THE IMPACT OF SPECTRUM QUALITY ON WIRELESS TELECOM COMPETITION

Stephen Zhu

Professor Michelle Connolly, Faculty Advisor

Honors Thesis submitted in partial fulfillment of the requirements for Graduation with Distinction in Economics in Trinity College of Duke University.

Duke University
Durham, North Carolina
2012

Acknowledgements

I would like to sincerely thank Dr. Michelle Connolly for her invaluable guidance in this completing this project. I would also like to thank Dr. Leslie Marx, Dr. Marjorie McElroy, Shane Hunt, Isabella Lin and Emily Bailey for the time, advice, and feedback which have made this undertaking possible.

The data/software used in this research was made available by the Center for the Study of Auctions, Procurements, and Competition Policy at Penn State with support from the Human Capital Foundation (http://www.hcfoundation.ru/en/).

Abstract

This paper explores the metrics used by FCC and others for evaluating competition between wireless telecom carriers. It focuses on the impact of wireless spectrum quality on the results of FCC spectrum auctions and the estimated market shares of wireless carriers. In this case, it is revealed that quality is affected by the physical attributes of and the policies that are imposed at auction. Further, accounting for quality can lead to changes in the perception of concentration in local markets. The findings here give insights that can be used to better evaluate the competitive landscape of telecom in the future.

I. Introduction

In the spring of 2011, AT&T made an attempt to acquire one of its main competitors, T-Mobile, in a move that was poised to alter the dynamics of the US telecom[1]. Influential parties such as Sprint and the Communications Workers of America (CWA) took sides for and against the merger, arguing on whether or not the merger would increase prices, improve network quality or stifle innovation. The heated public conflicts highlighted the difficulty of and lack of agreement on analyzing wireless telecom competition for economists at the Federal Communications Commission (FCC) and in the industry.

With these issues as a motivation, this paper sets out to determine what factors affect competition between mobile phone carriers and explore how they can be measured. One of the points of contention during the merger proceedings was whether competition in the telecom industry should be studied nationally or on a local market basis. Based on economic literature, it appears that the telecom industry, despite often boasting of nation-wide network coverage, interacts with consumers on a local level much like other media and broadcast industries[2]. In support of this conclusion is the fact that mobile spectrum licenses are divided and assigned locally and that mobile phone carriers sometimes offer localized price incentives based on the zip code of a potential new customer.

Thus, to properly analyze competition between telecom companies, one must be able to observe data that is broken down in a location-based way. Unfortunately, despite the majority of

[1] Savov, Vlad (Mar 20, 2011). AT&T agrees to buy T-Mobile USA. *Engadget.com.* Retrieved from http://www.engadget.com/2011/03/20/atandt-agrees-to-buy-t-mobile-from-deutsche-telekom/

[2] Marx, Leslie (Sept. 4, 2011). Report on the proposed acquisition of T-Mobile by AT&T.

wireless carriers being public corporations, such detailed pricing and subscription data is considered proprietary competitive information. Therefore, many direct measures of competition are unavailable to normal investors or researchers who are not directly involved in cases such as the recent merger.

However, the ownership of telecommunications spectrum licenses is known at the local level and, combined with the prices originally paid for the licenses, can provide insights on the competitive relationship of wireless companies. Distribution of spectrum ownership is a useful proxy for subscriber market share at the local level[3] since each firm will purchase the amount of spectrum that it believes will be optimal for its expected customer base in that area. With license data available from the FCC, researchers can perform tests, called "spectrum screens," that provide a rough analysis of concentration in local markets using this spectrum proxy. Spectrum screens are useful in highlighting markets that require further analysis using direct or otherwise more intensive methods of evaluating competitiveness.

Additionally, analysis of the prices that firms pay for these spectrum licenses at auction can reveal the factors that telecom companies use to value spectrum. The FCC periodically holds auctions during which it sells spectrum licenses that fall in a certain range of frequency, known as a band. Based on the design of these spectrum auctions, the winner of each license should be the firm that can obtain the most value from using the spectrum[4]. By modeling the winning bid prices from these auctions, this paper affirms that the auction mechanisms leads to predictably rational and efficient behavior by the firms. Of greater significance is the fact that these models

---

[3] Marx Report

[4] Connolly, M and Evan Kwerel (2007). Economics at the FCC. *Review of Industrial Organization*, 11/07, Vol. 31: 107-120.

give an understanding of what qualities and regulatory policies affect the value that firms can obtain from spectrum, and by how much the value is affected.

It is intuitively clear that licenses residing in different bands should have differing value based on the characteristics of the bands. This research demonstrates the magnitude of such differences, which have previously been ignored in the literature, and its possible implications. Besides auction policy applications, the importance of evaluating spectrum quality could be incorporated as weights into measures of spectrum ownership. The analysis in this paper shows that, since spectrum quality affects the value of a license, i.e. the amount of revenue the license could generate from consumers, it is logical to include such a measure in a market power analysis. Finally, market share tables will demonstrate that accounting for spectrum quality can alter the perceived level of spectrum ownership concentration and change conclusions of spectrum screen analyses.

The section that follows summarizes the regulation and literature surrounding telecom competition and spectrum ownership analysis. Then, Section III will introduce the theories and methodology used to approach license and auction data. Section IV describes the sources of information and gives examples that detail the data used in the regressions. Section V then performs regression analysis to study the impact of quality-adjustment factors on spectrum bid prices. Following the recognition of these factors, Section VI contains tables that demonstrate how quality-adjustment can affect perceived market concentrations. Finally, Sections XII & XIII conclude the paper, provide potential future research and list referenced works. Section IX includes the detailed appendices for the equations, data and analyses.

II. Literature & Regulatory Review

An initial review of a portion of the regulation involving wireless telecom companies is essential for understanding how federal economists would analyze the telecom industry. Their methodology functions as a guideline of how to assess competition between wireless carriers. Included in a study of this regulation are the rationale and mechanisms behind the FCC spectrum auctions, which play a central part in the models of this paper.

Examining the literature on evaluating wireless carrier competition also helps to provide a broad picture of the current state of this area and how this paper will contribute. Specifically, this covers arguments over the validity of analyzing telecom competition locally, reviews the usage of spectrum screens and finds a notable lack of consideration of spectrum quality when analyzing telecom competition.

II.A. Wireless Telecom Industry Regulation

The Department of Justice and The Federal Trade Commission (DoJ & FTC, collectively the Agencies) are responsible for analyzing companies in potential mergers and published the Horizontal Merger Guidelines (HMG) to "assist the business community and antitrust practitioners by increasing the transparency of the analytical process" behind approval or rejection of horizontal mergers.

The introduction stressed the theme: mergers are not permitted to enhance "market power" in the sense of raising prices, reducing output, harming innovation, or otherwise harming consumers. The discussion of techniques afterwards focused on how to measure potential impact from several dimensions. The end goals of the analytical techniques presented in the document align strongly with the objectives of this paper in analyzing the competitive landscape of the telecom industry.

The document overviewed how the Agencies collect different types of relevant evidence, how to identify relevant markets, how to judge the effects of market share and negative unilateral and coordinated events that could occur due to a merger. The ideas and techniques offered in each of these areas, such as the HMT (Hypothetical Monopolist Test), SSNIP (Small yet Significant Non-transient Increase in Price), HHI (Herfindahl–Hirschman Index), are all useful when evaluating the level of competition in a market.

Connolly and Kwerel (2007) provided a descriptive account of how economic analysis and techniques have helped shape policy at the FCC. The paper described an interesting study of local media markets that indicates that higher concentrations of market share in local markets may not be negative for consumers. Instead, it seemed that more concentrated local media markets push corporations to increase choices for consumers to avoid cannibalizing existing products. This dynamic could also have parallels in the wireless industry, which sees greater efficiencies of scale at higher market share concentrations.

More directly relevant to this paper, Connolly explained a series of experiments that lead to FCC choices in spectrum auction design. The basic mechanisms of FCC spectrum auctions involved Simultaneous Multiple Round (SMR) auctions that allow firms to continuously place bids for all spectrum licenses. It was a known phenomenon that cellular spectrum could be a complementary good with itself; that is, two adjoining pieces of spectrum could be more valuable as a whole than when separated.

With this in mind, the FCC tested tiered package auctions that allowed firms to bid on packages of spectrum license as an all-or-nothing bid. This reflected the fact that the value of a spectrum may exist only when all the licenses are acquired by one firm, led to more efficient bidding as well as higher FCC auction revenue. Following these findings, the FCC implemented this mechanism in the most recent 700 Band auction.

Finally, the FCC itself published the 14th and 15th update to its Mobile Wireless Competition (MWC) Report to reflect on its assessment of competition in the wireless telecom industry in 2008 and 2009. The document focused much attention on market concentration and industry structure, giving copious HHI information which be referenced here.

Besides providing useful data, the report also outlined the importance of unitizing spectrum as MHz-Population and spent a section discussing the advantage of lower frequency spectrum. The report stated that AT&T and Verizon had an insurmountable advantage for holding significant spectrum under the 1GHz Frequency level, but fails to elaborate further on how this advantage could actually impact the market. This represents a critical avenue to be explored in this paper. Overall, the report concluded that the level of competition in the industry has fallen from where it needs to be, a verdict which did not go unchallenged.

II.B. Literature on Evaluating Competition

Marx (2011) compiled a detailed report as part of an effort to assist the CWA and provide evidence in support of the AT&T-T-Mobile merger. The report had highly relevant background information on the dynamics of the wireless telecom industry and how spectrum is assigned. The report also devoted a section to explaining why telecom markets are locally based.

Intuitively, measuring local market share for carriers is more useful and revealing than finding national market share[5]. However, the report went into a more rigorous analysis by arguing that pricing behaviors by firms indicate local competition. Additionally, it noted that consumers chiefly consider local carrier quality when selecting a cell phone service, further suggesting the local nature of telecom markets.

The report explained the process of a spectrum screen, a rough test that observes for how many markets a telecom carrier's spectrum ownership share exceeds a set acceptable level. It also contained justifications for which frequency Bands would be relevant to spectrum share metrics and examined HHI based on spectrum share. Several times, it made disclaimers about the validity of the methodology, and stated that the methods were used due to the FCC's reliance on them. The metrics used in the analysis did not contain population adjusted figures, and did not mention quality of spectrum as a factor. Again, this makes an analysis of quality-adjusted metrics in spectrum share and HHI an interesting and useful area to study.

Newbery (2009) authored an interesting working paper that studied market power of electric companies, an industry that bears some relation to the wireless telecom industry. They are both utility industries with low elasticity of demand, are separated by local markets, and face oligopolistic suppliers. The problem Newbery noted was that conventional electricity market model expects higher price-cost markup than is observed because HHI was not suitable. He suggested an alternate model based on the Residual Supply Index (RSI) that analyzes whether a

[5] For example, if company A owned 100% of the market for 25 markets and company B owned 100% of the market for another 25 markets, a national average market share would show that each company owned 50% share, creating the perception of competition in the industry when there is actually a series of localized monopolies.

firm is a critical supplier in the market. This would be an interesting way to analyze the wireless industry, save for a few differences that make applying Newbery's model difficult. The paper used a proxy demand for electricity in peak usage, and relied on the spot markets & contract mechanisms to study electricity pricing, concepts which don't have ready parallels in the mobile telecom market.

Finally, Faulhaber, et al released a study, supported by AT&T, which reviewed and criticized the latest series of FCC Mobile Wireless Competition reports. In it, the authors declared market power conclusions based on indirect competition measures, such as HHI, outdated and incorrect. Nevertheless, they cede the usefulness of indirect measures as easy-to-implement screening tests.

The study contained two somewhat contradictory sections, one that seemed to argue that increased industry concentration reduced wireless prices and one that claimed increased wireless competitor entry as a positive factor. Overall, the paper pushed for the conclusion that the structure and concentration of the mobile wireless market was uncorrelated with consumer prices.

There was an interesting passage on the case of the FCC forcing Nextel to switch high quality spectrum for low quality spectrum. It strongly suggested the presence of value differences based on quality and speculated that higher frequency licenses were less valuable because they required more capital investment. In that case, it is possible that quality of spectrum holdings could give inferences about capital cost structures for wireless carriers, a topic that can be explored in the future.

The study concluded by explaining its policy stances and pushed for the FCC to release more spectrum as wireless space gets increasingly more crowded. If the FCC were, in fact, planning to release more spectrum, the results of this paper could be helpful in guiding the valuation of an auction for previously unlicensed spectrum.

III. Theory & Modeling Methodology

As this paper attempts to add a study of spectrum quality factors to the literature on telecom competition, this section opens with a discussion of the reasoning for seeking out quality-adjusted metrics. From there, the section details the economic theory that forms the basis for the quality-adjusted models and metrics used in the rest of the paper. This first involves the construction and usage of basic spectrum ownership quantities. The next step is explaining the characteristics of quality factors, Skin Depth and Regulation, and how they will be implemented. The section concludes with a complete model for spectrum winning bid-price and the theoretical implementation of quality-adjusted spectrum ownership shares.

III.A. Motivation for Quality Adjustment

After reviewing the literature and regulatory information, it is useful to explain the rationale behind examining quality factors. Intuitively, quality of spectrum should be a strong explanatory factor in predicting the value of spectrum, as better spectrum is an input that ultimately leads to a better product for the wireless carrier[6]. The value arising from that advantage in the market[7] is the cause for an increase in the value of a license offering higher quality spectrum.

It is possible that there exists a systematic disparity between carriers so that one or more holds relatively better spectrum across markets, and therefore has a systematic market advantage. This dynamic is unobserved when evaluating basic spectrum ownership share without

[6] FCC MWC Report

[7] If Carrier A owns better network spectrum than Carrier B, then A will be able to provide a better product than B, even if they own the same quantity of spectrum licenses. Then, if the two carriers have the same cost structure, A will be able to charge more for its product or attract more customers and drive B out of business by charging the same price.

adjusting for quality. As the purpose of performing spectrum screens and other spectrum tests is to analyze market power, leaving out factors that create significant market advantages means that the conclusions of such tests would be incomplete or inaccurate. Therefore, studying the impact of spectrum quality serves as an important step in analyzing market power and wireless telecom competition in general.

III.B. Measuring & Using Spectrum Ownership Share

The first step in creating a quality-adjusted market share model is constructing the basic market share measures that economists currently use in arguments before the Agencies. As covered in the literature, one method used to estimate market share is a spectrum share analysis in local markets. Observing spectrum capacity is an effective proxy for subscriber market share since carriers are incentivized to buy enough spectrum licenses for the number of customers they believe they will serve, as holding excess capacity would be an inefficient way for a firm to use its capital, especially considering some of the spectrum usage requirements imposed by the FCC. Thus, spectrum share is a way to represent potential or target market share for each firm[8].

The basic component of value for a spectrum license is the bandwidth, typically stated as the number of MHz attributed to a license. This quantity, known as a Block, is the amount of "space" that the winning bidder can use to wirelessly transmit data. As firms are purchasing spectrum licenses mainly to gain this wireless communications space as an input for their end product, bandwidth is an essential factor for explaining the variation of spectrum bid value.

[8] Marx Report

A record of how much spectrum a carrier owns in a local market is enough information to perform a spectrum screen test. For a spectrum screen, the total bandwidth of the spectrum licenses owned by a firm is determined for each firm. Then, a benchmark level of spectrum holdings is set, typically at 33.3%. This threshold is the FCC's recognition that the wireless telecom industry, like many other capital structure intensive industries, requires a large minimum efficient scale and significant fixed costs[9]. This benchmark balances that necessity with the concern for overconcentration of markets. Then, markets in which there is a carrier that holds more than that benchmark level will fail the screen. Finally, the total number of markets that fail the screen give an indication of concentration for the industry.

To be able to interpret spectrum ownership across different areas, market share for spectrum should be measured not only in terms of bandwidth, but population-adjusted bandwidth. This creates a number for quantity which is neutral between different markets and neutral within markets. This is necessary since the country is divided into areas of different sizes during different auctions[10]. By including population, the variations in bid value due to license districting are explained.

The winning bid values for each spectrum license can be deconstructed a price and quantity using these factors:

$$\exists\ Price\ P = \frac{Bid}{MHz \times Pop}\ and\ Quantity\ Q = MHz \times Pop \qquad (1)$$

$$\text{such that } P \times Q = Bid$$

[9] Marx Report

[10] For example, an 850MHz cellular license is designated to cover a Cellular Market Area (CMA), about the size of a county, while some licenses in the 700MHz band are attributed a Regional Economic Area (REA), which could cover the entire West Coast or Southeast region.

Equation 1 can be understood as meaning that the true price P of a spectrum license depends on quality factors that are separate from the size of the Block and population for which the license operates. This also makes sense for Q, since, all else equal, the buyer will want to pay more for a spectrum license when it offers more bandwidth or when it reaches more potential customers.

These population-weighted quantities can be used to generate basic spectrum ownership shares that make sense across different local markets:

$$q_1^{basic} = \sum_1^L MHz_i \times Pop_i \text{ where } i = \text{ each spectrum license, } L = \text{\# of licenses owned} \quad (2)$$

$$Q^{basic} = \sum_1^C \left(q_c^{basic}\right) \text{ where } c = \text{each carrier such that } Basic\ Spectrum\ Share\ \% = \frac{q_c^{basic}}{Q^{basic}} \quad (3)$$

The quantity-adjusted spectrum share of each carrier in each market can be calculated with Equations 2 & 3 and used to generate HHI figures for concentration of the spectrum market. HHI is based on the ability of a player to profit in a Cournot model, given the elasticity of the good and the relative market shares of all the players:

$$\frac{P - C}{P} = \frac{HHI}{|\varepsilon|} \quad (4)$$

$$HHI = \sum_1^N {S_n}^2 \text{ where } N = \text{\# of players, } S = \text{market share} \quad (5)$$

This can extend to a change in market shares due to players merging, entering or exiting:

$$\frac{P' - P}{P} = \frac{\frac{HHI'}{|\varepsilon|} - \frac{HHI}{|\varepsilon|}}{\frac{HHI}{|\varepsilon|}} \quad (6)$$

Equation 4 implies that, for a given industry, there exists an acceptable threshold for market concentration, as measured through HHI, before players are able to raise prices unacceptably. Equation 6 helps set a benchmark level of acceptable change in market concentration given an acceptable level of price change.

Although using HHI-based arguments to evaluate competition has been discouraged in the HMG and other literature, economists and corporations continue to quote the figures in their analyses. The main criticism of HHI, as covered in the literature, is that simple market share typically does not take into account the cost structures and other competitive dynamics unique to each industry[11]. However, quality-adjusted market share could be more accurate in reflecting true levels of market power, and can lead to a useful HHI figure for local telecom markets. Therefore, as an interesting exercise, the paper will explore the HHI concentration numbers that adjusted market share metrics lead to and compare them with original HHI figures.

For the wireless telecom industry, the FCC has used an HHI of 2800 as an acceptable limit for industry concentration and an HHI increase of 250 as a limit for acceptable concentration increase due to merger or acquisition[12].

III.C. Defining Spectrum Quality: Band Frequency & Regulations

The most direct way to measure the quality of spectrum is by examining the skin depth of the frequency[13]. With better skin depth, spectrum is better at penetrating objects, such as buildings,

[11] Newbery, David (Mar 2009). Predicting Market Power in Wholesale Electricity Markets. EUI Working Papers.
[12] Marx Report
[13] Skin Depth Calculator. Microwave Encyclopedia. http://www.microwaves101.com/encyclopedia/calsdepth.cfm

and therefore, the spectrum is of higher quality. Skin depth is calculated through a formula that measures the penetration depth of a radio wave at a certain frequency through a certain material:

$$Skin\ Depth\ \delta = \sqrt{\frac{2\rho}{2\pi f \mu_r \mu_0}} \text{ where } f = \text{frequency of radio wave} \tag{7}$$

The construction of the formula in Equation 7 indicates that Skin Depth δ has an inverse relation to Frequency *f*, such that higher frequencies will have worse penetration properties, with all else equal. For the analysis in this paper, the models only vary the Frequency of the spectrum and do not vary the penetration through different materials, since the Skin Depth simply scales proportionally to a different material. Therefore, it is sufficient for the bid price model to consider just the Frequency of the spectrum in a license as a quality factor.

Besides the physical quality of the spectrum endowed by a license, the restrictions and regulation placed on bands of frequency during auction also affect the value of the license. Most licenses carry a set of build-out rules, a timeline by which a firm must make commercial usage of spectrum[14]. There may also be various regulations, on what kind of technologies may be used, how extra spectrum can be leased out, and so on, which can affect the commercialization potential of the license.

The wireless industry's concern over regulation was most prominently highlighted during the latest set of auctions in 2008 for the 700MHz Band. Prompted by consumer advocacy groups and technology companies such as Google, the FCC imposed open-access requirements on the

[14] FCC Wireless Bureau. Auction Data. Retrieved from http://wireless.fcc.gov/auctions/default.htm?job=auctions_data

Upper 700 C Block that were initially met with heavy protest from the industry[15]. A public-private shared ownership structure for the Upper 700 D Block license, along with rumors of expensive service fees, caused wireless carriers to discount that spectrum so much that the reserve auction price was not met[16].

A complete model for the quality of a block of spectrum license might appear as in Equation 8:

$$Quality\ Y_b = \beta_0(f_b) + \sum_1^N \gamma_i(r_i) \text{ where } b = \text{block of spectrum}, \quad r = \text{regulation fixed effect} \tag{8}$$

However, modeling the impact of varying sets of rules on spectrum quality is difficult in a real world setting and falls outside the scope of this paper. To proxy for the regulatory aspect of spectrum quality, the models here will simply use fixed effects for each spectrum band. Since spectrum licenses are auctioned off by band, the blocks of spectrum in each band contain similar auction and ownership regulations, with the previously mentioned exceptions in the 700 Band. A fixed effect for Band functions as an interaction between physical quality and regulatory impact. A model including only this variable will not properly explain the influence of each component:

$$Band_b = \left(f_b \times \prod_1^N r_i\right) \tag{9}$$

Therefore, the bid price model will include a variable for Frequency and an indicator for Band to be more accurate in capturing the effects of quality factors. The Frequency variable captures

---

[15] Brome, Rich. (Mar 27, 2008). A Visual Guide to 700 MHz. PhoneScoop.com. Retrieved from http://www.phonescoop.com/articles/article.php?a=187&p=232

[16] As of this time, 4/16/12, the Upper 700 D license remains unsold as the FCC examines potential modified policies and their impacts. An auction for this block may be held later in 2012.

the effect of physical spectrum quality, while the Band fixed effect is expected to capture the residual impact of regulation on that Frequency.

III.D. Modeling Bid Price

The four components described, Bandwidth, Population, Frequency and Band, should produce a complete and effective model for the winning bid price of spectrum licenses. The linear specification of the winning bid price model appears as:

$$Winning\ Bid\ Value\ V = \beta_1(MHz) + \beta_2(Pop) + \beta_3(f) + \gamma_1(Band) \tag{10}$$

where *MHz* = Bandwidth in MHz

The significance of β_3 and γ_1 coefficients would indicate how much the firms involved in spectrum license auctions consider the quality of the spectrum license when placing winning bids. To put the model into natural logarithm form, the monotonic transformation is applied to the continuous variables:

$$\ln(V) = \beta_1(\ln MHz) + \beta_2(\ln Pop) + \beta_3(\ln f) + \gamma_1(Band) \tag{11}$$

This creates a model which provides more useful coefficients that explain the proportional impact of each factor. To gain additional accuracy in isolating the impact of quality, the model can incorporate additional variables and fixed effects for time, firm and license location, characteristics that have the potential to impact the bid price. The complete model as follows:

$$\ln(V_i) = \beta_1(\ln MHz_i) + \beta_2(\ln Pop_i) + \beta_3(\ln f_i) + \gamma_1(Band_i) + \beta_3(\ln Time_i) + \gamma_2(Winner_i) + \gamma_3(Location_i) \tag{12}$$

where *i* = each license, *Time* = year of auction

Details about the creation and possible impact of the additional factors will be discussed later in the Data section of this paper and in the Appendix.

III.E. Adjusting Spectrum Share for Spectrum Quality

With a better understanding of what factors affect spectrum quality and how to model these factors, the basic measures of spectrum share previously describe can be extended to include quality adjustments. For a given carrier, its quality-adjusted spectrum owned is given by Equation 13 below:

$$q_1^{adj} = \sum_1^L MHz_i \times Pop_i \times \beta(Y_i) \text{ where } L = \text{\# of licenses owned,} \quad (13)$$

$$\beta = \text{quality adjustment factor}$$

Note that the construction of this quality-adjusted q is essentially a rearrangement of Equation 1 that replaces the true Price P with Quality Y. The P derived from the Bid value served as a proxy for spectrum quality, but it also includes noise that could reduce its effectiveness. The complete model for Y includes exclusively factors that affect spectrum quality and will produce a more meaningful result.

The formula in Equation 13 includes an adjustment factor for quality in β. As the complete model for Quality Y in Equation 8 faced difficulties in implementation, specifying a proper adjustment factor not be achievable in this paper. Without a quantity isolating the impact of regulation, it is unclear as to how the value of rules should be weighted. The coefficient on the Band interaction term makes interpreting the impact of Frequency difficult as well.

Despite these limitations, it is still possible to create a quality-adjusted figure that carries some interpretive meaning. In this method, the impact of regulations is ignored and the weight of

Frequency is set to 1. Further, to give the quality of spectrum a positive effect on these figures, Frequency is converted to Skin Depth as in Equation 7. Then, market share figures can be adjusted as follows:

$$\hat{q}_1^{adj} = \sum_1^L MHz_i \times Pop_i \times \beta(\delta_i) \text{ where } L = \text{\# of licenses owned, } \beta = 1 \qquad (14)$$

As before, these quality-adjusted quantities can be combined to produce spectrum shares:

$$\hat{Q}^{adj} = \sum_1^C \left(\hat{q}_c^{adj}\right) \text{ where } c = \text{each carrier}$$

$$\text{such that } Quality\ Adj.\ Spectrum\ Share\ \% = \frac{q_c^{adj}}{Q^{adj}} \qquad (15)$$

Although the methods of generating Q^{basic} and Q^{adj} are similar, the actual quantities produced by the equations are not directly comparable. In the tables that this method produces, the *Spectrum Share* %'s of carriers between *basic* and *adj* can be compared, as can the resulting HHI figures.

Of course, because the quality adjustment factors in creating q^{adj} were not precise, the change in the resulting *Spectrum Share* %'s and HHI's can only be demonstrative. If there are systematic disparities between the qualities of spectrum licenses held by one or more firms, this method reveals the direction of the disparity for each firm, but not proper magnitude of disparity. Calculating the magnitude of the disparities and studying their impact on the market is a possible avenue for further research.

IV. Data Description

For this paper, I use data directly from the authoritative source of the FCC or other reliable sources that are freely available to researchers. When possible, detailed numbers and statistics are pertaining to local rather than national markets so that the full analysis can be performed. The below sections will detail omissions and limitations of the data, discuss the variables to be used in regressions, and explain how the data were processed.

IV.A. Data Choices

The spectrum auction prices and block winners from the last decade are available online from the FCC Wireless Bureau in PDFs that contain auction results[17]. However, the actual spectrum data used in this paper is sourced from Excel tables compiled by the Penn State University CAPCP (Center for the Study of Auctions, Procurements and Competition Policy)[18], for convenient formatting and because the tables include extra details on the characteristics of each spectrum license.

Subscriber market shares are self-reported in public documents[19], as the wireless carriers are public corporations. The 14th and 15th FCC Mobile Wireless Competition Reports, available online[20], contain many nationally aggregated statistics and, useful for this paper, locally designated HHI figures.

[17] FCC Wireless Bureau. Auction Data. Retrieved from http://wireless.fcc.gov/auctions/default.htm?job=auctions_data
[18] Penn State Center on Auctions, Procurements and Competition Policy. Retrieved from http://capcp.psu.edu/data.html
[19] Market shares from: Verizon About Us (http://aboutus.verizonwireless.com/ataglance.html); AT&T Press Release (http://www.att.com/gen/press-room?pid=22304&cdvn=news&newsarticleid=33762); Sprint Press Release (http://newsroom.sprint.com/article_display.cfm?article_id=2179); T-Mobile Coverage (http://www.bgr.com/2011/02/25/t-mobile-takes-a-beating-in-q4-2010-sheds-318000-customers-churn-at-3-6/)
[20] FCC MWC report

In choosing which frequency bands to study in the analysis, I decided upon those most commonly used for mobile communications and data - the AWS, PCS, SMR, Cellular and 700 Bands. Although not in full use, I also included data for the WCS band because the FCC has approved its use for more advanced communication starting in 2010[21]. I excluded the bands of MSS and BRS due to lack of organized, detailed auction data and because niche technologies based in these bands (i.e. Clear WiMAX, LightSquared LTE) are either being abandoned[22] or deemed unsuitable for commercial launch by the FCC[23].

Some observations were excluded for other reasons. The original goal of this empirical study was to compare auction results to consumer quality ratings for cell phone service across 21 major metropolitan areas. Therefore, although the current analysis does not relate to this topic, only auction data for these metropolitan areas were collected. However, The competitive effects displayed in data is still highly relevant as the licenses for these large metro areas represent cities across the entire United States and, in most cases, more than half of the population of the country.

In the case of the Cellular Band, the licenses were distributed to wireless carriers before the creation of spectrum auctions. As winning bids do not exist for this category, the Cell licenses are excluded from the regressions but are still used in the spectrum ownership comparisons.

[21] Marx Report, WCS Decision

[22] Rose, Brent (Oct 7 2011). Sprint Is Ditching 4G WiMax for 4G LTE. Gizmodo.com Retrieved from http://gizmodo.com/5847643/its-official-sprint-is-going-lte

[23] Riegler, Paul (Feb 14, 2012). FCC Bars LightSquared Broadband Network Plan. Frequent Business Traveler. Retrieved from http://www.frequentbusinesstraveler.com/2012/02/fcc-bars-lightsquared-broadband-network-plan/

Similarly, isolated cases of licenses lack winning bids will be excluded[24]. Naturally, I am leaving out the entire Upper 700 D block from the 2008 auction. This block is problematic because, as previously mentioned, the highest bid was below the reserve price such that the license never actually sold. It would also be inaccurate to include the block in an attempt to find the negative effect of regulation in this paper's models since the license is designated nationally and local market characteristics cannot be controlled.

As discussed earlier, the analysis in this paper does not attempt to quantify the various types of rules attached to spectrum licenses. Mainly, these are build-out and usage requirements that stipulate how much capital a company must devote to using a spectrum and in what time-frame, but the full lists of regulations are quite complex[25] and can easily form a separate topic.

IV.B. Variables

In the methodology section, a full specification for the Winning Bid Price model was introduced, involving variables that complement the essential factors of Bandwidth, Population, Frequency, and Band. In the regressions that follow, Bid values will be appropriately adjusted by CPI to 2008 dollars. Further, there will be an annual time trend variable, and fixed effect indicators for the carrier that won the license and the metropolitan area that the license covers. Respectively, these are intended to control for technological progress, firm-specific efficiencies, and location-specific densities and topography. The continuous variables are detailed below:

Table 1

[24] There is the SMR EE license in Tampa and 6 scattered WCS A & B licenses in Milwaukee, Minneapolis, St. Louis and San Francisco which sold for less than $10 each. This may have been an effort by the FCC to push spectrum into the market to help consumers.

[25] For example FCC regulation page for PCS and Cell bands: Federal Communications Commission (2010). Personal Communications Services. Code of Federal Regulations. Retrieved from http://www.gpo.gov/fdsys/pkg/CFR-2010-title47-vol2/xml/CFR-2010-title47-vol2-part24.xml

Summary of Regression Variables

Variable	Obs	Mean	Std. Dev.	Min	Max
Bandwidth (MHz)	1172	5.72	7.44	0.04	30.00
Population	1172	7474224	6100187	26586	49700000
Bid (USD)	1172	38500000	131000000	396	2060000000
Band Freq (MHz)	1172	1171.60	544.93	716.00	2347.50
Skin Depth (micrometers)	1172	2.04	0.37	1.35	2.44
Year	1172	2001	3	1995	2008
Time	1172	6.96	3.46	1.00	14.00
CPI Adjustment	1172	1.22	0.11	1.00	1.41
Ln Factors	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
log Bid (CPI Adj)	1172	13.27	3.80	6.28	21.64
log Bandwidth (MHz)	1172	0.43	1.93	-3.28	3.40
log Population	1172	15.57	0.72	10.19	17.72
log Skin Depth	1172	0.69	0.20	0.30	0.89
log Band Freq	1172	6.98	0.41	6.57	7.76
log Time (Year)	1172	1.79	0.59	0.00	2.64

IV.C. Data Samples

Below is an example of the auction data that is sourced from CAPCP, with minimal reformatting applied for display here:

FREQ_BLOCK	MARKET_DESC	MARKET	BANDWIDTH_MHZ	POPULATION	BLOCKS	BIDDER_NAME	BID_AMNT	BID_ROUND_NUM	FREQUENCY	COMMENTS
A	Atlanta GA-AL-NC	BEA040	12	5471412	2	Cellco Partnership d/b/a Verizon Wireless	103388000	20	698-704 / 728-734	Lower 700 MHz
A	Boston-Worcester MA-NH-RI-VT	BEA003	12	7954554	2	MetroPCS 700 MHz, LLC	313267000	26	698-704 / 728-734	Lower 700 MHz
A	Chicago-Gary-Kenosha IL-IN-WI	BEA064	12	10328854	2	Cellco Partnership d/b/a Verizon Wireless	152532000	20	698-704 / 728-734	Lower 700 MHz

A	Dallas-Fort Worth TX-AR-OK	BEA127	12	7645530	2	Cellco Partnership d/b/a Verizon Wireless	171956000	17	698-704 / 728-734	Lower 700 MHz
A	Denver-Boulder CO-KS-NE	BEA141	12	3984105	2	Cellco Partnership d/b/a Verizon Wireless	38056000	19	698-704 / 728-734	Lower 700 MHz

The data is already well-organized for the intended purpose of studying auction prices so only a few clean-up steps are necessary, such as renaming the designated markets and creating indicator variables for regressing qualitative values. The issue that remains is correlating the auction bidder with the spectrum owner. In many cases, the firm that is labeled as the winner of a spectrum license by the FCC is not a prominent wireless carrier. Rather, these bidders are shell companies of a major wireless carrier or, for past auctions, companies which have since been acquired by another firm. As the regressions in this paper analyze the winning bid values on spectrum at auction, the implications of these technicalities are not critical. However, the true owner of spectrum licenses is important for the analysis of spectrum shares and I have done my best to track down the histories of each company to determine who actually owns the spectrum. In any case, it appears that spectrum leasing and transfers are difficult and uncommon[26], so besides a few well known cases[27], it is safe to assume that owners of spectrum can be traced to the winners of licenses in a straightforward manner.

The next step is to organize each license by spectrum band and owner:

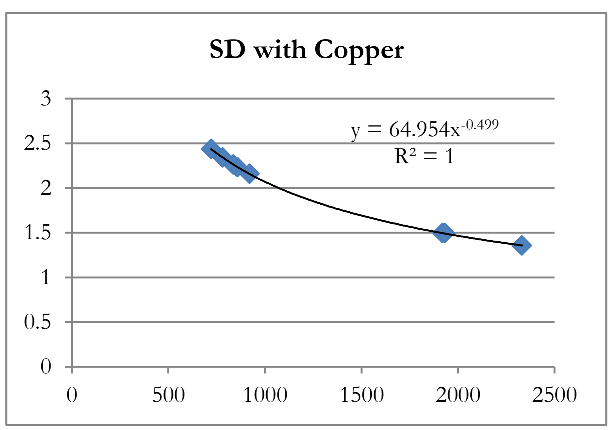
[26] Faulhaber, Gerald, Robert Hahn and Hal Singer. Assessing Competition in US Wireless Markets: Review of the FCC's Competition Reports. Retrieved from http://ssrn.com/abstract=1880964
[27] Engleman, Eric and Christ Strohm (Dec 23 2011). AT&T's $1.93 Billion Qualcomm Airwaves Purchase Wins Approval. Bloomberg. Retrieved from http://www.bloomberg.com/news/2011-12-22/qualcomm-1-93-billion-airwaves-sale-to-at-t-wins-u-s-approval.html

700 Band	Auction	73	Year	2008			
License	**A**						
Channel	**Lower**						
	Market	**MHz**	**Pop**	**Blocks**	**Owner**	**Bid**	**Winner**
Atlanta	BEA040	12	5471412	2	Verizon	103388000	Cellco Partnership d/b/a Verizon Wireless
Boston	BEA003	12	7954554	2	MetroPCS	313267000	MetroPCS 700 MHz, LLC
Chicago	BEA064	12	10328854	2	Verizon	152532000	Cellco Partnership d/b/a Verizon Wireless
Dallas	BEA127	12	7645530	2	Verizon	171956000	Cellco Partnership d/b/a Verizon Wireless
Denver	BEA141	12	3984105	2	Verizon	38056000	Cellco Partnership d/b/a Verizon Wireless

At this stage, the Upper 700 C block, presented a problem. This block is designated over 6 large REA licenses that cover the country, rather than many individual local licenses. Unlike the Upper 700 D block, this block was sold in its entirety to Verizon and its value cannot be ignored. To analyze the value of this license in each market, a weighted ratio of REA population based on CMA populations was used.

Separately, details on the frequency of each spectrum band were collected to simplify Skin Depth calculations. I used an online skin depth calculator[28] to generate Skin Depths at different frequencies for an arbitrary material (Copper). These figures were plotted and fit to an appropriate equation that perfectly mapped Frequency to Skin Depth:

	Avg Freq	**SD Copper**	
Cellular	859	2.232	μmeters
PCS-Narrowband	921	2.156	μmeters
PCS-Broadband	1920	1.493	μmeters
AWS	1932.5	1.493	μmeters
WCS	2332.5	1.355	μmeters
Lower 700	722	2.435	μmeters
Upper 700 Guard	781.5	2.34	μmeters



[28] Skin Depth Calculator

SMR	837.5	2.261	μmeters

With this mapping, the Skin Depth matching the Frequency of each license could be calculated:

Band	License	Start	End	Start	End	Avg Freq	Skin Depth
PCS-B	**D**	1865	1870	1945	1950	1907.5	1.4902
PCS-B	**E**	1885	1890	1965	1970	1927.5	1.4824
PCS-B	**F**	1890	1895	1970	1975	1932.5	1.4805
PCS-N		901	941			921	2.1430
L700	**A**	698	704	728	734	716	2.4299
L700	**B**	704	710	734	740	722	2.4198
L700	**C**	710	716	740	746	728	2.4098

To reiterate, the magnitude of the skin depth figures are based on the arbitrary choice of copper as a material. Therefore, the numbers that are weighted by Skin Depth in the market share analysis only carry relative, directional meaning.

There is also another notable calculation simplification here – the AWS band licenses are composed of very distinct upload and download channels, located in the 1700 and 2100 frequencies. When averaged for the regression model, the physical quality resembles that of the PCS-Broadband 1900 Band, when in practice this will not be the case[29].

Finally, the data that has been formatted for the regressions is presented:

AT&T	Verizon	T-Mobile	Sprint	Cricket	US Cellular	MetroPCS	Other	Bandwidth (MHz)	Population	Blocks	Owner	Bid Amount	Auction Winner	
0	0	1	0	0	0	0	0	20	3751674	1	T-Mobile	30048000	T-Mobile License LLC	
0	0	1	0	0	0	0	0	20	4279111	1	T-Mobile	36787000	T-Mobile License LLC	
0	0	1	0	0	0	0	0	20	8091720	1	T-Mobile	254821000	T-Mobile License LLC	
1	0	0	0	0	0	0	0	20	5120721	1	AT&T	50682000	Cingular AWS, LLC	
1	0	0	0	0	0	0	0	20	2405327	1	AT&T	12955000	Cingular AWS, LLC	

[29] Faulhaber, Assessing Competition in US Wireless Markets

(continued)

	Year	Avg Frequency	Skin Depth	AWS	WCS	PCS-BB	PCS-NB	SMR	Lower 700	Upper 700	700 Guard	License	Atlanta	Boston	Chicago	Dallas	Denver
	2006	1932.5	1.4888	1	0	0	0	0	0	0	0	A	1	0	0	0	0
	2006	1932.5	1.4888	1	0	0	0	0	0	0	0	A	0	1	0	0	0
	2006	1932.5	1.4888	1	0	0	0	0	0	0	0	A	0	0	1	0	0
	2006	1932.5	1.4888	1	0	0	0	0	0	0	0	A	0	0	0	1	0
	2006	1932.5	1.4888	1	0	0	0	0	0	0	0	A	0	0	0	0	1

V. Regressions Analyzing Bid Prices

To analyze components of Winning Bid Values at auction, I performed several sets of OLS regressions and have highlighted the four specifications below which provide the most interesting interpretations.

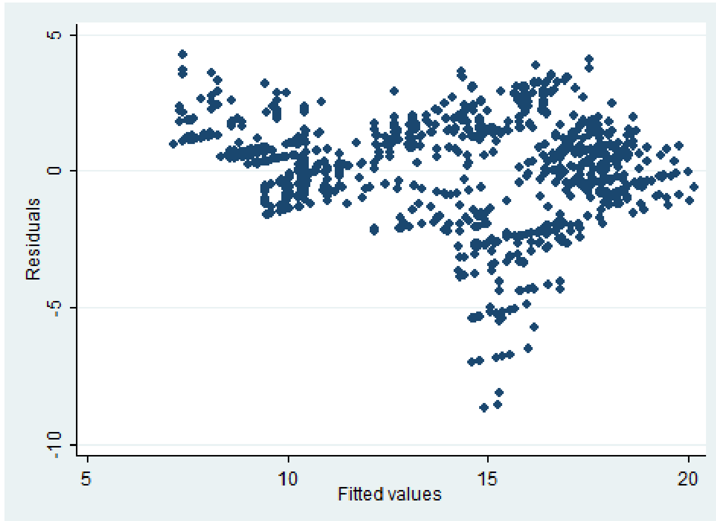
V.A. Adjusted Bid on Basic Factors

The initial model regresses the CPI-adjusted bid value against the basic explanatory factors, with the addition of Time as a control:

$$\ln(V_i) = \beta_1(\ln MHz_i) + \beta_2(\ln Pop_i) + \beta_3(\ln Time_i) \qquad \text{V.A.}$$

Observations	1172			
F(3, 1168)	1359.44		Prob > F	0
R-squared	0.7774		Adj R-squared	0.7768
log Bid (CPI Adj)	**Coefficient**	**Std. Error**	**t-stat**	**P-val**
log Bandwidth (MHz)	1.6925	0.0274	61.8100	0.0000
log Population	0.7637	0.0742	10.3000	0.0000
log Time (Year)	1.2767	0.0912	14.0100	0.0000
Constant	-1.6039	1.1518	-1.3900	0.1640

All the coefficients here are expected to be significant and positive as explanatory factors of bid value, except for the constant. This indeed is the case in the first regression, where the F-stat is very strong and the R^2 values are strong as well. However, the strange distribution of residuals indicates that more factors are likely at work here:



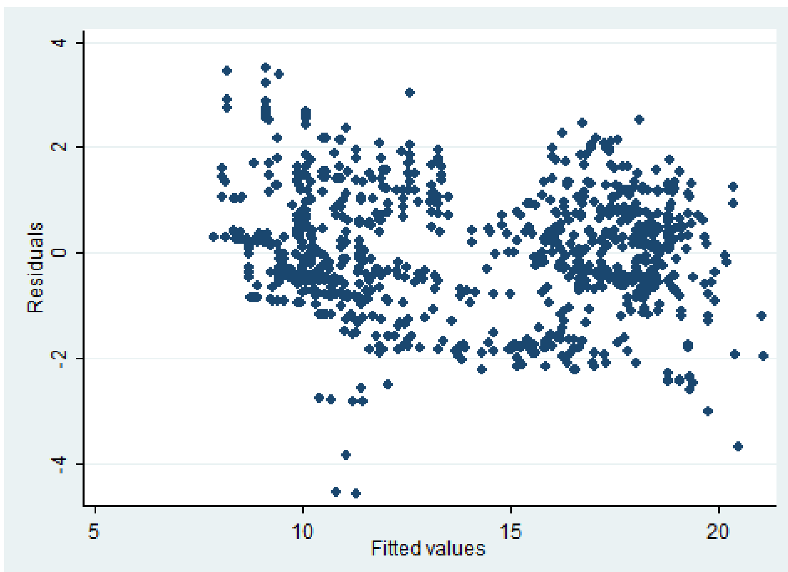
V.B. Adjusted Bid on Quality Fixed Effects (Bands)

The first sets of quality factors to examine are the fixed effect variables for each Band. These indicator variables account for both physical quality and rule-making in each license, and should have significant explanatory power:

$$\ln(V_i) = \beta_1(\ln MHz_i) + \beta_2(\ln Pop_i) + \beta_3(\ln Time_i) + \gamma_1(Band_i) \qquad \text{V.B.}$$

Observations	1172			
F(10, 1161)	1203.47		Prob > F	0
R-squared	0.912		Adj R-squared	0.9113
log Bid (CPI Adj)	**Coefficient**	**Std. Error**	**t-stat**	**P-val**
log Bandwidth (MHz)	1.9580	0.0504	38.8200	0.0000
log Population	1.0858	0.0497	21.8500	0.0000
log Time (Year)	1.6955	0.1074	15.7800	0.0000
AWS	0.9511	0.2709	3.5100	0.0000
WCS	-2.4901	0.3425	-7.2700	0.0000
PCS-BB	3.7702	0.3328	11.3300	0.0000
PCS-NB	3.6077	0.4120	8.7600	0.0000
SMR	1.9292	0.3585	5.3800	0.0000
Upper 700	(dropped)			
Lower 700	0.8178	0.2799	2.9200	0.0040
700 Guard	3.2482	0.3474	9.3500	0.0000
Constant	-9.3431	0.9495	-9.8400	0.0000

With this specification, simply adding in fixed effects for each Band adds a huge amount of explanatory power. Based on R^2 values, this regression explains just over 90% of variation in bid price. The residuals below appear more evenly distributed as well. The coefficients on the basic factors are still significant and positive, as expected. The coefficients on the fixed effects are all significant, but their signs and size are more difficult to predict and interpret. A notable observation is that most of the bands appear to be worth significantly more per-unit than the Upper 700 Band, which consists only of the 700 C Block carrying the open access rules.



V.C. Adjusted Bid on Quality Fixed Effects (Bands + 700) and Fixed Effects Controlling for City & Carrier

In the next stage, I add on two more sets of fixed effects indicators, one for the location of the license and one for the firm that wins the license, to examine whether companies or cities have any special effect on value. I also add more Band fixed effects by breaking the Lower 700 variable into five indicators, one for each block within the Lower 700 band, in an attempt to understand the discrepancy between the value for Upper 700 and Lower 700:

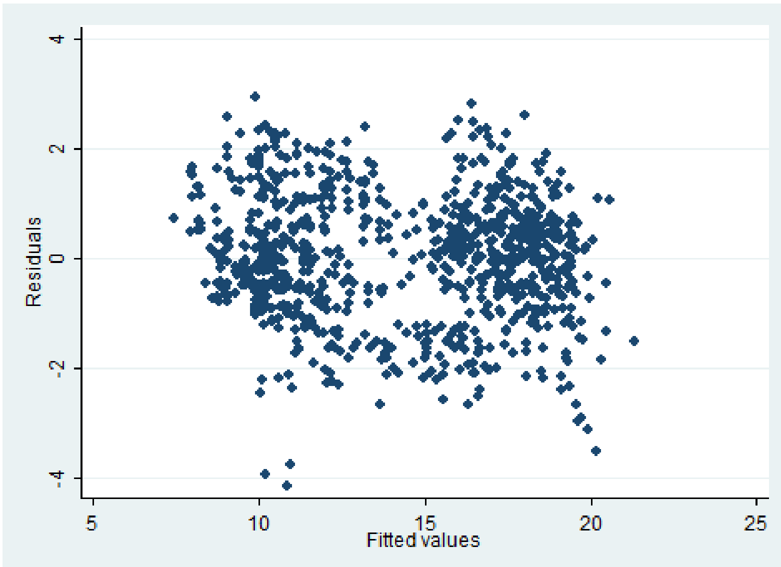
$$\ln(V_i) = \beta_1(\ln MHz_i) + \beta_2(\ln Pop_i) + \beta_3(\ln Time_i) + \gamma_1(Band_i) + \gamma_2(Carrier_i) + \gamma_3(City_i)$$

Observations	1172			
F(41, 1140)	398.05		Prob > F	0
R-squared	0.9352		Adj R-squared	0.9329
log Bid (CPI Adj)	**Coefficient**	**Std. Error**	**t-stat**	**P-val**
log Bandwidth (MHz)	1.8755	0.0450	41.7000	0.0000
log Population	1.2409	0.1001	12.4000	0.0000
log Time (Year)	1.3505	0.1012	13.3400	0.0000
AWS	1.0998	0.2594	4.2400	0.0000
WCS	-2.9856	0.3250	-9.1900	0.0000
PCS-BB	3.4414	0.3263	10.5500	0.0000
PCS-NB	3.1453	0.3937	7.9900	0.0000
SMR	1.7743	0.3728	4.7600	0.0000
Lower 700 A	1.5994	0.3176	5.0400	0.0000
Lower 700 B	2.8362	0.3519	8.0600	0.0000
Lower 700 C	-0.9050	0.3661	-2.4700	0.0140
Lower 700 D	-1.2039	0.3493	-3.4500	0.0010
Lower 700 E	1.8706	0.3516	5.3200	0.0000
Upper 700	(dropped)			
700 Guard	3.1131	0.3451	9.0200	0.0000
AT&T	0.5962	0.3840	1.5500	0.1210
Verizon	0.6143	0.3744	1.6400	0.1010
T-Mobile	0.1928	0.3818	0.5000	0.6140
Sprint	0.2563	0.4080	0.6300	0.5300
Cricket	0.2647	0.4247	0.6200	0.5330
US Cellular	(dropped)			
MetroPCS	0.9325	0.4414	2.1100	0.0350
Other	0.4688	0.3917	1.2000	0.2320
Constant	-11.5515	1.9057	-6.0600	0.0000

Not displayed: City Variables

After adding in numerous fixed effects, the loss of degrees of freedom brings down the F-stat but it remains at a highly significant level. The Adj. R^2 also increases with the addition of the variables. In this specification, it is revealed that the Lower 700 C & D licenses, sold in 2003, are valued much lower even after controlling for other factors. Further, none of the firms, besides

MetroPCS, appear to differ in their valuation of spectrum licenses. The coefficients of the city variables were omitted but generally, the larger cities had positive signs while the smaller city had negative signs. This could represent demographic factors or better efficiencies from density. The residuals of this regression cluster slightly closer together than in the last:



V.D. Adjusted Bid on Quality Fixed Effects (Bands + 700) and Fixed Effects Controlling for Frequency, City & Carrier

The final regression specification, based on the complete Bid Price model presented earlier as Equation 12, adds only the Frequency variable to the last regression. This importance of this factor leads to interesting results:

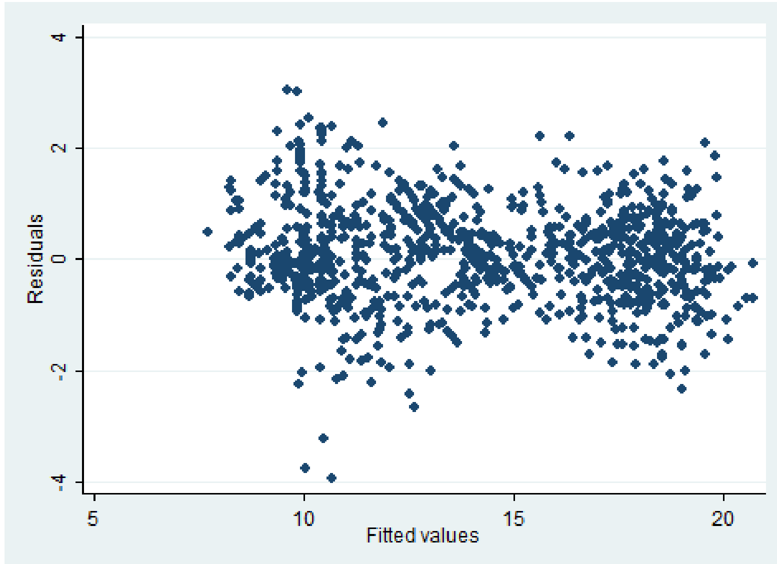
$$\ln(V_i) = \beta_1(\ln MHz_i) + \beta_2(\ln Pop_i) + \beta_3(\ln Time_i) + \beta_3(\ln Freq_i)$$
$$+ \gamma_1(Band_i) + \gamma_2(Carrier_i) + \gamma_3(City_i)$$

Observations	1172		
F(42, 1129)	509.75	Prob > F	0
R-squared	0.9499	Adj R-squared	0.948

log Bid (CPI Adj)	Coefficient	Std. Error	t-stat	P-val
log Bandwidth (MHz)	1.5011	0.0446	33.6500	0.0000
log Population	1.1085	0.0883	12.5500	0.0000
log Band Freq (MHz)	-95.0910	5.2305	-18.1800	0.0000
log Time (Year)	1.6255	0.0904	17.9900	0.0000
AWS	88.8125	4.8300	18.3900	0.0000
WCS	102.9879	5.8361	17.6500	0.0000
PCS-BB	91.2300	4.8373	18.8600	0.0000
PCS-NB	18.9220	0.9344	20.2500	0.0000
SMR	9.0008	0.5154	17.4600	0.0000
Lower 700 A	-5.1740	0.4657	-11.1100	0.0000
Lower 700 B	-3.0690	0.4487	-6.8400	0.0000
Lower 700 C	-5.8805	0.4227	-13.9100	0.0000
Lower 700 D	-7.4794	0.4622	-16.1800	0.0000
Lower 700 E	-3.7509	0.4374	-8.5800	0.0000
Upper 700	(dropped)			
700 Guard	2.9076	0.3039	9.5700	0.0000
AT&T	0.4035	0.3381	1.1900	0.2330
Verizon	0.6006	0.3295	1.8200	0.0690
T-Mobile	0.1970	0.3359	0.5900	0.5580
Sprint	0.5148	0.3593	1.4300	0.1520
Cricket	0.3153	0.3737	0.8400	0.3990
US Cellular	(dropped)			
MetroPCS	1.1175	0.3885	2.8800	0.0040
Other	0.1802	0.3450	0.5200	0.6020
Constant	622.8245	34.9341	17.8300	0.0000

Not displayed: City Variables

After controlling for both Frequency and the different 700 licenses, Adj R^2 reaches the highest value so far, explaining an incredible 95% of variation in Winning Bid Value. The coefficient on Frequency is highly significant and negative, as expected since higher Frequency spectrum is lower quality. A visual check of the residuals also indicates that the regression fits the observed bid values much more accurately:



The interesting difference here is in the 700 Bands. The Upper 700 C block is now shown to be worth more per unit rather than less when compared to the other 700 Band blocks. It is unclear as to why this would be the case, since the Open Access rules imposed on the block are disliked by the industry. One possibility is that Google helped push up the bid value of the block during the auction by setting a high initial bid[30]. Another potential explanation is the tiered-package bidding process and large designations implemented for the 700 C block auction. As explained in the literature, spectrum blocks can be complementary goods that are worth more when combined. With the structure of the 700 C block as 6 large, continuous Regional licenses and the ability to bid for them as all-or-nothing, it may be that the spectrum in C block is valuable for more than its propagation ability. Regardless, the continued significance of all the band fixed effects implies that spectrum policy and auction regulations still have an important effect on value when Frequency is isolated.

[30] To incentivize the FCC to impose Open Access rules, Google pledged a large initial bid for the Upper 700 C block of $4.6bil, above the reserve price so that the block was guaranteed to sell: http://www.wired.com/epicenter/2008/03/google-calls-70/

VI. Analyzing Quality-Adjusted Spectrum Shares

As the significance of quality factors, in particular Frequency and Skin Depth, are now established, this section can demonstrate the potential impact of including quality-adjusted in analysis of spectrum shares. There is a noticeable effect on non-population adjusted spectrum screen tests and a more dramatic effect on population adjusted spectrum shares. Finally, the potential impact of quality factors on HHI is demonstrated.

VI.A. Effect on Spectrum Screens

Here, I perform a standard spectrum screen as described in the methodology, using the cities and spectrum bands that were analyzed in the regression. The Cellular band that was previously excluded has been added back in. Before applying quality adjustments, 13 out of 21 markets pass the spectrum screen and afterwards, that figure becomes just 12 out of 21 markets.

Table 2
Basic & Quality-Adjusted Spectrum Screens (MHz %)

	Basic Spectrum Screen (% of MHz)		Quality-Adjusted Spectrum Screen (% of MHz-δ)	
	AT&T	**Verizon**	**AT&T**	**Verizon**
LOCATION				
Atlanta	35.7%	34.1%	35.7%	35.4%
Boston	29.3%	28.3%	31.9%	28.6%
Chicago	23.3%	37.3%	24.3%	39.6%
Dallas	37.0%	27.5%	40.1%	26.8%
Denver	27.8%	28.9%	29.8%	31.0%
Detroit	26.4%	23.5%	28.6%	26.6%
Houston	27.8%	34.1%	29.4%	35.3%
Kansas City	27.8%	26.2%	29.3%	28.8%
Los Angeles	38.2%	26.9%	37.5%	31.4%
Miami	31.2%	28.0%	33.1%	29.2%
Milwaukee	15.3%	24.9%	17.8%	24.9%
Minneapolis	18.0%	29.3%	20.0%	33.0%
New York	23.3%	34.2%	27.1%	35.2%
Philadelphia	25.1%	30.0%	28.5%	31.8%
Phoenix	26.4%	24.3%	25.8%	28.3%
San Diego	30.2%	27.4%	32.3%	28.3%

San Francisco	32.0%	23.5%		33.9%	26.6%
Seattle	19.8%	28.3%		23.2%	28.9%
St Louis	27.8%	17.7%		29.4%	20.2%
Tampa	35.7%	31.5%		35.7%	33.1%
Washington DC	35.9%	31.3%		36.3%	32.9%
	8 Concentrated Markets Highlighted			9 Concentrated Markets Highlighted	

VI.B. Effect on Population Adjusted Spectrum Share

The contrast using quality-adjusted figures becomes more prominent once the spectrum shares are stated as MHz-Pop quantities as the FCC reports commonly use[31].

Table 3

Basic Spectrum Ownership (% of MHz-Population)

	AT&T	**Verizon**	**T-Mobile**	**Sprint**	**Cricket**	**US Cell**	**MetroPCS**	**Other**	**Total**	HHI
LOCATION										
Atlanta	34.4%	**38.5%**	14.1%	5.2%	0.0%	0.0%	4.2%	3.6%	100%	2921
Boston	27.0%	**28.2%**	10.1%	18.1%	0.0%	0.0%	7.3%	9.3%	100%	2091
Chicago	21.0%	**40.4%**	17.1%	9.0%	5.5%	0.0%	0.0%	7.0%	100%	2527
Dallas	25.8%	**35.0%**	9.3%	15.3%	5.0%	0.0%	2.5%	7.1%	100%	2294
Denver	21.8%	**32.7%**	10.3%	14.0%	5.5%	2.8%	0.0%	12.9%	100%	2053
Detroit	23.0%	**27.5%**	18.9%	15.2%	5.3%	0.0%	2.2%	7.9%	100%	1970
Houston	25.8%	**35.4%**	9.1%	7.4%	7.4%	0.0%	0.0%	15.0%	100%	2335
Kansas City	20.7%	**36.5%**	11.9%	9.9%	3.6%	8.6%	0.0%	8.8%	100%	2168
Los Angeles	**36.0%**	27.5%	7.2%	6.8%	0.0%	0.0%	6.9%	15.6%	100%	2440
Miami	26.1%	**36.3%**	18.3%	12.5%	0.0%	0.0%	4.5%	2.2%	100%	2517
Milwaukee	11.4%	**31.7%**	6.2%	17.0%	6.6%	7.9%	0.0%	19.3%	100%	1938
Minneapolis	13.5%	**30.3%**	7.4%	15.0%	8.6%	0.0%	0.0%	25.3%	100%	2092
New York	18.4%	**35.7%**	10.2%	17.8%	0.0%	0.0%	7.2%	10.7%	100%	2202
Philadelphia	26.6%	**29.0%**	6.1%	6.6%	3.8%	0.0%	3.3%	24.7%	100%	2263
Phoenix	**28.3%**	24.0%	9.3%	12.7%	5.0%	0.0%	0.0%	20.7%	100%	2079
San Diego	**29.5%**	28.5%	11.7%	6.4%	6.8%	0.0%	5.0%	12.1%	100%	2080
San Francisco	**29.3%**	22.7%	6.6%	17.3%	0.0%	2.8%	10.0%	11.4%	100%	1950
Seattle	15.4%	**30.1%**	11.8%	15.0%	3.4%	0.0%	4.4%	19.9%	100%	1934
St Louis	24.4%	**30.3%**	13.1%	10.3%	2.2%	13.3%	0.0%	6.3%	100%	2017
Tampa	**34.0%**	33.2%	11.1%	7.4%	0.0%	0.0%	0.0%	14.4%	100%	2639
Washington DC	29.2%	**38.2%**	14.8%	5.4%	2.9%	0.0%	0.0%	9.4%	100%	2660
TOTAL	25.2%	**32.4%**	11.2%	11.9%	2.7%	1.2%	3.6%	11.8%	100%	2113

31 FCC MWC report

Table 4

Quality-Adjusted Spectrum Ownership (% of MHz-Population-Skin Depth)

	AT&T	Verizon	T-Mobile	Sprint	Cricket	US Cell	MetroPCS	Other	Total	HHI
LOCATION										
Atlanta	32.9%	**40.9%**	11.8%	6.1%	0.0%	0.0%	3.5%	4.7%	100%	2970
Boston	28.4%	**28.9%**	8.5%	18.4%	0.0%	0.0%	8.1%	7.8%	100%	2176
Chicago	21.4%	**43.6%**	14.0%	9.9%	4.5%	0.0%	0.0%	6.5%	100%	2720
Dallas	27.9%	**35.9%**	7.7%	15.3%	4.1%	0.0%	2.1%	6.8%	100%	2431
Denver	23.0%	**36.3%**	8.3%	14.1%	4.6%	2.3%	0.0%	11.4%	100%	2268
Detroit	23.8%	**31.7%**	15.6%	15.3%	4.4%	0.0%	1.8%	7.3%	100%	2127
Houston	26.8%	**37.9%**	7.5%	8.5%	6.1%	0.0%	0.0%	13.2%	100%	2496
Kansas City	20.1%	**41.8%**	9.8%	10.0%	3.0%	7.2%	0.0%	8.1%	100%	2476
Los Angeles	**35.2%**	32.5%	5.9%	8.4%	0.0%	0.0%	5.6%	12.3%	100%	2588
Miami	27.0%	**38.7%**	15.0%	12.6%	0.0%	0.0%	3.7%	2.9%	100%	2636
Milwaukee	12.8%	**33.1%**	5.3%	17.1%	5.6%	9.3%	0.0%	16.8%	100%	1979
Minneapolis	14.6%	**35.2%**	6.2%	15.2%	7.2%	0.0%	0.0%	21.7%	100%	2242
New York	21.8%	**37.2%**	8.4%	18.0%	0.0%	0.0%	5.9%	8.7%	100%	2364
Philadelphia	30.0%	**30.7%**	5.0%	8.3%	3.1%	0.0%	2.7%	20.2%	100%	2363
Phoenix	27.7%	**28.4%**	7.7%	12.7%	4.1%	0.0%	0.0%	19.4%	100%	2188
San Diego	**31.4%**	30.2%	9.1%	7.6%	5.3%	0.0%	3.9%	12.5%	100%	2240
San Francisco	**29.1%**	26.9%	5.6%	17.7%	0.0%	2.4%	8.5%	9.7%	100%	2090
Seattle	17.3%	**31.6%**	9.9%	15.5%	2.9%	0.0%	3.7%	19.2%	100%	2024
St Louis	23.8%	**35.2%**	10.9%	10.3%	1.9%	12.1%	0.0%	5.8%	100%	2214
Tampa	33.6%	**35.2%**	9.4%	8.2%	0.0%	0.0%	0.0%	13.6%	100%	2706
Washington DC	28.6%	**41.0%**	12.0%	6.7%	2.4%	0.0%	0.0%	9.3%	100%	2781
TOTAL	26.1%	**35.3%**	9.2%	12.6%	2.2%	1.1%	3.1%	10.4%	100%	2298

In these tables, the spectrum share leader is bolded in each market. The quality adjustment causes the market share order or even market leader to shift in some cases. This could be an indication that quality disparities are systematic among the different carriers.

Table 5

Difference in Spectrum Ownership (Quality Adj. – Basic)

	AT&T	Verizon	T-Mobile	Sprint	Cricket	US Cell	MetroPCS	Other	Total	ΔHHI
LOCATION										
Atlanta	-1.5%	2.4%	-2.3%	0.9%	0.0%	0.0%	-0.7%	1.1%	0%	50
Boston	1.4%	0.7%	-1.6%	0.3%	0.0%	0.0%	0.8%	-1.5%	0%	85
Chicago	0.4%	3.2%	-3.1%	0.9%	-0.9%	0.0%	0.0%	-0.5%	0%	194
Dallas	2.1%	0.9%	-1.5%	0.0%	-0.8%	0.0%	-0.4%	-0.3%	0%	137

Denver	1.2%	3.5%	-2.0%	0.2%	-0.9%	-0.5%	0.0%	-1.5%	0%	215
Detroit	0.8%	4.2%	-3.3%	0.1%	-0.9%	0.0%	-0.4%	-0.6%	0%	158
Houston	1.0%	2.5%	-1.6%	1.1%	-1.3%	0.0%	0.0%	-1.7%	0%	160
Kansas City	-0.6%	5.3%	-2.1%	0.2%	-0.6%	-1.4%	0.0%	-0.7%	0%	308
Los Angeles	-0.8%	5.1%	-1.3%	1.6%	0.0%	0.0%	-1.3%	-3.3%	0%	148
Miami	0.9%	2.4%	-3.3%	0.1%	0.0%	0.0%	-0.8%	0.7%	0%	118
Milwaukee	1.4%	1.4%	-0.9%	0.1%	-0.9%	1.4%	0.0%	-2.5%	0%	40
Minneapolis	1.1%	4.9%	-1.2%	0.2%	-1.4%	0.0%	0.0%	-3.6%	0%	150
New York	3.4%	1.4%	-1.8%	0.2%	0.0%	0.0%	-1.3%	-2.0%	0%	162
Philadelphia	3.5%	1.7%	-1.1%	1.7%	-0.7%	0.0%	-0.6%	-4.4%	0%	101
Phoenix	-0.7%	4.5%	-1.6%	0.0%	-0.9%	0.0%	0.0%	-1.3%	0%	109
San Diego	2.0%	1.6%	-2.6%	1.2%	-1.5%	0.0%	-1.1%	0.4%	0%	160
San Francisco	-0.2%	4.2%	-1.0%	0.4%	0.0%	-0.4%	-1.5%	-1.6%	0%	139
Seattle	1.9%	1.5%	-1.9%	0.5%	-0.6%	0.0%	-0.7%	-0.7%	0%	91
St Louis	-0.6%	4.8%	-2.2%	0.1%	-0.4%	-1.2%	0.0%	-0.5%	0%	197
Tampa	-0.4%	2.0%	-1.7%	0.8%	0.0%	0.0%	0.0%	-0.7%	0%	67
Washington DC	-0.6%	2.8%	-2.8%	1.3%	-0.6%	0.0%	0.0%	-0.2%	0%	122
AVERAGE	0.8%	2.9%	-1.9%	0.6%	-0.6%	-0.1%	-0.4%	-1.2%	0%	139

When looking at the change in apparent spectrum share, it appears that the market power of AT&T, Verizon and Sprint has increased on average, while the market power for the remaining carriers has decreased. In particular, Verizon's apparent market presence has increased in every city, strongly suggesting a systematic quality discrepancy in Verizon's favor. Further, the changes in HHI here suggest that dramatic shifts in perceived market concentration are possible after considering quality factors.

VI.C. Effect on HHI

Finally, the next two tables study the implications of HHI in more detail. In FCC reports, there are true HHI figures for each market, which can be averaged for an overall HHI figure. In Table 6, the basic spectrum share HHI's and quality-adjusted spectrum share HHI's for the same markets as the true HHI's are also averaged. In aggregate, the quality-adjusted HHI comes closer to the true HHI than the basic HHI, indicating that quality-adjusted shares could lead to a better proxy of actual market share.

Table 6

FCC Reported HHI by Market (as of 2009)

LOCATION	True HHI
Atlanta	2452
Boston	2752
Chicago	2070
Dallas	2614
Denver	2387
Detroit	2815
Houston	2268
Kansas City	2289
Los Angeles	2365
Miami	2238
Milwaukee	2100
Minneapolis	2689
New York	2556
Philadelphia	2498
Phoenix	2792
San Diego	2543
San Francisco	2662
Seattle	2702
St Louis	2669
Tampa	2257
Washington DC	2683

AVERAGES	
True HHI	2495
Basic HHI	2246
Δ Basic	-249
QA HHI	2385
Δ QA	-111

As a check on the true HHI figures from the FCC, the aggregate true HHI aligns closely with an HHI based on self-reported subscribership from each carrier:

Table 7

Self- Reported Nationwide Subscriber Numbers (as of Sept. 2011)

	AT&T	Verizon	T-Mobile	Sprint	Cricket	US Cell	MetroPCS	Other	Total	
No. of Subscribers (in mil)	100.7	107.7	33.711	53.4	5.934	5.891	9.3	6.264	322.9	HHI
% of Subscribers (in mil)	31.19%	33.35%	10.44%	16.54%	1.84%	1.82%	2.88%	1.94%	100.0%	2486

VII. Conclusions

This paper set out to better understand the competition in the mobile wireless industry by examining the value of local spectrum licenses, specifically in relation to spectrum quality. A review of the literature covering wireless telecom competition revealed many discussions on using spectrum as a measure of competitiveness and some commentary on the presence of higher quality and lower quality spectrum. However, it did not appear that any studies applied these two concepts to advance an understanding of spectrum value. The analysis in this paper works to bridge that gap and help bring new insights that can have important regulatory consequences.

A complete model for winning bid price is revealed to be highly accurate in predicting actual bid prices at auction and affirms the basic economic rationality of telecom firms. Given that the components of the model are intuitive, this result does not appear to be incredibly surprising. However, what may be interesting is the implication of the quality factors used in the model.

The impact of the quality factors appears to be two-fold: First, market share analyses can be skewed by systematic quality disparities. Second, accounting for quality factors can help design better regulation for spectrum bands and spectrum auctions.

The significance of spectrum quality in the regressions and some of the dramatic, uniform shifts in spectrum share figures suggest that quality of spectrum captures a competitive dynamic that is currently not considered in competitive studies of the wireless industry. This is certainly only a preliminary result, as study of quality factors distinct from frequency is incomplete in this paper. However, it appears to glance at an area of market share analysis that has yet to be explored by government economists.

The importance of quality in explaining bid value, as illustrated by the regressions, should also be of interest to FCC economists as the agency plans for more spectrum auctions. In the upcoming Upper 700 D re-auctions, understanding the impact of regulation on spectrum value will help to avoid the embarrassing lack of interest in the original Upper 700 D auction. Again, a more detailed specification including regulation variables should be developed to fully explain the impact of quality. In future auctions, understanding spectrum quality will help the agency to better predict the results of auctions and design auctions or even spectrum bands that can maximize value for both the FCC and the industry.

VIII. References

Data Sources

FCC Wireless Bureau. Auction Data. Retrieved from http://wireless.fcc.gov/auctions/default.htm?job=auctions_data

Penn State Center on Auctions, Procurements and Competition Policy. Retrieved from http://capcp.psu.edu/data.html

Skin Depth Calculator. *Microwave Encyclopedia*. Retrieved from http://www.microwaves101.com/encyclopedia/calsdepth.cfm

Literature

Connolly, M and Evan Kwerel (2007). Economics at the FCC. *Review of Industrial Organization*, November 2007, Vol. 31: 107-120.

Daljord, Oystein (2009). An Exact Arithmetic SSNIP Test for Asymmetric Products. *Journal of Competition Law & Economics*, 5(3)563-569.

Dobbs, M (2003). Demand, cost elasticities, and pricing benchmarks in the hypothetical monopoly test: the consequences of a simple SSNIP. *Applied Economics Letters* 2003, 10, 545-548.

Faulhaber, Gerald, Robert Hahn and Hal Singer. Assessing Competition in US Wireless Markets: Review of the FCC's Competition Reports. Retrieved from http://ssrn.com/abstract=1880964

Marx, Leslie (Sept. 4, 2011). Report on the proposed acquisition of T-Mobile by AT&T.

Newbery, David (Mar 2009). Predicting Market Power in Wholesale Electricity Markets. EUI Working Papers. RSCAS

Press Releases

Brome, Rich. (Mar 27, 2008). A Visual Guide to 700 MHz. *PhoneScoop.com*. Retrieved from http://www.phonescoop.com/articles/article.php?a=187&p=232

Engleman, Eric and Christ Strohm (Dec 23 2011). AT&T's $1.93 Billion Qualcomm Airwaves Purchase Wins Approval. *Bloomberg*. Retrieved from http://www.bloomberg.com/news/2011-12-22/qualcomm-1-93-billion-airwaves-sale-to-at-t-wins-u-s-approval.html

Federal Communications Commission (2010). Mobile Wireless Competition Report (14th Annual). Retrieved from http://www.fcc.gov/reports/mobile-wireless-competition-report-14th-annual

Riegler, Paul (Feb 14, 2012). FCC Bars LightSquared Broadband Network Plan. *Frequent Business Traveler*. Retrieved from http://www.frequentbusinesstraveler.com/2012/02/fcc-bars-lightsquared-broadband-network-plan/

Rose, Brent (Oct 7 2011). Sprint Is Ditching 4G WiMax for 4G LTE. *Gizmodo.com* Retrieved from http://gizmodo.com/5847643/its-official-sprint-is-going-lte

Savov, Vlad (Mar 20, 2011). AT&T agrees to buy T-Mobile USA. *Engadget.com*. Retrieved from http://www.engadget.com/2011/03/20/atandt-agrees-to-buy-t-mobile-from-deutsche-telekom/

Pinchefsky, Carol (Mar. 19, 2009). Ethical Concerns Swirl Around D Block Spectrum Auction. *eWeek.com.* Retrieved from *http://www.eweek.com/c/a/Mobile-and-Wireless/Ethical-Concerns-Swirl-Around-D-Block-Spectrum-Auction/1/*

Regulatory Documents

Federal Communications Commission (2010). Personal Communications Services. *Code of Federal Regulations*. Retrieved from http://www.gpo.gov/fdsys/pkg/CFR-2010-title47-vol2/xml/CFR-2010-title47-vol2-part24.xml

US Department of Justice, the Federal Trade Commission (2010). Horizontal Merger Guidelines.

IX. Appendices

A. Variable Descriptions

Winning Bid Price	The amount, in 2008 US Dollars, which a company bid to win the licenses for the blocks of spectrum in the local area. The same bands of spectrum space can be more valuable in different locations depending on the local market demographics, policies and geographic characteristics. This measure should show that firms are rational and efficient bidders for spectrum at unrestrictive auctions.
CPI	As spectrum auctions are only held sporadically, the prices at each auction must be adjusted by year held. Auctions are a recent practice, so CPI will only be listed back to 1994.
Bandwidth	The amount of spectrum, in MHz, that a given license covers. This variable controls for the different sizes of licenses that companies may own and for the different sizes of licenses in the same metro area. All else equal, a spectrum license with more bandwidth will be more valuable.
Population	The number of people, in millions, who reside in a location and will be served by a given spectrum license. This variable controls for varying populations in different metro areas and varying definitions of a metro area between different bands. All else equal, a spectrum serving more people will be more valuable.
Band Freq (Frequency)	The average frequency, in MHz, that a band of spectrum covers. Spectrum licenses operate on specific band categories and are sold in auctions by band category. This average assumption enhances the regression ability for frequency and simplifies the Skin Depth calculation. It also reduces some preciseness in measuring physical spectrum quality because many licenses are defined as paired channels with 2 different ranges of frequency. Since higher frequencies have worse propagation characteristics, it is expected that higher frequency spectrum will be less valuable.
Band (Fixed Effect)	This is an indicator for the spectrum band that a license belongs in. It is an effective proxy for the overall quality of a spectrum license since it can capture both the physical and regulatory quality of a block of spectrum. However, this also means that the cause of value from a fixed effect, whether it is physical or regulatory, for a band will be unclear.
Time (Annual)	A time trend variable based on the year the spectrum was sold. Since the auctions of spectrum only began in 1994, that year will be 0 and each year afterwards will increase Time by 1. As spectrum has become more valuable due to the proliferation of mobile phones, this variable will capture the effect of progress and technological change on price, independent of inflation.
Market (Fixed Effect)	The local market defined for a certain spectrum license. Each auction may have a different method of dividing up the areas of the US, such as Economic Area (EA), Cellular Market Area (CMA), etc, which leads to a different population size per market. Regardless, each license is still based around a major metropolitan area. This dummy accounts for fixed effects of locations, such as demographics and topography, which would make licenses more valuable.
Carrier (Fixed Effect)	The major carrier that owns the spectrum license in a given area. If the carrier is a smaller or unknown company, it is listed as Other. Oftentimes, licenses are won and transferred or held by shell companies. This dummy accounts for fixed effects unique to carriers, such as any efficiencies and proprietary technology, which would make spectrum more valuable.

B. STATA Output Script

lnregression.do

```
log using lnbidregress.log, replace
insheet using C:\Users\ssz3\Dropbox\Desktop\ECON198\regressions\specdata.csv

gen logadjbid = log((bid*cpi))
gen logmhz = log(mhz)
gen logpop = log(population)
gen logtime = log(time)
gen logsd = log(sd)
gen logfreq = log(avgfreq)

gen A700 = 0
gen B700 = 0
gen C700L = 0
gen D700L = 0
gen E700 = 0


replace A700 = 1 if a*l700 > 0
replace B700 = 1 if b*l700 > 0
replace C700L = 1 if c*l700 > 0
replace D700L = 1 if d*l700 > 0
replace E700 = 1 if e*l700 > 0

summarize

regress logadjbid logmhz logpop logtime

regress logadjbid logmhz logpop logtime logfreq

regress logadjbid logmhz logpop logtime logfreq A700 B700 C700L D700L E700 u700

regress logadjbid logmhz logpop logtime aws wcs pcsb pcsn smr A700 B700 C700L D700L
E700 u700 g700 att vzw tmo spr crk usc met oth atl bos chi dal den det hou kan los mia
mil min new phi pho sand sanf sea stl tam was

regress logadjbid logmhz logpop logfreq logtime A700 B700 C700L D700L E700 u700 att
vzw tmo spr crk usc met oth atl bos chi dal den det hou kan los mia mil min new phi
pho sand sanf sea stl tam was

capture log close
```

C. Additional Tables

	Basic Spectrum Ownership in MHz-Pop								
	AT&T	Verizon	T-Mobile	Sprint	Cricket	US Cell	MetroPCS	Other	Total
LOCATION									
Atlanta	786.6675	880.4	323.6	119.3	0.0	0.0	95.9	81.9	2287.8
Boston	708.8751	740.2	265.4	474.6	0.0	0.0	192.6	245.5	2627.3
Chicago	961.3143	1852.8	782.2	414.0	249.9	0.0	0.0	322.8	4582.9
Dallas	778.6822	1055.3	279.1	460.5	149.2	0.0	76.5	215.0	3014.2

Denver	307.3063	461.3	144.4	196.6	77.8	39.8	0.0	181.4	1408.6
Detroit	732.2541	875.3	599.7	482.7	168.5	0.0	69.6	251.6	3179.6
Houston	563.6578	772.0	197.8	160.8	160.4	0.0	0.0	326.3	2180.9
Kansas City	308.9111	544.3	177.9	146.8	53.0	128.3	0.0	130.6	1489.8
Los Angeles	2219.468	1691.5	444.3	419.0	0.0	0.0	428.2	959.3	6161.7
Miami	564.7661	787.0	397.4	270.6	0.0	0.0	98.1	48.5	2166.4
Milwaukee	133.9096	373.1	73.1	200.3	77.1	92.9	0.0	226.7	1177.2
Minneapolis	259.6078	584.3	141.8	288.5	165.6	0.0	0.0	486.8	1926.5
New York	1469.215	2852.3	817.3	1416.7	0.0	0.0	571.2	853.6	7980.3
Philadelphia	712.9082	779.5	162.4	177.0	100.7	0.0	89.3	661.5	2683.4
Phoenix	378.9904	320.6	124.6	170.0	66.5	0.0	0.0	276.7	1337.3
San Diego	245.6589	237.7	97.6	53.7	56.3	0.0	41.3	100.6	832.9
San Francisco	956.4334	742.2	216.2	565.2	0.0	91.1	326.4	372.1	3269.6
Seattle	211.1796	412.7	161.5	204.8	46.9	0.0	60.7	272.4	1370.1
St Louis	548.3735	681.1	294.6	230.8	50.4	298.8	0.0	140.9	2245.1
Tampa	473.2742	462.5	154.1	103.3	0.0	0.0	0.0	200.1	1393.3
Washington DC	832.2405	1089.8	422.9	154.0	83.7	0.0	0.0	268.6	2851.1
TOTAL	14153.7	18195.7	6277.8	6709.4	1505.9	651.0	2049.8	6622.7	56166.0

	Basic Spectrum Ownership in MHz								
	AT&T	**Verizon**	**T-Mobile**	**Sprint**	**Cricket**	**US Cell**	**MetroPCS**	**Other**	**Total**
LOCATION									
Atlanta	135	129	40	28.25	0	0	30	15.963	378.2
Boston	111	107	50	55	0	0	22	33.213	378.2
Chicago	88	141	70	45.5	10	0	0	23.713	378.2
Dallas	140	104	40	55.25	10	0	10	18.963	378.2
Denver	105	109	30	55.25	10	10	0	58.402	377.7
Detroit	100	89	90	55.5	10	0	10	23.713	378.2
Houston	105	129	30	35.5	20	0	0	58.713	378.2
Kansas City	105	99	30	55.5	30	10	0	48.713	378.2
Los Angeles	129	91	20	25.5	0	0	20	52.538	338.0
Miami	118	106	60	55.25	0	0	30	8.9625	378.2
Milwaukee	58	94	20	55.5	20	57	0	73.713	378.2
Minneapolis	68	111	20	55.5	30	0	0	93.713	378.2
New York	81	119	40	55.25	0	0	20	32.963	348.2
Philadelphia	91	109	20	25	20	0	10	88.213	363.2
Phoenix	100	92	30	55.5	10	0	0	90.713	378.2
San Diego	85	77	30	21.5	20	0	10	38	281.5
San Francisco	121	89	30	54	0	10	40	34.213	378.2
Seattle	75	107	40	55.5	20	0	10	70.713	378.2
St Louis	105	67	50	55.5	20	42	0	38.713	378.2
Tampa	135	119	40	41.5	0	0	0	42.713	378.2
Washington DC	125	109	30	20.5	20	0	0	43.713	348.2

	QA Spectrum Ownership in MHz-Pop-SD								
	AT&T	**Verizon**	**T-Mobile**	**Sprint**	**Cricket**	**US Cell**	**MetroPCS**	**Other**	**Total**
LOCATION									
Atlanta	1338.59	1664.08	481.72	247.49	0.00	0.00	142.43	192.00	4066.31
Boston	1327.05	1351.70	395.66	858.40	0.00	0.00	377.91	364.52	4675.23
Chicago	1759.06	3585.55	1146.94	814.33	372.05	0.00	0.00	536.57	8214.50
Dallas	1496.32	1923.72	415.06	821.19	222.17	0.00	113.83	366.92	5359.19
Denver	581.05	916.85	209.65	357.49	115.77	59.31	0.00	288.61	2528.73
Detroit	1346.74	1791.87	879.00	864.46	250.83	0.00	103.67	412.18	5648.76
Houston	1055.69	1490.80	294.50	334.31	238.60	0.00	0.00	520.68	3934.58
Kansas City	534.32	1112.49	260.90	266.60	78.84	191.06	0.00	215.27	2659.48
Los Angeles	3975.68	3666.97	661.45	953.18	0.00	0.00	636.51	1386.71	11280.50
Miami	1063.59	1525.11	591.73	496.53	0.00	0.00	145.70	115.88	3938.53
Milwaukee	261.38	677.16	108.77	351.10	114.81	191.11	0.00	343.12	2047.44
Minneapolis	497.74	1203.23	210.94	517.87	246.48	0.00	0.00	741.87	3418.14
New York	3161.51	5381.63	1218.53	2604.69	0.00	0.00	850.45	1260.14	14476.96
Philadelphia	1462.29	1495.59	241.77	402.61	149.97	0.00	132.95	986.15	4871.32
Phoenix	666.06	684.45	185.54	304.69	99.01	0.00	0.00	466.47	2406.22
San Diego	499.71	479.56	145.27	121.33	83.68	0.00	61.49	197.93	1588.97
San Francisco	1659.22	1534.79	321.90	1010.95	0.00	135.66	485.16	554.91	5702.59
Seattle	421.69	769.21	240.26	376.35	69.77	0.00	90.37	467.88	2435.54
St Louis	959.69	1414.93	438.58	416.00	74.99	485.64	0.00	234.06	4023.90
Tampa	818.86	858.08	229.48	200.63	0.00	0.00	0.00	332.39	2439.44
Washington DC	1496.09	2142.93	629.67	350.14	124.54	0.00	0.00	483.60	5226.97
TOTAL	26382.31	35670.71	9307.31	12670.36	2241.51	1062.78	3140.46	10467.86	100943.31

	QA Spectrum Ownership in MHz-SD								
	AT&T	**Verizon**	**T-Mobile**	**Sprint**	**Cricket**	**US Cell**	**MetroPCS**	**Other**	**Total**
LOCATION									
Atlanta	244.25	241.76	59.55	56.50	0.00	0.00	44.55	37.27	683.88
Boston	218.38	195.69	74.56	101.66	0.00	0.00	44.21	49.39	683.88
Chicago	166.50	270.70	102.77	87.84	14.89	0.00	0.00	41.19	683.88
Dallas	274.25	183.24	59.44	102.22	14.89	0.00	14.89	34.96	683.88
Denver	203.50	211.72	43.30	102.46	14.89	14.89	0.00	92.30	683.05
Detroit	195.55	182.02	132.57	102.79	14.89	0.00	14.89	41.19	683.88
Houston	200.77	241.48	44.66	72.93	29.74	0.00	0.00	94.30	683.88
Kansas City	200.52	197.00	43.32	103.02	44.61	14.89	0.00	80.53	683.88
Los Angeles	233.71	196.08	29.78	57.95	0.00	0.00	29.72	76.35	623.58
Miami	226.14	199.98	89.35	102.46	0.00	0.00	44.55	21.41	683.88
Milwaukee	121.40	170.54	29.78	103.02	29.78	115.17	0.00	114.21	683.88
Minneapolis	136.45	225.83	29.74	103.02	44.66	0.00	0.00	144.18	683.88
New York	173.33	225.01	59.65	102.22	0.00	0.00	29.78	48.83	638.81
Philadelphia	188.62	210.22	29.78	56.82	29.78	0.00	14.89	131.53	661.63
Phoenix	176.21	193.63	44.66	102.79	14.89	0.00	0.00	151.71	683.88
San Diego	173.72	152.39	44.66	48.57	29.74	0.00	14.89	73.69	537.66
San Francisco	231.82	181.77	44.66	99.62	0.00	14.89	59.44	51.68	683.88
Seattle	158.85	197.50	59.51	102.79	29.78	0.00	14.89	120.56	683.88

St Louis	200.91	137.81	74.42	102.79	29.78	73.99	0.00	64.20	683.88
Tampa	244.02	226.61	59.55	78.71	0.00	0.00	0.00	74.99	683.88
Washington DC	231.96	210.18	44.68	46.60	29.78	0.00	0.00	75.61	638.81

	True HHI	Basic HHI	Δ Basic	QA HHI	Δ QA
LOCATION					
Atlanta	2452	2921	469	2970	518
Boston	2752	2091	-661	2176	-576
Chicago	2070	2527	457	2720	650
Dallas	2614	2294	-320	2431	-183
Denver	2387	2053	-334	2268	-119
Detroit	2815	1970	-845	2127	-688
Houston	2268	2335	67	2496	228
Kansas City	2289	2168	-121	2476	187
Los Angeles	2365	2440	75	2588	223
Miami	2238	2517	279	2636	398
Milwaukee	2100	1938	-162	1979	-121
Minneapolis	2689	2092	-597	2242	-447
New York	2556	2202	-354	2364	-192
Philadelphia	2498	2263	-235	2363	-135
Phoenix	2792	2079	-713	2188	-604
San Diego	2543	2080	-463	2240	-303
San Francisco	2662	1950	-712	2090	-572
Seattle	2702	1934	-768	2024	-678
St Louis	2669	2017	-652	2214	-455
Tampa	2257	2639	382	2706	449
Washington DC	2683	2660	-23	2781	98
AVERAGE	2495	2246	-249	2385	-111