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MUTUALLY DESTRUCTIVE BIDDING: THE FCC AUCTION DESIGN PROBLEM

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Abstract

Dissatisfaction with previous assignment mechanisms and the desire to raise revenue induced Congress to grant the FCC authority to auction radio licenses. The debate over an appropriate auction design was wide ranging with many imaginative proposals. Many of the arguments and their scientific support are unfortunately not publicly available. Here, we present our side of this debate for the record.

Synergies across license valuations complicate the auction design process. Theory suggests that a "simple" (i.e., non-combinatorial) auction will have difficulty in assigning licenses efficiently in such an environment. This difficulty increases with increases in "fitting complexity." In some environments, bidding may become "mutually destructive." Experiments indicate that a combinatorial auction is superior to a simple auction in terms of economic efficiency and revenue generation in bidding environments with a low amount of fitting complexity. Concerns that a combinatorial auction will cause a "threshold" problem are not borne out when bidders for small packages can communicate.

Mutually Destructive Bidding:
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1. Introduction

In 1993, Congress passed legislation authorizing the Federal Communications Commission (FCC) to use an auction to assign portions of the electromagnetic spectrum to commercial users.[4] Prior to this, the FCC used either a lottery or an administrative process termed a "comparative hearing" to assign spectrum licenses. A growing budget deficit and substantial criticism of these assignment mechanisms contributed to the acceptance of using an auction to assign such licenses. The legislation also grants the FCC authority to identify the type of licenses to be auctioned. The FCC decided to auction spectrum licenses for a family of advanced wireless communications services, commonly referred to as Personal Communications Services (PCS). It is widely envisioned that PCS will permit users to receive and send voice and data messages using fully mobile handsets.

There are a number of important economic and policy elements to the PCS auction issue. First, the use of auctions to assign spectrum licenses represented an important spectrum management reform. In addition to expected efficiency improvements, this reform was a necessary first step in the difficult process of obtaining the even larger efficiency gains associated with reforming the procedure by which the FCC determines how spectrum will be employed (i.e., the "allocation process"). Second, while the Federal Government was required to reallocate 200 megahertz (MHz) to non-Federal users in the future,[5] the use of an auction to assign such spectrum depended on its performance in assigning PCS licenses. Finally, because of the significant amount of attention from applied and theoretical economists, this issue marked the beginning of a substantially improved quality of analysis, not only in regards to auction design, but in policy analysis generally.

The legislation provided the FCC broad discretion on the issue of action design. However, this design was to be consistent with the legislation's objectives, which are to: (1) encourage the development of emerging communications technologies; (2) recover for the public a portion of the value of the spectrum made available for commercial use; (3) encourage the efficient use of the spectrum; and (4) promote economic opportunity by promoting the ownership of licenses among a wide variety of applicants.[6]

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[4] Omnibus Budget Reconciliation Act (1993) [hereinafter OBRA].

[5] The requirement to make such a reallocation is found in the enabling legislation. OBRA, tit. VI § 113 (b) (1) (to be codified at 47 U.S.C. § 923).

[6] OBRA, tit. VI § 6002(a) (to be codified at 47 U.S.C. § (j)(3)(A)-(D)).

On September 23, 1993, the FCC began its rulemaking designed to solicit information regarding numerous technical auction design issues.[7] In response to its Notice of Proposed Rulemaking, the FCC received numerous auction proposals from interested parties. The submitted proposals fell within three principal categories—sequential, simultaneous with combinatorial bidding, and simultaneous without combinatorial bidding. The FCC's auction design problem attracted the attention of both theoreticians and experimentalists. Many of the arguments and their scientific support are, unfortunately, not preserved in a publicly available form. In this paper, we present our side of the debate for the record.[8]

In Section 2 we discuss the features of PCS licenses and the associated bidding environment that makes their efficient assignment an auction design challenge. Section 3 presents a theoretical framework highlighting the differences between a "single item" and a "package bid" auction. With this framework we examine whether or not a "single item" auction can both assign licenses in an economically efficient manner and guarantee that no bidder pays more for a collection of licenses than they think it is worth to them. We demonstrate some simple situations in which the answer is no. In Section 4 we discuss the results of economic experiments that examine specific features of this theoretical framework. Finally, in Section 5, we present our conclusions regarding the appropriate auction form.

2. Characteristics of the PCS Auction Instrument

Prior to addressing the issue of auction form, the FCC determined many of the important characteristics of PCS licenses.[9] It awarded two 30 MHz licenses in each of 51 Major Trading Areas (MTAs) in the United States. In addition, in each of the 492 Basic Trading Areas (BTAs) in the United States, the Commission awarded one 30 MHz license and three 10 MHz licenses. Thus, in any given locality, there will be at most six licensed PCS providers, although the geographic scope of and amount of spectrum associated with each license will vary. In total, the FCC planned to auction 2070 PCS licenses.[10] The term of each license was ten years, with a high renewal expectancy.[11]

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[7] Federal Communications Commission (Oct. 12, 1993) [hereinafter Auction NPRM]. In an earlier rule making, the FCC made decisions on such issues as the number of licenses to assign, the geographic extent of such licenses, and the manner in which it would encourage the ownership of PCS licenses by minority groups and women. Federal Communications Commission (Oct. 22, 1993) [hereinafter PCS Order].

[8] Many of these ideas were originally presented at a conference sponsored by NTIA at Caltech in January 1994. For other thoughts, see Milgrom (1997).

[9] Or so the FCC thought. Soon after the FCC published its PCS Order, numerous parties filed Petitions for Reconsideration in Docket 90-314 requesting the FCC to reexamine some of these earlier decisions.

[10] The FCC decided to allocate two blocks of spectrum for PCS service. One block, referred to as "wideband," extends from 1850 MHz to 2200 MHz. The other block, referred to as "narrowband," extends from 901 MHz to 941 MHz. The license decisions described above refer to the wideband licenses, the more valuable of the two sets of licenses. The recently auctioned narrowband licenses generated more than $850 million in revenues, an unexpectedly large amount.

[11] In its PCS Order, the FCC also established eligibility restrictions that limited the ability of some entities to bid on certain PCS licenses. Within its existing service areas, each cellular licensee is permitted to bid only on one 10 MHz license. Cellular licensees are free to bid on any license outside of their existing service areas or in any PCS service area where they serve less than 10% of the population. Local exchange carriers are free to bid on any PCS license, except to the extent they are precluded by their cellular interests.

Because of these decisions, the PCS auction involved assigning largely non-identical spectrum blocks to winning bidders. The non-uniformity in the value of PCS licenses occurred both across PCS license areas, as well as within a given license area. Regarding the former, a PCS license for New York City will certainly be, because of its high service demand, more valuable than one covering Pine Bluff, Arkansas. With regard to the latter, as noted, the amounts of spectrum per license vary in a given geographic area (i.e., 10 and 30 MHz). Moreover, the amount of signal interference experienced will vary across licenses because of differences in the signal propagation environment and the number of users that currently occupy some of the spectrum that PCS providers will soon occupy.[12] Because of these factors, the underlying value of PCS licenses will differ across geographic areas and among frequencies within some geographic areas.

Another important feature of the PCS bidding environment is the existence of synergies from owning specific collections of licenses. Because of these synergies, the value a bidder places on a particular PCS license depends upon what other, for instance, geographically adjacent spectrum licenses it owns.[13] Such value interdependency may be due to the demand side effects resulting from the desire of users to "roam" across PCS license boundaries or the returns to scale that may be present as a result of fixed investments incurred by the PCS service provider. Another source of such interdependency is the lower transactions costs associated with a firm's superior ability, relative to the market's, to resolve signal interference problems caused by transmissions from geographically adjacent licenses.

The final important feature of the PCS bidding environment is the likely existence of partially overlapping bidder preferences regarding the collection of licenses that give rise to the synergies. The extent of this overlap depends, in part, upon the number of bidders for whom that given PCS license is valuable. This, in turn, depends upon the variety of ways it can be used by bidders. According to many in the industry, the spectra allocated to PCS service is capable of providing, when combined with the other needed inputs, a wide variety of telecommunications services (Telocator, 1992). The variety of such services ranges from an enhanced cellular service to an input in the production process of an alternative access provider.[14] The wide variety of services possible in the PCS allocation increases the number and type of firms that are interested in competing for PCS licenses and, therefore, increases the likelihood of an overlap in bidder preferences.[15] Moreover, the overlap in preferences will likely be incomplete because of differences among bidders in financial resources and service complementarities.

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[12] The FCC issued an order setting forth the timetable and procedures for relocating these incumbent users. Federal Communications Commission (1993) [hereinafter Third Report and Order].

[13] Geographic adjacency of PCS licenses may not be necessary in some cases. A cellular telephone company may obtain returns to scale in owning a package of non-adjacent PCS licenses because it may be able to combine such licenses with spectrum it owns in its cellular telephone service area.

[14] "Access service" enables a subscriber to both receive and send messages outside the local telephone loop to which it is connected.

[15] It is not difficult to create examples of preference overlap. For example, cable television operators could desire PCS licenses that cover their franchise areas because PCS service may be an activity that is "complementary" to their existing business activities, as could occur if they intend to provide local telephone access service. However, other bidders may be interested in the same PCS licenses as cable operators, but for different purposes. For instance,

The FCC's challenge was to design an auction mechanism that assigns more than 2500 heterogeneous PCS licenses to those bidders that value them the most. In order to do so, the results of the auction should not be biased in favor of one type of bidder over another. The auction's outcome must be determined by the values that the bidders place on the licenses, and not on the type of auction form employed.[16] While auction theory has made great strides answering difficult questions in recent years, existing theory in 1994 was incapable of shedding substantial light on the auction form that will be unbiased and, therefore economically efficient, in its assignment of such licenses. In the following section, we develop a theoretical framework we found useful for identifying the conditions under which an auction can assign multiple items in an economically efficient manner, and the conditions in which it can not.

3. "Single Item" Versus "Package Bid" Auctions

Economists classify auctions according to the different rules that govern the asset's exchange. These rules are important because they can affect bidding behavior and, therefore, the terms (i.e., revenue) and the efficiency of an exchange. In a multi-item auction environment, two important auction categories are "single item" and "package bid" auctions. We define a "single item" auction as one in which bidders are allowed to submit bids for individual items only. A "package bid" auction is one in which bidders are allowed to submit bids on both individual items as well as on combinations of such items.[17]

The bidding environment for PCS licenses is so complicated that game-theoretic models are not computable. Because of this, we provide an alternative theoretical framework and demonstrate some findings through the use of examples and the application of basic concepts in mechanism design.[18]

Let there be a set X of K licenses $K=\{1,\ldots k\}$ to be allocated to a set of potential bidders, $I=\{1,\ldots,n\}$. A feasible allocation assigns a subset $X_i \quad X$ to each i so that the collection of sets $X_o,X_i,\ldots X_n$ is a partition of X.[19] Bidders possess valuations, defined by $U^i(X_i)\text{-}y_i$, for each subset of x where y_i is what the ith bidder will pay. An efficient feasible allocation $a=(X_i,\ldots,X_n)$ is one

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long-distance telephone service providers are likely to view PCS as a way of reducing the costs of completing calls. Local exchange carriers may desire some, but not all of the same licenses so that they can provide additional wireless service in their service areas.

[16] This property has implementation advantages as well. An auction that has an unacceptably high likelihood of assigning licenses to the wrong bidders may be challenged in the courts for being inconsistent with the enabling legislation.

[17] One of the first "package bid" auctions was designed to handle a resource allocation problem involving airport takeoff and landing slots. Airlines wish to acquire flight-compatible takeoff and landing rights at airports located at distinct city-pairs. Taken individually, a takeoff or landing right is worthless to airlines. An efficient solution to this allocation problem requires allowing airlines to express their combined valuations for takeoff and landing rights (Rassenti, Smith, and Bulfin, 1982).

[18] Many new papers are adding to our understanding. See, e.g., Bikhchandani and Ostroy (1998) and Benoit and Krishna (1998).

[19] $\bigcup_{i=0}^{N} X_i=X$ and $X_i \cap X_j=0 \quad I, j \quad I$. X_0 is the subset of unassigned resources.

such that there is no other feasible allocation $a^{\sim}=(X_{i}^{\sim},\dots X_{n}^{\sim})$ such that $U^i(X_{i}^{\sim})>U^i(X_i)$ for all *i*. Given this, if monetary transfers between bidders are possible, then an efficient allocation solves:

$$\max_{X_i,\cdots X_n} \sum_i \; U^i\,(X_i)$$
$$\textit{subject to} \bigcup_{i=1}^{n} \; X_i \quad X$$
$$\textit{and } X_i \cap X_j=0 \quad ij \quad I$$

If the true $U^i(X_i)$ for all bidders were known, this would be a standard non-linear maximization problem solvable with the right algorithm. However, the true $U^i(X_i)$ may not be known to the mechanism designer. Simply asking bidders to specify their $U^i(X_i)$ may not be particularly useful. Given the profits obtained from owning a license, individual welfare maximizing behavior may lead bidders, when asked, to overstate $U^i(X_i)$. The use of a standard algorithm to solve this problem will misallocate licenses because incentive compatibility constraints lead to biased information. The mechanism design problem involves determining what must be known about the respective bidders' $U^i(X_i)$ in order to solve the above problem.

One approach is to create a market for each $x_k \quad X$, with a price p_k, so that *i* would pay $\sum_{k \;\; X_i} \; p_k$ for the set X_i. A potential problem with such a market solution is the possible absence of a set of prices that is consistent with the economically efficient assignment of licenses[20] or, for that matter, any assignment. In the current context, in order for X_i^{o}, the economically efficient assignment, to be a market equilibrium assignment, the following must hold for all *i* and all $X_i^{\sim}$:

$$U^i\left(X_i^{o}\right)-\sum_{k \;\; X_i^{o}} p_k \geq U^i\left(X_i^{\sim}\right)-\sum_{k \;\; X_o^{\sim}} - p_k$$

If this condition is satisfied, there is no other assignment that *i* prefers that *i* can also afford to buy. On the other hand, the absence of a set of prices that is consistent with an economically efficient assignment of licenses means that at any set of prices some *i* will be able to afford a bundle that is preferred by them to the allocation they receive in the efficient assignment. If there is no set of prices consistent with the efficient assignment, then there is no market equilibrium.[21] In such a situation, prices will not perform their coordinating function of both

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[20] The possible absence of such a set of prices was first noted by Koopmans and Beckmann (1957) in the context of allocating indivisible resources. More recently, Banks, Ledyard, and Porter (1989) examine a similar problem in allocating uncertain and unresponsive resources. See also Bikhchandani and Mamer (1994) for additional relevant results on the non-existence of a full market equilibrium. More recent results can be found in Bikhchandani and Ostroy (1988).

[21] According to the first Welfare Theorem, if an equilibrium exists it is an optimal allocation. Therefore, if the optimal allocation is not an equilibrium, then no equilibrium can exist.

informing and motivating economic agents. The economic implications of this type of "market failure" are worth analyzing further.

If we consider an increasing price auction instead of a market with recontracting, we obtain a slightly different collection of equilibrium conditions. In a single item auction where bidders submit bids for individual licenses only, a bidder may be willing to bid a higher price on some items if, in doing so, it can increase its net utility.[22] In a standard English oral auction, a bidder can only (temporarily) acquire items with an accepted bid—it cannot usually divest itself of items unless it is subsequently out bid. So we propose the following "equilibrium" concept, which we call a local Nash equilibrium: The prices *p* and allocation X^o are a local Nash equilibrium if:

$$U^i (X^o) - pX^o \geq U^i (X^i) - pX^i \quad X^i \quad X^o$$

If $U^i (X^i) - pX^i \geq U^o(X^o) - pX^o + \varepsilon$ *for some* $X^i \quad X^o$, then by bidding $\hat{p} + (\quad /k)$ on each new item in X^i, *i* can acquire (temporary) ownership of X^i and be better off than they were with X^o at the price *p*. A local Nash equilibrium is a stationary point in the auction at which no agent can unilaterally improve its net utility.

While a full market equilibrium may not exist, local Nash equilibria always exist. Furthermore, when a full market equilibrium exists it is also a local Nash equilibrium. If the rules of the auction (such as the stopping, minimum bid increment, and activity rules) do not discourage it, intuition suggests that simultaneous ascending bid auctions will close at, or very near to, a local Nash equilibrium. Experimental data support this. Unfortunately, while full market equilibria have the property that everyone is at least as well off as they would be if they did not participate in the market, local Nash equilibria have the property that individual bidders may be paying more for their acquired collection of licenses than they think the collection is worth. That is, local Nash equilibria may leave participants worse off than if they had not participated in the auction. This may cause prospective bidders to stop bidding before a local Nash equilibrium is reached. In these cases, it is highly likely that an inefficient assignment will occur. As we show below, there are distributions of values under which the only single item auction outcome possibilities are inefficiency or individual losses—neither of which is desirable.

We illustrate these ideas by examining the ability of a single item auction to assign licenses in an economically efficient manner in three different bidding situations. The first of these is summarized in Table 1 by a set of hypothetical bidder valuations for spectrum licenses A, B, and C, and different combinations of such licenses. In this example, the value of each package is equal to the sum of its individual components.

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[22] As discussed below, the willingness of a bidder to increase its bid depends on the specific rules of the auction such as, for instance, the stopping rule and the degree of continuity in the bidding action.

TABLE 1: Bidder Valuations—No Synergies

Bidder	(ABC)	(AB)	(BC)	(AC)	A	B	C
#1	160	110	100	110	60*	50	50
#2	165	105	110	105	55	60*	50
#3	175	100	125	125	50	50	75*

* Denotes the economically efficient assignment.

In this environment, a single item, oral auction can solve the assignment problem and provide an unbiased outcome.[23] The bidders with the highest valuations for each license will obtain such licenses at a price approximately equal to the second highest valuation. This solution, which involves Bidder #1, Bidder #2, and Bidder #3 receiving licenses A, B, and C, respectively, yields the highest total value (195), and yields revenue of approximately 155. Such an assignment has the important characteristic of being both a local Nash equilibrium and a full market equilibrium assignment. That is, given existing prices of 55, 50, and 50 for licenses A, B, and C, respectively, no bidder has an incentive to increase any bid in an effort to alter its assignment.[24] Olson and Porter (1994) provide experimental evidence that a single item auction can efficiently assign (near 100 percent efficiency) licenses in a similar environment.[25]

Now, suppose that all three bidders experience synergies in owning licenses A and B together. Because of this assumption, there are no partial overlaps in bidder preferences regarding the licenses. Table 2 describes such a bidding environment.

TABLE 2: Bidder Valuations—Synergies in (AB) for All Bidders

Bidder	(ABC)	(AB)	(BC)	(AC)	A	B	C
#1	250	200*	100	110	60	50	50
#2	200	150	110	105	55	60	50
#3	250	175	125	125	50	50	75*

*Denotes the economically efficient assignment.

Observe that economic efficiency is maximized when Bidder #1 obtains licenses A and B, and Bidder #3 obtains license C. We can analyze the difficulty a single item auction may have in efficiency assigning such licenses by considering the price constraints on P(A), P(B), and P(C) that must be satisfied if the economically efficient assignment is to be a local Nash equilibrium assignment.[26]

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[23] It will not even matter whether items are auctioned sequentially or simultaneously.

[24] There are other local Nash equilibria but this one minimizes the revenue extracted from bidders and is, therefore, the most likely outcome in this environment.

[25] In the environment examined by Olson and Porter (1994), a collection of items were assigned to numerous bidders. Unlike the PCS bidding environment, such bidders desired only one item.

[26] It is easy to check that each of these is necessary. For example constraint (1a) follows from the condition that $U^1(ABC) - P(A) - P(B) - P(C) \leq U^1(AB) - P(A) - P(B)$.

(1a) $50 \leq P(C)$ (otherwise #1 bids on C)
(1b) $50 \leq P(A)$ (otherwise #3 bids on A)
(1c) $50 \leq P(B)$ (otherwise #3 bids on B)
(1d) $175 \leq P(A) + P(B)$ (otherwise #3 bids on A and B)
(1e) $55 \leq P(A)$ (otherwise #2 bids on A)
(1f) $60 \leq P(B)$ (otherwise #2 bids on B)
(1g) $50 \leq P(C)$ (otherwise #2 bids on C)
(1h) $110 \leq P(B) + P(C)$ (otherwise #2 bids on B and C)
(1i) $105 \leq P(A) + P(C)$ (otherwise #2 bids on A and C)
(1j) $200 \leq P(A) + P(B) + P(C)$ (otherwise #2 bids on A, B, and C)
(1k) $150 \leq P(A) + P(B)$ (otherwise #2 bids on A and B)

First, in order for Bidder #1 to receive license A, its bid must be equal to or exceed 55, the second highest stand-alone valuation for license A (see constraint (1e)). Observe that, in this case Bidder #1 does not have to bid in excess of the first highest stand-alone valuation because Bidder #1 has that valuation. The reasoning is similar regarding license B. In order for Bidder #1 to obtain license B, its bid must equal or exceed 60, the highest stand-alone valuation for license B (see constraint (1f)). A price constraint also applies to license C. To obtain license C, Bidder #3 must submit a bid that exceeds 50 (see constraint (1g)).

Because the economically efficient outcome calls for Bidder #1 to obtain both licenses A and B, two more constraints are needed. First, the sum of Bidder #1's individual bids for licenses A and B must be equal to or exceed 175, the second highest valuation for the package (AB) (see constraint (1d)). Finally, the sum of the bids submitted by Bidders #1 and #3 must exceed 250, the second highest valuation for package (ABC) (see constraint (1i)).

Taken together, these constraints imply that Bidder #1 must be willing to bid more than its stand-alone value for license B, and possibly A, if it wishes to obtain package (AB). Bidder #1's stand-alone values for A and B are 60 and 50, but Bidder #1 must bid (from constraint (1d)) an amount greater than 175. Therefore, Bidder #1 must bid at least 65 more than its stand-alone values for licenses A and B. However, it must do so carefully because it does not know whether it will acquire license A. If it does not, Bidder #1 will incur a loss in obtaining license B. In this situation, a single item, oral auction exposes a bidder to financial risk because each bidder must make a decision—with limited information—regarding the manner in which it should assign synergy values to a set of independent auctions.[27] Depending on the size of this potential loss and the bidder's risk preferences, such an auction may not assign the licenses efficiently if it induces bidders, because of financial exposure, not to bid despite the benefits from doing so. However, if bidders bid aggressively, the threat of financial exposure may not cause them

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[27] Recall that, although we know from the valuations that all three bidders want to package license A with license B, each bidder is uncertain about the other's packaging preferences.

problems. In such an environment, they may discover the economically efficient local Nash equilibrium.[28]

There are even more problematic, yet still unexceptional bidding environments in which a single item auction may simply be unable to assign licenses in an economically efficient manner without causing bidders to incur losses from their participation. Because of differences in corporate strategies and managerial abilities among bidders, the packages of licenses that give rise to synergies may differ among bidders and, moreover, these packages may contain some common licenses. These features give rise to a "fitting" problem. In the present context, a fitting problem refers to the degree of difficulty a bidder would encounter in attempting to substitute a license, or a set of licenses, from one package use to another. The magnitude of fitting problems (i.e., "fitting complexity") varies across environments. The degree of fitting complexity depends upon the extent of overlap in bidder preferences for a license and the amount of license substitutability within any bidder's desired packages. It also depends upon the extent of package substitutability and the size of the synergies bidders obtain from acquiring certain packages.[29]

Table 3 presents bidder valuations that create a fitting problem. These valuations were constructed by assuming that Bidder #1 has a locational advantage at A, Bidder #2 has a locational advantage at B, and Bidder #3 has a locational advantage at C. Further, the valuations indicate that bidders disagree regarding which packages of licenses yield synergies and, moreover, there is some overlap in the licenses that yield such synergies. For instance, Bidder #1 obtains substantial synergies form the package (AB), while Bidder #3 acquires substantial synergies from the package (AC). Therefore, the respective packages that yield synergies for Bidders #1 and #3 overlap with respect to license A. Economic efficiency is maximized when Bidder #1 obtains licenses A and B, and Bidder #3 obtains license C.

TABLE 3: Bidder Valuations—Synergies and Fitting Problem

Bidder	(ABC)	(AB)	(BC)	(AC)	A	B	C
#1	250	200*	100	110	60	50	50
#2	255	110	200	100	50	60	50
#3	250	100	125	200	50	50	75*

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[28] A sequential auction, another type of simple auction, may impose an even greater burden on each bidder because, in contrast to a simultaneous-independent auction, it does not provide bidders in the early part of the auction much information regarding the likely sale prices of licenses that will be auctioned later. Absent this information, bidders in the early auctions are uncertain regarding how much of the synergy value derived from a package of licenses it should assign in such auctions. Compared to a simultaneous auction, a sequential auction appears to increase such uncertainty. This feature of a sequential auction will likely have adverse effects on economic efficiency.

[29] In general, the degree of fitting complexity is increasing in the amount of overlap in bidder preferences. By contrast, fitting complexity generally decreases with increases in the amount of license and package substitutability. The larger the number of packages (licenses) that are substitutes for one another, the greater the bidder's ability to substitute away from those packages (licenses) where bidding competition is severe.

*Denotes the economically efficient assignment.

As with the previous example, we can examine the difficulty a single item oral auction may have in efficiently assigning such licenses by considering some of the price constraints that must be satisfied if the economically efficient assignment is to be a market equilibrium assignment:

(2a) $200 \geq P(A) + P(B)$ (for Bidder #1)

(2b) $75 \geq P(C)$ (for Bidder #3)

(2c) $200 \leq P(B) + P(C)$ (for Bidder #2)

(2d) $75 - P(C) \geq 200 - P(A) - P(C)$ (for Bidder #3)

Constraint (2a) states that, in order for Bidder #1 to obtain licenses A and B, the sum of their individual prices must be less than or equal to 200. Similarly, according to constraint (2b), in order for Bidder #3 to receive license C, the price of license C must be less than 75, Bidder #3's valuation for such a license. Constraint (2c) states that in order for the optimal assignment to occur, the sum of the prices for licenses B and C must be greater than or equal to 200, the value that Bidder #2 assigns to such a package. Finally, constraint (2d) states that in order for Bidder #3 to obtain only license C, its "net profit" from obtaining only license C must be equal to or exceed its net profit from obtaining licenses A and C. Simplification through substitution yields the following impossible constraint.

(2e) $200 \geq P(A) + P(B) \geq 250$

This constraint implies that, given the PCS license valuations listed in Table 3 and given a prohibition on package bidding, there does not exist a set of prices for licenses A, B, and C that satisfy the necessary conditions (i.e., constraints) for the efficient assignment—to Bidders #1 and #3—of such licenses. More formally, the above condition implies that there does not exist a set of prices for licenses A, B, and C such that their assignment to Bidders #1 and #3 is an equilibrium assignment.

The absence of a set of prices that is consistent with the economically efficient assignment creates serious problems. For example, suppose the bid prices for licenses A, B, and C are 125, 75, and 75, respectively. At these prices, an assignment of licenses A and B to Bidder #1, and license C to Bidder #3 leaves both bidders satisfied. But Bidder #2 can gain by continuing to bid for licenses B and C because the sum of the existing bids (150) is less than its combined valuation for such licenses (200). Suppose Bidder #2 decides to submit a bid of 76 for licenses B and C. Under these conditions, Bidder #1 loses license B because the price of B, combined with the price for license A, exceeds 200. However, by failing to obtain license B, Bidder #1 stands to lose 65 on its bid for license A [125 (bid) - 60 (stand-alone value for license A)]. In this instance, Bidder #1 may wish to withdraw its bid for license B. If Bidder #1 is not permitted to withdraw its bid, the single item auction creates a "last mover" advantage for the last bidder.[30] In this instance, Bidder #2 has such an advantage. A bidder can attempt to wait until other bidders have fully assigned their synergy values to different licenses and, when completed, increase its bid on those licenses it wishes to obtain. As in this example, not only may such a strategy be profitable (Bidder #2 earns 40 in this example), but it may also succeed in imposing a financial burden on a prospective competitor.[31]

We can be more precise about the bids and allocations that may occur in a simultaneous single item auction by considering the local Nash equilibria for this example. First, let us ask what prices would make the economically efficient allocation (licenses A and B to Bidder #1, and license C to Bidder #3), an equilibrium:

(3a) $250 - P(A) - P(B) - P(C) \leq 200 - P(A) - P(B)$ (or Bidder #1 bids on C)
(3b)$125 \leq P(A)$ (or Bidder #3 bids on A)
(3c) $50 \leq P(B)$ (or Bidder #3 bids on B)
(3d)$175 \leq P(A) + P(B)$ (or Bidder #3 bids on A and B)
(3e) $50 \leq P(A)$ (or Bidder #2 bids on A)
(3f) $60 \leq P(B)$ (or Bidder #2 bids on B)
(3g) $50 \leq P(C)$ (or Bidder #2 bids on C)
(3h)$200 \leq P(B) + P(C)$ (or Bidder #2 bids on B and C)
(3i) $100 \leq P(A) + P(C)$ (or Bidder #2 bids on A and C)
(3j) $255 \leq P(A) + P(B) + P(C)$ (or Bidder #2 bids on A, B, and C)
(3k)$110 \leq P(A) + P(C)$ (or Bidder #2 bids on A and B)

Constraints (3b) and (3h) reveal the core of the assignment problem. Together, they imply that $P(A) + P(B) + P(C) \geq 325$ in order for the economically efficient allocation to be an equilibrium. But the maximum value bidders place on the license is only 275 (i.e., the economically efficient assignment). Therefore, one or more bidders must incur a loss if the auction proceeds to this stage, which it will if bidders are aggressive and bid when they can improve their net profit. Indeed, for this example it is true that, given any assignment and prices such that the net profits of those assigned are positive, some bidder will want to bid those prices higher as long as it considers only the gain and ignores the financial exposure from making such a move. So all local Nash equilibria involve at least one bidder losing money. The situation is similar to a Dollar Auction Game in which bidders have local incentives to keep bidding in the presence of losses even though they recognize that additional losses are possible. Data derived from economic experiments show that in a Dollar Auction Game it is possible to sell \$1 for as much as \$20.[32]

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[30] We note also revenue is very high. In this instance, revenue is 277 (i.e., 125+76+76), which exceeds by 2 the maximum value for all licenses.

[31] Indeed, for this example it is true that, given any assignment and prices such that the net profits of those assigned are positive, some bidder will want to bid those prices higher as long as it considers only the gain and ignores the financial exposure from making such a move. So all local Nash equilibria involve at least one bidder losing money.

[32] See Plott (1986). Sales for up to \$200 have been claimed informally.

Of course, if bidders think ahead and anticipate these losses they may be hesitant to bid aggressively, thereby reducing revenue and impairing economic efficiency. If no one bids aggressively for fear of experiencing financial exposure, then any one bidder can "steal" one or more items for a very low price. However, if someone bids, others should also bid and soon one or more bidders are winning licenses at prices that exceed their stand-alone values. Bidders that find themselves in this bind can reduce their own losses by bidding higher, but that action imposes more losses on the other bidders.[33] In the end, the auction generates considerable revenue—more than the value of the items—and many bidders would have been better off not participating in the auction.

It is our belief that those who argued strenuously for the use of a single item auction to assign PCS licenses suspected this phenomenon of "mutually destructive bidding" because they also proposed that bidders be allowed to withdraw their bids during the auction. But allowing withdrawals will not solve the assignment problem that arises when there is no set of prices consistent with the economically efficient allocation and no losses for bidders.[34] For example, permitting winning bidders to withdraw from the auction at zero cost, combined with the ability to re-enter, will cause the auction to cycle indefinitely, with no clear end point. The auction will be stopped at some arbitrary time, revenue will be low, and the allocation inefficient.

On the other hand, if winning bidders can withdraw when they are bidding $\hat{p}$ and pay the larger of $\hat{p}$-q or zero, where q is the final selling price,[35] a different result occurs. The same type of mutually destructive bidding occurs as before although now the incentives to refrain from bidding are reduced. Under these conditions, it is even more likely that a local Nash equilibrium will occur. One increases the likelihood that an efficient allocation occurs but at the cost of increasing the likelihood that some bidders will be left worse off than if they had not participated in the auction. The reason is that once a bidder has withdrawn at a price $\hat{p}$, $\hat{p}$-q represents a sunk cost and therefore will not affect the bidder's local Nash equilibrium behavior. It also has no effect on other bidders' payoffs. So the final price q, will be part of a local Nash equilibrium. We already know that the total revenue collected at the local Nash equilibrium exceeds the total value of the licenses. If we then throw in $\hat{p} - q \geq 0$—the withdrawal payments made by defaulting bidders—even more revenue is collected.

Bid withdrawal creates a dilemma for bidders. Withdrawal lowers an individual bidder's risk of loss while, at the same time, it increases total losses. It apparently reduces individual risk because if a bidder holds a winning bid of $\hat{p}$ for an item they value at $\hat{v}$, which can happen if they lose other synergistic items, their withdrawal may yield a loss of only $\hat{p} - q < \hat{p} - \hat{v}$ if the

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[33] This game is similar in some respects to an arms race between two countries. With each additional expenditure on military hardware, both countries increase their potential loss, but neither has necessarily increased its chances of winning a war.

[34] If a set of such prices exists, a bid withdrawal rule is unnecessary and innocuous.

[35] We do not consider here the natural ways to adjust this rule to allow for multiple withdrawals.

final winning bid offered by a competitor is $q > \hat{v}$. Therefore, the bidder's expected losses are partially insured against. However, this insurance should increase the willingness of bidders to risk bidding for synergistic packages and, therefore, increase the probability of mutually destructive bidding. At any local Nash equilibrium, the revenue collected, when withdrawal is allowed, will be at least as high as when withdrawal is not allowed. Losses in aggregate will be higher with withdrawal.[36]

We have seen that single item simultaneous auctions can have serious problems, such as subjecting bidders to losses, if the distribution of bidder values is such that there is no set of equilibrium prices. Such bidding environments are easy to construct because of the synergies that exist from owning collections of licenses. It is also true that individual bidders may be unaware whether they are in one of these dangerous bidding environments (i.e., significant fitting problems with no equilibrium prices—Table 3) or in one of the more favorable ones (i.e., no fitting problems with equilibrium prices—Table 2). Bidder #1, for example, has exactly the same valuations in each case and will not know for sure, until it is too late, whether it will win licenses A and B at a price of P(A) + P(B) = 180 for a net profit of 20 (the bidding environment depicted in Table 2), or win licenses A and B at a price of P(A) + P(B) ≥ 250 for a loss of 50 (a possible bidding outcome depicted in Table 3). Allowing withdrawal represents a futile attempt to protect bidders from financial exposure. As we have just shown, permitting bidders to withdraw their bids may actually impose greater financial uncertainty upon bidders in bidding environments where there is no set of equilibrium prices consistent with the efficient allocation. One method of protecting bidders from such exposure is to allow bidders to place contingent bids. If Bidder #1 can bid for license A contingent on getting license B, then Bidder #1 can protect itself and losses can be avoided. Let us examine how this can be done in a straight-forward manner.

The preceding examples demonstrate that a single item auction may have difficulty assigning licenses to those bidders that value them the highest when license synergies exist (e.g., returns to scale). The solution to this problem is to employ a mechanism that does not force bidders to make decisions regarding the best way of assigning synergy values from owning multiple licenses. But if package bidding is permitted, the fundamental issue that remains is which types of packages of licenses should be permitted? Specifically, should the FCC predetermine the allowable packages on which bids can be submitted, or should bidders be free to determine such packages? It appears clear that to avoid misidentifying packages that create such returns to scale, bidders should be given the opportunity to select those packages that they believe will generate such returns. Therefore, the solution to the problem created by the single item auctioning of synergistic items involves permitting bidders to submit bids for self-defined packages of licenses. With package bidding, prices that satisfy the following necessary and

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[36] This is very much like a commons dilemma. Individual insurance yields an increase in aggregate risk. Each individual is better off if they can withdraw—and no one else can—but all are worse off if withdrawal is allowed. Recent experimental evidence in Porter (1998) supports this.

sufficient conditions produce an equilibrium consistent with the efficient assignment of PCS licenses.[37]

(3a) 200 > P(AB) > 185
(3b) 60 < P(C) < 75
(3c) P(AB) + (PC) > 255.

A price of 191 for the package (AB) and a price of 70 for C satisfy the above set of price constraints. Such a set of prices eliminates the financial exposure in bidding on licenses A and B and the last mover advantage. But if there are *K* items auctioned, does one need 2^K prices in order to allocate the items? If so, there would be serious computational and informational difficulties. Luckily, the answer is no. There is an auction procedure which allows bidders to bid for desired packages (e.g., place a 100 bid for package (AB)), but does not require bids on all packages. One such mechanism is called AUSM (Adaptive User Selection Mechanism). AUSM consists of: (i) a bid, (A^i, b^i) where $A \quad x$ and $b \quad R$, read as *i* bids b^i to receive A^i, and (ii) a provisional allocation $(X_0, X_1, \ldots X_n)$, where X_i is composed of provisionally accepted bids and $X_i = \quad {}_k A_{ik}$. The bid acceptance rule is: (A^{i*}, b^{i*}) is accepted if $b^{i*} > \sum_{jk \quad z} b^{jk}$ where $z = \{jk | A^{jk} \cap A^{i*} \neq 0\}$ (Ledyard, Noussair, and Porter, 1994). This rule states that in order for bidder *i* to be a part of the current assignment, it must offer to pay at least as much as those who will be displaced if its bid is accepted. With this rule, the sum of the accepted bids $\sum_{jk} b^{jk}$ is always increasing, but no bidder is ever financially exposed—*i* either gets A^i or nothing. The continuous version of an AUSM allows bids to be submitted at any time. Bidding stops according to some pre-specified closing rule.

AUSM has been used successfully in both the laboratory and in the real world.[38] It has been described by some as a complex process, but experience suggests it is easier on bidders than complex versions of single item simultaneous auctions where the complexity is added in attempts to reduce the hazards bidders face, such as financial losses and bidder regret, created by the synergistic nature of the individual licenses that comprise certain packages.

The use of an AUSM-like mechanism may create a "threshold" problem. Specifically, bidders who wish to obtain single or small subsets of the licenses may have difficulty coordinating their bids with other bidders to displace bidders who have successfully bid for a large subset. To illustrate the problem, consider the hypothetical valuations listed in Table 4.

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[37] The above constraints ensure that the prices of all other packages will be high enough to drive their demand to zero. Therefore, separate price constraints for these packages are unnecessary.

[38] An AUSM-like mechanism was used by Sears Logistics Services to successfully to acquire logistics services across 850 connected routes. The version employed allowed bidders to submit bids (for as many packages as they wished) on spreadsheets. In between each bidding round, bids were processed using an R/S 6000. The maximum computation time in each round was less than 30 minutes, although bidders had more time than that to rebid. The auction stopped after only five rounds. Bidders received information about the current winning allocation in the form of a spreadsheet. The mechanism saved the firm an estimated $10-15 million on a total cost of $150 million.

TABLE 4: The Threshold Problem

Bidder	A	B	C	(AB)	(AC)	(BC)	(ABC)
#1	60	30	30	100	100*	60	156
#2	30	62	20	90	94	82	170
#3	40	75*	20	115	60	95	161

*Denotes the economically efficient assignment.

The efficient assignment of license involves allocating licenses A and C to Bidder #1 and license B to Bidder #3. In an oral ascending-bid auction, the seller would earn approximately 156 (i.e., 94 + 62) from such an assignment.[39] However, because of package bidding, an oral ascending-bid auction may assign all three licenses to Bidder #2 for a price of 161. The efficient assignment of licenses would occur if either Bidder #1 or Bidder #3, or both, volunteer to increase the sum of their bids by 5.01 (i.e., 161 - 156 +   ). However, because of the "public good" nature of a unilateral bid increase, the sum of the combined bids may not increase by this required amount. Specifically, because the full costs (i.e., forgone revenue) from unilaterally increasing one's bid falls entirely on the cooperating bidder while the benefits extend to the non-cooperating bidder as well, each bidder may elect not to increase its bid.

Many parties involved in the PCS auction issue describe this incorrectly as a "free-rider" problem. [See Milgrom (1997).] It is more properly called a "threshold" problem. In free-rider problems, the dominant strategy for bidders is never to contribute to the provision of the public good. However, in the PCS bidding environment, it may be in the bidder's best interest to contribute to the effort to surpass the "threshold" created by the large combinatorial bidder. To illustrate, consider a game in which each bidder must decide whether to increase its bid by 5.01, which is the game that Bidders #1 and #3 face in the previous example. The possible outcomes or payoffs of any pair of bidding strategies are shown in Figure 1.

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[39] In an ascending bid auction, the bidder with the highest valuation will pay a price approximately equal to the second highest valuation.

		Bidder #3	
		I	N
Bidder #1	I	7.99 .99	13 .99
	N	7.99 6	0 0

Figure 1: Coordination Payoff Matrix

The columns of this matrix represent the strategies available to Bidder #3, while the rows indicate those available to Bidder #1. An “I” represents an increase in the initial bid, while an “N” indicates no increase in the initial bid. The numbers in each cell of this matrix represent the payoff each bidder will receive as a result of each pair of strategies. The lower left number represents Bidder #1’s payoff, while the upper right number represents Bidder #3’s payoff.

If neither bidder increases its bid, the status quo obtains—Bidder #2 acquires all three licenses and receives a payoff of 9 (i.e., 170-161), while Bidders #1 and #3 receive zero payoff. Bidders #1 and #3 can improve their respective welfares if the sum of their combined bids increases by 5.01. However, myopic self-interest may prevent this outcome from occurring. For instance, if Bidder #1 increases its bid for licenses A and C by a combined 5.01 while Bidder #3 stands pat, Bidder #3’s payoff increases by 13 (i.e., its valuation for license B (75), less its previous bid (62)), while Bidder #1’s payoff increases from zero to .99 (i.e., its valuation for licenses A and C (100), less its previous bid (94), less its contribution of 5.01). On the other hand, if Bidder #3 increases its bid for license B by 5.01, and Bidder #1 stands pat, Bidder #1 receives 6 (i.e., its valuation for licenses A and C (100), less its current bid (94)), while Bidder #3 receives 7.99 (i.e., its valuation for license B (75), less its previous bid (62), less its contribution of 5.01). Therefore, each bidder is better off not increasing its bid when the other bidder increases its bid. In this situation, neither bidder wants to be the one to increase its bid. Instead, each prefers to “free-ride” off of the others’ bid increase.

But notice that, unlike a true free-rider problem, each bidder has the incentive to cooperate because the payoffs associated with all the other pairs of strategies dominate the payoffs associated with the status quo (i.e., no cooperation). For instance, if Bidders #1 and #3 both increase their bids by 5.01, Bidder #3’s payoff increases from zero to 7.99, while Bidder

#1’s payoff increases from 0 to .99. Moreover, as shown in Figure 1, even if one bidder increased its bid, and the other bidder did not, the cooperating bidder receives a larger payoff than if it did not act cooperatively. In this standard game of “Chicken,” each player would most prefer to be “tough” (i.e., not raise its bid), while the other is “weak” (i.e., raise its bid by 5.01), but the worst possible outcome occurs when both players play “tough.”

As it stands, this game contains two non-cooperative, pure strategy, Nash equilibria (i.e., (I,N) and (N,I)), neither of which is Pareto dominant. Therefore, the players’ task is to coordinate their actions to select one of the equilibria. This task is facilitated significantly by the existence of a “provision point.” A provision point is simply a minimum-aggregate contribution value (e.g., 5.00) which, if exceeded, would enable the players to move to a mutually desirable equilibrium. In the current example, 5.00 is a provision point because any increase in bids less than 5.00 yields a return of zero. Importantly, the existence of a provision point creates additional Nash equilibria.

One can solve this problem by designing a mechanism that gives such bidders an opportunity to coordinate to defeat package bids. Banks, Ledyard, and Porter (1989) describe a modification of AUSM that provides bidders with such an opportunity. Through what is termed a “stand-by queue,” bidders are able to publicly announce via a bulletin board their willingness to pay a certain price for a specific combination of licenses. The following example describes how bidders use the stand-by queue when there are five licenses at auction. Figure 2 depicts bid information showing, on the left, the revenue maximizing assignment of such licenses and, on the right, the highest standing offers for individual or different combinations of such licenses.

FIGURE 2

AUSM STAND-BY QUEUE

PROVISIONAL ALLOCATION	STAND-BY QUEUE
Licenses - Bid	Licenses - Maximum Bid
(AB) - 10	(A) - 5
(CDE) - 15	(BC) - 4
	(CD) - 4
	(D) - 3
	(DE) - 10
	(E) - 5

A bidder wishing to obtain, for instance, package (CD) must displace the highest bid for package (CDE=15). But the bidder need not bid 16 to obtain package (CD). To determine the minimum bid it needs to displace the (CDE) bid, the bidder must locate the highest bid for license (E=5), and subtract this bid from the (CDE) bid. In this example, the bidder must bid only slightly more than 10 to be the provisional winner for the package (CD). Similarly, a bidder wishing to obtain package (BC) must displace the highest bids for both the (AB) and (CDE) packages. But it need not bid 25. It determines the minimum bid it needs by finding the highest bids for individual or license packages in the queue that, when combined with its bid for (BC), will defeat the bids for both (AB) and (CDE). In this example, the bidder must bid only just more than 10 to be the provisional winner for the package (BC).

The stand-by queue is based on experimental evidence that communication improves cooperation and that such cooperation can overcome the threshold problem. In environments where a threshold problem exists, there are typically many non-cooperative equilibria, each of which may be optimal, and none of which is dominant. In such an environment, the players' tasks are to coordinate their actions to select an equilibria.[40]

4. Experimental Results

In an effort to examine the properties of the different proposed auction forms, economic experiments were conducted by Caltech's Charles Plott and Dave Porter.[41] That economic experiments were conducted to examine this important public policy issue is an intriguing story by itself. See, e.g., Plott (1997) and Ledyard, Porter, Rangel (1997). The following section discusses the results of some of these experiments.

The proposed auction forms fell within two broad categories—single item and package bid auctions.[42] The primary members of the first category are the "simultaneous-independent" and the sequential "Japanese" auctions. In the simultaneous-independent auction, all licenses are auctioned-off at the same time via numerous bidding rounds, with bidders being permitted to submit bids only on individual licenses. A Japanese auction is akin to English oral auctions. In oral auctions the auctioneer continues to raise the price of the item as long as one bidder indicates that he or she is willing to remain in the auction. In the simplest Japanese auction, bidders begin by raising their hands. The auctioneer then increases the price of the auctioned item, and bidders exit the auction by putting down their hands when the auctioneer's price exceeds their willingness to pay for the item. The auctioneer continues to raise the price until only one bidder remains. In a sequential Japanese auction, licenses are arranged in order according to some criteria. Once the first license is sold, the auctioning of the second license starts. The auction continues until all licenses are sold.[43]

A number of parties proposed a combinatorial auction.[44] The most sophisticated of these was proposed using AUSM with stand-by queue.[45] Under this proposal, bidders would be permitted to submit individual as well as package bids for any package of licenses they desire. The authors of this paper participated in the development of some economic experiments designed to examine the assignment properties of the two major single item auctions, and the combinatorial auction with a stand-by queue. The performance of the respective auctions was evaluated according to their ability to assign items in an economically efficient manner and

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[40] Evidence of the ability of communication to enhance cooperation can be found in numerous studies. See Ledyard (1994) for a survey of these studies and other factors that improve cooperation.

[41] The experiments conducted by Porter were sponsored by NTIA. Plott's experiments were sponsored by Pacific Bell and Nevada Bell.

[42] Bykowsky and Cull (1993), Harris and Katz (1993), Isaac (1993), McAfee (1993), Milgrom and Wilson (1993), Nalebuff and Bulow (1993), Weber (1993).

[43] The sequential Japanese auction proposed by one of the parties also includes the use of a single package bid for the package containing all the licenses. Therefore, this proposal has elements of a simple and complex auction. Because of its potential, in some instances, to expose bidders to financial risk, we characterize it as a simple auction.

[44] Bykowsky and Cull (1993), Harris and Katz (1993), Chakravorti, Sharkey, Spiegel, and Wilkie (1994).

[45] Bykowsky and Cull (1993).

generate revenue. The experiments were conducted in environments that mirror the environments discussed in Section 3.[46] We discuss the results of such experiments below.

Efficiency with Low Fitting Package bidity

Charles Plott conducted experiments on a sequential Japanese auction and a simultaneous-independent auction.[47] These auctions were examined in a nine-item, eleven-bidder environment. In some trials, subjects received private valuations for each item individually, and a valuation for the package of nine items. The valuations were assigned in a manner that created a relatively low degree of overlap in bidder preferences and a low degree of license repetition (i.e., substitutability) within any bidder's desired packages. Despite the low degree of license substitutability, these factors created an environment with a "low" degree of fitting complexity. In the simultaneous-independent environment, bidders submitted bids on the nine items simultaneously. In some instances, a bidder attempting to amass all nine licenses was forced to bid above its valuations on individual licenses. To partially counteract this "exposure" problem, some of Plott's simultaneous-independent auctions employed a "release provision" which allowed bidders to withdraw bids, but at a penalty equal to the difference between the withdrawn bid and the final sales price of the item. If the item eventually sold at a price above the withdrawn bid, the bidder paid no penalty.

Each bidder in Plott's sequential experiments first submitted a sealed package bid for the nine items. The highest package bid was publicly announced via computer before the sequential auctions for individual items. After the announcement, the individual items were auctioned sequentially. The sum of the high bids in the individual auctions was compared with the highest package bid to determine whether the items would be assigned on an individual or on a collective basis.

In Plott's nine-item package environment, a simultaneous-independent mechanism with the release provision produced, on average, a slightly more efficient assignment than did the sequential Japanese auction with a sealed package bid. The average efficiency of the simultaneous-independent auction was 95%, while the same statistic for the sequential Japanese auction was 92.5%. The efficiency values for the sequential Japanese auction conceal an interesting feature of this auction. When a sealed bid for all nine items exists and is known to the bidders, those bidders who obtain items early in the sequence of Japanese auctions have profits that can only be realized if the sealed bid is defeated. They often, therefore, have an incentive to bid above their valuations—an efficiency reducing behavior—for items auctioned later in the sequence to ensure the defeat of the sealed bid.[48] The existence of the sealed bid may substantially harm bidders that are interested in acquiring licenses that come late in the sequence.

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[46] See Bykowsky and Cull (1994) and Ledyard, Porter, and Rangel (1997) for detailed discussions of the experimental designs.

[47] In Plott's computerized version of the Japanese auctions, however, bidders knew how many other bidders remained in an auction, but did not know their identities.

[48] Bykowsky and Cull (1994).

The inability of either single item auction to achieve 100 percent efficiency may indicate that they are “biased” in that, in each auction, some bidders were disadvantaged relative to others. These bias results are also reflected in the average efficiencies (expressed as a percentage of the optimal allocation) that each mechanism produced in fourteen experiments in which direct comparison of the simultaneous with the sequential Japanese mechanism is possible (Table 5).[49] The sequential mechanism achieved relatively lower efficiencies when the sum of the highest individual valuations was greater than the highest collective valuation—86.3% of optimum versus 97.6%. When the reverse was true, the simultaneous-independent mechanism achieved relatively less efficient allocations—92.2% versus 98.5%.

TABLE 5: Efficiency Comparisons Between Sequential Japanese and Simultaneous-Independent Auctions

	Average Efficiency of Final Assignments as a Percent of Optimum	
	Japanese Auction with Sealed Package Bid for All Items	Simultaneous-Independent Auction with Release Provision
Nine-item Package Value > Sum of the Highest Valuations on Individual Items	98.5%	92.2%
Nine-item Package Value < Sum of the Highest Valuations on Individual Items	86.3%	97.6%

Allowing bids on only single-item packages may seem “fair,” but fear of financial exposure on the part of bidders trying to amass large combinations may impair the performance of simultaneous-independent mechanisms. For example, in two of seven trials in which the optimal allocation[50] required that one bidder be assigned all nine licenses, this bidder did not attempt to assemble such a package (presumably for fear of losing money by assembling only a partial package). Plott’s experiments also indicate that when the large combination bidder did assemble its complete package, it often did so at a price higher than the sum of the highest valuations for individual licenses. This indicates that some bidders were willing to bid above their valuations for individual licenses in an attempt to drive up the total price paid by the bidder trying to obtain all nine licenses.

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[49] The sequential Japanese auctions summarized in Table 5 ordered the items in terms of expected value from largest to smallest.

[50] “Optimal” refers to the allocation that maximizes the total valuation of all licenses, given the valuations of all of the bidders.

Efficiency with Low and Moderate Fitting Package bidity

Dave Porter conducted experimental auctions in two different environments—one with five bidders and six items, and another with ten bidders and 54 items.[51] The extent of bidder preference overlap and license repetition in the private valuations assigned in the five-bidder and six-item environment resulted in a relatively "moderate" degree of fitting complexity. Such complexity was augmented by a strict bid release provision in the simultaneous-independent environment. If a bidder withdrew a bid on one item, all of its bids were declared null and void for that trial, thereby precluding them from further bidding.

In the 54-item environment, bidders received valuations (which contained both private and common value elements) for each individual item and for packages. The 54 items (licenses) were arranged in a rectangular grid (six rows, nine columns). For most of the bidders, these synergistic packages centered on a nine-item "region." One bidder, however, received synergies from acquiring all 54 items. In some trials, the "large" bidder's valuations for all licenses surpassed the sum of the highest regional bidders' valuations. In others, the reverse was true. Although most bidders' valuations were non-overlapping, the degree of overlap was greater than in Plott's experiments. Similarly, while the amount of license substitutability within any bidder's desired packages was low, the degree of package substitutability was greater than in Plott's experiments. The first factor increases the level of fitting complexity, while the second factor reduces it. On balance, these factors created an environment with a higher degree of fitting complexity than Plott's.[52]

Porter tested three mechanisms in the six-item environment—a package bid auction, a simultaneous-independent auction, and a sequential Japanese auction.[53] In the 54-item environment, he tested only the package bid and the simultaneous-independent auctions. Unlike Plott's sequential Japanese auctions, Porter's were conducted orally. As a result, bidders knew the identities of those who remained in the auction. Also, whereas Plott employed a sealed bid for all items previous to the Japanese auctions for individual items, Porter used a Japanese auction for the entire collection of items, followed by Japanese auctions for individual items. The results of the experiments are shown in Table 6.[54]

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[51] Porter also conducted experiments in a three-bidder, three-item environment. For detailed discussions of the results of these experiments, see Bykowsky and Cull (1994) and Ledyard, Porter, and Rangel (1997).

[52] At the present time, there does not exist a reliable method of determining the absolute level of fitting complexity. Because of this, we resort to a comparison of such complexity in the analyzed environments.

[53] For a detailed discussion of the instructions given to bidders and the data, see Bykowsky and Cull (1994).

[54] Porter's sequential experiments were run at the end of his simultaneous-independent and AUSM trials. The subjects were, therefore, familiar with the experimental environment—that is, the way valuations were created—by the time the sequential auctions occurred. Such familiarity with the experimental environment is said to "contaminate" a subject pool, making it difficult for the experimenter to infer how much of the observed bidding behavior should be attributed to learning effects.

TABLE 6: Efficiency and Revenue Comparisons Between
AUSM and Single item Auctions

Environment	Mechanism	Average Efficiency (as a % of optimum)	Average Revenue (as a % of optimum)
5 X 6	AUSM	92%	70%
	Seq. Japanese	57%	61%
	Simul.-Indep.	64%	51%
10 X 54	AUSM	100%	74%
	Simul.-Indep.	93%	56%

In both environments, the combinatorial auction (i.e., AUSM) outperformed the single item auctions in terms of efficiency. In the five-bidder, six-item environment—the environment where the degree of fitting complexity was the highest—the disparity in average efficiency is most striking: 92% for AUSM, 57% for the sequential mechanism, and 64% for the simultaneous-independent mechanism. In this environment, AUSM also produced more revenue (70% of optimum) than did the single item mechanisms (61% and 51% of optimum for simultaneous and simultaneous-independent mechanisms, respectively).

In the ten-bidder, 54-item environment, AUSM achieved 100% efficiency, compared with 93% for the simultaneous-independent mechanism, while yielding more revenue (74% versus 56% of optimum).[55] The experimental evidence suggests that a stand-by queue can be effective in substantially limiting the auction bias associated with the threshold problem. In the environments considered, bidders for subsets of licenses were generally able to coordinate their bids through the stand-by queue to "bump off" large combinatorial bids in those instances where the sum of the small bidders' valuations was higher than that of the large bidder. This provides empirical evidence that is contrary to the predictions made by some proponents of simultaneous-independent auctions.

Milgrom and Wilson (1993) conjectured that large combinatorial bidders might employ "jump bids" in an attempt to disadvantage smaller bidders. A jump bid is a preemptive bid submitted by a large combinatorial bidder that is much larger than that necessary to surpass the sum of the present smaller combinatorial bids. The large combination bidder submits this bid to

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[55] Despite the small disparity in efficiency, a large revenue disparity exists between the simultaneous-independent and AUSM mechanisms. In the 54-item environment, the degree of fitting complexity was such that while package bidding did not alter license assignment substantially, it did force winning bidders to bid more to maintain their win. They were forced to increase their bids because package bidding allows bidders to more completely reflect the synergies they obtain from owning sets of licenses. While the second highest valuations for such licenses have not changed, the willingness of bidders to fully express these valuations has increased, resulting in an "effective" increase in such valuations.

maximize the bidding coordination difficulties between the smaller bidders. In one of the three trials of the AUSM mechanism in the 54-unit environment, a bidder submitted such a bid for all 54 items. However, the smaller bidders (whose summed valuations were higher than the large bidder's in this particular trial) were able to coordinate through the stand-by queue to defeat the 54-item package bid. The effect of this attempted strategic maneuver was simply to increase auction revenue.

5. Summary and Conclusions

Auction theory indicates that single item auctions are capable of efficiently assigning multiple items in single item environments. However, when the bidding environment contains synergies, our theory suggests that single item auctions have difficulty in assigning items efficiently. This difficulty increases with increases in fitting complexity. The possibility exists that, under a set of bidder valuations, it would be impossible for such an auction to assign items in an efficient manner without the bidders incurring significant losses. One solution to this problem is to employ a combinatorial auction.

The economic experiments conducted to date support inferences of our derived theory. The existence of a fitting problem caused the efficiency of both single item auctions to decline substantially. The greater the degree of fitting complexity, the lower the efficiency performance of these auctions. The existence of a fitting problem increases the financial risk bidders are exposed to when they attempt to acquire sets of licenses that provide synergies. The higher the degree of fitting complexity, the greater this risk. This increased risk causes some bidders to become less aggressive in their pursuit of groups of licenses for which they were the highest valued users. Such behavior reduces single item auction efficiency. By contrast, the experimental results also revealed that a package bid auction, in the chosen environments, can assign items in a relatively efficient fashion. In addition, concerns regarding the tendency for full combinatorial bidding to cause a threshold problem appear overblown. The efficiency levels achieved indicate that bidders can effectively use the stand-by queue to counteract package bids.

The economic experiments also indicate that both single item auctions create unique strategic problems for bidders. For instance, Plott's simultaneous-independent auction experiments indicate that some bidders, in an attempt to make another bidder's acquisition of a set of licenses more costly, bid above their valuations for individual licenses. Therefore, when a combination bidder did assemble its desired package of licenses, it did so at significant expense. Similarly, Plott's sequential Japanese auction results indicate that when a package bid for all items is publicly known, some bidders may have an economic incentive to bid above their valuations on individual items, increasing the likelihood of an inefficient assignment of PCS licenses. While the potential of strategic behavior through the use of jump bids is possible in combinatorial auctions, results show that smaller bidders were able to coordinate through the stand-by queue to defeat the jump bid.

Uncertainty over the existence and strength of some important bidding environment factors (e.g., fitting complexity, risk-aversion) makes it difficult to offer an unconditional auction form prescription. While economic experiments indicate that AUSM outperforms the simultaneous-independent and sequential auction forms both in regard to economic efficiency and revenue generation in a number of environments, in some environments a combinatorial auction is not needed. For example, the FCC used a simultaneous-independent auction to assign ten nationwide narrowband PCS licenses. This auction was characterized by a low degree of fitting complexity because of the absence of synergies among licenses. In such a bidding environment, a single item auction is the preferred auction form.

However, the appropriateness of a simultaneous-independent auction for the sale of 30 regional narrowband licenses is less clear. Because of the smaller geographic size of the licenses and the existence of license synergies, the regional narrowband auction created a more difficult fitting problem for bidders. Consistent with the principles outlined earlier, in such an environment a single item auction exposes bidders to substantial financial uncertainty. One bidder apparently experienced financial exposure, causing it to incur a withdrawal penalty of $2.1 million.[56] This bidder would have been able to avoid such a penalty if the FCC had chosen a combinatorial auction.

Some bidders (e.g., PCS Primeco (i.e., Airtouch, NYNEX, Bell Atlantic, US West); WirelessCo (i.e., Sprint, TCI, Comcast, Cox)) have reduced the threat of financial exposure by merging their cellular operations and having this newly formed entity bid on behalf of the respective owners. A common governance structure should reduce the extent of preference overlap and, therefore, the degree of fitting complexity in the bidding environment. It may well have shifted them from an environment that looks like our third example—Table 3—to one that looks like our second—Table 2. They still face some financial exposure, but it is, perhaps, less pernicious. Other bidders (e.g., MCI) may have avoided the PCS auction altogether because of the concerns over assembling, in a simultaneous-independent auction, their desired license packages. These responses to financial exposure may have substantially reduced auction revenue.

Finally, opponents have argued that a combinatorial auction is operationally difficult to implement. But AUSM has been used in the type of bidding environment (i.e., some degree of fitting package bidity) that exists in the broadband PCS auction. In this real-world case, AUSM performed very successfully.[57] While the most sophisticated version of AUSM does require the development of software capable of handling bidding information in real time, there are batch process versions which do not restrict packaging *a priori* and which are being used successfully by non-specialists. For a description and evidence see Kwasnica, et. al. (1998). Further, as the FCC has discovered, it is also true that the simultaneous-independent auction with activity rules, batch process bidding, several stages of increment requirements, and more requires computer

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[56] Two bidders withdrew a bid during the auction. One bidder dodged a withdrawal penalty because the license's final sale price exceeded the price at which it withdrew its bid. The other bidder was not so lucky.

[57] See supra note 36 and accompanying text.

software just to track, among other things, bidding and bidder eligibility. It is a very “complex” simple auction.

Analysis and the results of actual combinatorial auctions lead us to conclude that AUSM-like auction procedures possess important design advantages over simultaneous-independent and sequential auctions in bidding environments with a low degree of fitting complexity. The analysis of others, such as Bikhchandani and Mamer (1994) and Chakravorti, Sharkey, Spiegel, and Simon (1994), support our position. We believe that the growing body of experimental, theoretical, and actual auction data concerning bidding in such environments will further demonstrate the theoretical desirability and the practical usefulness of AUSM-like mechanisms.

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