better off raising the sum of their bids by 1, but each one is better off still if the raise is made by the other bidder. There are many efficient equilibria, but the bidders need to coordinate on a particular equilibrium.

Although a problem with the mechanism proposed in the NPRM, this bias towards a national license can be overcome if the auction mechanism is sufficiently flexible to reveal whether economies of scale and scope are present and if the coordination problem is solved. One way to achieve this flexibility is to allow bidders to select

21. Recall that one of the main goals of the legislation is to "promote efficient use of the spectrum." This requires that licenses be aggregated such that all economics of scale and scope would be realized.

the bundles on which they wish to bid rather than to have the FCC preset them before the start of the auction. Furthermore, as we argue below, there are several ways to mitigate the coordination problem. Thus, this criticism of the FCC's initial proposal does not apply to all combinatorial auction formats.

An alternative way to achieve an efficient aggregation of licenses across geographical areas would be to allow winners to trade their licenses after the auction ends. But trading is restricted by the FCC's build-up requirements and restrictions on "unjust enrichment." Furthermore, because of asymmetries of information among participants, the trading process may lead to costly delays in the introduction of PCS, which the legislation seeks to avoid. Therefore the concept of a combinatorial auction seems appealing.[22]

The argument in favor of combinatorial auctions is illustrated by the following example. Suppose again that there are two licenses, East and West, and three bidders, B1, B2, and B3. Each bidder's valuation for a single license is drawn from a uniform distribution on the interval [0,5]. Suppose that B1's actual valuations are 2 for East, 1 for West, and 3 for the bundle East–West. B2's actual valuations are 1, 1.5, and 2.5, respectively, and B3's valuations are 0, 0, and 4. Note that efficiency requires that B3 wins both licenses, but this means that B3's bids during the auction must exceed his stand-alone valuations of each license. Now, consider an FCC style auction, and suppose that the price of each license has reached 1. Since B3 knows that B1's and B2's valuations are uniformly distributed over the interval [1,5], the expected winning price of each license from his perspective is 3. Therefore, if B3 were to stay in the auction and raise his bids on East and West, he would expect to make a loss. Thus B3 should drop out of the auction. Consequently, the outcome is inefficient. Note that, holding the other values constant, the outcome is always inefficient if B2's value for West lies between 1 and 3.

A second problem can be illustrated by changing the values slightly. Suppose that B1 values East at .9, and West at 0, that B2 values East at 0 and West at 3.2 or higher. B3 has the same values as before. Efficiency requires that B1 wins East and B2 wins West. Note, however, that when the price of both licenses reaches .9, B3 could win license West with a bid of 1, a move with a positive expected return if the price of East stood at .9 or less. Thus, the outcome may not only be inefficient, but some participants may end up paying in excess of their valuations. This problem has been referred to by Bykowsky, Cull, and Ledyard (1995) as "financial exposure."

Both problems are overcome by using a combinatorial auction

22. For an early analysis of combinatorial auctions see Rassenti, Smith, and Bulfin (1982).

that allows bidders to bid not only on individual licenses but also on bundles. In the first scenario described above, B3 can always win the auction by bidding slightly more than 3 for the bundle East–West. The outcome is efficient and raises higher revenues than the auction for individual licenses. Moreover, by bidding only on the bundled licenses, B3 avoids any financial exposure.

Extensive experimental work supports the use of combinatorial auctions. Banks, Ledyard, and Porter (1989) introduced a combinatorial mechanism called the *Adaptive User Selection Mechanism* (AUSM), to solve allocation problems. In the initial round of AUSM, each bidder requests a desired bundle of commodities and offers a price for that bundle. The mechanism then provisionally accepts the collection of offers that maximizes revenue subject to the set of accepted offers being feasible. In subsequent rounds, bidders whose bids were rejected can make a new offer on a bundle. If a bidder's new offer is such that the price bid is higher than the sum of all the bids that it would displace to give the new bidder this bundle, then the new offer is accepted. The auction ends when no new offer is accepted. Banks, Ledyard, and Porter (1989) found that AUSM outperformed simple non-combinatorial auctions in terms of efficiency. Further experiments were conducted by Charles Plott and David Porter to test alternative auction procedures for the spectrum auction.[23] Plott's experiments used both first-price ascending-bid sequential and simultaneous auctions for individual licenses. When economies of scale existed, he found that both auction formats failed to be efficient because the economies of scale were not captured, and that some bidders lost money due to the financial exposure problem. Porter's experiments compared the adapted AUSM combinatorial mechanism against both the first-price ascending bid sequential and the simultaneous auction formats. He found strong support for the superior efficiency of the combinatorial auction. These findings were strongest when the benefits from bundling were highly idiosyncratic,[24] which, as we shall argue below, is likely to be the case with the spectrum auction.

There are two main arguments against combinatorial auctions: First, that they lead to too much aggregation of licenses due to the so-called free-rider problem and, hence, are inefficient. Second, it is argued that combinatorial auctions are computationally too complex, both for bidders to calculate their optimal strategies and for the auctioneer to implement. We next discuss each of these arguments.

As we argued above, the first argument against combinatorial

23. Plott's experiments were sponsored by Pacific Bell and Nevada Bell. Porter's experiments were sponsored by NTIA.

24. These findings are discussed in Bykowski, Cull, and Ledyard (1995).

auction is really a coordination problem. This problem, however, can be mitigated by running and stopping the two auctions simultaneously and by having multiple rounds in which bidders can make small raises to their bids. To see why, consider the example from McMillan that we discussed above. If B1 stops bidding in a given round, he attains a positive payoff only if B2's bid on West is sufficiently high to ensure that the sum of the bids on East and West exceeds B3's bid on the bundle East–West. In contrast, by raising his bid for East slightly, B1 can keep the auction alive and lower the amount that B2 needs to contribute, thereby increasing the probability that B2 will indeed do so. Moreover, note that if B2 fails to raise his bid, B1's payoff would remain unchanged. This suggests that, with enough rounds in which bids can be raised by sufficiently small amounts, the coordination problem is mitigated.[25]

As to the second argument against combinatorial auctions, we argue below that the engineering and economic considerations suggest that efficiency requires bundling of licenses across geographic areas in merely one of a few competing partitions of the United States, and that none of these partitions are either national, or neatly based on the MTA or BTA partition. This implies in turn that there are actually only a few likely combinatorial calculations. Moreover, we argue that the ability to place a single bid on a bundle rather than several bids on its components may significantly simplify one's strategy.

The FCC envisions a situation where PCS will primarily compete with cellular telephony. The cellular market, however, is about to witness an increase in competition as Nextel launches a third network using digital technology. Additionally, the incumbent cellular firms are introducing digital technology. Although there is still an ongoing debate about standards (CDMA or TDMA), either technology will have a dramatic impact. TDMA (the older technology) will increase capacity by at least a factor of 3 and CDMA by a factor of 20.[26] Moreover, the industry seems to be leaning toward CDMA, since now it may also be cheaper to deploy than TDMA.[27] Thus, even without

25. Charles Plott has informed us that he has found experimental evidence to support this hypothesis.

26. Under CDMA, by utilizing different codes, multiple users can occupy the same spectrum at the same time; all receivers see all signals but retrieve only the desired signal by using the appropriate code. Under TDMA, all users use the same channel but at different time slots. For more details about the debate regarding the two competing technologies see "TDMA vs. CDMA: The great digital cellular debate." *Telephony*, January 10, 1994, pp. 16–24.

27. See "CDMA vs. GSM, a comparison of the seven C's of wireless communications" paper presented by James Madsen to the 22nd Telecommunications Policy Research Conference, October 3, 1994, Solomon Island, MD. (GSM is a TDMA-based technology currently used in Europe).

PCS, there will be a dramatic increase in wireless capacity, which will mean lower prices. This observation has lead some industry commentators to question the wisdom of the government's PCS strategy.[28]

How then do the PCS auction winners plan to recoup their investment? As mentioned above, the local wireline access market has revenues of roughly $100 billion a year, an order of magnitude larger than the cellular market. Thus, by pricing their services sufficiently low to make them seen as an alternative to wireline services rather than to cellular, the auction winners can potentially earn huge revenues. This strategy seems reasonable, especially since the small and low-powered handsets are not very suitable for mobility, but nonetheless allow for *ubiquitous* telephony. That consumers value this feature is evident from the popularity of hand-held cellular flip-phones. Since wireline services are inexpensive, competing successfully with them would require a large market penetration and a good quality of service. To achieve these goals, PCS providers may wish to use small cells (micro-cells) along with sufficiently low-powered handsets. The easiest way to transmit the signals received at the cell site to the switch and on to the caller's destination would be over cables, particularly optical fiber cables if a lot of traffic is to be carried, (Minoli, 1991, chapter 5). The cost of building such a network from scratch, let alone the state and local regulatory hurdles, is significant and could easily outweigh the cost of winning the licenses. Therefore, if a firm already has fiber in the ground, it possesses an enormous cost advantage. These firms are few: the local exchange carriers (the seven RBOCs and GTE), cable companies, cellular operators, and interexchange carriers. Furthermore, as Huber (1993) argues, these firms currently have enormous excess capacity on their fiber lines. For example, Sprint with 10% of the U.S. long-distance market has the capacity to handle all the U.S. long-distance volume. Thus, it is likely that the highest-value bidder for a set of licenses will be one of the firms that enjoys this cost advantage. Even if this is not the case, it will still be cheaper for the license winners to lease infrastructure from one of the players who already has this excess capacity rather than build a new network infrastructure.[29] In either case the synergies are defined by the existing network topologies.

This view of the PCS market significantly strengthens the case for a combinatorial auction for two reasons. First, it suggests that the efficient level of aggregation of licenses will not be at the BTA, MTA, or national level, but rather at a patchwork partition based on the

28. See, "Is there really room for PCS?" *Telephony*, Nov. 8. 1993, pp. 30–36, and "Auctioning the Airways," *Forbes* ASAP, April 11, 1994 pp. 98–112.

29. Indeed, six of the seven RBOCs have formed a consortium named "Unibridge" precisely to lease, lines, switching, and network access to new licensees.

existing industry infrastructure. This partition is therefore expected to be highly idiosyncratic. Second, this view suggests that although there is a total of 2^{99} possible combinatorial bundles at the MTA auction, only a few well-defined (and constant) partitions of the country are actually relevant. Thus, the actual computational complexity added by combinatorial bidding would be quite small.

Indeed, for the bidders a combinatorial auction may be simpler than the procedure adopted by the FCC. Consider, for example, the bidding strategy for Wireless Co. (the Sprint-TCI-Cox-Comcast alliance), who placed the required deposits to become eligible to bid on 39 licenses at the MTA auction. Without combinatorial bidding, they would have to bid on all 39 in the MTA auction, or perhaps 100 individual licenses in the BTA auction, to assemble their most desired package. In a combinatorial auction, they could bid on only one bundle that best fits in with their competitive strategy. Combinatorial bidding thus simplifies rather than complicates their strategy. Furthermore, under the procedure adopted by the FCC, they might have to bid highly on some licenses, without knowing if they will eventually win their desired package. This uncertainty could depress their bidding and lead to an inefficient outcome. A combinatorial auction, in contrast, would allow Wireless Co. to restrict their bids to bundles, thereby avoiding the financial exposure that might arise if eventually Wireless Co. finds itself with only part of its most preferred bundle.

What kind of evidence can support our hypothesis that the lack of combinatorial bidding may create inefficiencies? One piece of evidence would be bid withdrawals. If a bidder withdraws his high bid and pays a substantial penalty, this suggests then it might be that the bidder was trying to put together a package and decided to withdraw when the cost of one of the components became too high.[30] A second piece of evidence would be the abstaining of major industry players from the auction. A bidder who desires a large combination of licenses might decide against taking the risk of financial exposure and try to assemble its desired bundles on the secondary market. Consistent with this observation, MCI and Time Warner, two of the largest players in the telecommunications industry, decided to forgo the broadband auction.[31] Moreover, Ameritech and BellSouth both announced that they will only bid on MTA licenses within their respective regions, where they enjoy a cost advantage, and are not prohibited from bidding because of cellular ownership.[32] Third, we would expect to

30. In the regional narrowband auction, we saw two major withdrawals, one of which incurred a $2.5 million penalty.

31. *New York Times*, national edition, October 28, 1994, p. C3.

32. *New York Times*, national edition, October 28, 1994, p. C3.

see coalition formation to "internalize the externality" and limit the risk of mutually destructive bidding. Indeed, two major coalitions were formed before the spectrum auction. Sprint formed an alliance with three of the largest cable companies, TCI, Cox and Comcast,[33] and Bell Atlantic has joined with USWest, Nynex, and Air Touch. Fourth, we would expect to see the bidding process progressing at a slow pace, because jump bids by rivals would increase the size of financial exposure from failing to attain the desired bundle. Finally, we would look for licenses being sold on the second-hand market as early as possible, or license winners lobbying to have the build-out and resale requirements relaxed.

4.3 Alternative Auction Procedures

Several papers have argued for the use of combinatorial bidding, including Bykowski and Cull (1993), Bykowski, Cull, and Ledyard (1995), Chakravorti et al. (1994), and Harris and Katz (1993). Based on our earlier discussion, we now briefly explain some of these alternative procedures for the spectrum auctions. It should be emphasized that, given the huge number of licenses to be auctioned and the fact that their values are interrelated, it may be impossible to find a perfect auction procedure. Also, since the implementation of combinatorial auctions may involve an extra layer of complexity, using this format seems desirable only when the underlying technologies are such that economies of scale are present.[34]

The NTIA proposal (Bykowski and Cull, 1993), adapted the AUSM mechanism presented in Banks, Ledyard, and Porter (1989). Under this mechanism, bidders submit at each round a list of the licenses that they wish to obtain and the total amount they agree to pay. The auctioneer then computes the most valuable partition of licenses, and the high bids in this partition are provisionally accepted. In the next round, a bid is accepted if the price bid on the bundle exceeds the sum of the displaced bids on all the packages that include licenses that are also included in the desired bundle. The auction stops either when no new bids are accepted or according to some prespecified stopping rule. In order to minimize the risk of an equilibrium coordination failure, the mechanism is modified by adding a "stand-by queue." That is, bidders on small packages whose bids

33. *New York Times*, national edition, October 26, 1994, p. A1.

34. For example, a strong case could be made in favor of combinatorial auctions if the FCC were to auction radio spectrum for direct broadcast satellite services. Given the huge ground coverage of a single satellite, it appears that this technology exhibits significant economies of scale. (The efficient level of bundling may in fact be at the national level.)

were displaced by a bid on a larger package are allowed to coordinate their bids via a bulletin board. If these bidders can agree to increase the sum of their bid sufficiently to top the provisionally accepted bid on the larger package, then their bids are accepted.[35]

The procedure suggested by Chakravorti et al. (1994) allows each bidder to specify up to k, groups of licenses that he wishes to buy. Each bidder then can place bids not only on individual licenses but also on the groups of licenses he chose. Thus, if there are n individual licenses, each bidder will have to specify in each round of the auction at most $n + k$ bids: n bids for individual licenses and at most k bids for his selected groups of licenses. To prevent the auction from becoming too complex, k could be kept small. From the bidders' perspective, this procedure has the advantage of providing each bidder with the flexibility of choosing his most preferred groups of licenses. Moreover, this procedure has the advantage that the most efficient partition of licenses will be determined by the market rather than being imposed by the FCC.[36]

The auction then proceeds in several rounds, with the "high bids," that is, those that make up the most valuable partition of the licenses, being posted as the provisional allocation at the end of each round. The set of high bids may consist of both bids on individual licenses as well as bids on groups of licenses. In subsequent rounds, participants can revise their bids. High bids, however, are only allowed to be raised. In contrast, all other bids can be revised in any manner that bidders see fit, including being withdrawn completely.[37] When the bidding ceases, the FCC should award licenses in accordance with the partition of licenses that raises the maximum total revenue. Winning bidders then either have to fulfill their bids or be penalized.[38]

35. For more details on this mechanism and its performance in experiments, see Bykowski, Cull, and Ledyard (1995).

36. From the FCC's Notice of Proposed Rule Making, it is obvious that the task of prespecifying groups of licenses is not only very hard but also requires information which the FCC may not have.

37. Without this provision, a budget constrained bidder may be at a disadvantage, because his bids on some licenses may be a part of a winning combination, in which case he would be unable to pursue a backup strategy if he wanted to (say, because he realizes that he can't win other licenses that he wanted to obtain before some of his bids became part of a winning combination). For further discussion on this issue, see Chakravorti et al. (1994). Note also that a similar problem cannot arise in the NTIA proposal, since either a bidder gets the single bundle that he last bid on or else he gets nothing.

38. Allowing bidders to costlessly withdraw their high bids may cause problems. First, it is not clear who should receive the license and at what price if the winner withdraws his bid. Second, bidders may intentionally submit extremely high bids and withdraw them upon winning in an attempt to manipulate the process. For a discussion of this problem in an Australian spectrum auction, see McMillan (1994).

Returning to the complexity issue, notice that from the bidders' standpoint, the bidding process in either the NTIA or the Chakravorti et al. proposal may actually be much simpler than the current FCC mechanism. This is because bidders could place at each round a single bid on the group of licenses that they chose rather than place separate bids on each one of the group's components as they have to do under the FCC's mechanism. From the FCC's standpoint, the computation of the high bid(s) is certainly more complex, but since it is centralized, it can be accomplished by the use of computing equipment. We therefore believe that the proposals for combinatorial auctions described above are practical, and could improve on the efficiency of spectrum auctions.

5. Conclusion

Auctioning radio spectrum for the provision of PCS represents a radical change in the way that radio spectrum is being allocated. The objective of this change is to enhance the efficiency of the allocation process and to ensure the rapid deployment of PCS. In addition to its importance as a shift in policy, the spectrum auctions raise a number of interesting theoretical issues such as the optimal design of auctions of multiple units (especially in the presence of interrelated valuations), the optimality of combinatorial auctions, coalition formation to participate in auctions and preauction bargaining.

In this paper we have surveyed the relevant economic literature on auctions and examined its implications for the problem at hand. Consistent with the goals of the legislation, achieving an efficient outcome, and obtaining significant revenues, the procedure adopted by the FCC is designed to maximize the amount of information transmitted through the auction process. However, we argue that the underlying PCS technology suggests that there are significant economies of scale and that the current auction mechanism may not fully capture these economies of scale. Therefore, we propose that in future spectrum auctions, when the technology to be used, strongly suggests economies of scale, that the auction mechanism be modified to include combinatorial bidding.

References

Ashenfelter, A., 1989, "How Auctions Work for Wine and Art," *Journal of Economic Perspectives*, 3, 23–36.

Banks, J., J. Ledyard, and D. Porter, 1989, "Allocating uncertain and unresponsive resources: an experimental approach," *The Rand Journal of Economics*, 20, 1–25.

Black, J. and D. DeMeza, 1993, "Systematic Price Difference Between Successive Auctions Are No Anomaly," *Journal of Economics & Management Strategy*, 1, 607–628.

Burns, P., 1985, "Experience and Decision Making: A Comparison of Students and Businessmen in A Simulated Progressive Auction," *Research in Experimental Economics*, v. 3, Greenwich, CT: JAI Press, Inc.

Bykowsky, M. and R. Cull, 1993, "Issues in Implementing a Personal Communications Services Auction," attached to Comments of the National Telecommunications and Information Administration in PP Docket No. 93-253.

Bykowsky, M., R. Cull, and J. Ledyard, 1995, "Mutually Destructive Bidding: The FCC Auction design Problem," CalTech Social Science Working Paper No. 916.

Capen, E., R. Clapp, and W. Campbell, 1971, "Competitive Bidding in High-Risk Situations," *Journal of Petroleum Technology*, 23, 641–653.

Cassady, R., 1967, Auctions and Auctioneering, Berkeley: University of California Press.

Chakravorti, B., B. Dansby, W. Sharkey, Y. Spiegel, and S. Wilkie, 1994, "Auctioning the airwaves: The contest for radio spectrum," Bellcore Economics WP 105.

Chari, V. and R. Weber, 1992, "How the U.S. Treasury Should Auction Its Debt," *Federal Reserve Bank of Minneapolis Quarterly Review*, Fall 1992, pp. 3–12.

Cramton, P., 1995, "Money Out of Thin Air: The Nationwide Narrowband PCS Auction," *Journal of Economics & Management Strategy*, 4, 267–343.

Gandal, Neil, 1994, "Sequential Auctions of Cable Television Licenses: The Israeli experience," Tel Aviv University, Mimeo.

Harris, M. and A. Raviv, 1981, "Allocation Mechanisms and The Design of Auctions," *Econometrica*, 49, 1477–1499.

Hausch, D., 1986, "Multi-object Auctions: Sequential vs. Simultaneous Sales," *Management Science*, 32, 1599–1610.

Hausch, D. and L. Li, 1986, "A Common Value Auction Model with Endogenous Entry and Information Acquisition," *Economic Theory*, 3, 315–334.

Harris, R. and M. Katz, 1993, "A Public Interest Assessment of the Spectrum Auctions for Wireless Telecommunications Services," attached to the Comments of Nynex Corporation in PP Docket No. 93-253.

Huber, P., 1993, *"The Geodesic Network II."* Washington, D.C.

Krishna, K., 1993, "Auctions with Endogenous Values: The Persistence of Monopoly Revisited," *American Economic Review*, 83, 147–160.

Marshall, R., M. Meurer, J. F. Richard, and W. Stromquist, 1994, "Numerical Analysis of Asymmetric First Price Auctions," *Games and Economic Behavior*, 7, 193–220.

Maskin, E. and J. Riley, 1984, "Optimal Auction with Risk Averse Buyers," *Econometrica*, 52, 1473–1518.

Matthews, S., 1984, "Information Acquisiton in Discriminatory Auctions," In M. Boyer and R. Kihlstrom (eds.), *Bayesian Models in Economic Theory*, Amsterdam: North Holland.

McAfee, P., 1993, "Auction Design of Personal Communication Services," attached to Comments of PacTel Corporation in PP Docket No. 93-253.

McAfee, P. and J. McMillan, 1987, "Auctions and Bidding," *Journal of Economic Literature*, 25, 699–738.

McAfee, P. and D. Vincent, 1993, *"The Declining Price Anomaly," Journal of Economic Theory*, 60, 191–212.

McMillan, J., 1994, "Selling Spectrum Rights," *The Journal of Economic Perspectives*, 8(3), 145–162.

Milgrom, P., 1987, "Auctions Theory," in T. Bewely (ed.), *Advances in Economic Theory: Fifth World Congress*, Cambridge MA: Cambridge University Press.

Milgrom, P., 1989, "Auctions and Bidding, A Primer," *Journal of Economic Perspectives*, 3, 3–22.

Milgrom, P. and R. Weber, 1982a, "A Theory of Auctions and Competitive Bidding," *Econometrica*, 50, 1089–1122.

Milgrom, P. and R. Weber, 1982b, "A Theory of Auctions and Competitive Bidding, II," Northwestern University, Mimeo.

Milgrom, P., and R. Wilson, 1993, "Affidavit of Paul R. Milgrom and Robert B. Wilson," attached to Comments of Pacific Bell and Nevada Bell in PP Docket No. 93-253.

Minoli, D., 1991, *Telecommunications Technology Handbook*, Boston: Artech House.

Nalebuff, B. and J. Bulow, 1993, "Designing the PCS Auction," attached to Comments of Bell Atlantic Personal Communications Inc. in PP Docket No. 93-253.

Pitchik, C. and A. Schotter, 1988, "Perfect Equilibria in Budget-Constrained Sequential Auctions: An Experimental Study," *The Rand Jouanl of Economics*, 19, 363–388.

Pitchik, C., 1989, "Budget-Constrained Sequential Auctions With Incomplete Information," London School of Economics, STICERD Discussion Paper No. TE/89/201.

Porter, R. and D. Zona, 1993, "Detection of Bid Rigging in Procurement Auction," *Journal of Political Economy*, 101, 518–538.

Rassenti, S. J., V. L. Smith, and R. L. Bulfin, 1982, "A Combinatorial Mechanism for Airport Slot Time Allocation," *Bell Journal of Economics*, 13, 402–417.

Riley, J. and W. Samuelson, 1981, "Optimal Auctions," *The American Economic Review*, 71, 381–392.

Robinson, M., 1985, "Collusion and The Choice of Auction," *The Rand Journal of Economics*, 16, 141–145.

Salant, D., 1994, "One wire or two? Economics of scale in telecommunications," GTE Labs, Mimeo.

Thaler, R., 1988, "Anomalies: The Winner's Curse," *Journal of Economic Perspectives*, 2, 191–202.

Wilson, R., 1993, "Strategic Analysis of Auctions," In R. Aumann and S. Hart (eds.), *Handbook of Game Theory*, Amsterdam: North Holland.

Vickrey, W., 1961, "Counterspeculation, Auctions and Competitive Sealed Tenders," *Journal of Finance*, 16, 8–37.