LICENSED OR UNLICENSED:

THE ECONOMICS OF INCREMENTAL SPECTRUM ALLOCATIONS

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At present, market mechanisms do not exist that allow trading of radio spectrum between licensed and unlicensed uses. Whenever spectrum is made available for reallocation, the Federal Communications Commission faces a dilemma in determining whether to allocate the frequencies to licensed or unlicensed use. Since both are potentially valuable, allocation decisions must be based on a clear understanding of the trade-offs between the two choices.

This paper defines, for the first time, economic criteria that can be used in making these important decisions. Standard economic theory tells us that the value of an additional unit of spectrum is equal to the increase in socially beneficial services it produces. For licensed spectrum allowed to trade in markets, this value is relatively easy to calculate. The equation is much more complex, however, when unlicensed spectrum is involved.

The current value of unlicensed spectrum bands is equal to the sum of the value of the spectrum in all uses in those bands. The incremental value of additional spectrum for unlicensed uses is based on the relief to congestion that the additional spectrum will provide. Unlicensed spectrum also has an option value from future innovations associated with lower transaction costs. This option value increases with additional allocations of unlicensed spectrum, leading to the benefit of incremental option value from additional unlicensed spectrum. The formula can be summarized as “congestion alleviation plus incremental option value.”

Initial calibration of the economic criteria that determine the trade-off between incremental licensed and unlicensed spectrum allocations indicates that incremental allocations should go to licensed uses.

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I. INTRODUCTION

Radio spectrum is an unnecessarily scarce resource. The current management regime of "Command and Control"[1] largely segregates federal from non-federal users, licensed from unlicensed, private wireless from commercial wireless and communications from broadcast. It is effective at protecting authorized users of radio spectrum from unwanted interference from other users. This protection, however, comes at a great cost: there is no mechanism for radio spectrum to migrate from low valued uses to higher valued uses, even if gains from trade would benefit both the original and new users of the radio spectrum.[2] This inability to move radio spectrum to higher valued uses creates artificial scarcity.

Under the current regulatory structure, from time to time opportunities to reallocate radio spectrum arise. A current example of this is found in the portions of the band allocated for television, but not directly used for broadcasting – the so called "white space" of the TV band. (It is beyond the scope of this paper to evaluate how much white space is available for non-broadcast uses.[3]) Other recent opportunities include reallocations in the 3 GHz band and the 5 GHz band. A threshold question associated with these opportunities for reallocation is whether or not they should be reallocated to licensed or unlicensed uses. This paper offers an economic perspective on how to answer that question. I recognize and fully support that politicians and regulators do and often should consider more than just economic factors when making decisions – they should, however, have an accurate understanding of those economic factors so as to make an informed decision.

The focus of this paper is on *incremental* allocations. Allocations of unlicensed bands are largely irreversible. Once unlicensed devices populate a band it becomes very difficult to clear them to make the band available for a licensed use. Recent licensed reallocations to licensed uses in the form of fairly liberal property rights associated with the radio spectrum licenses have vested interests – often in the form of auction winners with significant investments in acquiring licenses – that make reversing these allocations very unlikely. Consequently, I take both the existing unlicensed and liberally licensed allocations as given. Future reallocations, therefore, are most likely to come from the majority of radio spectrum that is either used by the federal government or licensed by the FCC with inflexible use restrictions.

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[1] *See* Federal Communications Commission, Spectrum Policy Task Force, *Report*, ET Docket No. 02-135 (Nov. 2002).

[2] For just one example of potential gains, see Evan Kwerel and John Williams, *Changing Channels: Voluntary Reallocation of UHF Television Spectrum* (Federal Communications Commission, Office of Plans and Policy, Working Paper No. 27, Nov. 2002).

[3] All sides of the debate over the TV white space agree that there is some spectrum available for non-broadcast uses. *See, e.g.*, J. H. Snider, Reclaiming the Vast Wasteland: The Economic Case for Re-Allocating the Unused Spectrum (White Space) Between TV Channels 2 and 51 to Unlicensed Service, New America Foundation, Wireless Future Program, Issue Brief #18 (Feb. 2005) ("Snider 2004"); Victor Tawil and Charles Einolf, Interference from the Operations of Unlicensed Devices in the Broadcast TV Bands (Nov. 2004).

Any reallocation from lower value to higher value uses will reduce overall scarcity of radio spectrum. Therefore, if the choice were to allocate to licensed or do nothing, the unambiguous answer would be to allocate to licensed uses. Similarly, if the choice were to allocate to unlicensed or do nothing the unambiguous answer would be to allocate to unlicensed. Fortunately, we are not so constrained. For candidate reallocations we have the superior choice of deciding between licensed and unlicensed allocations. The question is, Which one will more efficiently utilize incremental radio spectrum and consequently reduce spectrum scarcity more?

The second section briefly reviews existing allocations. The third section will develop the basic analytical framework for the economic choice between licensed and unlicensed spectrum allocations. The fourth section will review some empirical evidence used to calibrate the equilibrium condition derived in the second section. The fifth section performs that calibration and concludes.

II. EXISTING ALLOCATIONS

Liberally licensed spectrum allocations have been growing and soon will account for about one-sixth of the radio spectrum below 3 GHz. See Table 1. For the most part, these bands are used for mobile voice and data communications.

TABLE 1. BASE OF LIBERALLY LICENSED RADIO SPECTRUM

Band Name	Location	MHz	Available
PCS	1.9 GHz	120 MHz	Now
Cellular	800 MHz	50 MHz	Now
SMR	800 MHz / 900 MHz	14 MHz + 5 MHz	Now/Within a few years
Nextel 1.9 GHz	1.9 GHz	10 MHz	Now/Very soon
BRS/EBS-low*	2.5 GHz	132 MHz	Within a few years
BRS/EBS-high†	2.5 GHz	42 MHz	Within a few years
AWS	1.7 GHz / 2.1 GHz	90 MHz	Within a few years
700 MHz	700 MHz	78 MHz	Within a few years

* Includes low-powered licenses only.
† Includes high-powered licenses only.
Sources: Congressional Budget Office, Where Do We Go From Here? The FCC Auctions and the Future of Radio Spectrum Management, (Apr. 1997); FCC Wireless Telecommunications Bureau, *Cellular Services*, *available at* http://wireless.fcc.gov/services/cellular/; FCC Wireless Telecommunications Bureau, *900 MHz SMR*, *available at* http://wireless.fcc.gov/smrs/900.html; *Improving Public Safety Communications in the 800 MHz Band*, Report and Order, Fifth Report and Order, Fourth Memorandum Opinion and Order, and Order, 19 FCC Rcd 14969 (2004); FCC Wireless Telecommunications Bureau, *BRS & EBS Radio Services*, *available at* http://wireless.fcc.gov/services/brsebs/; *Amendment of Part 2 of the Commission's Rules to Allocate Spectrum Below 3 MHz for Mobile and Fixed Services to Support the Introduction of New Advanced Wireless Services, Including Third Generation Wireless Systems*, Second Report and Order, 17 FCC Rcd 23193 (2002).

Several bands of spectrum, including some under 3 GHz, are allocated to unlicensed uses. See Table 2. These uses include, among others, cordless phones, wireless LANs and baby monitors.

TABLE 2. BASE OF UNLICENSED RADIO SPECTRUM

Band Name	Location	Width
900 MHz	900 MHz - 928 MHz	28 MHz
2.4 GHz	2,400 MHz - 2,483.5 MHz	83.5 MHz
Unlicensed PCS	1,920 MHz - 1,930 MHz 2,390 MHz - 2,400 MHz	20 MHz
U-NII	5,150 MHz - 5,350 MHz 5,725 MHz - 5,850 MHz	325 MHz
3,650 MHz	3,650 MHz - 3,700 MHz	50 MHz
Millimeter Wave	57 GHz - 64 GHz	7 GHz

Source: Kenneth Carter, Ahmed Lahjouji and Neal McNeil, *Unlicensed and Unshackled: A Joint OSP-OET White Paper on Unlicensed Devices and Their Regulatory Issues* (Federal Communications Commission, OSP Working Paper Series No. 39, May 2003).

III. ANALYTICAL FRAMEWORK

This analysis takes existing allocations of unlicensed and liberally licensed radio spectrum as given. Because the analysis focuses on the allocation of the next available portion of radio spectrum, the marginal analysis of economics is particularly well suited. Marginal analysis allows us to characterize the conditions when a resource is used as efficiently as possible and as a consequence economic welfare is maximized. The key result when an input can be put to two different uses is that in equilibrium an additional increment of the input would be used equally efficiently[4] in either use. Maximum efficiency in the allocation of radio spectrum between licensed and unlicensed uses is therefore characterized by the condition that an incremental allocation to either would be equally beneficial.

The corollary to this result is that if the resource can be used more efficiently in one use—that is, create more economic value in that use—then incremental deployments should be in that use. The law of diminishing returns implies that as more of a resource is devoted to one use, the incremental benefit of the resource in that use diminishes. Equilibrium is achieved when the additional allocations to one use bring the incremental returns to both uses in line with each other. In the case of radio spectrum allocations, the

[4] Efficiency of use of radio spectrum is an *economic* concept, not an engineer's metric.

implication is that incremental allocations should go to the use that, on the margin, can put the incremental radio spectrum to higher valued uses.

To show this more formally, I specify the spectrum planner's optimization problem in equation (3.1) and (3.2). The spectrum planner should seek to maximize total social welfare (TSW) by allocating spectrum to private, liberally licensed uses ("private uses" for short), BW^P, and unlicensed uses, BW^U, subject to total spectrum allocated to private uses and unlicensed uses is less than or equal to the total spectrum the spectrum planner can allocate to both uses, $\overline{BW}$. $\overline{BW}$ is the amount of spectrum available to the two uses considered here and does not include allocations to the government (federal, state or local) or other incumbent private uses such as broadcasting or amateur radio. If $\overline{BW}$ were to increase, it would come from these other uses. This is consistent with taking the current allocation of radio spectrum as given, characterizing the trade-offs between spectrum for private uses and unlicensed spectrum, and looking at what that trade-off implies for incremental allocations of spectrum.[5]

$$\max_{BW^P, BW^U} TSW = PS^P(BW^P) + CS^P(BW^P) + PS^U(BW^U) + CS^U(BW^U) + EX^U(BW^U) \quad (3.1)$$

$$s.t. \quad BW^P + BW^U \le \overline{BW} \quad (3.2)$$

TSW consists of social surplus in private uses and in unlicensed uses. For spectrum in private uses total surplus is equal to producer surplus, $PS^P(BW^P)$, and consumer surplus, $CS^P(BW^P)$. Both producer and consumer surplus are characterized as a function of the amount of private use spectrum, BW^P. For unlicensed spectrum total surplus equals producer surplus, $PS^U(BW^U)$, and consumer surplus, $CS^U(BW^U)$, but also includes a term for externalities associated with unlicensed spectrum use, $EX^U(BW^U)$. What each term captures will be explored in more detail below.

Assuming equality in (3.2) and substituting into (3.1)[6], taking the FOC and rearranging gives,

$$\frac{\partial PS^P}{\partial BW^P} + \frac{\partial CS^P}{\partial BW^P} = \frac{\partial PS^U}{\partial BW^U} + \frac{\partial CS^U}{\partial BW^U} + \frac{\partial EX^U}{\partial BW^U}. \quad (3.3)$$

[5] I do not directly analyze relaxing the constraint $\overline{BW}$ because if we were in equilibrium the policy proscription would be trivial. Namely, if we were in equilibrium, we would be indifferent between allocating incremental spectrum to liberally licensed, private uses or unlicensed uses. Rather, I analyze the equilibrium condition for a given $\overline{BW}$ and postulate that if the equilibrium condition does not hold empirically, then incremental allocations should be used to move toward equilibrium.

[6] Note $\frac{\partial PS^U}{\partial BW^P} = -1 * \frac{\partial PS^U}{\partial BW^U}$.

In this section I characterize the value of incremental allocations of radio spectrum for licensed and unlicensed uses. The empirical question of weather one of the two uses creates more value will be addressed in subsequent sections.

A. CHARACTERIZATION OF THE INCREMENTAL VALUE OF RADIO SPECTRUM IN LICENSED USES

Producer Surplus

Firm ***i*** will choose a level of BW_i^P to maximize total profits, including the cost of spectrum,

$$\max_{BW_i^P} PS_i^P = \Pi_i(BW_i^P) - C_i(BW_i^P)\,. \tag{3.4}$$

Taking the FOC and rearranging gives,

$$\frac{\partial \Pi_i}{\partial BW_i^P} = \frac{\partial C_i}{\partial BW_i^P}\,. \tag{3.5}$$

In a competitive market the marginal cost of spectrum to any and all firms is its market price, P^P. Therefore,

$$\frac{\partial \Pi_i}{\partial BW_i^P} = \frac{\partial C_i}{\partial BW_i^P} = P^P = \frac{\partial C_j}{\partial BW_j^P} = \frac{\partial \Pi_j}{\partial BW_j^P}\,. \tag{3.6}$$

Total producer surplus in the private use of spectrum, PS^P, is the sum of the individual firms' producer surplus.

$$PS^P(BW^P) = \sum_{i=1}^{n} PS_i^P(BW_i^P)\,. \tag{3.7}$$

Because use of private spectrum is mutually exclusive,

$$BW^P = \sum_{i=1}^{n} BW_i^P\,. \tag{3.8}$$

Substituting for any arbitrary firm's licensed spectrum,

$$BW_i^P = BW^P - \sum_{j \neq i} BW_j^P\,. \tag{3.9}$$

Substituting (3.9) into (3.7), recognizing that firm *i*'s payment for spectrum is some other entity's receipt, and taking the FOC gives,

$$\frac{\partial PS^P}{\partial BW^P} = \frac{\partial \Pi_i}{\partial BW_i^P} * \frac{\partial BW_i^P}{\partial BW^P} + \sum_{j=1}^{n} \frac{\partial \Pi_j}{\partial BW^P} - \frac{\partial C_i}{\partial BW_i^P} * \frac{\partial BW_i^P}{\partial BW^P} + P^{P*} > 0, \qquad (3.10)$$

where,

$$P^{P*} = P^P + \frac{\partial P^P}{\partial BW^P}. \qquad (3.11)$$

In (3.10), arbitrary firm *i* is the recipient of the incremental spectrum, so $\frac{\partial BW_i^P}{\partial BW^P}=1$. The marginal cost of spectrum to firm *i* is equal to the market price of spectrum, so the last two terms in (3.10) cancel out.[7] We know from (3.6) that,

$$\frac{\partial \Pi_i}{\partial BW_i^P} = P^{P*}. \qquad (3.12)$$

Therefore, the marginal effect of increasing private-use spectrum on private-use producer surplus is equal to the market price of spectrum less the loss in profits to all producers from the decrease in the spectrum price resulting from the marginal increase in supply of spectrum. This last effect is lost private use producer surplus from decreases in the prices of spectrum based services brought on by lower private-use spectrum prices.

Consumer Surplus

The marginal effect on private use consumer surplus of a marginal increase in private use spectrum is approximately equal to the loss in producer profits from the increased supply of the fixed spectrum resource.[8]

$$\frac{\partial CS^P}{\partial BW^P} \approx -\sum_{j=1}^{n} \frac{\partial \Pi_j}{\partial BW^P} \qquad (3.13)$$

Producer Surplus plus Consumer Surplus

[7] If the government is the seller of the incremental spectrum to private users then there is the additional benefit of the possibility of reducing distortionary taxes. *See* Michael H. Rothkopf and Coleman Bazelon, *Interlicense Competition: Spectrum Deregulation Without Confiscation or Giveaways, in* Obtaining the Best from Regulation and Competition 135-159 (Michael A. Crew and Menahem Spiegel, eds., Kluwer Academic Publishers) (2005).

[8] The difference between the gain in consumer surplus and the loss in producer surplus is equal to the consumer surplus associated with the incremental quantity of spectrum based services (analogous to the Harbinger Triangle). Consequently, the producer losses slightly underestimate the consumer gains.

Taking producer and consumer surpluses together, the loss in profits to producers from increased supply of private-use spectrum is off-set by gains to consumers. The net effect from a marginal increase in private use spectrum is

$$\frac{\partial PS^P}{\partial BW^P} + \frac{\partial CS^P}{\partial BW^P} \approx \frac{\partial \Pi_i}{\partial BW_i^P} = P^P . \tag{3.14}$$

B. CHARACTERIZATION OF THE INCREMENTAL VALUE OF RADIO SPECTRUM IN UNLICENSED USES

Producer Surplus

Firm *i* will choose a level of BW_i^U to maximize profits.

$$\max_{BW_i^U} PS_i = \Pi_i(BW_i^U) - C_i(BW_i^U) \tag{3.15}$$

Taking the FOC and rearranging gives,

$$\frac{\partial \Pi_i}{\partial BW_i^U} = \frac{\partial C_i}{\partial BW_i^U} . \tag{3.16}$$

Unlicensed spectrum is unpriced so the marginal cost of additional spectrum is zero.

$$\frac{\partial C_i}{\partial BW_i^U} = 0 \Rightarrow \frac{\partial \Pi_i}{\partial BW_i^U} = 0 . \tag{3.17}$$

Consequently, increased allocations of unlicensed spectrum for firm *i* do not lead directly to increases in producer surplus.

Unlike with licensed spectrum, unlicensed spectrum is not mutually exclusive in its use. All users have access to all unlicensed spectrum. Consequently,

$$BW_i^U = BW^U \quad \forall\, i \tag{3.18}$$

Therefore,

$$\frac{\partial \Pi_i}{\partial BW^U} = \frac{\partial C_i}{\partial BW^U} = 0 . \tag{3.19}$$

Consumer Surplus

Consumption of unlicensed spectrum or unlicensed spectrum based goods is not constrained by the availability of unlicensed spectrum, so

$$\frac{\partial CS^U}{\partial BW^U} = 0\,. \qquad (3.20)$$

Consequently, increased allocations of unlicensed spectrum do not lead directly to increases in consumer surplus.

Externalities

Incremental allocations of unlicensed spectrum create social value through their effects on externalities. The first obvious externality associated with an increase in unlicensed spectrum is congestion relief. Users of unlicensed spectrum do not internalize the cost to other users of consuming unlicensed spectrum. Given the low power restrictions on unlicensed bands, this cost is typically zero, but can be positive at times and places where numerous users are trying to access the same spectrum or a user with numerous devices is trying to access the same spectrum.

The second externality associated with unlicensed spectrum is the potential innovation effects from having unlicensed spectrum available.[9] For example, a manufacturer could release a new device without negotiating with spectrum owners for access to licensed spectrum.

These two externalities are represented in (3.21). Other externalities associated with unlicensed spectrum may exist that could be added to (3.21), but I am not aware of any at this time.

$$EX^U(BW^U) = EX^{Congestion}(BW^U) + EX^{Innovation}(BW^U) \qquad (3.21)$$

Taking the FOC characterizes the incremental effect of unlicensed spectrum allocations on these externalities as,

$$\frac{\partial EX^U}{\partial BW^P} = \frac{\partial EX^{Congestion}}{\partial BW^U} + \frac{\partial EX^{Innovation}}{\partial BW^U} \qquad (3.22)$$

[9] *See, e.g.*, William Lehr, *Dedicated Lower-Frequency Unlicensed Spectrum: The Economic Case for Dedicated Unlicensed Spectrum Below 3GHz* (New America Foundation, Spectrum Policy Program, Spectrum Series Working Paper #9, Jul. 2004) ("Lehr 2004").

IV. EMPIRICAL ANALYSIS

In this section I will provide rough preliminary empirical estimates of the components of (3.3).

Producer Surplus plus Consumer Surplus from Licensed Spectrum. Equation (3.14) characterized the sum of producer and consumer surplus as equal to the market price of private-use spectrum. The recently concluded AWS auction raised approximately $13.7 billion for 90 MHz of spectrum nationwide.[10] That is approximately $152 million per MHz. Consequently,

$$\frac{\partial PS^P}{\partial BW^P} + \frac{\partial CS^P}{\partial BW^P} \approx \frac{\partial \Pi_i}{\partial BW_i^P} = P^P = \frac{\$152\ million}{MHz}. \qquad (4.1)$$

Producer Surplus plus Consumer Surplus from Unlicensed Spectrum. I demonstrated above that the marginal value of producer surplus and consumer surplus from unlicensed spectrum is zero. Consequently,

$$\frac{\partial PS^U}{\partial BW^U} = 0 \qquad (4.2)$$

and

$$\frac{\partial CS^U}{\partial BW^U} = 0\,. \qquad (4.3)$$

Congestion Externality Value From Unlicensed Spectrum. I can identify three types of potential congestion in the unlicensed bands. The first is congestion in the home. This would occur if someone tried to simultaneously use more unlicensed devices in the home than the available unlicensed spectrum could support. This problem could be exacerbated by spill-over of unlicensed devices from neighbors. The second type of congestion identified would occur in public spaces, such as public WiFi hotspots. The third type of congestion identified is that experienced by wireless ISPs (WISPs) that use unlicensed bands to provide commercial broadband services, typically in rural areas. These three types of congestion are represented in equation (4.4).

$$EX^{Congestion}(BW^U) = EX^{Cong:Home(BW^U)} + EX^{Cong:Public}(BW^U) + EX^{Cong:WiSP}(BW^U) \quad (4.4)$$

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[10] *See* Federal Communications Commission, *Auction of Advanced Wireless Services Licenses Closes*, Public Notice, DA 06-1882 (Sept. 20, 2006).

Assuming the three types of congestion are independent, the FOC of (4.4) is,

$$\frac{\partial EX^{Congestion}}{\partial BW^U} = \frac{\partial EX^{Cong:Home}}{\partial BW^U} + \frac{\partial EX^{Cong:Public}}{\partial BW^U} + \frac{\partial EX^{Cong:WiSP}}{\partial BW^U}. \tag{4.5}$$

MARGINAL VALUE OF ALEVIATING CONGESTION IN THE HOME. I have not been able to find any studies on the marginal willingness to pay to alleviate congestion of unlicensed devices in the home. A search of news articles describing interference in unlicensed bands found no articles describing congestion in the home.[11] Nevertheless, I hear the occasional anecdote about congestion in the home. The anecdotes typically involve a cordless phone and could presumably be solved by purchasing a 900 MHz cordless phone.

I will now take an initial cut at estimating one potential upper bound on the willingness to pay for incremental unlicensed spectrum in the home. This estimate is based on purely speculative guesses at values and is included simply to illustrate the point. I assume that interference in the home is only likely to happen in homes that have baby monitors as well as WiFi units and cordless phones. According to the CEA, in 2002 on average 81% of homes had 1.5 cordless phones and 10.5% of homes had 1.38 baby monitors.[12] By one account, at the end of 2005, 13.2 million homes had WiFi units.[13] I do not know how many homes use all three devices or experience interference in the home. Given the lack of serious complaints, I will arbitrarily assume 1 million households experience interference in the home. I further assume each household would be willing to pay $50 to alleviate that interference and that it would take an additional 10 MHz of unlicensed spectrum to do so. With these assumptions I roughly estimate the marginal value of alleviating congestion in the home to be $5 million per MHz or

$$\frac{\partial EX^{Cong:Home}}{\partial BW^U} = \frac{\$5\,million}{MHz}. \tag{4.6}$$

This estimate is extremely rough and only meant as a placeholder pending further research. Revising estimates of the number of homes affected, their willingness to pay or the amount of additional unlicensed spectrum needed to alleviate the congestion will proportionally affect the final estimate.

MARGINAL VALUE OF ALEVIATING CONGESTION IN PUBLIC. A search of news articles and the academic literature did not find any documented congestion of public WiFi hotspots outside of convention centers. In fact, to study the effects of congestion on WiFi network

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[11] A Nexis and Factiva search returned only articles that promoted newly developed devises to alleviate congestion in the unlicensed bands. No study actually reported any specific or verifiable examples of congestion in homes.

[12] *Consumer Electronics Association Comments*, Docket 02-135, (Sept. 30, 2002). Federal Communications Commission, Spectrum Policy Task Force, *Report of the Unlicensed Devices and Experimental Licenses Working Group*, 6 (Nov. 15, 2002).

[13] Erika Chavez, Wireless Not Free of Risks, SACRAMENTO BEE, (Jul. 4, 2005), at A1.

operations, Jardosh et al had to set up their testing equipment in a convention hall hosting over one thousand engineers.[14] Without demonstrated congestion in public areas I cannot identify a cost or assign a value to alleviating this source of congestion with incremental allocations of unlicensed spectrum. Consequently,

$$\frac{\partial EX^{Cong:Public}}{\partial BW^{U}} = 0 . \tag{4.7}$$

MARGINAL VALUE OF ALLEVIATING CONGESTION FOR WISPS. WISPs that use unlicensed spectrum to provide commercial broadband access services have chosen not to offer those services over licensed frequencies. WISPs using unlicensed spectrum typically operate in rural areas. This seems to be because wireless broadband access in urban areas is more appropriately provided on licensed frequencies, presumably to be able to provide the quality of service needed for a commercial service. In the AWS auction, the minimum opening bid for spectrum covering the population of rural counties was $0.03/MHz-pop. The average price of all RSAs was $0.11/MHz-pop or $7.1 million per MHz of covered population. The value of congestion alleviation for WISPs cannot be more than this amount.

$$\frac{\partial EX^{Cong:WiSP}}{\partial BW^{U}} \leq \$7.1\, million \tag{4.8}$$

<u>Innovation Externality Value From Unlicensed Spectrum.</u> Several analysts argue that one of the benefits of unlicensed spectrum is that it allows for innovation.[15] I have found no characterization of the value from innovation. Further, I have found no characterization of the incremental value from innovation. It is likely to be non-negative or

$$\frac{\partial EX^{Innovation}}{\partial BW^{U}} \geq 0 . \tag{4.9}$$

V. CONCLUSION

The valuations from the previous section create the following characterization of the equilibrium condition (3.3),

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[14] Amit Jardosh, Krishna Ramachandran, Kevin Almeroth and Elizabeth Belding-Royer, <u>Understanding Congestion in IEEE 802.11b Wireless Networks</u>, USENIX Association Internet Measurement Conference (2005).
[15] *See, e.g.*, Lehr 2004; Snider 2004.

$$\frac{\partial PS^P}{\partial BW^P}+\frac{\partial CS^P}{\partial BW^P}=\frac{\partial PS^U}{\partial BW^U}+\frac{\partial CS^U}{\partial BW^U}+\frac{\partial EX^U}{\partial BW^U}$$

$$\$152\ \mathit{million} \overset{?}{=} \$0 + \$0 + \begin{matrix} \$5\ \mathit{million} \\ +\ \$0 \\ +\ \$7.1\ \mathit{million} \\ +\ \dfrac{\partial EX^{Innovation}}{\partial BW^U} \end{matrix} . \qquad (5.1)$$

The incremental value of a MHz of licensed spectrum is estimated here to be $152 million. The identifiable incremental values of a MHz of unlicensed spectrum are estimated here to total $12.1 million, with the incremental innovation value unknown. If the allocation of licensed and unlicensed spectrum is in equilibrium, then the incremental innovation value of spectrum in unlicensed uses would have to be approximately $139.9 million. This seems to me to be an implausibly large amount of *additional* value from potential innovations—additional to the innovation value associated with existing unlicensed bands—implying that the allocation between licensed and unlicensed spectrum is not in equilibrium, with the marginal value of licensed spectrum allocations exceeding the marginal value of unlicensed spectrum allocations. The policy implication of this imbalance is that incremental spectrum allocations should go to licensed uses.