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Efficiency gains from using a market approach to spectrum management ☆

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ABSTRACT

This paper is concerned with the merits of employing market forces to address the issues of wireless spectrum congestion and the allocation of spectrum between firms seeking licensed and unlicensed spectrum rights. We show that when unlicensed spectrum is assigned to all competing users during periods of excess demand an inefficient outcome related to the "Tragedy of the Commons" is likely to result. This inefficiency can be substantially reduced when the assignment of users to unlicensed spectrum is based on the bandwidth and latency tolerance needs of the competing users. Further efficiency gains can also occur when users are required to bid to have their "unlicensed spectrum" needs met in the presence of congestion. The paper also examines the merits of creating an auction based market in which firms providing spectrum based services to users bid to have their "spectrum regime" needs satisfied. The objective of this approach is to reduce the incentive that service operators have to misstate their expressed value for a given license regime. The efficiency of this approach is based in large part on the auction mechanism's ability to solve a "collective action problem" in which firms desiring unlicensed spectrum have an incentive to "free-ride" on the bidding behavior of other unlicensed firms. Together our results open up the possibility that a wide variety of spectrum policy issues may be efficiently solved using a market-based approach. They further suggest that there may be a "hybrid" regime that combines the best features of the license and unlicensed regimes and, thus, lead to a more efficient use of spectrum at any moment in time.

1. Introduction

Regulators have established two distinct sets of rules, or "regimes," that define the usage rights of radio spectrum users and licensees. Under "licensed" use, the licensee has the right to exclude others from using its assigned spectrum. Under "unlicensed" use, however, multiple users are able to share the designated spectrum on a free and open-access basis.[1] This means that under unlicensed use, prices are typically not employed to allocate spectrum among competing users. Moreover, rational users may "over-consume" freely available spectrum and "under-consume" non-freely available spectrum compared to the levels that would promote both consumer and society's interests.[2]

☆ The analyses and conclusions in this paper are those of the authors and do not necessarily reflect the view of other members of the Office of Strategic Planning and Policy Analysis, other Commission Staff, or any Commissioner. The authors thank Chuck Needy and James Miller for very helpful comments on an earlier draft.

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[1] With both licensed and unlicensed spectrum, the term "use" refers to technical rules that define, among other things, allowable emitted radiation over a particular geographic area.

[2] Economists call this welfare-reducing problem the "Tragedy of the Commons." It refers to a situation in which myopic, self-interested behavior leads to the excessive use of a common pool resource (e.g., spectrum designated to unlicensed operations) because economic actors have too little incentive to take into account the negative effect of their spectrum consumption decisions on the value that other actors place on using the same spectrum. Due to this excessive use, the welfare of individual users is not maximized and, further, society fails to obtain the most efficient use of its scarce resources.

Given the high cost of constructing wireline facilities and the strong and growing demand for mobile services, radio spectrum has become a very valuable and important resource. Consequently, it is particularly important that spectrum designated to either licensed or unlicensed use is efficiently employed. It is equally important that the economy has the efficient amount of spectrum designated to licensed and unlicensed use. When guided by an informed price discovery process, markets are generally considered superior to administrative processes in allocating resources to their highest and best use. Accordingly, the Federal Communications Commission (FCC) recently released three studies that evaluate the merits of employing a market to determine whether spectrum should be designated to either licensed or unlicensed use, as well as the merits of using a market to allocate spectrum among competing users on a real-time basis.[3] The purpose of this paper is to summarize the important conclusions reached in each of these studies. In particular, our results shed important light on a long-standing spectrum policy issue – whether spectrum should be designated to either licensed or unlicensed use. Proponents of licensed use argue that demand for unlicensed spectrum will simply lead to the "Tragedy of the Commons."[4] In contrast, others argue that unlicensed use stimulates experimentation and innovation and, in so doing, will limit excessive use.[5] This paper suggests that there may be a "hybrid" regime that combines the best features of both systems.

2. Allocating unlicensed spectrum among competing users

Like other forms of congestion (e.g., highway and airport congestion), spectrum congestion reduces the value that society places on the affected resource and, in so doing, imposes a real cost on society.[6] In the communications field, congestion concerns appear highest in situations where wireless spectrum is treated as a common pool resource that users can access at essentially zero price. The resulting congestion hinders the efficient use of that wireless spectrum. Moreover, because of the substitutability between services that use licensed and unlicensed spectrum, too much consumption of free wireless spectrum means too little consumption of spectrum used for subscription service. Measuring the magnitude of such inefficiency and assessing different approaches to lowering it, including several market-based approaches, is the subject of the first part of this paper.

2.1. A simple economic model of efficient spectrum use

Suppose there are eight prospective spectrum users within a given wireless environment. Further suppose that there is substantial variation in the minimum amount of bandwidth that each user needs to satisfy its service needs, as well as variation in the value that each user places on having its service needs met. Because of these differences in service needs, users also vary in the extent to which they can tolerate spectrum congestion. For example, a user requiring a very high service quality (e.g., video streaming or other applications requiring a high and reliable data transmission rate) might find service quality unacceptable whenever aggregate demand exceeds 60% of system capacity. Users that can tolerate a lower service quality, however, may find service quality acceptable when aggregate demand exceeds a higher percentage of system capacity (e.g., 80%). In what follows, we measure a user's demand for service quality by the user's "congestion limit," expressed as the maximum amount of spectrum congestion the user can tolerate before the value it places on employing spectrum falls from some expressed value to zero.[7] These conditions for our eight hypothetical spectrum users are shown in Fig. 1. These data include the value that each user places on spectrum expressed on a per megabit (MB) basis, the minimum amount of spectrum required by the user, and each user's quality of service requirement as measured by its congestion tolerance limit.

Spectrum users often face a choice between available spectrum that is either provided for a fee on a managed basis by a service provider or shared spectrum that is designated to unlicensed devices.[8] In our example, we therefore assume that each user has two potential subscription options. In one option, he or she can subscribe to a reliable and well-managed non-congestible transmission system requiring a fixed payment of 130 units. In a second option, each user can use a transmission system that is "free" but in which the user's value depends on the

[3] This paper summarizes the results contained in OSP Working Paper #41, "Enhancing Spectrum's Value Through Market-Informed Informed Congestion Etiquettes," OSP Working Paper #42, "Modeling the Efficiency of Spectrum Designated to Licensed Service and Unlicensed Operations," and OSP Working Paper #43, "A Market-Based Approach to Establishing License Rules: Licensed versus Unlicensed Use of Spectrum." All three studies are available on the FCC's website at http://www.fcc.gov/osp/workingp.html.

[4] See Hazlett, T., (2001) "The Wireless Craze, the Unlimited Bandwidth Myth, the Spectrum Auction Faux pas, and the Punchline to Ronald Coase's 'Big Joke': An Essay on Airwave Allocation Policy," *Harvard Journal of Law and Technology*, vol. 14 (2), pp. 335–545 and Faulhaber, G., and Farber, D (2002) "Spectrum Management: Property Rights, Markets and the Commons," paper presented at the 14th Biennial Conference of the International Telecommunications Society, Seoul, August 18-21.

[5] See Benkler, Y., (2002) "Some Economics of Wireless Communications," *Harvard Journal of Law and Technology*, vol. 6 (1) pp. 26–83.

[6] Efficiency losses may also occur as a result of strategic behavior. For example, users may impose efficiency losses on society by restricting the supply of a resource in an effort to raise prices. This and other sources of scarcity-related efficiency losses in the current context are beyond the scope of this paper.

[7] For purposes of our analysis, we assume that the relationship between service quality and spectrum congestion for unlicensed service follows an "Ethernet curve." At low levels of congestion users can obtain bit rates close to the maximum the air link can support. As system demand approaches 80% of total system capacity, the bit rate drops precipitously. For example, when demand is equal to 90% of capacity, bit rates are approximately 50% of the maximum possible. The Ethernet curve can be well approximated by a function f of $z = X/K$, where K is maximum capacity, $f(0) = 1$, $f(1) = 0$ and $f'(z) < 0$ for all z such that $0 < z < 1$. In the theoretical analysis of this paper, and in the experiments based on that theory, we approximate this function by a simple step function in which user valuations are constant until demand reaches a critical percentage of available capacity. This "congestion limit" is allowed to vary by user type.

[8] For a discussion of spectrum sharing in the context of the larger debate on spectrum management reform, see Peha, Jon, "Emerging Technology and Spectrum Policy Reform," *International Telecommunications Union (ITU) Workshop for Spectrum Management, ITU Headquarters, Geneva*, January, 2007.

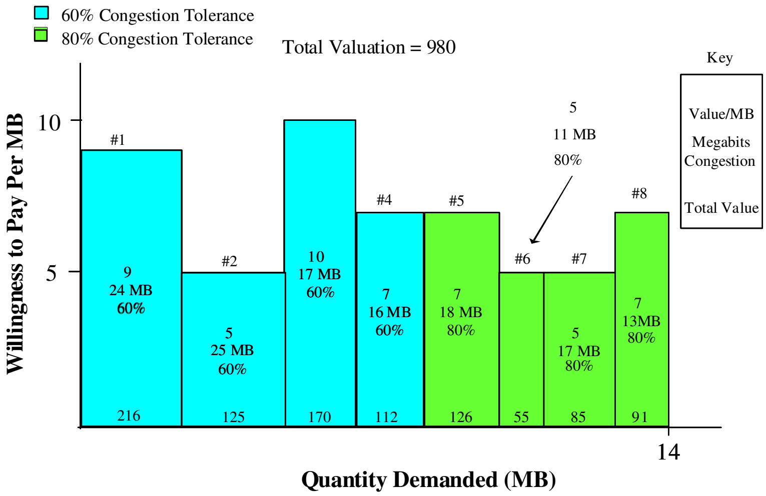

Fig. 1. Spectrum user values and congestion tolerance.

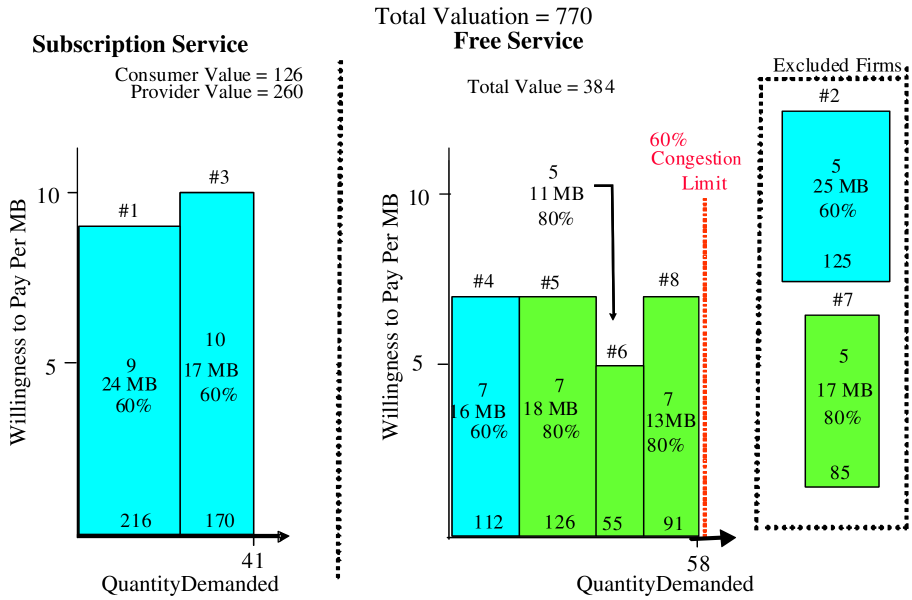

Fig. 2. Efficient assignment of spectrum among users.

congestion level of the free service's transmission system.[9] The capacity of the free service is assumed to be 100 MBs, which is less than the aggregate demand of 141 MBs when all users select that same service.

There are a large number of feasible assignments of spectrum to users, each of which generates a different total social value. For example, in the above example, when all users chose the free service, the value society places on that assignment is zero because the total number of MBs demanded by the users exceeds the congestion limits of every user. There is exactly one assignment of spectrum to users that maximizes the value that society places on the available spectrum, given the demands of all users, user valuations, and the minimum service quality that each user needs to obtain that value. This "efficient assignment," as Fig. 2 shows, assigns spectrum to users #1 and #3 through subscription service, and to users #4, #5, #6, and #8 through free service.[10]

Fig. 2 also shows that under the efficient assignment, users #2 and #7 receive no value because neither of them is assigned any spectrum under either type of service. The reasoning is straightforward. If either user #2 or user #7

[9] Certainly it is a simplification to assume that the provider of the subscription service has constructed a transmission system with enough capacity to accommodate the spectrum and quality-of-service demands of all users.

[10] Identifying the efficient assignment involves solving an integer programming problem.

were assigned spectrum under subscription service, that user would receive negative value because the value this user places on service under that option is less than the subscription fee of 130. As for the free service, user #2 cannot achieve positive value when all users choose free service because this assignment would increase total demand above 60, the congestion limit for user #2. Moreover, while user #7 has a congestion limit of 80 and thus could be accommodated under free service, that accommodation would reduce total social value. The reason is that total demand would rise above 60%, causing user #4 to lose 112 units of value, an amount far exceeding the gain of 85 units for user #7. It is equally important to note that under the efficient assignment, capacity utilization of spectrum designated to unlicensed use is 58%.[11] The efficient assignment generates 770 units of surplus, of which 386 units are captured by the provider and users of the subscription service, while 384 units are captured by users of the free service.

2.2. Allocation mechanisms chosen for testing

Because the source of inefficiency in our economic model is spectrum congestion, we selected a number of different allocation mechanisms to determine how successful each would be in reducing the congestion problem; i.e., how close each would get to the efficient assignment shown above. Toward that end, we chose two decidedly different types of congestion etiquettes. The first type, which we refer to as the "Fairness Etiquette," assigns some spectrum to every user requesting it.[12] This etiquette attempts to solve the congestion problem by simply reducing, without guidance from any market information, the amount of bandwidth assigned to each user. Without market information, however, the desire to be "fair" may cause serious problems. As the above example demonstrates, raising the capacity utilization rate may make service quality unsatisfactory for some, if not most, users and thus may be highly inefficient.[13]

Not surprisingly, this approach produced the most inefficient results in our study, as we show below in Section 2.3. Hence, although we examined the Fairness Etiquette, we focused our study on three congestion etiquettes utilizing market information: randomization, willingness to pay, and Full Optimization.

2.2.1. Randomization Etiquette

Our first market-informed approach uses a random number generator to assign a priority level to potential users. This Randomization Etiquette employs a "greedy algorithm," an optimization procedure that, in this instance, sequentially evaluates each user's spectrum demand and the admissibility of that demand given the reported service quality needs of accepted users. The term "greedy" refers to the "take what you can get now" strategy inherent in its solution rule. Under such an approach, prospective users choosing unlicensed spectrum are asked to report their personal congestion limits to a system manager.[14] Upon reporting these limits, the prospective users are each assigned a priority level by a random number generator. If the demand of the highest priority user results in a congestion level below that user's congestion limit, that user is guaranteed service. The etiquette then considers each additional user's demand and personal congestion limit in decreasing order of priority. The main advantage of this approach, beyond its simplicity, is that it ensures total demand will never exceed the minimum congestion limit of all users who are guaranteed service. That limit cannot be exceeded because, with each new user, the relevant system congestion limit is set equal to the minimum limit of the current user being considered and the limits of all higher ranking users already guaranteed service. As long as total demand, including the current user, does not exceed the congestion limit, that additional user is granted service. Otherwise, that user is not served and the next highest priority user is considered. The etiquette continues to examine users until all have been considered, or until demand is exactly equal to the system limit as determined by the currently served users.

Fig. 3 shows a particular implementation of the Randomization Etiquette to the eight users in our economic model. With the exception of users #1 and #3, all users are assumed to select the free service, and the random priority assignment ranks users in the order {#5, #8, #2, #4, #7, and #6}.[15] Under this etiquette, users #5, #8, and #2 are provided spectrum associated with free service. User 2's demand for service quality requires that total market demand not exceed 60% of the available capacity, which in this case equals 60 MBs (or 60% of the free service's capacity). All lower priority users are excluded because including any additional user would raise total demand above the 60% congestion limit of user #2. A comparison

[11] Solving for the economically efficiency allocation involves identifying the efficient capacity utilization rate because the value that users place on their assigned spectrum depends on that utilization rate. Here, the economically efficient utilization rate is 58%. This is one of the interesting insights that economics can bring to the study of spectrum efficiency.

[12] One approach involves the use of administrative rules that restrict the technical characteristics of radio equipment so that excessive use of unlicensed spectrum, in its common pool resource form, is an acceptably low probability.

[13] Unlicensed devices (e.g., Wi-Fi routers) often employ the fairness etiquette to address the congestion problem. Such routers, however, can also employ more efficient priority-based etiquettes. See, for example, Doherty, J., N. Anderson, and P. Della Maggiora (2008), *Cisco Networking Simplified*, Indianapolis, IN: Cisco Press, p. 37, which states:

"Ethernet is a shared resource in which end stations (computers, servers, and so on) all have access to the transmission medium at the same time. The result is that only one device can send information at a time. Given this limitation, two viable solutions exist:

Use a sharing mechanism: If all end stations are forced to share a common wire, rules must exist to ensure that each end station waits its turn before transmitting. In the event of simultaneous transmissions, rules must exit for retransmitting.

Divide the shared segments, and insulate them: Another solution to the limitations of shared resources is to use devices that reduce the number of end stations sharing a resource at any given time."

See also, pp. 48–53.

[14] The term "informed" refers to the fact that the algorithm utilizes such information in addressing the congestion problem. The system manager would most likely be embodied in a hardware device, and user reports about personal congestion limits would correspond to priority bits under existing internet protocols.

[15] This example focuses on the efficiency effects associated with employing different congestion etiquettes involving the free service. Later, we discuss how etiquettes may also influence a user's decision about whether or not to choose the free service or the fee based service.

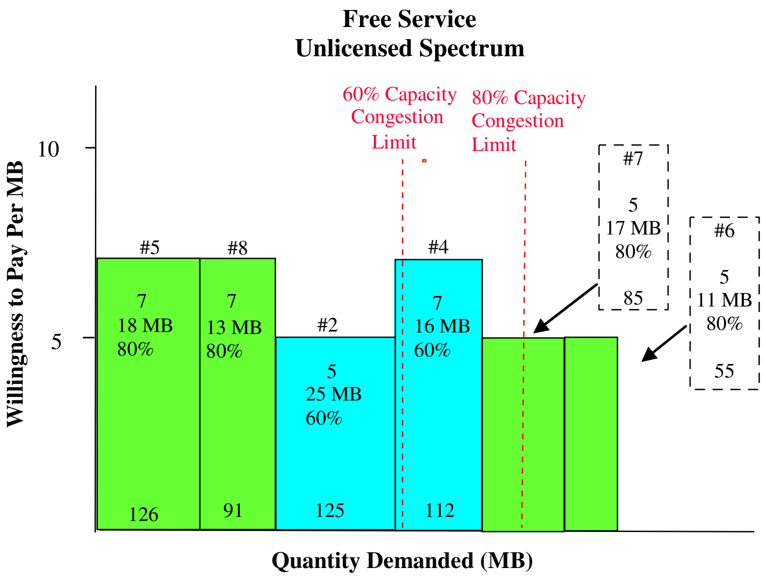

Fig. 3. Randomization Etiquette.

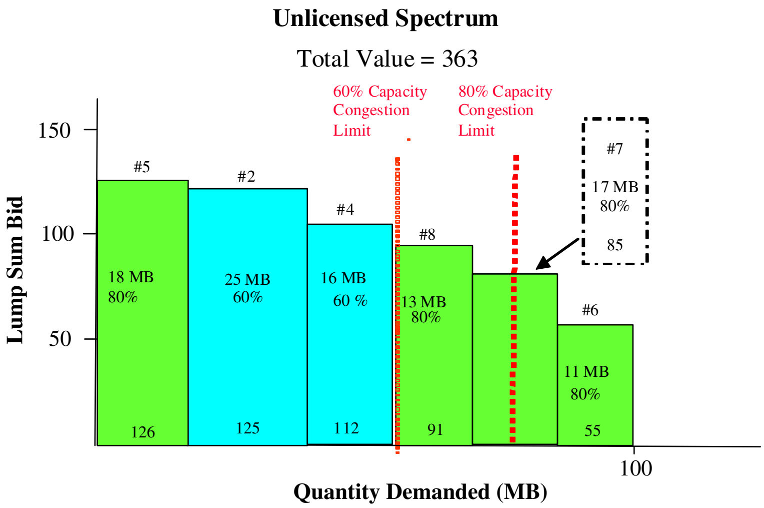

Fig. 4. Willingness-to-pay etiquette.

of the spectrum assignment in Fig. 3 with the efficient assignment in Fig. 2 reveals the potential inefficiency of the randomization approach. Under the efficient assignment, 384 units of total value (i.e., consumer value) are generated under unlicensed use, while under the randomization approach, only 342 units (i.e., 126 + 91 + 125) of value are generated. This inefficiency results from the fact that the approach fails to reconsider its initial decisions in light of new information about user valuations.[16] In particular, the inclusion of user #2 displaces, by virtue of the quality of service constraint, users #4 and #6, whose valuations together exceed user #2's valuation. This result suggests that a congestion etiquette that considers the demands of all users simultaneously may be more efficient (i.e., may reach the global surplus optimum).

[16] For example, it is possible that global welfare optimization considerations might require that a high priority user, who is initially guaranteed service, should later be excluded in order for one or more higher-valued but lower priority users to be served.

2.2.2. *Willingness-to-pay etiquette*

Another congestion etiquette based on a greedy algorithm utilizes not only a spectrum user's reported personal congestion limit but also that user's willingness to pay (WTP) for receiving or sending information. In one version of a WTP etiquette (hereafter called the "Lump Sum WTP

Etiquette"), the reported WTP values are used to define a priority ranking of users, and the etiquette then proceeds in a manner similar to the Randomization Etiquette (but without the random component). In one important difference, however, the WTP etiquette requires users to actually pay to receive service when congestion conditions indicate that payment enhances economic efficiency. Under this etiquette, the price is determined by the reported willingness to pay of the "marginal user" who is excluded from service by the etiquette. Only users who are guaranteed service under the etiquette are required to pay this price.[17]

For example, suppose that all users that decide to use unlicensed spectrum (e.g., #5, #2, #4, #8, #7, and #6) bid their actual valuation, which for each of the users is in this case less than the subscription price (i.e., 130) for the non-congestible service. As illustrated in Fig. 4, user #5 would have the highest priority, followed in order by users #2, #4, #8, #7 and #6. Given this prioritization, a greedy algorithm assigns unlicensed spectrum to users #5, #4, and #2 and would each pay a price slightly larger than 91, which is the highest rejected bid. No other users are assigned spectrum, since the addition of any other user would violate the algorithm's requirement that total demand remains less than or equal to the minimum congestion limit of all users who are guaranteed service. Note that under the efficient assignment, 384 units of consumer surplus are generated in the free service, while under the Lump Sum WTP greedy algorithm, only 363 units of surplus are generated.

2.2.3. Full Optimization

Another important class of etiquettes are those addressing the congestion problem by *simultaneously* evaluating the stated preferences, expressed in terms of willingness to pay and service quality, of all prospective users. These etiquettes then find the set of spectrum users whose assignment of spectrum generates the greatest value to society. We refer to this class of etiquette as the "Full Optimization" congestion etiquette. Like the WTP etiquette, these etiquettes require users to pay a price to receive service in the presence of spectrum scarcity. Prices are set in a manner consistent with the efficient assignment of spectrum at that moment based on reported willingness-to-pay and user-requested quality of service.[18]

2.3. Nash predictions and experimental results

The efficiency with which spectrum is assigned to users when spectrum is designated to both licensed and unlicensed operations depends both on the service choices of spectrum users and, in the context of spectrum designated to unlicensed operations, on the congestion etiquette employed to deal with spectrum congestion.[19]

2.3.1. Nash equilibrium predictions

Fortunately, economic theory can shed some light on the service choices economic actors may make and, conditional on these choices, calculate the efficiency with which spectrum is employed.[20] Suppose users simultaneously and independently choose whether to select free service, subscription service, or neither of those options. A Nash equilibrium is a particular joint selection such that no individual user could increase its payoff by selecting an alternative strategy that assumes all other users maintain their equilibrium strategy choices. We can now see immediately that the efficient assignment in the example is not a Nash equilibrium. For example, suppose that user #7 contemplates joining the free service. Such a change would increase the total demand for this service from 58 to 75 units, but because user #7 expects to receive acceptable quality of service as long as total demand is less than 80 units, this alternative selection would increase user #7's surplus from zero to 85 valuation units.[21] Under Nash equilibrium assumptions, user #7 would therefore choose this alternative. With a total demand of 75 for free service, however, user #4 could not receive a satisfactory quality of service, forcing it to forfeit its entire surplus of 112 valuation units.

While the efficient assignment cannot be sustained as a Nash equilibrium, there are alternative joint user selections that satisfy the Nash equilibrium conditions. The magnitude of the congestion problem in the example is measured by the difference between the total surplus under the efficient assignment and total surplus under the Nash equilibrium condition. The value of this measure, as predicted by Nash equilibrium theory, depends on the joint user selection. One common element of each Nash assignment is that both users #1 and #3 must choose subscription service. To see this, suppose that these two users make that choice while users #5, #6, #7, and #8 select free service and users #2 and #4 choose neither option. These selections satisfy the Nash equilibrium conditions. If either user #1 or user #3 attempts to switch to the free service in order to avoid paying the subscription fee, demand for the free service would rise above either of these two users'

[17] This pricing rule is based on standard "second-price" auction theory. In the present context, there is some ambiguity about the definition of the marginal user. The present version of the etiquette assumes that the extra-marginal user is defined as the highest priority user who is excluded from service, and such that no lower priority user is assigned service.

[18] For a more detailed discussion of this congestion etiquette, see OSP Working Paper #41.

[19] Economic theory suggests that there is substantial room for inefficient spectrum user choices. According to theory, markets work best when the choices economic actors make reflect the cost their decisions impose on society. Due to the free entry, open access condition inherent in unlicensed use, prices are not available to provide that coordinating and allocation function. Thus, rational users may "over-consume" freely available spectrum and "under-consume" non-freely available spectrum, compared to the efficient outcome. The likelihood of a "tragedy of the commons" is made all the more likely by several characteristics of the radio spectrum market. For example, to avoid a common's problem, spectrum users must not only recognized that their spectrum use negatively affects other users, but that the extent to which it affects other users depends on the specific demands of other users. The likelihood of a common's problem is greatly enhanced by the absence of such information.

[20] For those readers that have had limited exposure to Game Theory, this section can be skipped without substantially reducing one's understanding of what comes next.

[21] User #7 has a congestion tolerance of 80%. Given that the free service's capacity is 100 MBs, user #7 would obtain value from selecting free service.

Table 1
Nash predictions and experimental results.

Etiquette	Environment 1 Efficiency		Environment 2 Efficiency	
	Observed (%)	Nash prediction (%)	Observed (%)	Nash prediction (%)
Non-market informed (fairness)	42	50.1	57	91.4
Market informed				
Informed randomization	70	72.8	63	54.7
Lump sum WTP	72	66.5	68	76.9
Full Optimization	75		73	

congestion limits and they would consequently forfeit the value received by selecting the subscription service. Each of the users choosing free service would clearly see a reduction in surplus by switching to subscription service since they would be required to pay the subscription fee of 130, under which they receive negative surplus. Finally, users #2 and #4 receive zero surplus by choosing neither option, but would do no better by choosing either subscription or free service.

Total surplus in this equilibrium selection is equal to 743 valuation units. In fact, this is the highest total surplus obtainable in any of the Nash equilibria, although it is lower than the surplus of 770 obtained under the efficient assignment. Thus, if the 743 valuation units in this equilibrium were obtained, the social cost of the Tragedy of the Commons problem would be very small. However, as noted earlier, there are many joint user selections that satisfy the Nash equilibrium conditions, and many within this subset generate much lower levels of total surplus.

While there a large number of outcomes predicted under the assumption that users follow Nash equilibrium behavior, there are strong theoretical grounds for assuming that the outcomes that generate the greatest amount of social loss are the ones that are the most likely to occur. To see this point, note that users who select free service are guaranteed to receive at least a zero payoff, and there is a possibility that they could receive a positive payoff if other users deviate (contrary to Nash assumptions) from the assumed equilibrium. Those who select "neither option" receive a zero payoff with certainty. In the language of non-cooperative game theory, a strategy in which a user chooses "neither option" is in this case "weakly dominated" by the strategy in which that user chooses free service. There is only one equilibrium in which no user selects a weakly dominated strategy. In this equilibrium, users #1 and #3 again select subscription service, while all remaining users (i.e., users #2, #4, #5, #6, #7 and #8) select the free service.

2.3.2. Experimental results

We conducted a set of economic experiments to examine whether economic agents make the optimal choice between a free and a subscription service and, if not, whether, the absence of such a choice significantly affects the efficiency with which spectrum is used.[22] Further, an economic framework was devised so as to shed light on whether the Fairness Etiquette and market-informed congestion etiquettes previously discussed differ in their ability to minimize the economic loss associated with spectrum congestion. To that end, eight subjects were assigned a set of characteristics, including the value they place on having the ability to transmit or receive information, the minimum amount of bandwidth needed to transmit or receive such information, and a "congestion limit," expressed as the maximum amount of spectrum congestion the user can tolerate before the value it places on employing spectrum falls from some desired value to zero.[23]

Two different valuation environments were created. One environment used the valuations shown in Fig. 1 above. We refer to this set of valuations as Environment 1. A second environment (Environment 2) was created in which five of the eight users could potentially afford to purchase the subscription service, while in Environment 1 only two of eight could do so. This is a more interesting environment, since a larger number of users must decide whether to pay a fee for guaranteed quality of service or choose the free service in which service quality depends on the subscription decisions of all other users.

Table 1 presents the experimental results. In each environment, both the observed experimental outcomes and the theoretical Nash predictions are shown for each etiquette. As shown in Table 1, depending on the valuation environment, society captures only between 42% and 57% of the gains that are available from its spectrum resource when the Fairness Etiquette is used to address spectrum congestion involving unlicensed use. The results also show

[22] For a detailed discussion of the economic experiments, see OSP Working Papers #41, "Enhancing Spectrum's Value Through Market-Informed Congestion Etiquettes."

[23] In addition to his or her own private information, each subject knew the number of other subjects, but not the value, bandwidth requirement or congestion limit of any other subject. In contrast to the game of complete information discussed in Section C.1, the experimental game is therefore a game of incomplete information. The experiments were not, however, designed to test the validity of the theory discussed in Section C.1, but rather to test the allocation mechanism. The game theoretic outcomes are best viewed simply as a "point of reference" and are intended to provide additional insight into the allocation problem. While it would have been possible to model the game as a Bayesian Game, this would have, at a minimum, required defining a probability distribution over the set of values. It cannot be guaranteed that the subjects' subjective probability distributions over the set of values would correspond with the objective probability distribution of values used in the experimental environment, and hence the Bayesian Game used to model that environment. This would be true with any presentation of information that we could have provided the subjects. We would have then found ourselves in the same situation as with the Nash equilibrium predictions: a theoretical game structure that does not "exactly" match the experimental environment.

that in both valuation environments the average efficiency under this etiquette is consistently less than the average efficiency achieved by the other examined etiquettes. For example, the Full Optimization Etiquette achieves average efficiency levels across the two environments that are consistently and substantially higher than the efficiency levels achieved by the Fairness Etiquette. The results therefore indicate that society can experience a substantial increase in its welfare from using the Full Optimization Etiquette to handle spectrum congestion involving unlicensed use. Interestingly, as shown in Table 1, each member of the class of new market-informed etiquettes performed better than the Non-Market-Informed etiquette.

2.3.3. Comparison of model and experimental results

As noted above, the Nash predictions in Section 2.3.1 and the experimental results in Section 2.3.2 are based on two different game forms. Hence, there is no reason to expect that experimental outcomes should conform exactly to Nash predictions, even when learning through repeated play was allowed to occur. Nevertheless, we find it instructive to compare the results of the two different approaches. The experimental results are largely, but not fully, consistent with outcomes predicted by Nash equilibrium theory.[24] As shown in Table 1, while Nash Predictions regarding efficiency are close to the efficiency levels observed in the experiments for the Greedy algorithm (Randomization) and Lump Sum – WTP Etiquettes, the theory does not accurately predict the efficiency performance of the Fairness Etiquette.

Because the willingness-to-pay and Full Optimization Etiquettes use market prices to address the spectrum congestion problem, it is useful to assess how spectrum users fare under these etiquettes versus the Fairness Etiquette. The experimental results show that consumers are typically much better off under the proposed market-informed congestion etiquettes than under the Fairness Etiquette. In particular, despite paying a fee at times of excessive congestion, spectrum users are better off under these market-informed etiquettes than under the Fairness Etiquette. The reason is that spectrum congestion is really two problems in one. Because of the heterogeneous needs of spectrum users, society obtains the highest value from its spectrum resource only if: (1) spectrum is being employed by the highest valued users, and (2) the "right" quality of service is being provided.[25] Solving this problem involves obtaining information on the valuation each user places on sending and receiving information and their congestion limit. The new etiquettes presented above incorporate this information in varying degrees, in addressing the spectrum congestion problem and, in so doing, identify a more efficient assignment of users to spectrum. This greater efficiency makes it possible for individual users to be better off under these new etiquettes than under the original Fairness Etiquette, despite paying a fee in the presence of excessive congestion.

3. Allocating spectrum between licensed and unlicensed usage

The previous section analyzed whether a given amount of spectrum designated to licensed and unlicensed use will be efficiently used, given different congestion etiquettes applied to spectrum designated to unlicensed use. In contrast, this section addresses the related issue of whether society has the "right" amount of spectrum designated to licensed versus unlicensed use. It is a question that policy makers address on a repeated basis. Currently, policy makers employ an administrative process for identifying the most desirable license regime for a given band of spectrum. Yet, despite their repeated use of this approach, they have expressed substantial dissatisfaction with relying on it as a basis for such decisions.[26] The dissatisfaction stems, in part, from the manner in which the process obtains information on the value firms that place on alternative license regimes.

In contrast to a market mechanism, where firms pay a price for having their needs met, an administrative process relies simply on the reported needs of interested parties. Because the cost of misrepresenting one's needs is small relative to the potential private value of spectrum acquired, each firm has an incentive to exaggerate the value it places on a given license regime, as well as how much spectrum to which that regime should apply. Therefore, for policy makers trying to identify the most desirable set of licensing rules, the administrative process necessarily involves attempts to measure the amount by which interested parties have exaggerated their license regime needs.[27] This problem faced by policy makers is an example of a broader class of "incentive problems" that have been considered in the economics literature. In this instance, a potential solution involves creating a mechanism that induces interested parties to reveal their private information regarding the value they place on spectrum and the license regime applicable to that spectrum. One approach involves the creation of a market for license regimes (i.e., license rules) in which participants bid to have their license regime needs met. By reducing the incentive that interested parties

[24] The largest divergence is in the predicted efficiency of the Fairness Etiquette in Environment 2. In this case, a larger number of users could afford to choose the subscription service than in Environment 1, and theory suggests that such users would correctly anticipate the overuse of the free service and voluntarily choose to pay the subscription fee. In the experiments, subjects did not respond in this way.

[25] Because service quality depends upon the number of users, all things being equal, one can also express this condition in terms of the "quantity" of service being provided.

[26] The European Commission has recently stated that an administrative process for determining licensing rules is neither transparent nor objective. See *Study of Legal, Economic and Technical Aspects of "Collective Use of Spectrum" in the European Community – Final Report*, by Mott MacDonald Ltd., Aegis Systems Led., IDATE, Indepen Ltd., and Wik Consult (November 2006), pg 13. Recently, Professor Martin Cave called the administrative approach to determining license rules "arbitrary and unsatisfactory." See "New spectrum-using technologies and the future of spectrum management: a European policy perspective," by Martin Cave, in *Communications: The Next Decade*, edited by Ed Richards, Robin Foster and Tom Kiedrowski, Ofcom (November 2006), pg. 224.

[27] The problem policy makers face is similar to other assignment problems where an administrative process is used to identify the best use of a given resource. For example, city planners are often confronted with the problem of determining whether a given parcel of land should be designated to public or private use.

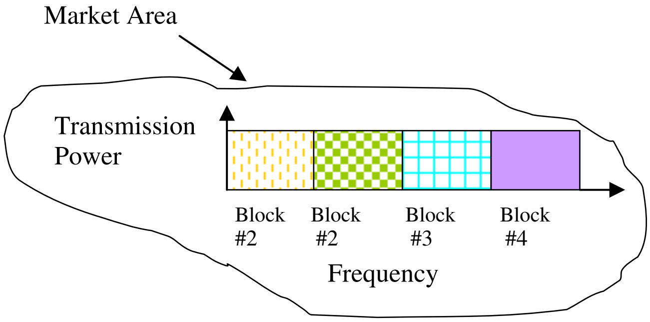

Fig. 5. Hypothetical band plan.

have to misrepresent their economic interests, this approach may substantially improve the efficiency of spectrum management, thereby increasing the economic benefit society receives from one of its most valuable resources.

3.1. A simple economic model of spectrum assignment

As part of its spectrum management responsibilities, the FCC determines the set of rights that are assigned to a given block of spectrum used by commercial and non-commercial entities. At one end of the spectrum rights regime is *unlicensed use,* where spectrum is treated as an open access resource that is available to all without charge.[28] Each user is free to demand as much spectrum as it wishes, employing the appropriate FCC-certified equipment operating at authorized power levels. The most successful example of unlicensed operations is Wi-Fi service, which operates in the 900 MHz, 2.4 GHz, and 5.8 GHz bands and is employed by millions of users each day to access the Internet.[29]

At the other end of the spectrum licensing regime is *licensed use.* In this case, the license owner is granted the right to determine the service to be offered, the technology to be employed in providing that service, and the extent to which non-payers will be excluded from the service. In addition, the license owner is protected from harmful interference by other service providers, and is given the right to sell its license to another party. A prominent example of licensed operations is the highly successful Personal Communications Service, which operates in the 1.9 GHz band. In what follows, we propose a simple model that includes assumptions about the service rules that are adopted by the FCC, preferences of participating firms for those rules, and spectrum valuations by these firms. Given these assumption, we calculate the efficient assignment of license regimes to bands of spectrum, and the efficient "owners" of such bands.

[28] While spectrum is available to makers of FCC authorized devices without charge, whether spectrum is free to firms depends upon the service and the business enterprise. For example, Panera Bread offers free Wi-Fi service to its customers, while Starbucks does not.

[29] More precisely, the FCC has authorized devices to operate on an unlicensed basis in these bands. Moreover, technological improvements continue to enhance the transmission capabilities of spectrum designated to unlicensed operations. For example, in an attempt to compete with other local wireless broadband providers, Cablevision has recently announced plans to construct the nation's largest Wi-Fi network.

3.1.1. Spectrum service rules

In modeling the license regime problem, we assume that as a result of an engineering and policy analysis, the FCC has established a set of technical performance parameters, including maximum power and out-of-band emission limits (i.e., service rules), for a set of four bands of spectrum located in a single geographic area (see Fig. 5). We further assume that as part of its traditional spectrum management responsibilities, the FCC is confronted with the problem of identifying whether each block should be designated to either licensed or unlicensed use. For licensed use, the FCC must further identify the firm(s) that most highly value the block(s). The current analysis assumes that each block of spectrum has the same authorized transmission power regardless of whether the block is designated to either licensed or unlicensed use.

3.1.2. License regime preferences of firms

In an auction to allocate spectrum between licensed and unlicensed use, participating firms fall into two distinct categories as a result of differences in their business models. The business model of "L-Type" firms (e.g., Verizon, AT&T, T-Mobile) involves constructing the necessary telecommunications infrastructure and earning a return on that investment based on revenue obtained from subscribers. Consequently, all L-Type firms strongly prefer to acquire spectrum with licensing rules that enable them to exclude non-payers and to receive protection from harmful interference coming from other service providers.

Another type of bidder – a "U-Type" firm – has a preference for licensing rules that promote free, open access to spectrum. A variety of firms fall within the U-Type category. Rather than derive revenue from subscribers, one class of U-Type firms earns revenue from advertisers and/or retail customers that sell good/services to customers via the Internet. The most prominent examples are firms (e.g., Ask.-com, Google, Microsoft, Yahoo) that obtain revenue from selling to advertisers access to viewers/listeners that are attracted to Internet-based content and services. Another class of U-Type firm (e.g., Cisco, Fujitsu, Juniper Networks, Motorola) obtains revenue from selling hardware (e.g., wireless routers) to firms that provide Wi-Fi service (e.g., Marriott Hotels, Panera Bread, Starbucks, Cablevision) or obtains revenue directly from consumers that purchase products (e.g., cellular handsets or automatic garage door openers) that utilize spectrum designated to unlicensed use.

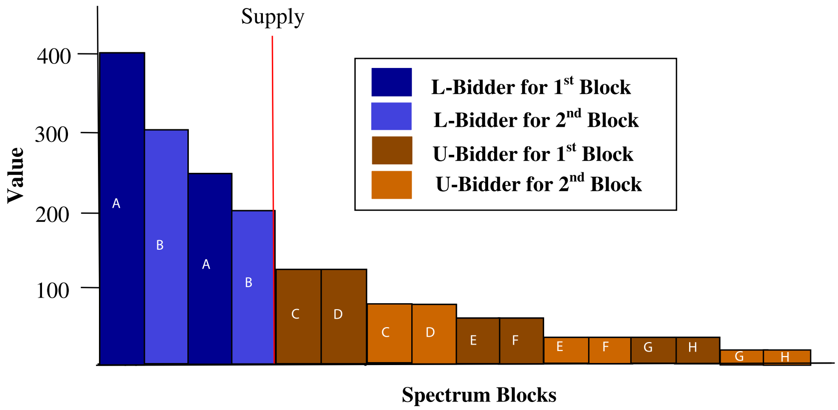

Fig. 6. Valuations by firms in Session 1.

The greater the number of viewers or firms to which a U-Type firm can obtain access, all things being equal, the greater the value it places on licensing rules that provide for non-exclusive, open access use. It also follows that the greater the demand for a product that is necessary to either provide Wi-Fi service or to enable consumers to utilize spectrum designated to unlicensed use, the greater the value the U-Type firm places on licensing rules that provide for non-exclusive, open access use. Because market participants vary in the demand for their products, as well as in their profit margins, U-Type firms will vary in the value they place on having spectrum allocated to unlicensed use, but they nevertheless have a common interest in having spectrum designated to unlicensed use.

3.1.3. Spectrum valuations by firms

In designing spectrum auctions, the FCC has strongly attempted to avoid making service rule choices that favor a particular business plan. Instead, the FCC typically tries to assess the minimum amount of spectrum a firm needs to provide a given service. However, because of variations in business plans across bidders, some firms may wish to acquire multiple blocks of spectrum. Moreover, because of technical considerations, the value each firm places on the first block of spectrum may exceed the value a firm places on additional blocks of spectrum.[30] In addition, given the stronger ownership and use rights associated with spectrum designated to licensed versus unlicensed use, our model assumes that L-Type firms uniformly place a higher value on a block of spectrum than U-Type firms.[31]

In the present analysis, the valuations assigned to market participants are driven less by actual market valuations derived from empirical data than by a desire to stress test our market approach to achieving the most efficient allocation of spectrum. We therefore wish to establish a valuation environment that tests whether the proposed mechanism efficiently designates spectrum to unlicensed use in two extreme environments: (1) when it should clearly do so and (2) when doing so is highly problematic. Accordingly, we have established two valuation environments. In the first environment (Session 1), there are two L-Type bidders (A and B) and six U-Type bidders (C through H) having the distribution of valuations across bidders shown in Fig. 6. In the second environment (Session 2), there are two L-Type bidders and five U-Type bidders having the distribution of valuations across bidders shown in Fig. 7.

3.1.4. Efficient assignment

Because each bid is associated with a given license regime, identifying the efficient assignment of spectrum simultaneously identifies both the efficient set of licensing rules for the blocks of spectrum that are up for auction and the set of winning bidders, given the bids submitted in the auction. Identifying the economically efficient set of licensing rules involves measuring the value society would receive from each license regime. The value society obtains from having one or more blocks of spectrum designated to licensed operations is equal to the value L-Type firms place on licensed use. In contrast, the value that society obtains from having one or more blocks of spectrum designated to unlicensed use, given their unfettered open access nature, is equal to the summation of the valuations that U-Type firms place on having such a designation. Because spectrum allocated to unlicensed use is collectively utilized by all U-Type firms, such firms face a collective decision problem in bidding for spectrum in competition with L-Type firms. In particular, each U-Type firm has an incentive to "free ride" on the bidding behavior of other U-Type firms by bidding less than his true value for a block of unlicensed spectrum.

Fig. 8 shows the efficient assignment of spectrum, including the efficient set of licensing rules, involving Session 1's valuation set. As shown, efficiency considerations dictate that one block of spectrum be assigned to subjects A and B (for licensed use) and two blocks of spectrum to subjects C–H (for unlicensed use).

[30] A market participant's demand for spectrum is derived from the demand consumers express for the participant's wireless service. In a competitive market, consistent with a firm's attempt to maximize its profits, a firm will acquire spectrum to the point where its marginal revenue product of spectrum is equal to its cost.

[31] The fact that a U-Type firm has never participated in a spectrum auction, let alone place a winning bid in an auction, provides weak proof that up to now U-Type firms place a lower value on a given block of spectrum than L-Type firms.

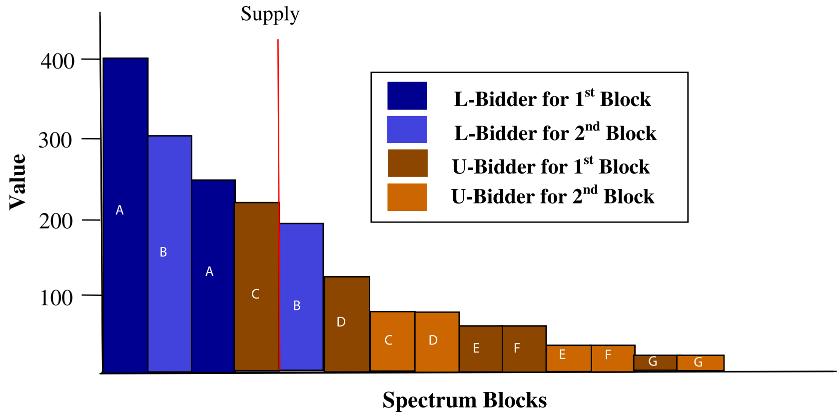

Fig. 7. Valuations by firms in Session 2.

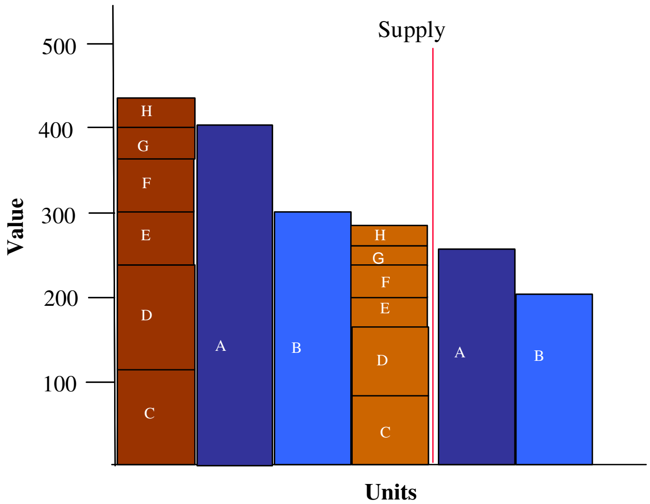

Fig. 8. Efficient assignment in Session 1.

The objective of our study is to examine – in proof of concept terms – whether a market can be used to efficiently designate spectrum between licensed and unlicensed use.[32] At the minimum, the chosen market mechanism should designate spectrum to unlicensed use where it is obvious, from an efficiency perspective, that it should do so. Here, we define the level of "obviousness" by the size of the discrepancy between the value U-Type bidders place on having spectrum designated to unlicensed use and the value society would receive from having the extra-marginal unit included in the allocation. For example, as shown in Fig. 8, the sum of the values U-Type subjects place on having spectrum designated to unlicensed use (i.e., 440) is substantially greater than the value Subject A places on a second block of spectrum (i.e., 250). Therefore, in this environment a successful mechanism is one that nearly always designates at least one block of spectrum to unlicensed use.

[32] A "Proof of Concept" is a realization of a given process or technique that is designed to demonstrate the feasibility and workability of a set of core ideas.

Ideally, the chosen market mechanism should also allocate spectrum between licensed and unlicensed use efficiently in difficult as well as simple valuation environments. The difficulty that each U-Type firm faces in selecting a bidding strategy in turn depends on the auction mechanism's pricing rule. As will be discussed later, under the proposed mechanism, all blocks of spectrum are sold at a uniform price which is equal to the highest rejected bid. For example, as shown for Session 1 in Fig. 8, in order for U-Type firms to collectively obtain 30 units of value from having a second block of spectrum allocated to unlicensed use (i.e., 280–250), they must give up 250 units of value (88% of the combined total value).

Fig. 9 shows the efficient assignment of spectrum, including the efficient set of licensing rules for Session 2's valuation set. As before, efficiency considerations dictate that one block of spectrum should be assigned to bidders A and B under licensed uses, and two blocks of spectrum to bidders C–H under unlicensed operations. As measured by the difference in value between the fifth highest valuation (i.e., 250) and the value U-Type bidders collectively place on having a first block of spectrum allocated to

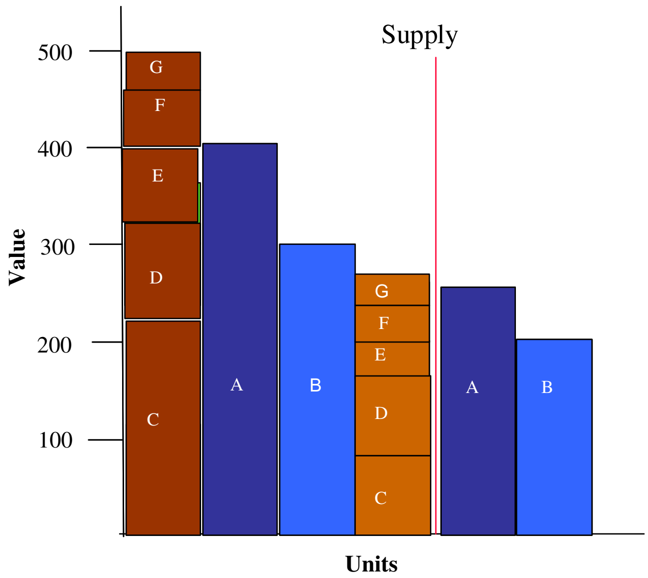

Fig. 9. Efficient assignment in Session 2.

unlicensed operations (i.e., 500), a successful mechanism is one that consistently designates at least one block of spectrum to unlicensed operations. While the Session 2 valuation environment poses less of an allocation challenge for the market mechanism in the case of the first block of spectrum, it is substantially more difficult than Session 1 in the case of the second block of spectrum. As shown in Fig. 9, in order for U-Type bidders to obtain 10 units of value (i.e., 260–250) from having a second block of spectrum allocated to unlicensed use, they must collectively give up 250 units of value (96% of the combined total value).

3.2. Using a clock auction to designate spectrum between regimes

Experiments conducted for other spectrum auctions have revealed that bidders may engage in "jump bidding" in an ascending English auction in an effort to forestall or signal competition, and an inefficient assignment of items may result.[33] More recent analysis indicates that the threat of financial exposure increases the likelihood of jump bidding behavior during a simultaneous multiple round auction involving multiple heterogeneous items.[34] Moreover, jump bidding appears to be a significant feature of FCC spectrum auctions.[35] One solution to this problem is a "clock auction," an iterative auction procedure whereby bidders express their willingness-to-pay for one or more units of an item based on prices established by the auctioneer and whereby a set of rules determines the efficient allocation and a set of market clearing prices.

Here, we propose a new auction mechanism that is based, in part, on previous clock auctions. The proposed auction begins with the auctioneer (e.g., the FCC) announcing a single opening price – the clock price – for each spectrum block up for auction.[36] Subjects respond by identifying the number of blocks they wish to acquire at that clock price. All responses, including the identities and license regime preferences of bidders, are kept private. Our auction mechanism includes market rules for assessing bidder valuations, for aggregating bids, for establishing a single uniform price, and for sharing the cost among U-Type bidders conditional on one or more spectrum blocks being designated to unlicensed use.

3.2.1. Rules for assessing bidder valuations

A simple set of rules enables the auctioneer to assess the value bidders place on having one or more blocks of spectrum designated to licensed versus unlicensed operations.

1. If a bidder requests zero blocks at the initial clock price, then the value the bidder places on the first and second blocks of spectrum is equal to zero.
2. If a bidder requests one block of spectrum at the initial clock price, then the value the bidder places on a second block of spectrum is equal to zero.
3. To preserve the increasing price nature of the auction, bidders are prevented from increasing the number of spectrum blocks they desire as the clock price increases.

[33] Jump bidding occurs in an ascending bid auction when one or more bidders place bids in excess of the minimum bid increment established by the auctioneer. See McCabe, K., Rassenti, S. and Smith, V. (1988) "Testing Vickrey's and other Simultaneous Multiple Unit Versions of the English Auction," revised by Isaac, R.M., ed. (1991) *Research in Experimental Economics* (JAI, Greenwich, CT), vol. 4. See also Avery, C., (1998) "Strategic Jump Bidding in English Auctions," *Review of Economic Studies*, Vol. 65 (2), pgs 185-210.

[34] Porter, D, Rassenti, S, Roopnarine, A, and Smith, V., (2003) "Combinatorial Auction Design," *Proceedings of the National Academy of Sciences*, vol. 100.

[35] Cramton, Peter, (1997), "The FCC Spectrum Auctions: An Early Assessment," *Journal of Economics and Management Strategy* Vol. 6(3), pgs. 497-527.

[36] The number of clock prices is equal to the number of heterogeneous items. For simplicity, we have assumed that blocks up for auction were homogeneous.

4. If a bidder reduces its spectrum block demand from two to one as the clock price increases from one level to the next, the lower clock price represents the value the bidder places on a second block of spectrum.
5. If a bidder reduces its spectrum block demand from one to zero blocks as the clock price increases from one level to the next, the lower clock price represents the value the bidder places on a single block of spectrum.
6. For subsequent rounds, if a bidder reduces its spectrum block demand from two to zero blocks in response to the latest clock price increase, the lower clock price represents the value the bidder places on both the first and second blocks of spectrum.

If the number of blocks desired by one or more bidders exceeds zero at a given clock price, the ''clock ticks up'' – meaning that the price for a block of spectrum goes up by a pre-determined amount.[37] Participants are then given the opportunity to reveal to the auctioneer (and not to the market) the number of blocks they desire at that clock price. The auction closes when there is zero demand for a spectrum block at the going clock price.

3.2.2. Rule for aggregating bids

Determining the efficient allocation of spectrum across license regime type and firms requires a comparison of the value society will obtain from designating spectrum to licensed versus unlicensed use. In contrast to licensed use where license owners have exclusive use rights to the allocated spectrum, unlicensed firms have unfettered access to spectrum designated to unlicensed operations. The open access nature of unlicensed operations requires that we apply the same ''non-exclusive'' treatment to the bids submitted by participants that wish to see spectrum designated to unlicensed operations. Such treatment requires that we aggregate the bids that U-Type bidders place in the auction. However, such aggregation must be performed with care because in our model bidders desire multiple blocks of spectrum designated to a given license regime and they have different willingness to pay across these blocks. For example, because U-Type bidders may express a higher valuation for a single block of spectrum than for a second block of spectrum, those bidders submit two distinct bids. One bid applies to a single block of spectrum, while a separate bid applies to a second block of spectrum.[38] Constructing the correct aggregate bids requires keeping this distinction in mind. To this end, a simple algorithm adds together the highest bids from each U-Type bidder to form one aggregate bid (U1) for the first item allocated to unlicensed use, and simultaneously sums the lowest bids from each U-Type bidder to form a second aggregate bid (U2) for a second item allocated to unlicensed use.

Once the two aggregate bids are constructed, identifying the efficient allocation of spectrum to a license rule regime and, in the case of licensed use, to the most efficient firm(s), is straightforward. Under the allocation rule, bids U1 and U2 are ranked, along with the bids submitted by L-Type bidders, from highest to the lowest. Given that there are four blocks of spectrum up for auction, the four highest bids are each assigned a single block of spectrum. Because each bid is associated with a given license regime, this assignment also determines whether a block is allocated to either licensed or unlicensed use. For example, if the U1 and U2 bids are among the four highest bids, two blocks are designated to unlicensed operations. If the four highest bids include two bids from L-Type bidders, then two spectrum blocks are allocated to licensed operations and to the participants whose bids were among the four highest.

The effect of this bid aggregation rule can be seen in Fig. 8 by supposing that the auction has closed and that bidders have truthfully revealed the value they place on having two blocks of spectrum allocated to either licensed and unlicensed operations.[39] Under these assumptions, the clock auction would generate an outcome in which two blocks of spectrum are assigned to bidders A and B on a licensed basis, and two blocks are allocated to unlicensed use.

3.2.3. Uniform pricing and cost sharing rules

The ''public good'' aspect of the demand by unlicensed bidders gives rise to a ''threshold'' problem, in which U-type bidders must coordinate their bidding strategies in order to reach a favorable outcome. The presence of a threshold problem highlights the importance of establishing a pricing rule that encourages subjects to reveal the value they place on having spectrum allocated to one use type versus the other. To that end, all trades in the experimental study occur at a uniform price, where this price is equal to the highest rejected bid. In the above example, because there are four blocks of spectrum up for auction, the highest rejected bid is equal to the fifth highest bid, including U1 and U2. While L-Type bidders pay the highest rejected bid, U-Type subjects pay a price that is ''based on'' the highest rejected bid. In particular, U-Type subjects that bid in the auction are assigned a cost that is proportional to the share their bids represent in the aggregate bid.

The effect of these pricing rules is illustrated in Fig. 10. We assume that the auction has closed and that bidders have truthfully revealed the value they place on having spectrum allocated to licensed and unlicensed use. Under these conditions, Bidders A and B would receive one block of spectrum each, while two blocks of spectrum would be designated to unlicensed use. Moreover, all four blocks are sold for a uniform price of 250, which represents the highest rejected bid. In addition, the winning U-Type bidders are assigned a cost proportional to the share that their bids represent in the aggregate bid. For example, consider Bidder C, a U-Type bidder, and its contribution of 120 to the aggregate bid for allocating a single block of spectrum to unlicensed use. Because Bidder C's bid of 120 represents 27% of the value of the accepted aggregate bid of 440,

[37] In most clock auctions, the clock price only ticks up if the demand for the auctioned item exceeds its supply. See Porter et al. (2003) *op cit*.

[38] Licensed bidders also submit distinct bids for the first and second units of desired spectrum.

[39] Truthful bidding is assumed here only to illustrate the allocation and pricing rules in the auction mechanism. Later, it will be demonstrated that unlicensed bidders rarely have an incentive to bid completely truthfully.

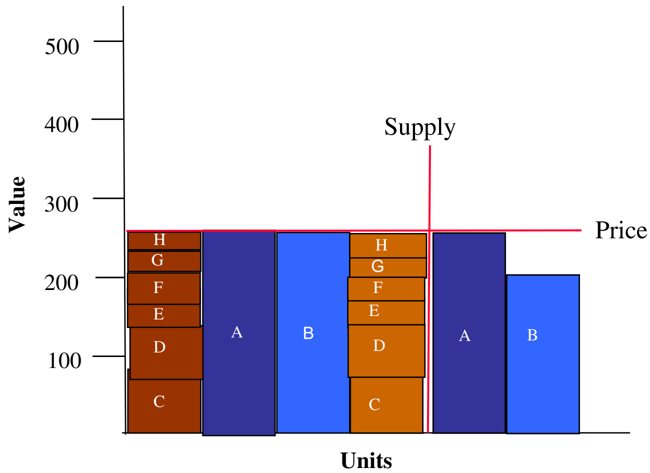

Fig. 10. Effect of pricing rules in Session 1.

Bidder C is required to pay 27% of the final transaction price (i.e., 250), or 68.2. Similarly, because Bidder C's bid of 80 to have a second block of spectrum designated to unlicensed use represents 29% of the value of the accepted aggregate bid of 280, Bidder C is required to pay 29% of the final transaction price, or 71.4.

3.3. Mechanism design problem

There are several reasons why a market may have difficulty allocating different license regimes to blocks of spectrum in an efficient manner. One general source of market failure is the unwillingness of bidders to reveal the true value they place on a particular license regime.[40]

A major cause of under-revelation in the current example is free riding behavior involving unlicensed use. The economics are straightforward. Spectrum designated to unlicensed operations provides an alternative means by which firms can access the Internet. Unlicensed use makes it possible for Internet firms and entities (e.g., Google, Microsoft, Yahoo) that wish to sell access to such firms to advertisers to do so without the possibility of paying a fee to an intermediary (e.g., Verizon, Comcast). Because of the common pool resource nature of spectrum designated to unlicensed use, the benefit that a given firm receives from expending the effort to avoid such a fee extends to every U-Type firm. The ability of a given firm to benefit from the actions of another firm introduces a public good aspect to the economic problem. In the current context, although it is in every U-Type firm's interest to have spectrum designated to unlicensed use, any individual U-Type firm has an incentive to "free ride" off the bids of other bidders in an attempt to maximize its own profits. If a significant number of U-Type firms elect to free ride, then the efficient designation of spectrum to licensed and unlicensed use may not occur.[41]

In many public good problems, free riding behavior is a *dominant strategy*.[42] In particular, it is welfare maximizing for the firm or agent to refrain from engaging in behavior that promotes the welfare of the group *independent* of the behavior of the other firms. This is so because the cost of contributing to the welfare of the group always exceeds the private benefit from doing so.[43] In the current collective action problem, however, it is not a dominant strategy for any one U-Type firm to always "free-ride" off another

[40] Although not unique to this problem, there are other reasons why a market may "fail." One reason is the existence of non-competitive prices in the retail service market. The price signals generated by a market reflect the willingness of buyers and sellers to complete a trade. If the expressed willingness to trade is the result of competitive forces, the price signals generated in the market will themselves be competitive and will, thus, efficiently allocate resources. One instance where the willingness to trade is too high is when a buyer wishes to acquire an asset, in part, because it wishes to avoid having the asset employed by a competitor. In this instance, the willingness of the buyer to trade, as measured by the value the buyer places on the asset, is inefficiently high. This reasoning points to a possible inefficiency in the use of market forces to guide the licensing rule determination process. In particular, if the value that L-Type bidders place on spectrum is driven largely by the profits they would earn from not having the spectrum in the hands of a competitor, an auction outcome that relies on market prices to guide the licensing rule determination process may not lead to the efficient outcome. There are several possible solutions to the problem. One solution involves preventing L-Type bidders from participating in the market process. This can be achieved by establishing a spectrum cap that limits the amount of spectrum each licensee may own in a given geographic area. Another approach involves allowing the firm to participate in the market, but discounting the firm's bid by an amount equal to the value the firm places on owning the asset for purely anticompetitive reasons.

[41] Notwithstanding the public good aspect to spectrum acquisition costs for unlicensed bidders, these bidders may also compete with each other for retail customers.

[42] The classic example of an inefficient dominant strategy equilibrium is the "prisoners' dilemma," in which each prisoner has an incentive to confess even though their combined welfare is maximized if neither confesses.

[43] A variety of experimental studies have shown that even in instances where, according to game theory, free riding behavior is a dominant strategy, individuals fail to behave in such a manner. See Marwell, G., and R. Ames (1979), "Experiments on the Provision of Public Goods: Resources Interest, Group Size, and the Free-Rider Problem," *American Journal of Sociology* 84(6):1335-60, Isaac, M, J. Walker, J., and S. Thomas, "Divergent Evidence on Free Riding: An Experimental Examination of Possible Explanations," *Public Choice* 43(1):113-49.

U-Type bidder's efforts in order to have a given band of spectrum allocated to unlicensed use.[44] One distinguishing feature of the current problem is the existence of a "provision point."[45] A provision point is the minimum aggregate contribution that firms must collectively make in order for any given firm to obtain value from its contribution.[46] In the current context, in order for a single block of spectrum to be allocated to unlicensed use, the sum of the bids submitted by U-Type bidders must exceed the lowest bid submitted by the L-Type bidders. This bid represents for U-Type bidders the provision point for that first block of spectrum. The provision point represents a Nash equilibrium since any unilateral deviation below the provision point value is unprofitable for the contributors.[47]

The likelihood that an equilibrium without significant free riding will be achieved is increased as a result of the so-called "give back" option at work in the current economic environment. In a typical public good problem, a player's payoff is often reduced by the amount of its contribution, independently of whether other parties have made a contribution. In the current example, a contribution by the U-Type bidder only reduces its payoff if the sum of the U-Type bids exceeds the provision point. A similar effect is achieved when organizations conduct fund drives under the rule that the public good will not be provided unless a certain minimum level of funding is achieved. By reducing a U-Type bidder's risk of making a contribution, the give back option can be expected to increase the contributions made by such bidders.[48] However, the give back option and provision point features may not always lead to the efficient outcome. Both features give rise to multiple Nash equilibria when participants need contribute only a portion of the value they place on having a public good provided. The existence of multiple equilibria may create an important coordination problem because participants will typically have differing equilibrium preferences.[49] The non-dominance of a pure free-riding behavior and the existence of multiple equilibria can be demonstrated using the parameters included in the Session 1 experimental set-up.

3.4. Nash predictions and experimental results

In this section, we will examine the efficiency outcomes predicted by Nash equilibrium theory and will report the results of our experimental analysis.

3.4.1. Nash equilibrium predictions

Economic theory predicts that, at a minimum, participants in a mechanism design problem will rationally select bidding strategies that are sustainable as Nash equilibrium outcomes. As explained earlier, a Nash equilibrium represents a set of bidding strategies such that no bidder can expect to increase its payoff by following a different bidding strategy, assuming that every other bidder continues to play its own equilibrium strategy. In the absence of a strictly dominant strategy for each bidder, there can in general be a large number of Nash equilibria. A full description of these equilibria depends on a detailed description of the information available to each bidder about the auction mechanism itself and each bidder's beliefs about the private valuations of all rival bidders. In a set of auction experiments to be described later, experimental subjects were told the rules of the auction and their individual assigned valuations, but were given no information about other subject's valuations other than the total number of subjects participating. Suppose, contrary to this experimental setup, that each bidder has complete information about the number of other bidders, the type (i.e., licensed/unlicensed) of each bidder, and each bidder's true valuation. In the remainder of this section we will show that under these assumptions it is possible to enumerate the full set of Nash equilibrium outcomes.

In the experiments, the auction was conducted as a particular type of "clock auction" as described above. In a complete information environment, the tested clock auction can be shown to be strategically equivalent to a sealed bid auction in which each bidder submits two bids – one for the first unit of spectrum acquired and a different bid for the second unit. In the experimental set up, the clock price started at 10 and advanced in units of 10. In order to simplify the present analysis, it will be assumed that bids can be submitted in any integer units, making the minimum bid increment equal to 1. As in the experiment, the market clearing price is equal to either the highest rejected bid for licensed use or the highest rejected aggregate bid for unlicensed use, whichever is the highest. Winning licensed bidders pay this price, while each winning unlicensed bidder pays an amount proportional to his actual bid, such that the sum of the unlicensed prices add up to the market clearing price. The values assigned in Session 1 of the experiments are shown in Table 2.

Assuming complete information, there are a large number of Nash equilibria in the auction game, one of which is shown in Table 3. In this equilibrium, licensed bidders submit winning bids for three of the four licenses, and the remaining block of spectrum is awarded to unlicensed bidders collectively. The market price is determined by the highest rejected bid, which in this case is made by both li-

44 In this case, the public good problem is more closely related to two other well known game situations. In the game of "chicken" both players want to follow aggressive strategies as long as their opponent is expected to be passive. Nevertheless, the equilibrium outcomes call for only one, but not both of the players to be aggressive. In a somewhat different game known as the "battle of the sexes", one player wishes to attend an event (e.g., a boxing match) and the other player wisher to attend a different event (e.g., a ballet). In spite of these preferences, both players would rather go to the same event rather than different ones. In both "chicken" and "battle of the sexes" there are multiple Nash equilibria, which are welfare superior to the "free riding" equilibrium which also exits in these cases.

45 The role of a provision point in public good problems is discussed in detail by John Ledyard, "Public Goods: A Survey of Experimental Research," in *Handbook of Experimental Economics*, edited by J. Kagel and A. Roth, Princeton University Press 1995.

46 Marwell and Ames (1979) were the first to introduce the notion of a provision point in a public good experiment.

47 For the first and more detailed discussion of this point in the context of spectrum auctions, see Bykowsky, M. M., Cull, R. J., and J. O. Ledyard (2000) "Mutually Destructive Bidding: The FCC Auction Design Problem," *Journal of Regulatory Economics*, 17:3 205-228.

48 Experimental evidence indicates that the "give back" option has the effect of increasing contribution rates in some public good environments. See Isaac, M, D. Schmidtz, and J. Walker (1989) "The Assurance Problem in a Laboratory Market," *Public Choice*, 62, 217-236.

49 See Isaac, Schmidtz, and Walker (1989) *op cit*.

Table 2
Assigned valuations in Session 1 of the experiment.

Bidder	Subject type (L/U)	Value unit 1	Value unit 2
A	L	400	250
B	L	300	200
C	U	120	80
D	U	120	80
E	U	60	40
F	U	60	40
G	U	40	20
H	U	40	20
Sum C–H		440	280

Table 3
Example of Session 1 Nash equilibrium.

Bidder	Bid 1	Bid 2	Price	Surplus
A	400	250	200	250
B	300	200	200	100
C	56	55	55.72	64.28
D	55	55	54.73	65.27
E	27	27	26.87	33.13
F	27	27	26.87	33.13
G	18	18	17.91	22.09
H	18	18	17.91	22.09
Sum C–H	201	200	200	240

censed bidder B and collectively by unlicensed bidders C through H.[50]

To verify that the bidding strategies shown in Table 3 are a Nash equilibrium, one needs to show that no bidder can unilaterally benefit by changing either one of its bids. Given the bids in Table 3, bidder A wins 2 units; bidder B wins 1 unit; and the unlicensed bidders together win 1 unit. Bidder B's bid for a second unit and the combined bids of bidders C–H for a second unit tie as extra-marginal (rejected) bids equal to 200. These bids establish the market clearing price. No winning bidder can gain by either increasing its bid for the *first* unit of spectrum (since it is already winning and the market price is determined by the tie bids for a *second* unit of spectrum) or reducing its bid for that unit (since each bidder gets positive surplus for each unit won, and reducing a bid can only result in the loss of that surplus). If bidder B increases its bid for the second unit to 202 or greater, it will become a winning bidder, but it will have bid above its true valuation, and will therefore be worse off.[51] Since bidder B's second bid is tied with the second aggregate bid of C–H, bidder B cannot change the market price by reducing its bid for a second unit of spectrum, and therefore cannot increase the surplus attained for the first unit.

None of the unlicensed bidders C–H can benefit by unilaterally reducing their bid for the *first* unit of spectrum, since doing so would convert their collective bid into a losing bid (or tie for losing) which would result in forfeiting the surplus each bidder obtains. Similarly, none of the unlicensed bidders C–H can benefit by unilaterally increasing their bid for a *second* unit of spectrum. In order to displace bidder A's winning bid for a second unit and, in so doing, obtain a second block of spectrum for unlicensed designation, the unlicensed bidders must increase their aggregate bid to 251 or more. Such a bid would increase the market clearing price to 250, thereby reducing by 50 the surplus that any individual bidder obtains on their first block of spectrum. This reduction in surplus exceeds the 30 units of surplus (i.e., 280–250) such bidders collectively would obtain from having a second block of spectrum designated to unlicensed operations.

There are a large number of Nash equilibria for the auction game associated with the valuations shown in Table 1.[52] These equilibria can be sorted into three different "Types" according to the number of blocks of spectrum which are won collectively by the unlicensed bidders. A "Type 1" equilibrium, as represented in Table 3, results in three blocks of spectrum being designated to licensed operations and one block to unlicensed operations. In a "Type 2" Nash equilibrium, the two licensed bidders win all four blocks of available spectrum. Finally, in a "Type 3" Nash equilibrium two licensed bidders each win one block of spectrum, and two blocks of spectrum are designated to unlicensed operations. Therefore, the efficient license regime only occurs in a Type 3 Nash equilibrium. While each type of equilibrium permits a large number of equilibrium bidding strategies, the total surplus and the surplus for each bidder depend only on the bids of the extra-marginal bidders that determine the market price. These results are summarized in Table 4.

Given the substantial difference in total surplus across the three equilibrium types, an important question is which equilibrium type market participants will settle on. Note that licensed bidders A and B unambiguously prefer Type 2 equilibria while unlicensed bidders C–H unambiguously prefer Type 1 equilibria.[53] Nevertheless, game theory does not shed light on which type of equilibrium is most likely. In the following section we examine the equilibrium outcomes selected by market participants in two different experimental environments.

3.4.2. Experimental results

A series of 34 separate auction experiments were conducted, 13 of which were conducted under the Session One valuation set, while 21 were conducted under the Session Two valuation set. The information that subjects had about the economic environment was limited. Each of the subjects knew their own valuations, the total number of subjects in the experiment, the total number of available blocks of spectrum, and that each subject had a demand for exactly two blocks. Subjects were unaware of the number of participants that preferred licensed versus unlicensed

[50] We will demonstrate later that the efficient allocation cannot be sustained as a Nash equilibrium if all bidders bid their true values. However, it will also be shown that the efficient allocation can be sustained as an equilibrium with different bidding strategies.

[51] If B bids 201 for a second unit it will win with a 50% probability assuming that ties are settled by a coin toss, and this will also result in a loss of surplus.

[52] For a detailed description of the nature of each type of equilibrium, see OSP Working Paper #42, "Modeling the Efficiency of Spectrum Designated to Licensed Service and Unlicensed Operations."

[53] No bidder prefers a Type 3 equilibrium given that auction revenue and total surplus are highest in this type.

Table 4
Summary results of Nash equilibria for Session 1 valuations.

	Number of winning unlicensed bids	Market price (P)	A surplus	B surplus	C–H Surplus	Total surplus
Type 1	1	200	250	100	240	1390
Type 2	0	$P < 200$	650 – 2 P	500 – 2 P	0	1150
Type 3	2	$P \geqslant 250$	400 – P	300 – P	720 – 2 P	1420

Table 5
Bids submitted in Session 1 of the experiment.

Bidder	Bid 1	Bid 2	Price	Surplus
A	460	240	200	250
B	300	200	200	100
C	80	80	61.54	58.46
D	100	60	76.92	43.08
E	20	20	15.38	44.62
F	10	10	7.69	52.31
G	20	10	15.38	24.62
H	30	20	23.08	16.92
Sum C–H	260	200	200	240

Table 6
Experimental results.

		Average efficiency	Blocks designated to unlicensed operations		
			Zero	One	Two
Session #1	Number of Auctions		0	11	2
	Efficiency	.95	.82	.98	1.00
Session#2	Number of Auctions		2	17	2
	Efficiency	.95	.80	.99	1.00

use, as well as the value each subject placed on having one or two blocks of spectrum designated to a given license regime.[54]

To induce behavior reminiscent of the naturally occurring environment, subjects earned profits based on their performance in the experiment. In particular, subjects were paid an amount that is equal to the difference between the value they place on having spectrum allocated to their preferred use minus the price they paid for that unit of spectrum. Therefore, continuing the example of Section 3.2.3 (which assumes truthful bidding), Bidder C would earn 51.8 (i.e., 120–68.2) from having one block of spectrum designated to unlicensed operations, and would earn an additional 8.6 (i.e., 80–71.4) from having a second block of spectrum allocated to unlicensed operations. In the experimental framework, a U-Type bidder has the option to bid less than his or her value, or even to not submit a bid in the auction, deciding instead to simply free-ride off the bids submitted by other U-Type bidders. In such a circumstance, if the spectrum is allocated to unlicensed use, a bidder who chooses to free ride is not allocated a cost share and thus, earns an amount equal to its full assigned valuation for that spectrum block.

The Nash predictions presented in Table 4 identify three possible "types" of equilibria, but they do not give any insight about which type is most likely to occur. Therefore, while we again emphasize that the theoretical and experimental results are based on different underlying game forms, it is instructive to classify the experimental outcomes on the basis of their comparable type in the game of complete information. The experimental results reveal outcomes that resemble Type 1 equilibria are approximately attained in a large number of experimental sessions. For one session, the final experimental bids are shown in Table 5 along with the prices paid and surplus earned by each subject. While the unlicensed bidders somewhat overbid for the first unit of spectrum, by collectively bidding 260 instead of 201, the experimental bidding exactly conforms in all other respects to a Type 1 equilibrium.

Summary results for all experimental sessions are shown in Table 6. In 28 of the 34 auctions (i.e., 82%), the competitive process resulted in one spectrum block being designated to unlicensed use. By comparison, in only two out of the 34 auctions (i.e., 6%) did the competitive process lead to all four blocks being designated to licensed operations (Type 2 equilibria). Finally, in four out of the 34 auctions (i.e., 12%), two spectrum blocks were designated to unlicensed use, which was the efficient allocation.

Consistent with the observation that Session 2 valuations presented a greater coordination challenge for U-Type bidders than did Session 1 valuations, U-Type bidders were always able to coordinate their bids in the Session 1 valuation environment so that at least one block of spectrum was allocated to unlicensed use. In contrast, there were two instances in which U-Type bidders were unable to coordinate their bids under the Session 2 valuation environment so that no blocks were allocated to unlicensed use.

The inability of the mechanism to achieve a higher efficiency value is due, in part, to the incentive that U-Type bidders have to strategically reduce their demands for the second block of spectrum. It is well known that in instances where bidders have multi-unit demands and a simultaneous ascending-bid auction with uniform pricing is employed to allocate items, bidders can find it in their mutual interest to reduce demand in an effort to maximize their profits.[55] Such "demand reduction" would be profit-

[54] As in the congestion analysis in Part II of the paper, the experimental analysis in this section is formally a game of incomplete information, while the Nash predictions assume a game of complete information.

[55] Such an effect is referred to as strategic demand reduction. For a discussion of strategic demand reduction in FCC spectrum auctions, see Weber, Robert, (1997) "Making More With Less," *Journal of Economics and Management Strategy*, 6, 529-548.

able if the buyer's surplus from consuming n units at a given price is greater than the surplus from consumer $n + 1$ units at a higher price. In the current example, U-Type bidders would earn greater profits if they collectively failed to bid for a second block of spectrum, electing instead to have the market generate a lower market clearing price.

The average efficiency obtained under each session valuation environment was 95%. In evaluating the performance of the market, it is important to recognize that the lower bound for the assignment efficiency is the level of efficiency obtained when zero blocks of spectrum are assigned to unlicensed operations. As shown in Table 6, the minimum possible efficiency of the market (when zero blocks of spectrum are assigned to unlicensed operations) is 82% in Session 1 and 80% in Session 2.

4. Conclusion

Policy makers are very interested in ensuring that the spectrum currently designated to licensed and unlicensed operations is efficiently used. They are also interested in ensuring that, on a going forward basis, society has the efficient amount of spectrum designated to licensed and unlicensed operations. This paper examines whether market mechanisms can promote each of these goals. We have obtained a number of important conclusions. First, because of the heterogeneous nature of spectrum users, spectrum congestion is a particularly difficult issue to address. Indeed, in the specific environments that we examined, spectrum congestion may cause society to leave as much as 50% of the available economic surplus "on the table." Our results show, however, that this inefficiency can be substantially reduced when a market mechanism is utilized to guide user decisions regarding the choice of licensed versus unlicensed service. Such a mechanism could rely on the bandwidth and latency tolerance needs of competing users, and potentially on the values that each user places on the service. Different mechanisms, or etiquettes, address the potential inefficiency differently. Some mechanisms seek only to ration the demand for use of unlicensed spectrum so as to prevent excessive total demands from destroying potential surplus that would otherwise be available to at least a subset of users. Other mechanisms seek in addition to allocate service to those users expressing the highest value for use of the spectrum. There may, however, exist subtle strategic effects that can diminish a market's ability to allocate resources. For example, when users choose between a subscription-based non-congestible service and a less expensive congestible service, an etiquette that efficiently rations unlicensed spectrum use among users who choose that service can paradoxically lead to less efficient choices of service overall, since too many users may decide to choose that service.[56] Our results also show that the efficient use of spectrum may be perfectly consistent with capacity utilization levels well below 100% and, further, that spectrum users may be better off when spectrum is allocated through congestion pricing than when spectrum is always available on a free, open access basis. Taken together, these results suggest a solution to the standing question of whether spectrum should be designated to either licensed or unlicensed use. One answer suggested by our analysis is to designate spectrum to unlicensed use, but require that the facilities or equipment owners engage in a form of congestion pricing in which spectrum users are only charged when society's welfare would otherwise be reduced. This decidedly "hybrid" regime would appear to combine the best features of both licensed and unlicensed use.

The second part of this paper has examined the merits of creating a market in which firms which can supply spectrum services to consumers using either licensed or unlicensed spectrum compete to have their spectrum license needs satisfied. The objective of this approach is to reduce the incentive that service operators have to misstate their expressed value for a given license regime. One general source of market failure is the unwillingness of bidders to reveal the true value they place on a particular license regime. A major cause of under revelation in the current instance is "free riding" behavior involving unlicensed use. If a significant number of bidders that wish to see spectrum designated to unlicensed use free ride on the bids made by other similarly-interested bidders, then the efficient designation of spectrum to licensed and unlicensed use may not occur. Our results show that a carefully designed auction mechanism can, indeed, improve the efficiency in the assignment of license rules. The efficiency of the approach is based in large part on the mechanism's ability to solve the "free-rider" problem, which is more broadly viewed as a "collective action problem." Interestingly, such problems exist in a wide variety of spectrum policy problems. For example, the reliance on market forces to determine the extent to which a platform is "open" versus "closed" requires solving an important collective action problem. Thus, our results open up the possibility that a wide variety of spectrum policy issues may be efficiently solved using a market-based approach.

[56] Our experimental results show that this strategic effect is not sufficient to negate the beneficial effects associated with the mechanisms considered.