Using a Market to Obtain the Efficient Allocation of Signal Interference Rights

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Abstract

Before blocks of spectrum can be assigned through an auction process, it is necessary for the Federal Communications Commission to define a set of service rules that precisely define the rights and obligations of a final license holder for a given block. Two important rules are the authorized transmitting power that the license holder can use and the out-of-band emission limits. Higher power levels and higher out-of-band emission limits are potentially beneficial to the license holder, but at the same time they may generate signal interference for other license holders in adjacent blocks of spectrum.

Typically service rules are determined in an administrative process which seeks to balance, particularly in the case of unlicensed spectrum, the benefits and costs to all relevant parties. However, parties are likely to have information about the true benefits and costs that is unavailable to the Commission. Moreover, because it doesn't impose a cost on parties for misrepresenting the benefits and harms associated with a particular rule, an administrative process may lead to highly inefficient outcomes.

Coase (1959) suggested that the Commission can solve this problem by, first, establishing and assigning secure and tradable signal interference rights to either the parties benefiting from a particular service rule or the parties harmed by such a rule and, second, allowing market forces to allocate such property rights among the interested parties. This paper examines possible alternatives to the current administrative process for identifying the efficient allocation of signal interference rights.

Using a game theoretic framework, this paper demonstrates that a market mechanism may be able to efficiently allocate interference rights. However, to achieve an efficient outcome, participants may have to solve an important "collective action problem" (i.e., free-rider or hold out problem). The collective action problem is made more difficult due to the absence of an efficient Nash equilibrium that is superior to all other Nash equilibria.

This paper also examines the possibility of employing a market to identify the efficient set of service rules, as well as the efficient licensee, for yet-to-be-auctioned spectrum (e.g., Advanced Wireless Services-3). There exist Nash equlibria that yield the efficient outcome, but typically there also exist a larger number of other Nash equilibria. Future experimental work can assess whether the efficient outcome is likely to be attained and explore the effects of relaxing the assumption of complete information.

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William W. Sharkey[1]

1. Introduction

A spectrum license includes a set of rules established by the Federal Communications Commission (Commission) that identify acceptable licensee behavior and responsibilities. Among the more important rules are "service rules" that identify the licensee's authorized transmitting power, the amount of bandwidth over which it can operate, limits on the amount of radiation outside the licensee's assigned bandwidth that adjacent and non-adjacent bands can experience (i.e., out-of-band emission limits), and the spectral and geographic location of the licensee's bandwidth.[2] In establishing those rules, the Commission attempts to identify that set of service rules that promotes the efficient use of spectrum.[3] Consider authorized transmitting power.[4] A decision by the Commission to increase a licensee's authorized transmitting power may cause harmful interference to authorized services utilizing adjacent spectrum.[5] In making its decision, economic efficiency requires that the Commission take into account the possible

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[2] More technically, Commission service rules refer not to transmitting power but, rather, the maximum amount of energy that can be emitted out of the licensee's antenna. The amount of energy emitted is a function of transmitting power, transmission mode (e.g., directional vs. non-directional antennae), and transmitter quality. For expositional simplicity, the paper will simply refer to transmitting power.

[3] Interference responsibility is typically placed on the licensed transmitter. However, signal interference occurs in the affected entity's receiver. Therefore, one approach to resolving the interference problem involves encouraging the use of more sophisticated filters that can better distinguish between wanted and unwanted signals. See De Vries, P., "Radio Regulation Summit: Defining Inter-channel Operating Rules: A Report on a Silicon Flatirons Summit on Information Policy, Held 8/9 September 2009" (Dec. 2, 2009).

[4] In what follows, any reference to transmitting power also implies a reference to a limit on out-of-band emission.

[5] For example, in 2003 Crown Castle International (Crown Castle) acquired at auction a nationwide license in the 1670-1675 MHz band. Arguing that it would substantially reduce its network deployment cost, Crown Castle in 2005 requested that the Commission authorize an increase in its transmitting power. Over the objections of several parties, the Commission approved a transmitting power increase, but only for a limited number of basic trading areas (BTAs). See "OP LLC, Licensee of WPYQ831, Request for Waiver, Statement in Support of Request of OP LLC and Crown Castle International Corp. for Waiver of Section 27-50(f)(1) of the Commission's Rules," ULS File No. 0002271317.

Another example involves the issue of identifying the efficient set of service rules for Advanced Wireless Services-3 (AWS-3) licenses in the 2155-2180 MHz band. Here, license winners in the AWS-1 auction (e.g., T-Mobile, Verizon) have argued that the Commission's proposed transmitting power and out of band emissions limits for the AWS-3 band would create harmful interference for service providers that operate in adjacent bands. See "Service Rules for Advanced Wireless Services in the 2155-2175 MHz Band," WT Docket No. 07-195, *Further Notice of Proposed Rulemaking*, FCC 08-158 (rel. June 20, 2008) ("AWS Further Notice"), published at 73 Fed. Reg. 35995 (June 25, 2008).

negative effects on one or more other services as a result of an increase in that power.[6] The Commission confronts the same problem when making a service rule decision regarding unlicensed devices. One notable example is its recent decision to allow both fixed and personal/portable unlicensed devices to operate in the unused portion of the broadcast television spectrum, colloquially referred to as "white spaces."[7]

In every case, the Commission employs an administrative process to resolve service rule issues.[8] One alternative is to employ a market to resolve service rule issues among interested parties.[9] As in all markets, the process of finding the efficient outcome may be hampered by high transaction costs. In the current context, transactions costs can arise from the multiplicity of participants involved in the exchange and the difficulty that a subset of the participants may have in coordinating their interests.[10] In particular, a firm that wishes to acquire the ability to increase its transmitting power may need the consent of two or more firms that own the right to prevent an increase in transmitting power. The market process is subject to a "hold out" problem when one or more interference rights holders attempt to obtain a high payment for its right. Another coordination problem arises when multiple firms wish to acquire the ability to prevent additional signal interference and that ability can most easily be obtained when multiple firms contribute to the purchase of the right to prevent such interference. Loosely stated, under these conditions the market process is subject to a "free-rider" problem.

This paper examines possible alternatives to the current administrative process for identifying the efficient allocation of signal interference rights among existing licensees. The remainder of this paper is organized as follows. Section 2 presents a simple theoretical model in which an existing licensee seeks authorization to increase its transmitting power, which would benefit it but would impose harmful interference on two spectrally adjacent licensees.[11]

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[6] If the benefit society receives from changing a service rule for one license is greater than the cost it incurs from making that change, the economically efficient use of spectrum requires that the service rule change be made. Under the economically efficient use of spectrum, all welfare enhancing service rule changes are completed.

[7] The issue involved identifying a set of service rules and other requirements that would ensure that incumbent spectrum users – in particular both full-power and low-power television broadcasters, cable system operators, and wireless microphone users – are not interfered with as a result of the use of such devices. Proponents of white space use (e.g., Microsoft, Google, Phillips Electronics) argue that such spectrum can be used to provide broadband data and other services for consumers and businesses.

Opponents of such use (e.g., TV Broadcasters) argue that the use of unlicensed devices would create harmful interference and, in so doing, substantially diminish the value of their services. See "Unlicensed Operation in the TV Broadcast Bands," *First Report and Order and Further Notice of Proposed Rulemaking*, ET Docket Nos. 04-186, 02-380, FCC 06-156 (released Oct. 18, 2006) ("FNPRM").

[8] The goal of arriving at the efficient outcome is complicated by the less than perfect incentive properties of an administrative process. In particular, because it does not impose a cost on parties for misrepresenting the value they place on (or the cost they incur from) a service rule change, an administrative process encourages interested parties to misrepresent the value they place on a given service rule while encouraging those that are negatively affected by the service rule to exaggerate the extent of their harm.

[9] As part of this process, the Commission would first need to assign secure and tradable signal interference rights to either the parties benefiting from a particular service rule or the parties harmed by such a rule and, second, allow market forces to freely allocate such property rights among the interested parties. See R.H. Coase, "The Federal Communications Commission," *Journal of Law and Economics*, 2, (Oct. 1959) pgs. 1-40.

[10] Coase (1959) pg. 30.

[11] For purposes of the analysis we assume that the Commission will continue to be the arbiter regarding whether signal interference actually occurs. We leave for another paper an analysis of whether market forces can be employed to determine the extent to which interference occurs.

Economic efficiency requires that the modification be authorized if and only if the benefit to the requesting licensee exceeds the costs imposed on the other licensees.

In one environment, the requesting licensee must bid for the right to increase its transmission power, while the other two licensees must bid for the right to preserve the status quo. The requesting licensee wins if and only if its bid exceeds the sum of the other licensees' bids. In this environment, participants may have to solve an important "collective action problem" in order for the market to achieve an efficient outcome. The collective action problem stems from the fact that each of the negatively affected participants is better off if it bids "low" when the other negatively affected participant bids "high." However, excessive shading (i.e., free-riding) might be mitigated if the payoff each negatively affected licensee receives under an efficient Nash equilibria dominates the payoff each receives from purely self-interested behavior.

In the second environment, the adjacent licensees own the right to prevent the requesting licensee from increasing its transmission power unless it purchases from them the right to do so. In this environment, we assume that the efficient outcome requires that the service rule modification should be accepted.[12] Therefore, in order for the efficient outcome to occur, the requesting licensee must offer a price that exceeds the sum of the prices requested by the two adjacent licensees. As in the first environment, participants may have to solve an important "collective action problem" in order for the market to achieve an efficient outcome. This time, the collective action problem stems from the fact that each of the negatively affected participants has an incentive to exaggerate the amount of its harm as much as possible, but not so much as to make the sum of the asking prices greater than the bid offered by the E-Type bidder in the proposed equilibrium.[13]

Section 3 of the paper extends the analysis to the problem the Commission faces in identifying the appropriate set of service rules for yet-to-be-auctioned spectrum (e.g., Advanced Wireless Services-3). In this situation, the economic problem involves identifying both the efficient owner of a license and the efficient set of service rules that apply to that license. We find that in a three-person game with complete information, where participants have two possible bidding strategies, the majority of Nash equilibria are inefficient. Our example, however, demonstrates that there exists a Nash equilibrium that is Pareto superior to the others. With more than two possible bidding strategies, there are multiple Nash equilibria that achieve the efficient outcome, though they are still a minority of all the equilibria.

2. Economic Model: Identifying the Efficient Service Rules for an Existing License

Could a market be relied upon to approve a service rule modification leading to a more efficient use of spectrum and to reject modifications leading to a less efficient use of spectrum?[14]

[12] If it is efficient to reject the rule modification, then no mutually beneficial payments exist.
[13] This issue is commonly known as the "hold out" problem.
[14] A more complex environment can be created by relaxing some of these assumptions. For example, in practice there may be a continuum of authorized transmitting power level enhancements from which the Commission may choose. In such an instance, one objective of the market is to identify the most efficient transmitting power level. Whether a participant plays the role of either a buyer or seller in such a market depends on the rights that are owned by a licensee.

We explore this issue by considering two different market environments in which an incumbent licensee is requesting that the Commission authorize a fixed increase in the transmitting power associated with its license that would cause harmful interference to two licensees in spectrally adjacent bands.[15] In one environment, the parties that are negatively affected by the proposed service rule change do not own the right to prevent additional signal interference and must outbid the party requesting the change if they wish to preserve the status quo. In a second environment, the negatively affected parties own the right to prevent additional signal interference.[16] As we will show, a market may yield efficiency gains in both of these environments if it is not undermined by coordination problems.

2.1 Assumed Valuations

Our analysis begins with some simple notation and valuation assumptions. We label the requesting licensee's desired service rule modification as "Service Rule Set E" (where "E" refers to "Enhanced") and refer to a firm that prefers such a set as an "E-Type Firm." Further, we label a firm that would be negatively affected by the modification as an S-Type firm (where "S" refers to Status quo), and the service rule set that reflects the absence of a transmitting power increase as "Service Rule Set S." Table 1 shows a set of hypothetical values that the different types of firms place on their respective licenses under each service rule condition.

Table 1: License Valuations by Bidder

Bidders	Bidder License Valuations	
	Service Rule E	Service Rule S
Requesting Licensee (E-Type)	$18	$6
Spectrally Adjacent Licensee #1 (S-Type)	$6	$14
Spectrally Adjacent Licensee #2 (S-Type)	$4	$11

As shown in Table 1, the requesting incumbent licensee places a value of $18 on its spectrum license under Service Rule E, but only $6 under Service Rule S. The difference in these two values (i.e., $12) represents the premium the incumbent licensee is willing to pay for the right to operate at the higher transmitting power. The two S-Type firms that own licenses adjacent to the licensee that is requesting an increase in its authorized transmitting power place a value of $14 and $11, respectively, on their licenses under Service Rule S. However, because of

[15] The issue of signal interference has been, and in some cases, continues to be an important technical and economic issue in a number of contexts, including 800 MHz, WCS/SDARS, and AWS-3 Proceedings. See De Vries (2009) pgs. 8-12. Signal interference can occur between two operations when using the same frequency in adjacent geographical areas (i.e., co-channel interference) or when using adjacent frequencies in the same geographic area (i.e., adjacent channel interference). For a discussion of the various technical and institutional factors that give rise to signal interference problems, see De Vries (2009) pgs. 18-23.

[16] For purposes of the analysis we assume that the Commission will continue to be the arbiter regarding whether signal interference actually occurs.

the additional adjacent channel interference, both operators place a lower value on having the requesting incumbent licensee operate its own license under Service Rule E.[17]

The difference in the two values can be thought of as the maximum amount each is willing to pay to ensure that the requesting incumbent license does not have the right to operate under Service Rule E. In particular, the two spectrally adjacent licensees are willing to pay $8 and $7, respectively, to acquire the right not to be interfered with. Alternatively, these values represent the minimum amount that each S-Type firm would accept in order to voluntarily give up the right to maintain Service Rule S.

Based on the valuations shown in Table 1, economic efficiency is maximized when the Commission denies the incumbent licensee's request to operate at the higher transmitting power. This is because the benefit the requesting licensee receives from the increased transmitting power ($12) is less than the value of the harm experienced by the two spectrally adjacent licensees ($15). Below, we consider two situations that differ according to the particular property rights that initially prevail.

2.2 Environment #1 – No Party Has an Enforceable Property Right

In this subsection, we assume that (i) the spectrally adjacent licensees do not have the right to prevent the incumbent licensee from generating additional signal interference and (ii) that the requesting incumbent licensee does not have the right to generate such additional interference. The proposed market mechanism requires both the E-type firm and the S-type firms to place bids which reflect their perceived benefit or harm from the proposed rule change. Consequently, depending on the market outcome, either the requesting licensee pays a third party (e.g. the U.S. Department of the Treasury) to acquire the authority to increase its transmitting power, or the S-Type firms pay the same party for the right to prevent another licensee from subjecting them to greater signal interference.

There are several reasons why a market may have difficulty in attaining the efficient service rule – defined here narrowly to mean the rule that maximizes the sum of the net benefits to the three licensees that may bid for or against the change in the service rule. One general source of market failure is the unwillingness of bidders to reveal the true value they place on a given set of service rules or changes in that service rule. A major cause of under-revelation here is the possibility of free-riding behavior involving S-Type firms. The economics are straightforward. The benefit that a spectrally adjacent firm receives from raising its bid closer to its true value, in order to prevent the change in service rule, extends to every other S-Type firm. The ability of the other S-Type firms to benefit from the actions of the truthful firm reduces their incentive to be truthful.[18] If one or both S-Type firms elect to free ride, then market forces may

[17] In practice, communications systems vary in their ability to accommodate an increase in the amount of signal interference experienced by their receiving equipment. For example, satellite systems are currently much more sensitive to an increase in signal interference than either television or radio broadcast systems.

[18] A bidder's profit is equal to the difference between the value that a bidder places on a given outcome and the price it pays to secure that outcome. Thus, the lower a spectrally adjacent firm's bid to ensure that the Commission does not grant the incumbent licensee's request, the greater its profit.

have difficulty establishing the efficient set of service rules.[19] However, even though each S-Type firm has an incentive to free ride, it may also be in each bidder's interest to contribute to the effort to make sure that the Commission does not grant the incumbent licensee's request for an increase in its transmitting power.[20]

We assume throughout this section that each bidder knows the actual valuations of all other bidders for each bidding alternative. We also assume that each bidder simultaneously and anonymously submits a bid for or against the rule change and the winner(s) are required to pay their bid price(s). If the incumbent's bid in favor of the enhanced service rule exceeds the collective bids of S-Type bidders, the service rule modification is granted. Under the auction's "first-price" rules, the incumbent receives a payoff equal to its valuation under Service Rule E minus its winning bid, and each S-Type bidder receives a payoff equal to the value placed on the spectrally adjacent license when the requesting licensee operates under the enhanced service rule. On the other hand, if the collective bid of the S-Type bidders exceeds the incumbent's bid, the incumbent receives a payoff equal to the valuation under Service Rule S, and each S-Type bidder receives a payoff equal to the valuation placed on having the requesting licensee operate under Service Rule S, minus the bid submitted by each S-Type bidder.

Assuming that bids can be submitted at arbitrary prices,[21] it is a straightforward exercise to compute a set of weakly undominated *epsilon*-Nash equilibrium strategies.[22] In each of the Nash equilibrium outcomes, the E-bidder places a bid less than or equal to the value for enhanced service ($12) and greater than or equal to this value minus *epsilon*.[23] The S-bidders collectively bid an amount greater than the E-bid and less than this bid plus *epsilon*. Under these conditions, an efficient outcome is assured.

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[19] Economists refer to the situation in which the incentives of individual firms or players are at odds with the incentives of the group as a "public goods" problem. Political scientists employ the more descriptive term, "collective action" problem, to describe the same problem. In such a situation economic theory suggests that individual firms have an incentive to contribute to the provision of the public good (e.g., to "free-ride" off the willingness of firms to reveal the value they place on ensuring that the service rule is not changed). See Ledyard, J., "Public Goods: A Survey of Experimental Research," *Handbook of Experimental Economics*, edited by J. Kagel and A. Roth, Princeton University Press (1995).

[20] Technically speaking, in a "free-rider" problem it is a dominant strategy for participants never to contribute to the provision of the public good. However, in this instance, participants have an incentive to contribute to the provision of the public good in the effort to surpass the "threshold" amount needed to move to a mutually desirable equilibrium. Thus, the problem is more accurately referred to as a "threshold problem."

[21] Therefore, the bidding strategy set is equal to the set of non-negative real numbers.

[22] *Epsilon*-Nash equilibria are defined as equilibria in which no player can benefit by more than a small amount (*epsilon*) by choosing an alternative strategy. See, for example, R. Radner, "Collusive Behavior in Non-cooperative Epsilon Equilibria of Oligopolies with Long but Finite Lives," *Journal of Economic Theory*, 22 (1980), pgs. 121-157. A strategy is *weakly* dominated for a given player if a different strategy results in a higher payoff to that player for some joint strategy choice of the remaining players, and a payoff that is at least as high for all possible joint strategy choices of the remaining players. Elimination of *weakly* dominated strategies may in some cases exclude Nash equilibrium strategies in the original game. Our analysis abstracts from certain details which require consideration of the tie breaking rules and generally a more detailed description of the payoff functions of each bidder as a function of collective strategies.

[23] If the E-bidder submits a bid greater than his or her true value ($12) and wins, then the E-bidder's payoff is negative, and this bidder would prefer to reduce his or her bid below the collective S-bid. If the E-bidder wins the auction with a bid less than or equal to $12 minus *epsilon*, and the collective S-bid is less, then at least one S-bidder must have bid below its true value (since the sum of S-Type valuations is greater than $12). Consequently, at least one S-bidder could increase its payoff by increasing its bid.

While each of the full information Nash equilibria are efficient, the S-Type bidders face significant collective action problems. The issue can be illustrated in the simplified example of Figure 1, in which the E-Type bidder is assumed to place a truthful bid equal to his or her incremental value (equal to $12) of having the enhanced service rule. S-Type bidders are assumed to submit bids equal to either $0.5 or $2 less than their actual harm from the enhanced service rule (i.e., bids of $7.5 or $6 for Bidder 1 and $6.5 or $5 for Bidder 2). There are two pure strategy Nash equilibria represented by the top right and lower left portions of Figure 1. In each of these equilibria, the service rule modification is denied, and hence both of these equilibria are efficient. The efficient outcome results from the fact that, by bidding "high," a single S-Type bidder was able to generate a collective "S-bid" that exceeds the bid submitted by the E-Type bidder. However, because each S-Type bidder is better off not placing a high bid when the other S-Type bidder bids "high," neither bidder wants to be the one that bids "high."[24] Thus, in order to obtain an efficient outcome, the S-Type bidders must coordinate on the selected equilibrium.[25] Notice also that the upper left portion of Figure 1 also represents an efficient outcome, but one that is not a Nash equilibrium. In this case, each S-Type bidder would prefer to switch to its lower bidding option.[26] If the two S-Type bidders cannot agree on a chosen equilibrium, the result will be an inefficient outcome where the payoffs to each bidder are dominated by the payoffs achieved from all other joint strategy pairs.

Figure 1: E-Bid = $12

		Bidder #2 Strategies	
		$6.5	**$5**
Bidder #1 Strategies	**$7.5**	$4.5 ($6) $6.5	$6 ($6) $6.5
	$6	$4.5 ($6) $8	$4 ($6) $6

[24] More formally, neither Nash equilibria is Pareto superior to the other.

[25] In a static game with complete information and in which no Nash equilibrium is Pareto superior to others, economic theory sheds little light on which equilibrium will be selected. In this context, players face the challenge of "agreeing" on which equilibrium will be chosen.

[26] There is, in addition, a mixed strategy equilibrium to the above game which further illustrates the strategic issues involved. In this equilibrium, each S-Type bidder bids the higher bidding option with probability 0.25. The result is that the efficient outcome is chosen only 44 percent of the time, and the expected payoffs to the S-Type bidders are equal to $6.5 and $4.5, respectively.

2.3 Environment #2 – Spectrally Adjacent Licensees Own Enforceable Property Rights

In the previous example, we assumed that the spectrally adjacent firms did not own the right to prevent the requesting incumbent licensee from imposing additional signal interference on its business operations. In a second version of the problem, we assume that current owners of spectrum licenses own the right to prevent such interference that may result from adjacent channel interference. In the market mechanism that we analyze, these owners are entitled to receive a payment in exchange for accepting additional signal interference.[27]

Suppose initially that the valuations that each firm places on the different interference levels, as shown in Table 1, are unchanged from the previous example. As before, the efficient outcome requires that the service rule modification be denied. Acting as sellers, the S-Type firms would be expected to, at the minimum, submit an ask price that equals the financial harm that each would incur from the additional signal interference. Similarly, the incumbent licensee will bid no more than the value it places on generating additional interference. Under these conditions, the sum of the ask prices necessarily exceeds the incumbent licensee's bid price. As a result, there is no need for the spectrally adjacent licensees to solve a coordination problem. In this case, a market clearly can be relied on to achieve the efficient outcome given the incentive that S-Type firms have to submit an ask price that at least equals the harm they face from the additional interference.

Given this outcome, it might appear that policy makers should always assign non-interference rights to spectrally adjacent licensees. However, such a recommendation would be misplaced. To see this, we now change our basic example so that the value the requesting licensee places on the service rule change exceeds the value of the financial harm to the spectrally adjacent licensees from additional signal interference. As shown in Table 2, the incumbent licensee now values an enhanced service rule at $30, while the spectrally adjacent licensees have the same values for both the enhanced rule and the status quo as they did in Table 1. The total benefit from enhanced rules ($24) now exceeds the total collective harm ($15), so the efficient outcome involves a multi-lateral trade involving the incumbent licensee and the two spectrally adjacent licensees.

[27] This is in contrast to the previous version of the problem in which neither the S-Type nor the E-Type firms own any rights initially. In that instance, all the revenue generated in the market flowed to the U.S. Department of the Treasury. In this instance, the revenue generated in the auction flows to the spectrally adjacent licensees.

Table 2: Alternative License Valuations by Bidder

Bidders	Bidder License Valuations	
	Service Rule E	Service Rule S
Incumbent Licensee (E-Type)	$30	$6
Spectrally Adjacent Licensee #1 (S-Type)	$6	$14
Spectrally Adjacent Licensee #2 (S-Type)	$4	$11

In order for the market to arrive at the efficient service rule, the bid that the requesting licensee places on the enhanced service rule must now exceed the sum of the financial harms reported – in the form of an ask price – by the spectrally adjacent licensees. As sellers in this market, S-Type firms have an incentive to exaggerate the financial harm they would experience from additional signal interference. Here, exaggeration occurs whenever a licensee submits an ask price that exceeds the true value of the financial harm it incurs from additional signal interference.

We therefore examine the incentives that spectrally adjacent licensees would have to coordinate their ask prices in the context of a multi-lateral bargaining mechanism that is closely related to a sealed-bid auction.[28] Toward that end, we assume that both E-Type and S-Type firms simultaneously submit a bid (E-Type) and an ask (S-Types). If the bid exceeds or equals the collective ask, then the rule modification is granted, and the incumbent E-Type firm pays each S-Type firm a payment based on their asking price.[29]

Assuming a game of complete information and continuous strategy sets, the set of (weakly dominated, *epsilon*) Nash equilibria is similar to those described in Section 2.2 above. In each equilibrium, the E-Type bidder places a bid equal to the collective value of the S-Type bidders ($15), and the sum of the bids submitted by the S-Type bidders is less than the value of the E bid, but greater than the E-bid minus *epsilon*. The resulting outcome is efficient. Each bid submitted by S-Type bidders is constrained to be no less than the individual harm to each such bidder resulting from Service Rule E. In this case, S-Type bidders again face a collective action problem, since each S-Type bidder has an incentive to exaggerate the amount of its harm (i.e., ask price), but not so much as to make the sum of the asking prices greater than the bid offered

[28] Most bargaining environments are bilateral in that in order for an agreement to be reached only two parties have to come to an agreement. However, in numerous other instances, more than two parties have to come to an agreement in order for an agreement to be reached. Solutions to such "multilateral" bargaining problems range from mechanisms that facilitate sequential bilateral bargaining to mechanisms that facilitate simultaneous multilateral bargaining.

[29] When the bid is strictly greater than the total ask price, then it is assumed that the final negotiated price is midway between the bid and ask prices. S-Type firms are then paid a proportion of the negotiated price based on the relative sizes of their ask prices.

by the E-Type bidder in the proposed equilibrium.[30] As discussed in Section 2.2, if the S-Type firms behave "myopically," the market outcome will be inefficient and the payoffs they each receive would be lower than they would have received if they resisted the temptation of maximizing their individual payoffs.

2.4 Policy Implications

The economic reasoning presented in Sections 2.2 and 2.3 suggests that market forces have the potential to efficiently allocate signal interference rights regardless of whether the negatively affected parties initially own the right to prevent such interference. Here, we note several important caveats. First, our models assume that each participant is able to accurately predict the rational behavior of other players. This assumption is less likely to hold in the field where market participants do not have complete information. Second, there are mixed strategy equilibria in these games where the efficient outcome is not selected 100 percent of the time.[31] Third, in both environments, an efficient outcome requires a degree of coordination among the unlicensed bidders. As shown in Section 2.2, while the temptation for myopic self-interest is mitigated by the fact that the payoff each receives under the two Nash equilibria dominates the payoff each receives from purely self-interested behavior, there is no one equilibrium to which both S-Type bidders will naturally gravitate.

3. A Market for Service Rules: The Case of AWS-3 Licenses[32]

In this section we extend the principles discussed in Section 2 to the problem the Commission currently faces in identifying the appropriate set of service rules for Advanced Wireless Services-3 (AWS-3) licenses. Here, T-Mobile, Verizon, ICG Global Communications, and a collection of manufacturers of Advanced Wireless Services-1 (AWS-1) equipment have argued that the Commission's proposed service rules for the AWS-3 band (2155-2175 MHz, 1915-1920 MHz) would negatively affect them by generating harmful interference in an adjacent or nearby band.[33] On the other hand, one or more entities – e.g., M2Z Networks ("M2Z") – believe that the proposed service rules are consistent with the efficient use of spectrum.[34]

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[30] The strategic issue that spectrally adjacent licensees face in this example is similar to the strategic issue that television broadcasters would face when submitting an ask price in a two-sided market (e.g., a two-sided "incentive auction") in which broadcast television operators and providers of mobile broadband service, among others, have the opportunity to buy and sell spectrum.

[31] For example, in the environment where no party has an enforceable property right, there exists a Nash equilibrium in mixed strategies in which the efficient outcome is chosen 44 percent of the time.

[32] As in the previous section of this paper, the discussion in this section is based on hypothetical values of parties who are potentially interested in service rule modifications.

[33] See "Service Rules for Advanced Wireless Services in the 2155-2175 MHz Band," WT Docket No. 07-195, *Further Notice of Proposed Rulemaking*, FCC 08-158 (rel. June 20, 2008) ("AWS Further Notice"), published at 73 Fed. Reg. 35995 (June 25, 2008). Within any given geographic area, the Commission divided the AWS-1 band (1710-1755 MHz and 2110-2155 MHz) into 6 separate pair blocks (i.e., Blocks A – F). As discussed in De Vries (2009), at issue is the co-existence of Frequency Division Duplex (FDD) systems (i.e., AWS-1 licensees) and systems that transmit using Time Division Duplex (TDD) procedures (i.e., AWS-3 licensees). See De Vries (2009) pg. 12.

[34] See "Comments of M2Z Networks, Inc, In the Matter of Service Rules for Advanced Wireless Services in the 2155-2175 MHz Band," WT Docket No. 07-195 (Dec. 14, 2007).

For purposes of the analysis, we assume that the negatively affected parties (e.g., AWS-1 licensees T-Mobile, Verizon) do not own the right to prevent the owner of the AWS-3 licenses from generating additional adjacent-channel signal interference. Further, we assume that the Commission must choose between two sets of service rules for the AWS-3 band. One set permits a high level of transmitting power ("Service Rule E"), while another set ("Service Rule S") permits a low level of transmitting power. At least one entity (e.g., M2Z) has a strong preference for Service Rule E, a rule that, because of the proximity of the AWS-3 band to other bands, would negatively affect the wireless service of spectrally adjacent license owners (e.g., T-Mobile, Verizon).[35]

3.1 A Proposal for a New Market Mechanism

The AWS-3 assignment problem is more complicated than the assignment problems discussed in Section 2. In the previous section, the economic problem simply involved finding the efficient service rule associated with an incumbent's license. In the current section, the economic problem involves identifying the party that values an auctioned license the most, while also identifying the efficient service rules associated with that license. Achieving the efficient outcome requires that bidders express the value they place on three different market outcomes: acquiring the license on both a Service Rule S and a Service Rule E basis, as well as preventing the winning bidder from operating under Service Rule E.[36]

Following the terminology of Section 2, we refer to firms that place the highest value on owning the license under Service Rule E as "E-Type" firms, and we refer to firms that prefer to maintain the status quo, whether they wish to own the license or not, as "S-Type firms." Table 3 shows a set of hypothetical values that the different types of firms might place under each service rule and property right condition.

Table 3: Valuations for New Block of Spectrum

Bidders	Bidder Valuations		
	Service Rule E	Service Rule S	Not Service Rule E
Bidder 1 (E-Type)	19	8	0
Bidder 2 (S-Type)	12	12	8
Bidder 3 (S-Type)	8	8	7

Bidder 1, an E-Type firm, is assumed to place a value of $19 on owning the spectrum license under Service Rule E but only $8 under Service Rule S. The difference in these two values (i.e., $11) represents the premium this bidder is willing to pay for the right to operate at

[35] In addition to the AWS-1 licensees, several other parties (e.g., Nokia and ICG Global) have indicated that they would be financially harmed.

[36] In the typical spectrum auction, the efficiency of the allocation is based solely on the highest reported ownership value for a given block of spectrum. Here, economic efficiency takes into account not only the surplus generated from ownership of the spectrum block under a given service rule, but also the harm that bidders report from that service rule.

the higher transmitting power. For purposes of the analysis, we assume that there are two S-Type firms that own licenses spectrally adjacent to the AWS-3 license up for auction.

Bidders 2 and 3 are assumed to place a value of $12 and $8, respectively, on acquiring the license and employing it under Service Rule S. Furthermore, these firms are also assumed to place these same values on owning the AWS-3 license on a Service Rule E basis, based on the assumption that each firm's business plan and technology cannot take advantage of a higher power level. The fourth column of Table 3 represents the amount that each firm would be willing to pay to prevent any other firm from acquiring the spectrum block under Service Rule E. Each value reflects the financial harm an adjacent licensee would experience from the higher transmitting power. Since Bidder 1 is assumed to own no adjacent blocks, its harm is equal to zero. The harms for Bidders 2 and 3 are assumed to be equal to $8 and $7 respectively.[37]

The efficient service rule set is the one that, once applied to a license and assigned to the bidder that values that license the most, generates the greatest economic surplus. The maximum value that society places on Service Rule E is equal to the value that Bidder 1 places on winning the license under that service rule ($19). The maximum value that society places on Service Rule S is $23 which is equal to the value that Bidder 1 places on the license under that service rule ($8) plus the financial harms ($15) that Bidders 2 and 3 avoid from not having another owner operate the license under Service Rule E.[38] Efficiency considerations therefore dictate that Bidder 1 should be assigned the license and should operate under Service Rule S.

The efficient outcome might be obtained through an auction in which parties bid to own the license under each service rule *and* to prevent another party to own the block under the enhanced Service Rule E. One option is a "first-price" (winner pays its bid) sealed-bid auction in which each of the parties would be asked to submit three distinct bids based on their values corresponding to the three columns of Table 3.[39] Based on these bids, the auctioneer (i.e. the Commission) would compute the social surplus under each of the six possible outcomes and identify that outcome that maximizes surplus. If social surplus is maximized when the block is assigned under Service Rule E, then only the high bidder pays its bid.[40] In contrast, if social surplus is maximized when the block is assigned under Service Rule S, then both the high bidder for ownership and the bidders who reported harms under Service Rule E are required to pay their actual bids.

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[37] The values that the S-Type bidders place on owning the new block of spectrum are necessarily greater than or equal to the value they place on preventing that block from being used under Service Rule E by another party. This follows from the fact that, by owning the block, each firm can internalize the externality associated with higher power levels. Under the assumed values, the incremental values of acquiring the new block, conditional on its use under Service Rule S, are equal to $4 (i.e., $12 – 8) and $1 (i.e., $8 – 7), respectively, for Bidders 2 and 3.

[38] Even though Bidder 2 is assumed to value ownership of the spectrum under Service Rule S more than Bidder 1, the social surplus under this outcome is $19 (i.e., $12 + 7), compared to $23 when the spectrum is assigned to Bidder 1. The incremental value of ownership by Bidder 2, conditional on avoiding interference associated with Rule E, is only $4 (i.e., $12 – 8) for Bidder 2 instead of $8 for Bidder 1.

[39] In this example, there are three possible owners of the spectrum block and two possible service rules. The surplus generated from ownership of the spectrum block under Service Rule E is computed by subtracting from any bidder's ownership value the harms reported by all other bidders.

[40] In the current example, economic efficiency is defined in two dimensions – the license owner dimension, and the service rule dimension. Under the efficient allocation, Bidder #1 wins the auction on the license ownership dimension, but loses to the two S-Type bidders on the service rule dimension.

3.2 Insights from Economic Theory

In order to evaluate the performance of an auction as described above, we now consider a stylized game that the three potential bidders might face when bidding in a first-price, sealed-bid auction. As in Section 2, we assume that each bidder knows with certainty the actual valuations (but not the bids) of all other bidders. Moreover, it is common knowledge that Bidder 1 (who owns no spectrum adjacent to the contested block) would incur no harm if another bidder won the spectrum under enhanced Service Rule E. Similarly, it is common knowledge that both Bidders 2 and 3 place no additional value for owning the block of spectrum under Rule E over their value under Rule S. Based on these assumptions, we can therefore assume that each bidder places two distinct bids.[41] Bidder 1 places bids for winning the block under Rules E and S, while Bidders 2 and 3 place bids for winning the block under Rule S and for denying any other bidder the right to operate the block under Rule E.

In the resulting game of complete information, six bids are made by the three bidders, but only four possible outcomes need to be considered by the auctioneer. In one outcome, the block is awarded to Bidder 1 under Service Rule E, and the total bid for this outcome is simply Bidder 1's bid. In the three remaining outcomes, the block of spectrum is awarded to either Bidders 1, 2 or 3 under Service Rule S. The relevant bids for this outcome consist of the bid by each party for ownership under Rule S plus the sum of the bids by all other parties for the right to deny any use under Rule E.[42]

Even in the relatively simple three-person framework with the simplifying assumptions we have made, we are not able at this time to describe the set of pure strategy Nash equilibrium outcomes as we were able to do in Sections 2.2 and 2.3. Nevertheless, we can gain some insights into the performance of the proposed market by placing some additional restrictions on the allowed bidding strategies. Instead of assuming that bids of any amount can be submitted, we assume that bidders are allowed to bid only specific fractions of their actual valuations for each relevant bid that they make. The resulting game is therefore a game with a finite strategy space, and pure strategy Nash equilibria can then be explicitly computed.[43]

For example, suppose that each bidder is allowed to place a bid equal to either 25% or 75% of his or her valuations for each alternative. (Recall that in a first-price auction it will be optimal for bidders to bid less than their true values.) Since six bids are allowed, each with two alternative values, the number of possible bidding strategies is $2^6 = 64$. Given the assumed bidding strategies and valuations, it is possible to compute the payoffs to each bidder under each joint strategy combination and, therefore, to compute the set of Nash equilibrium outcomes in which no individual bidder can increase his or her payoff by deviating to an alternative bidding strategy. As shown in Table 4, with two possible bids as a percentage of each bidder's total value, there are eight Nash equilibria in the current example. However, there is a single Nash equilibrium that maximizes Total Surplus (i.e., is "efficient") and that equilibrium yields higher

[41] In the absence of this assumption, S-Type bidders would submit three distinct bids.

[42] It is assumed to be common knowledge, however, that Bidder 1 does not bid for the right to deny use under Rule E.

[43] Due to the large number of possible joint strategy combinations a computer algorithm has been used to compute the set of Nash equilibria in the results reported below.

payoff to each of the three parties than any other equilibrium (i.e., Pareto dominates the others). Thus, it could be argued that bidders select this equilibrium.

Table 4: Nash Equilibria with Two Possible Bidding Strategies

Nash Equilibrium Bids						Winning Outcomes (Including Tie Bids)	Bidder Payoffs			Total Surplus
B1 E	B1 S	B2 S	B2 Not E	B3 S	B3 Not E		P1	P2	P3	
4.75	2	3	2	2	1.75	B1 wins S	6	6	5.25	23
14.25	2	3	2	6	1.75	B1 wins E	4.75	0	0	19
14.25	2	3	6	6	1.75	B1 wins E	4.75	0	0	19
14.25	2	9	2	2	5.25	B1 wins E or B2 wins S	2.375	1.5	0.875	19
14.25	2	9	2	6	5.25	B1 wins E or B2 wins S	2.375	1.5	0.875	19
14.25	2	9	6	2	5.25	B1 wins E or B2 wins S	2.375	1.5	0.875	19
14.25	2	9	6	6	5.25	B1 wins E or B2 wins S	2.375	1.5	0.875	19
14.25	6	3	2	6	1.75	B1 wins E	4.75	0	0	19

In Table 5, we report the results of a similar set of computations in which each bidder is allowed to place between 2 and 6 bids for each of the two items. The bids are assumed to be evenly distributed over the possible bids which range from zero to the actual value.[44] This time, there are multiple Nash equilibria that yield the efficient outcome (which raises a coordination issue that was absent in the two-bid case) and, as before, those equilibria are a minority of all the Nash equilibria.

[44] Formally, if k bids are offered, then the set of possible bids is equal to $\{1/2k, 3/2k, \ldots, (2k\text{-}1)/2k\}$ as a percentage of total values.

Table 5: Outcomes of Restricted Strategy Auctions

# Bids	# Strategies	# Nash Eq (NE)	# Efficient NE	% Efficient NE
2	64	8	1	12.5%
3	729	21	5	23.8%
4	4,096	62	17	26.6%
5	15,625	112	20	17.9%
6	46,656	171	36	21.1%

While not in any way conclusive, the results of Table 5 suggest that a first-price, sealed bid auction would achieve efficient results in some, but not the majority, of the Nash equilibrium outcomes. In the next section we offer some comments on both the limitations of this analysis and the prospects for a realistic auction mechanism that could be used in future policy decisions.

3.3 Toward a More Realistic Analysis

In the previous two sections, we suggested a format for a new auction process that could be used to assign license ownership and the rules under which the licensee would be allowed to operate. Our theoretical analysis led to mixed results in which roughly 20% of the Nash equilibrium auction outcomes in a highly stylized auction were shown to be efficient. As a guide for both future policy work and future theoretical analysis, a number of comments on the above results are in order. First, it should be clear that a possibly large number of the equilibrium outcomes identified in Tables 4 and 5 results from the discrete set of bidding strategies available to each bidder. That is, certain bidding strategies may result in an equilibrium because an allowed bidding response (e.g., reducing a bid by the minimum possible increment) would result in a lower payoff, while a less constrained bidding response (e.g., reducing one's bid by a very small amount) would increase a bidder's payoff, and therefore eliminate the original outcome as an equilibrium. At present, we do not know whether the elimination of equilibria based on such integer effects would change the balance of results toward or against the proportion of efficient equilibria reported.

Second, it is important to remember that the results reported in Sections 3.1 and 3.2 are based on one specific example of bidder valuations. In particular, the assumed difference in total surplus in the efficient outcome ($23) and the next best inefficient outcome ($19) is relatively small. Our computational results have shown that, if the difference in these values were larger, the likelihood of an efficient Nash equilibrium outcome would increase accordingly.[45]

Finally, and perhaps most importantly, the analysis assumed that market participants interact in a manner that is consistent with a Nash equilibrium. In particular, participants are assumed to play rationally and have rational expectations about the play of other market participants. This and other assumptions (e.g., complete information) may not hold in a more realistic modeling setting. On the other hand, depending on its rules, a market mechanism may be able to reliably identify an efficient outcome in the discussed settings. For example, while incomplete information can be expected to result in more "noise" in the set of equilibrium

[45] In future work, we will document these results as bidder valuations are allowed to vary.

outcomes, a market mechanism that includes an informed price discovery process might be able to fully address the challenges raised by incomplete information.[46] Whatever the specific auction form, the assumptions that hold true "in the field" will likely pose substantial challenges for a purely theoretical analysis. For this reason, we suggest that careful experimental testing of one or more market mechanisms, across a range of signal valuation environments, should be conducted to further examine the ability of a market to efficiently allocate signal interference rights.

4. Conclusions

An enhanced service rule, such as the right to transmit at a higher power level, could potentially benefit an existing license holder while simultaneously harming holders of spectrally adjacent licenses. Nevertheless, a modification of an existing rule would increase overall efficiency if the benefit to an existing licensee exceeds the harm experienced by the spectrally adjacent licensees. Yet, because an administrative process imposes little cost on a firm that misrepresents its service rule needs, that process may be unable to identify initially, or at any moment in time, the efficient set of service rules.

As suggested by Coase (1959), one approach to solving this problem is to create a market in which interested parties express their willingness to buy or sell a set of rights associated with a given set of service rules and a license. This paper demonstrates that, in a three-person game in which market participants know the value that other participants place on different signal interference levels (i.e., have complete information), a market might be able to efficiently allocate interference rights. However, the maintained assumptions may not be entirely satisfied "in the field." Moreover, even putting aside these issues, participants may have to solve an important collective action problem in order for the market to achieve an efficient outcome. Such a problem can only be solved if parties avoid the temptation of acting in a myopic, purely self-interested fashion.

The challenge of myopic self-interest on the part of market participants is not restricted to the problem of the efficient assignment of signal interference rights. For example, the Commission has recently proposed that incumbent television broadcasters have the opportunity to voluntarily give up either some or all of their spectrum in exchange for a payment.[47] Here, the efficient reallocation of spectrum to an alternative use may require that incumbent licensees within a given geographic area coordinate their interests in an attempt to release sufficient spectrum, at a sufficiently low price, to meet the needs of a prospective new licensee.[48] Some

[46] The existence of incomplete information about the characteristics of the other players, including the value they place on different service rules, changes the game from a non-Bayesian game to a Bayesian game. In a Bayesian game, a Bayesian-Nash equilibrium is a strategy profile that maximizes the expected payoff for each player given their beliefs about the other players' "types" and given the strategies played by the other players. In order to obtain the Nash equilibrium, the beliefs or conjectures that participants have regarding the valuations that other market participants place on different interference levels must be correct. Thus, game theoretic principles suggest that a market may have more difficulty in reaching the efficient outcome when the market game is characterized by incomplete information versus complete information.

[47] See *National Broadband Plan: Connecting America*, Federal Communications Commission (March 2010), pgs. 81-82.

[48] An additional and important complicating factor for the Commission is Congress's desire to receive a portion of the gains of trade associated with any exchange between a winning bidder and a television broadcaster.

additional theoretical work, complemented by a set of economic experiments, may be able to address this market design issue.

Similarly, the Commission often faces the difficult problem of identifying the appropriate set of service rules for yet-to-be-auctioned spectrum (e.g., Advanced Wireless Services-3). To achieve the efficient outcome, a market would need to "endogenize" an important characteristic (e.g., service rules) of the auctioned licenses. This paper demonstrates that in a three-person game with complete information where participants have two possible bidding strategies, the vast majority of Nash equilibria are inefficient. However, there exists one Nash equilibrium that is Pareto superior to the others and, importantly, it is efficient. The prediction that market participants will select that equilibrium rests on the complete information assumption, an assumption that is unlikely to hold in the field. However, a market mechanism that includes an informed price discovery process might be able to fully address the challenges raised by incomplete information.

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