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Spectrum Concentration and Performance of the U.S. Wireless Industry

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Abstract

This paper estimates the empirical relationship between concentration in mobile carriers' holdings of radio spectrum and the performance of the U.S. wireless industry. Reduced-form regressions that use a 2012-2013 cross-section of approximately 700 Cellular Market Areas reveal a robust inverted-U relationship between spectrum HHIs and subscriber penetration rates—a measure of consumer welfare. The marginal effect of spectrum concentration is positive throughout the range of sampled markets—contrary to the conventional concentration-performance hypothesis. This pattern persists when spectrum concentration is separately measured for bands below 1GHz and for rural areas. It is also shown not to be biased by the potential endogeneity of spectrum HHIs. This paper is distinguished by relating subscriber penetration rates to the quality and coverage of operator networks that supports efficiency explanations for operator size, and hence the benefits of structural concentration. These findings cast doubt on federal policies adopted as early as the 1927 Radio Act that attempt to equalize ownership of spectrum. Instead, our empirical results recommend measures that promote investment in wireless infrastructure and other non-spectrum factors.

Keywords: spectrum concentration; industry performance; mobile wireless services

JEL Codes: L11, L13, L86, L96

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I. INTRODUCTION

Since the birth of the U.S. cellular industry, policy makers have allocated radio spectrum with the aim to limit concentration in the downstream mobile services market. To promote this competition, the Federal Communications Commission (FCC) has used its authority to ensure that commercial airwaves did not end up concentrated among a few owners. Similarly, antitrust authorities have been wary of threats to competition posed by aggregation of radio spectrum. The anticompetitive use of spectrum licenses was foreseen as far back as the *Radio Act of 1927*, which cautioned against issuing broadcast licenses that could be used "to substantially lessen competition or to restrain commerce."[1] More recently, the Department of Justice expressed concern that incumbent wireless carriers could acquire spectrum licenses for the purpose of foreclosing new entrants or constraining smaller rivals.[2]

The economic underpinnings of these spectrum policies can be traced to the conventional structure-conduct-performance paradigm of industrial organization. The Commission's spectrum policies are consistent with the proposition that poor performance is a likely consequence of concentration in the supply of mobile services, and further, that structural concentration that is measured in terms of subscriber market shares is inherited directly from concentration in spectrum holdings.[3]

This paper tests this causal chain empirically by estimating the relationship between spectrum concentration and mobile subscription penetration where subscriptions serve as the measure of consumer welfare. Using reduced-form regressions on a 2012-2013 cross-section of approximately 700 U.S. Cellular Market Areas (CMAs), an inverted-U relationship between the two variables emerges. In addition, the marginal effect of spectrum concentration is positive in

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[1] 47 U.S.C. 4 – Radio Act of 1927 (Feb. 23, 1927), Sect. 17.

[2] U.S. Department of Justice, *Ex parte* submission of the U.S. Department of Justice, in the matter of Policies Regarding Spectrum Holdings, WT Docket 12-269, 11 April 2013 ("DOJ *Ex Parte*"). http://apps.fcc.gov/ecfs/document/view?id=7022269624

[3] The FCC adopted this paradigm in its annual assessment of wireless competition. FCC, Implementation of Section 6002(b) of the Omnibus Budget Reconciliation Act of 1993, Annual Report and Analysis of Competitive Market Conditions with Respect to Mobile Wireless, Including Commercial Mobile Services (Mobile Wireless Competition Report). Available at https://www.fcc.gov/wireless/bureau-divisions/competition-infrastructure-policy-division/mobile-wireless-competition . Beginning with the 2004 publication of its 9th Mobile Wireless Competition Report (2004), the FCC arranged its analysis of the industry under the three chapter headings of structure, conduct, and performance. That arrangement continued through the release of its 16th Report in 2013. Beginning with 17th Report in 2014, the FCC deviated somewhat from this organizational structure.

the sampled markets−contrary to the conventional concentration-performance hypothesis. The vast majority of CMAs in 2012-2013 have spectrum HHIs that lie in the increasing portion of the inverted-U—which suggests that consumer benefits would be sacrificed if steps are taken to reduce spectrum concentration in those markets.

Before we turn to the econometric analysis, a couple of simple scatterplots offer a preview of these results. The scatterplot in Figure 1 shows the relationship between spectrum concentration and subscriber penetration by CMA. Spectrum concentration is measured by the Herfindahl-Hirschman Index (HHI) of operators' shares of spectrum holdings, and subscriber penetration is given by an estimate of the percentage of adults that subscribe to a mobile wireless service. Both variables are expressed as residuals after they have been regressed on a suite of control variables that will be described below. Figure 1 shows little relationship between spectrum concentration and subscriber penetration. Additionally, a LOWESS (locally weighted estimation of smoothing scatterplots) curve suggests an inverted-U pattern between the two variables that will be explored in regression models below.

The same type of scatterplot was created using residuals for subscriber HHIs and spectrum HHIs by CMA. The resulting plot in Figure 2 does not show a clear relationship between the two concentration measures−after "partialling out" the same set of control variables.[4] It suggests that attempts to deconcentrate spectrum holdings do not mechanically reduce concentration in the mobile wireless industry.

It has often been argued that, because of attractive propagation characteristics, spectrum bands below 1GHz convey competitive advantages on its licensees. This assumption has guided Commission policy that governs the assignment of mobile spectrum in these lower bands.[5] To examine this proposition, the concentrations of license holdings above and below 1GHz are separately measured for each CMA market. For the most part, the same pattern appears—which casts doubt on claims that aggregation in those bands harm industry performance.

[4] Note that the simple correlation between the HHI of spectrum holdings and the HHI of subscribers is 0.1292.
[5] For example, in its AT&T-Qualcomm Order, the FCC states that it is concerned by possible aggregation of "…below 1GHz spectrum, that has technical attributes important for other competitors to meaningfully expand their provision of mobile broadband services or for new entrants to have a potentially significant impact on competition." *See* FCC, Application of AT&T Inc. and Qualcomm Inc. for Consent to Assign Licenses and Authorizations, WT Docket No. 11-18, Order, (2011) at ¶ 51.

Another claim that shapes federal spectrum policies is based on a belief that consumers who are located in sparsely-populated rural areas are especially vulnerable to spectrum concentration in those markets. Certainly, the higher costs of infrastructure deployment result in fewer wireless carriers that serve those markets, and a correspondingly high concentration of spectrum holdings. The FCC takes steps to counteract aggregation of spectrum in rural areas, as when it recently provided spectrum bidding credits to small businesses and rural telephone companies in the incentive auctions.

The regression results will show that the urban and rural areas alike display an inverted-U relationship between spectrum concentration and subscription penetration. In the meantime, Figures 1 and 2 suggest little or no relationship depending on whether the CMA is urban or rural. In those scatterplots, urban CMAs are indicated by circles and rural CMAs by triangles. To the naked eye, the two types of markets exhibit no clear relation between spectrum concentration and subscription penetration.

Reduced-form concentration-performance regressions are well known to be infected by endogeneity, and that concern arises here. In the present case, the concentration in spectrum holdings in certain areas may be determined by unobserved factors that simultaneously affect mobile subscriptions in those same areas. Absent a valid instrument for spectrum concentration, techniques of treatment effects are applied where here different levels of spectrum concentration serve as a continuous treatment across markets. Regression-adjusted treatment regressions continue to affirm the inverted-U relationship that emerged from the reduced-form regressions.

What explains the relationship between spectrum concentration and industry performance that contradicts the usual industrial organization paradigm? One potential answer follows from Demsetz's (1973) challenge to the concentration-performance orthodoxy: He proposed that industry concentration could be a product of efficient operation and desirable products of a select few firms. This alternative explanation is tested by examining how carriers' market penetration rates are related to various metrics of network quality and coverage. These regressions show a strong correlation between fast, reliable data transmissions as well as coverage of 4G wireless technologies, and subscription to carriers' services. In addition, the measures of network quality and coverage are in turn directly related to local aggregation of spectrum holdings. This latter finding suggests that the spectrum held by the largest carriers was combined with complementary investments to deliver better service to consumers.

The next section, Section II, reviews the existing literature that explores empirically and theoretically the relationship between spectrum concentration and industry performance. This review suggests a reduced-form cross-sectional model. Section III describes the data that were collected to estimate this relationship. Section IV presents the main regressions of market-wide and carrier-specific penetration rates on spectrum concentration. In this section we also explore hypotheses about concentration in low-frequency bands and in rural markets. Section V addresses the possibility that spectrum concentration is endogenous and concludes that the main findings are unchanged. Section VI investigates how high-quality service rewards mobile operators with higher subscription rates relative to those with relatively poor service. Section VII concludes by examining the merits of policies that are aimed at non-spectrum factors to foster competition and benefit consumers.

II. LITERATURE REVIEW AND MODELING APPROACH

Despite the central roles that spectrum allocation and structural concentration have played in federal wireless policy, little is known empirically about their relationship to the performance of wireless markets. Typically, research on spectrum concentration considers how licenses are auctioned, with scant attention to how those auctions affect the resulting structure of the industry. Along these lines, Cramton *et al.* (2011) explored how auction rules—such as set-asides, bidding credits, and spectrum caps—could, in theory, determine the concentration in mobile spectrum holdings of the downstream carriers. Nevertheless, few papers have assessed what effect, if any, spectrum auctions have had on the structure of the mobile wireless industry. One exception is Madden *et al*. (2014), who attempt to connect empirically the choice of spectrum auction format (and other spectrum allocation mechanisms) and the extent of new entry into mobile wireless markets.

A related question that is the focus of this paper is: What effect does the concentration in holdings of spectrum licenses have on retail mobile wireless competition? In one contribution, Bajari *et al.* (2008) found that consolidation through market-extension mergers of U.S. wireless carriers—and hence increases in spectrum concentration at the national level—generated significant consumer value by creating nationwide footprints. Beard *et al.* (2011, Fig. 4) observed that nationwide concentration ratios of the mobile wireless industry increased during the 1993-2009 period despite the fact that the *total* amount of allocated spectrum had steadily increased. Looking at the concentration of spectrum holdings at a more granular level, Israel and Katz (2013) found that market and spectrum HHIs were negatively correlated across CMAs.[6]

The analysis should not be limited to spectrum concentration, or even to structural concentration in the provision of mobile services, but rather should assess the ultimate effect on wireless consumers. This was emphasized by Hazlett and Munoz (2009), who urged that research in this area should "shift analytical focus to efficiency in output markets." In their panel analysis of 28 developed economies, they find a positive relationship between consumer welfare and the aggregate amount of spectrum released to prospective mobile operators.[7] Nevertheless, Faulhaber *et al*. (2011) found no statistical relationship between concentration among mobile operators and subscribers' average monthly residential bills which served as their proxy for consumer welfare.

As for the theoretical literature, aside from references to general models of oligopoly equilibrium, research has recently begun to shed light on the connection between spectrum allocation and market outcomes in the downstream mobile services industry. Several papers trace the implications of a given allocation of spectrum on equilibrium in downstream service industry. Treating spectrum as a durable input of production, Hazlett and Munoz (2009) employ the symmetric Cournot oligopoly model to establish the relationship between spectrum holdings and equilibrium pricing.

Loertscher and Marx (2014) model wireless oligopolists that compete on price given their quality-differentiated services and given their spectrum holdings that—like physical capacity—reduces total and marginal operating costs. In the context of their model, an exogenous transfer of spectrum from a lower-quality to a higher-quality carrier may boost consumer surplus. After

[6] They separately fitted the relationship for the largest 50 CMAs and also for CMAs outside the largest 50. Also, they came to similar conclusions when the spectrum HHIs were computed for holdings below 1GHz.
[7] Note also that, for some specifications, they found a U-shaped relationship between mobile prices and industry HHIs with the average industry HHI on the downward portion—contrary to the market power hypothesis.

calibrating their model to nationwide industry data, they confirm this pattern by simulating a complex spectrum transfer that occurred in 2012.[8]

Lhost *et al*. (2015) also analyze a model in which mobile operators set prices for quality-differentiated services. However, in contrast to Loertscher and Marx (2014)—in which a carrier's quality is predetermined—service quality in Lhost *et al*. (2015) is directly related to the relative amounts of spectrum that are held by a carrier and its rivals: the more spectrum a carrier holds, the lower the traffic congestion on its network, and so the higher relative demand for its service by consumers. After calibrating their model to industry data, they simulate the effects of spectrum transfers, and find that an increase in spectrum concentration when a small carrier transfers some spectrum to a large one could lead to *lower* quality-adjusted prices that are charged by every carrier.

Other papers do not take spectrum allocation as exogenous but draw the connection between the auction of an input (*e.g.,* radio spectrum) and the structure of the downstream industry. In a general model, Eső *et al*. (2010) show how auctions that efficiently assign a scarce input can nevertheless give rise to a concentrated downstream industry even when the downstream firms are initially symmetric.

In another general model that is motivated by the mobile wireless industry, Mayo and Sappington (2016) show how differences in the ability of downstream providers to use spectrum (or another essential input in fixed supply) to enhance their services or to reduce their costs affect who wins an auction and what are the welfare consequences for end-consumers. Specifically, bidders with greater "value margins" —the difference between consumer value and unit cost—will win the bidding for the spectrum, and these same carriers will garner larger market shares because they offer consumers greater net value, which leads to greater subscription penetration and higher consumer welfare.

[8] In 2011, Cox and SpectrumCo proposed to transfer AWS-1 licenses to Verizon in various CMAs, and also to make exchanges of Lower 700 MHz, PCS and AWS-1 licenses between Verizon and Leap Wireless. To address competitive concerns, the Commission conditioned the transaction on Verizon's transferring many of its acquired AWS-1 licenses to T-Mobile (and receiving a few in return). *See* FCC, Memorandum Opinion and Order and Declaratory Ruling in the Matter of Applications of Cellco Partnership d/b/a Verizon Wireless and SpectrumCo LLC *et al*., WT Docket Nos. 12-4, 12-175, adopted Aug. 21, 2012, available at http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-12-95A1.pdf .

Spurred by concerns over mergers of mobile operators in developed economies, research has surfaced that studies the role of competitiveness on various outcomes in wireless markets. Using a quarterly panel of OECD countries over 2002-2014, Genakos *et al.* (2018) estimate the effect of industry structure on mobile prices and investment. They find that mobile service prices are declining in country-wide HHIs, but also that industry capital investment increases with those HHIs. Looking at data from about the same time frame, Houngbonon and Jeanjean (2016) analyze the countervailing forces with the use of another quarterly panel of mobile operators. They find an inverted-U relationship by estimating a quadratic model that relates industry capital expenditures and an indicator of industry competitiveness (ratios of operator's variable operating cost to average price). This finding is related to the pattern that is found in the regression analysis that I report below.

A formal theoretical model is not developed in this paper, but instead I appeal to the standard homogeneous-good Cournot model of oligopoly equilibrium to motivate the regression specifications. Cowling and Waterson (1976) and many others find a monotonically increasing relationship between market HHIs and the equilibrium price level, and therefore, a decreasing relation with industry quantity. In the regression analysis here, I make two substitutions in the standard regression specification in which market prices (or industry profits) are regressed on a measure of industry concentration such as the market share HHI.

First, in place of price as the proxy for consumer welfare, I substitute the market penetration rate of mobile subscriptions. In the wireless industry, prices are generally uniform across the entire U.S., which makes it difficult to identify the effects of concentration with the use of cross-sectional data. In this paper I use quantity as the metric for consumer welfare. The quantity of mobile services consumed captures the level of consumer welfare in the same way that price does. Textbook microeconomics teaches that, if product quality does not change, a higher market price translates into lower aggregate quantity. In the standard analysis of imperfect competition, firms exercise market power by restricting output in order to drive up prices. Using quantity rather than price avoids the knotty problems of collecting and collapsing complex wireless pricing schedules, and yet provides a sound indicator of consumer welfare. In that case, if overall consumption is higher in one area, then consumers are better off compared to areas where consumption is lower—provided pricing is the same in both.[9] Presumably, more consumers subscribe to mobile services and use those services more intensively due to the availability of better service quality and/or more innovative wireless services.

Second, in place of the usual market share HHI as an explanatory variable, I substitute the HHI calculated from population-weighted carrier shares of spectrum holdings. I chose to measure spectrum concentration to form the usual Herfindahl-Hirschman index (HHI) by summing the squares of carriers' market shares in terms of carriers' MHz-Pops. While the spectrum HHI lacks the same theoretical basis as sales HHI as a measure of structural concentration, it is reasonable to expect that spectrum concentration accurately captures regulators' concerns about agglomeration of licenses.[10] If a strict fixed-proportions relation exists between spectrum and other inputs in production of mobile services, then subscriber and spectrum HHIs should be close to one another. In fact, at one time the FCC had used the HHI of allocated spectrum to measure mobile carrier concentration, but it has since retreated from that position.[11]

A reduced-form model of spectrum concentration and mobile penetration that follows a quadratic relationship is estimated using cross-sectional data. Of course, these regressions do not establish a causal relationship. Nevertheless, the presumption of a causal relationship does appear to justify federal policies that seek to reduce concentration in spectrum holdings, and so we wish to test its validity. While we take steps to correct for bias that could arise in our

[9] The combined surplus derived by individual consumers from mobile access is likely to underestimate aggregate welfare. Like other communications technologies, mobile services convey "network effects" in direct relation to the fraction of the population that adopts them. In that case the benefits of increased mobile penetration will be amplified when it generates spillovers for existing subscribers. The magnitude of this source of consumer welfare will likely be smaller for smaller geographic areas (e.g., CMAs) compared to larger ones such as that entire nationwide market.

[10] The 1992 version of the FTC/DOJ Horizontal Merger Guidelines endorsed the use of HHI for assets in addition to output and sales to evaluate mergers. *See* Sect. 1.41 of the FTC-DOJ Horizontal Merger Guidelines, reprinted in 4 Trade Reg. Rep.

[11] In response to a Circuit Court remand of its rules on ownership of PCS-band licenses, the FCC conducted an analysis of spectrum concentration in which it used spectrum HHIs. *See* FCC, Amendment of Parts 20 and 24 of the Commission's Rules – Broadband PCS Competitive Bidding and the Commercial Mobile Radio Service Spectrum Cap, Report and Order, FCC 96-278 (Jun. 24, 1996), at ¶¶ 96-100 and Appendix A (showing a calculation of spectrum HHIs without weighting the bandwidth by population). More recently, however, the Commission has declined to use spectrum HHIs; the Commission noted that it "would mark a substantial departure from our traditional approach." *See* FCC, In the Matter of Policies Regarding Mobile Spectrum Holdings, Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Report and Order, 29 FCC Rcd 6133 (2014) (Mobile Spectrum Holdings R&O), at ¶ 249.

specification, we do not estimate a fully-specified structural model of wireless industry equilibrium. Nevertheless, we note that such a model is unlikely to uncover a causal relationship if no correlation is found in the reduced-form regressions of the sort that are reported here.[12]

Not all oligopoly models deduce an inverse relationship between concentration and output. For instance, Salant and Shaffer (1999) show how, in equilibrium, industry performance increases as the (quantity) HHI increases when Cournot firms have asymmetric costs. This occurs when Cournot oligopolists' marginal costs become more disperse while keeping their average marginal costs unchanged. Nor do all Cournot models conclude the concentration-performance relationship is necessarily monotonic. As an example, Daughety (1990) demonstrates how, in theory, there can be an inverted-U relationship between concentration measured by the usual HHI and total industry output due to a behavioral asymmetry among firms.[13]

III. THE DATA

In this section I describe the dataset that was built to explore the relationship between spectrum concentration and industry performance. Finer-grained details of variable construction are placed in a data appendix.

The geographic unit of the dataset is the Cellular Market Area (CMA) that the FCC defined for original analog cellular licenses that were awarded in the 1980s.[14] The raw data are often not available by CMA, in which case the variables were recast to reflect CMAs. For instance, the Census Bureau provides many of the demographic variables for the 3,100+ counties in the 50 States and the District of Columbia. Conveniently, each CMA is composed of one or more counties, so these data need only be properly weighted and aggregated to the CMA.

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[12] *See, e.g.*, Angrist and Pischke (2008, p.213): "If you can't see the causal relationship in the reduced form, it's probably not there." *See,* also, Angrist and Krueger (2001, p.80): "Most importantly, if the reduced form estimates are not significantly different from zero, the presumption should be that the effect of interest is either absent or the instruments are too weak to detect it."

[13] Daughety (1990) varies industry structure, and the HHI, by increasing the fraction of firms that behave as Cournot leaders competing with each other and with the remainder of the firms that behave as Cournot followers.

[14] There are 722 CMAs in the U.S. The first 305 of these included metropolitan areas (MSAs) that are defined by the Office of Management and Budget; the Gulf of Mexico was added later; the remaining 416 Rural Service Areas (RSAs) were established by the FCC. Collectively these areas are referred to as "CMAs." *See* FCC, Cellular Market Areas, DA 92-109 (Jan. 24, 1992).

Table 1 lists the variables that are used in the analysis. The summary statistics are given by CMA. After missing information is taken into account, there are just under 700 CMA markets that are represented in the estimation sample.[15] Data for the variables were not recorded for the same point in time, but they did fall in the same 2012-2013 time frame.

The key variables of the analysis are subscriber penetration rates and the spectrum concentration HHIs. Estimates of the number of lines that subscribed to each mobile carrier were collected as of the end of 2013. These figures excluded *data-only* subscriptions, such as wireless connections for tablets, dongles and WiFi access points. Both pre-paid and post-paid subscriptions were included as well as both consumer and business subscription accounts. Wholesale customers and resale customers of a Mobile Virtual Network Operator (MVNO) were added to subscribers of the "parent" carrier. As a result, the additional competition that was exerted by MVNOs' differentiated services was not taken into account.[16] The four national carriers have some subscribers in all CMAs; but that is not the case for regional carriers, such as U.S. Cellular and C Spire.

To estimate penetration rates, I divided the subscription counts by the adult population. To measure this population, children under 14 years old were removed, under the assumption that they did not represent potential subscribers (at least as of 2012). Also, the typical wireless user has other connected devices in addition to her primary mobile phone. This could include laptops and tablets that have wireless connections. Using an estimate that the average American user has 1.51 wireless connections, the count of subscribers, and hence the rate of subscriber penetration, was adjusted accordingly. Details of these calculations are found in the data appendix.

The other key variable—spectrum concentration—was constructed from data on holdings of cellular, SMR, 700 MHz, PCS, AWS, BRS, and WCS bands that were downloaded from the FCC's Universal Licensing System the end of 2012.[17] We follow the convention of expressing the amount of spectrum in units of MHz-Pop (the product of MHz of spectrum and the CMA

[15] Discrepancies with regard to boundaries between some adjacent CMAs resulted in misaligned subscription counts. In those cases, two or three CMAs were combined into one area so as to preserve the information. As a result of this aggregation, 12 mostly rural CMAs were absorbed, which further reduced the sample size.
[16] Burton *et al.* (2000) described the ways in which resellers increase competition in mobile services markets.
[17] Located at: http://wireless.fcc.gov/uls/

population). This was done for the four national carriers plus U.S. Cellular. All holdings by other mobile operators were placed in an "Other" category. Carriers' shares were then used to form the HHI of spectrum concentration for each CMA. This same calculation was done for frequencies below 1GHz (*i.e.,* cellular, SMR, and 700 MHz bands) and also for those above 1GHz (*i.e.,* the PCS, AWS, BRS, and WCS bands).

I gathered a suite of demand and cost variables that were expected to affect subscriber levels across CMAs. These factors included average demographic characteristics of individuals and households in each CMA such as: personal income per capita; household size; home ownership and tenure; and high school graduation rate.[18] This information was aggregated to the CMA level by taking the appropriate weighted averages of the counties that make up each CMA.

Other sources provided population density, land surface topography, and average commute time of work trips. These variables are principally supply shifters but may also affect users' quality of service, and hence their demand. The unit cost of building and maintaining all kinds of telecommunications networks falls with the density of subscribers and their usage intensity. Irregular topography tends to raise the costs of maintaining quality of wireless connections. Customarily, commute time is included as a demand shifter. This made sense when cellular phones were primarily car phones, but that is no longer true. A CMA with long commute times may, however, find that the cost of engineering the network to meet the challenges of significant urban road congestion is higher.[19]

In addition to these control variables, I also include fixed effects in the regressions for the contiguous 48 states and the District of Columbia.[20] These fixed effects would capture variation in pricing of both fixed and mobile services across markets. In particular, they should pick up variation in stringency of state public utility commission regulation of fixed service rates, and

[18] These same control variables (income, education, commute travel time) have been used in several studies of cellular subscription demand. *See*, *e.g.,* Parker and Roller (1997), Busse (2000), Rodini *et al*. (2003), Ward and Woroch (2010), Seim and Viard (2011), and Macher *et al*. (2017).

[19] The FCC has often measured the extent of wireless deployment in terms of "road miles" that are covered by the networks. It is likely that travel time and road miles are highly correlated.

[20] The few CMAs that are located in Alaska and Hawaii were dropped from the estimation sample due to incomplete data.

also the substantial variation in *ad valorem* and excise taxes that are imposed at the state level on wireless services.[21]

Finally, I collected several measures of wireless network quality and coverage of the largest mobile carriers. These metrics focus on the speed and reliability of the voice and data signals that are delivered over the carriers' networks, and the extent to which the operators have upgraded their facilities with 4th generation (4G) technology. I also use an estimate of the density of cell towers located in each CMA under the assumption that it is directly related to signal strength and hence consumer demand.[22]

Table 1 summarizes the sample statistics for all of the variables that are used in the regressions that will be describe below.

IV. REGRESSION ANALYSIS OF SPECTRUM-PENETRATION RELATIONSHIP

This section presents the results of several variations on a basic regression of subscriber penetration on spectrum concentration. The overall fit of the regressions is quite good considering that the data are cross sectional. And although the relationship is weak in a statistical sense, I find consistent evidence of an inverted-U relationship.

A. Spectrum Concentration and Market Penetration

Table 2 contains the least-squares coefficient estimates for four models of the relationship between market-wide subscriber penetration and different spectrum HHIs. My primary interest is on the sign, size, and significance of the coefficients on spectrum concentration. In all of the models, the spectrum HHIs enter quadratically: This specification is motivated by the nonparametric results presented above. Fixed effects for states were included in all of the models, but their estimates were suppressed.

In each model, the coefficient on the linear term was positive and the coefficient on the squared term was negative, which shows an inverted-U relationship. Not one of the linear or

[21] *See* Mackey (2012) for state and local taxes that are applied to mobile wireless services in mid-2012. Those taxes ranged from a low of 7.67% in Oregon to a high of 24.49% in Nebraska exclusive of the federal USF rate of 5.82%.
[22] Sun (2016) constructed a comprehensive dataset for the state of Connecticut and estimated a structural model that shows that increases in a carrier's base station density result in a greater market share for the carrier and reduced shares for its rivals.

squared terms in the four regressions was statistically significant. At the same time, in many cases the data rejected that both coefficients were jointly zero.[23] Most likely, the collinearity of the linear and quadratic terms inflated their standard errors.

To draw conclusions about the net effect of spectrum HHIs, Table 2 also includes estimates of the average marginal effects evaluated with the estimation sample. In the case of first regression model, the marginal effect of an increase in HHI of all spectrum bands at the sample mean is 0.0088 and is highly statistically significant. In other words, if (in the vicinity of the sample mean) a CMA had spectrum HHI that was 100 points greater than another CMA, and otherwise conditions in the two CMAs were identical, then the former would have a higher penetration rate of slightly less than 1 percentage point. Of course, because of the quadratic specification, the marginal effect of any given CMA will depend on specific values of its spectrum HHI.

Depending on the magnitude of the coefficients, penetration could be increasing or decreasing with spectrum concentration. The two estimated coefficients on the spectrum HHI imply that peak penetration occurs at 2,614. The vast majority of CMAs fell below this critical value: 682 of the 697 CMAs in the estimation sample fell below this value on the inclining portion of the inverted-U, or nearly 98% of the sampled CMAs.

To illustrate the relationship graphically, I plot the penetration rates that are predicted by the quadratic regression at specific values of spectrum HHI that span the range of actual values found in the data. This plot appears in Figure 3a (along with 95% confidence intervals) and clearly illustrates the inverted-U relationship. Overall, spectrum concentration is *positively* related to subscriber penetration within the range of actual spectrum HHIs that are found in the data.

In every regression in Table 2, the same suite of demand and cost shifters was included to account for variability that is not attributable to spectrum concentration. Most of these control variables entered into the model as was expected, but not all. As expected, average per-capita income was directly related to mobile penetration rate for a CMA. Mobile penetration was consistently found to be decreasing in the rate of home ownership. It is likely that markets with

[23] The F-tests of the joint hypotheses that both coefficients are zero are not reported here because they parallel the outcomes of the tests of the margins that are found at the bottom of Table 2.

high rates of home ownership substitute fixed lines for mobile phones compared with markets that have a high percentage of renters. As is typical of communications demand models, population density was positively related to subscription penetration and was highly statistically significant across the models.

Results for some of the factors, however, were more puzzling: Penetration rates were decreasing in the CMA-average of time to travel to work—even though one might think that commute times would capture average mobility of the local population and induce consumers to subscribe to mobile phone services. As suggested above, however, the technical demands in areas with long drive times may degrade service level or may raise the cost of building an adequate network.[24]

B. Low-Frequency Spectrum Concentration

As mentioned above, it has been alleged that licenses for lower-frequency bands—especially those below 1GHz—confer a competitive advantage on their owners.[25] As one example, mobile operators without access to substantial low-frequency spectrum will suffer quality problems because their signals will not be able to penetrate buildings. If that is true, under the concentration-performance framework, markets with higher concentrations in the low-frequency bands should show lower consumption of wireless services as a result of the reduced competition.

To address this aspect, spectrum bands are partitioned between those above and below 1GHz, and a separate HHI is computed for each of the two groups of bands. The two spectrum HHIs are then included in the regression model. The results of the regression can be found in the second column of Table 2.

Compared to the model that uses the HHI of all mobile bands, the results are mixed when the bands are split in this way. Again, we calculate the sample average marginal effects of the HHIs of two frequency ranges. Concentration in spectrum below 1GHz does not have a

[24] Unexpected coefficients such as this could also be caused by severe multicollinearity. As a check I computed the Variance Inflation Factors for variables in the base regression and found the VIF for log of travel time to be 2.81. None of the control variables suggested a problem, as they had VIFs ranging from 2.47 to 5.84. As expected, the VIFs of the linear and squared terms were enormous. Thanks to Jim Prieger for suggesting this check.
[25] *See* 20th Mobile Wireless Competition Report (2017) at ¶ 35 and DOJ *Ex Parte* at 12-13.

statistically significant effect on subscriber penetration.[26] Concentration in holdings of bands above 1GHz is positively related and statistically significant, which is what we found for the case when all frequencies were lumped together to form the HHIs.

C. Differences between Urban and Rural Markets

Proponents of the position that low-frequency spectrum confers a competitive advantage on their owners often argue that the propagation properties of those bands make them especially well-suited to serving rural areas.[27] If that were the case, the agglomeration of lower frequencies in the hands of a few operators should be detrimental to mobile subscriptions. As before, if this proposition is correct, the data should confirm that rural markets that have higher concentrations of spectrum below 1GHz should perform worse than those where concentrations are lower.

I follow FCC convention by classifying a CMA as "rural" when it has fewer than 100 residents per square mile.[28] About 55% of the CMAs (384 of 697) in our estimation sample meet this criterion. I estimate the same penetration-concentration regression but make the distinction between HHIs of spectrum holdings above and below 1GHz. The estimation results appear in the third and fourth columns of Table 2. Notice that the incremental effect of interacting the spectrum HHIs with the rural dummy variable are presented as a second set of coefficient estimates in each column.

Consider first the regression results when the HHI of all spectrum bands is interacted with the rural dummy variable in the third column of Table 2. The same inverted-U pattern emerges, regardless of the population classification: Linear coefficients are positive, and quadratic coefficients are negative (but numerically smaller) for both urban and rural CMAs. Penetration rates in rural CMAs are, nevertheless, lower than in the cities. This can be seen by plotting predicted penetration rates for different HHIs with the use of the third model. As can be seen in Figure 3b, predicted penetration rates for urban areas are uniformly higher than rural

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[26] In addition, we cannot reject the null hypothesis that both the linear and quadratic coefficients on low-frequency HHIs are both equal to zero.

[27] *See* DOJ *Ex Parte* at 12-14.

[28] The FCC adopted this criterion in the context of spectrum policy making. *See* FCC, Facilitating the Provision of Spectrum-Based Services to Rural Areas and Promoting Opportunities for Rural Telephone Companies to Provide Spectrum-Based Services, WT Docket No. 02-381, Report and Order and Further Notice of Proposed Rule Making, 19 FCC Rcd 19078, 19123 (2004) ¶¶ 2, 79-80.

areas for all levels of spectrum concentration, and for mid-range values of HHIs their 95% confidence intervals do not overlap.

The differences between urban and rural penetration can also be seen by simulating the impact of re-classifying urban CMAs as rural. In that case, the 313 urban CMAs would have subscriber penetration rates that would be *lower* on average by 4.2 percentage points (and statistically significant).

The last regression model in Table 2 (fourth column) includes interactions between the HHIs above and below 1GHz and the rural dummy variable. Estimation of the spectrum coefficients and their interactions with the rural dummy variable are mixed, but the implications are qualitatively the same as when there are no interactions.

The results shed some light on a contention that is often heard in spectrum policy debates: that lower frequencies are particularly well suited to sparsely-populated areas, and hence concentration in these bands is particularly harmful to rural consumers. I do not find confirmation for this claim in the data. In particular, the regression results show a slightly positive marginal effect of spectrum concentration below 1GHz, but this effect is not statistically different from zero.

V. ENDOGENEITY OF SPECTRUM CONCENTRATION

The above estimation results may be vulnerable to a criticism that is often leveled at industry concentration-performance regressions: The estimated concentration effect would be biased if the concentration measure is endogenous. This would occur if the regression specification omitted variables that affect spectrum concentration and subscription penetration, or because causality runs in the reverse direction. For instance, physical and economic properties of market areas will affect the costs of deploying mobile wireless services, and some of those same properties will affect consumer demand for these services. High-cost areas will likely see greater concentration in spectrum holdings, and those areas likely also have poorer quality of service which will dent demand for mobile wireless services.

A standard prescription for correcting the resulting bias is the use of instrumental variables. The challenge, as usual, is to find valid instruments. The endogenous variable here—

concentration among spectrum holdings—is the outcome of a complex process that involves spectrum auctions and secondary transactions that, in turn, are related to subscription levels in the markets along with supply factors. Furthermore, the geographic areas—the CMAs—are no longer exclusively used to delineate markets for spectrum licenses since the original analog cellular licenses were assigned in the 1980s.[29]

I pursued several standard strategies to generate valid instruments without much success. One common approach is to use lagged concentration as an instrument. Even if we had time series data on spectrum holdings, spectrum HHIs will be highly correlated with current HHIs since spectrum holdings adjust so infrequently, and so not likely to be exogenous. Another approach is to take as an instrument the concentration from a neighboring area with the expectation that it will be moderately correlated.[30] Given how CMAs partition geographic areas, a CMA is likely weakly and possibly negatively correlated with its neighbor because lightly populated areas often adjoin a highly developed area. I also investigated the subscription concentration (HHI), but it was very weak (*viz*., Fig. 2) and also likely not exogenous relative to subscription penetration.

An increasingly popular means to address endogeneity is to exploit a "natural experiment", which approximates a controlled experiment. Typically, events that would qualify as natural experiments occur over time; but here there are only cross-sectional data. It is possible that there are differential conditions across space. I have argued that states are likely to vary due to local policies that affect mobile service deployment: *e.g.*, rights of way, and tower placement. Assembling a geographically-granular dataset, Sun (2016) constructed an instrument for signal quality with the use of local land use zoning regulations. Unfortunately, I do not have this kind of information for my nationwide sample of CMAs.

Instead, to identify the effect of spectrum concentration on mobile penetration, I adapt a technique that comes from the same family of treatment econometrics as natural experiments. Observed values of spectrum HHIs were classified into three categories with approximately

[29] Spectrum licenses have since been issued for a variety of geographic areas including basic and major trading areas, economic areas, partial economic areas, and counties, among other delineations. Auctions that allow combinatorial bidding further obscure the boundaries of the geographic regions that are covered by spectrum licenses.

[30] Hausman (1997) adopted this method to construct instruments for endogenous prices.

equal number of CMAs. The lowest HHIs were taken as the "control group", and the two groups of higher HHIs as two "treatment groups". Techniques allow us to estimate the effect of the counterfactual experiment when a CMA has a higher or lower spectrum concentration than the actual level. To estimate this counterfactual—the potential outcome—we predict the but-for penetration rate using the fitted regression of the sample of CMAs that have the counterfactual levels of concentration.[31]

Results of this estimation are found in Table 3. After making the regression adjustment for differences in CMAs that fall in the three treatment categories, the message is very similar to what was found for the quadratic regressions: a positive relationship between spectrum concentration and mobile penetration, followed by a downward pattern of an inverted-U. This can be seen by inspecting the sample mean penetration rates for the three categories in Table 3, along with the potential outcome means for which matching with counterfactual penetration rates have been performed.

Table 3 also gives the average treatment effect (ATE) of moving from one spectrum concentration group to another. Notice that the estimated ATE of moving up from the control group to the first treatment group of spectrum concentrations increases mobile penetration by 6.90%, and the increase is highly statistically significant. Also notice that the effect of moving from the lower to the higher treatment group of CMAs of spectrum concentration is: 3.05% − 6.90% = −3.85%, which is statistically significant.

Included in Table 3 are estimates of the average treatment effects on the treated (ATET), where the "treated" are the CMAs that have spectrum concentration levels that are higher than the control group. The results are very similar to those for the entire sample. ATET estimates would be relevant if one was to consider a spectrum de-concentration policy that was applied only to markets with spectrum concentration above some threshold.

[31] Three conditions must hold to ensure consistent estimation of treatment effects: conditional independence; treatment overlap; and independence of outcomes across treatment groups. *See*, *e.g.*, Cameron and Trivedi (2005, Sect. 25.4). The assumption of conditional independence—the assignment of CMAs to treatment groups is as-if random conditional on covariates—is not testable. It helps to have an abundance of covariates, and that is one reason that I included state fixed effects in the model. The overlap assumption—CMAs with similar covariate values receive all three treatments—is easily confirmed in our data.

These estimates were calculated without the state fixed effects that we included in the previous regressions because of insurmountable problems with convergence. I was able to include state fixed effects by using the Frisch-Waugh method of "partialling out" state fixed effects from all of the regressors and the dependent variable before estimating the treatment effects. The lower panel of Table 3 reports the results of this procedure. With this correction for state differences, the effects are smaller in magnitude, but the same inverted-U pattern persists. An increase in spectrum concentration from the control to the first treatment group leads to a 3.36% increase in penetration, and this is followed by a 1.67% – 3.36% = −1.69% decrease in penetration with a further increase in spectrum concentration.

VI. EFFICIENCY EXPLANATIONS FOR CARRIER PERFORMANCE

The relationship between spectrum concentration and mobile industry performance that is revealed by the regressions was foreshadowed by the plots in Figures 1 and 2 above. In retrospect, the weak links that connect consumer subscriptions to spectrum concentration might have been anticipated.

First, we would expect that the variation in subscription rates across CMAs will necessarily be dampened because the major wireless carriers establish pricing plans, handset offerings, and advertising programs on a nationwide basis. Since those carriers do not vary their policies over local markets, it is not necessary to control for the differences in these determinants across markets in the regression model. The operators' uniform strategies should not eliminate the effect of spectrum concentration on subscriptions if one exists.

Second, there are engineering reasons why concentration in spectrum holdings would not translate lockstep into subscriber concentration. To a considerable degree, carriers can substitute different spectrum bands for one another to carry their wireless traffic. Also, carriers can adopt wireless technologies (*e.g.*, LTE) and deploy mobile equipment and infrastructure (*e.g.*, small cells) that economize on their spectrum holdings. Consequently, there is not a rigid relationship between the amount of spectrum that is held by a carrier and the number of subscribers that it can support.

Third, besides the investments to make more efficient use of spectrum holdings, carriers can pursue many other tactics to attract and retain subscribers and, in the process, increase structural concentration. They can open retail stores in convenient locations, erect cell towers and antenna in high traffic areas, and train their field technicians and customer service representatives. Operators can augment their coverage by providing for WiFi offload of traffic.

By reversing the causal direction of industry concentration and performance, Demsetz (1973) pioneered the view that firm size—and corresponding industry concentration—may be the outcome of superior products and efficient operation quite independent of the exercise of market power.[32] Little research is available that relates subscribership to the technical qualities of carriers' services.[33]

The story of how T-Mobile reversed its fortunes in the U.S. wireless industry − after AT&T abandoned its attempt to acquire the company in 2011 − illustrates the possibilities: In 2013, T-Mobile launched its "Un-Carrier" campaign that broke with tradition by dropping annual contracts and handset subsidies. It followed with a steady stream of innovative marketing policies that were popular with consumers, and T-Mobile also invested in its network.[34] The result was success in the marketplace. Between 2013 and 2016, T-Mobile's share of industry revenue increased from 10.9% to 15.4%.[35] In both 2015 and 2016 T-Mobile attracted the largest number of net subscriber additions among all carriers.[36]

To test the proposition that carrier size is earned through market competition, carrier-specific penetration rates were regressed on various metrics of network quality and coverage. Uniformly, carriers experience greater market success when they make investments that result in faster and more reliable networks, and when they deploy the latest wireless technologies (*i.e.,* 4G) to more potential subscribers in their market areas. In addition, we find that the network

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[32] Demsetz (1973, p. 3) observed that "… output will tend to be concentrated in those firms fortunate enough to have made the correct decisions." U.S. antitrust case law had earlier carved out an exception for firms that grew large as a result of such superior business decisions. Courts cautioned antitrust enforcers to make the distinction between "the willful acquisition or maintenance of that power as distinguished from growth or development as a consequence of a superior product, business acumen, or historic accident." *United States v. Grinnell Corp.*, 384 U. S. 571 (1966).

[33] While it was not the focus of their paper, Zhu *et al.* (2015) noted that Verizon had higher penetration in markets where its signal strength was above its nationwide average, and where AT&T's signal strength was below its average.

[34] These included its "Binge On" feature in November 2015 and its unlimited "ONE Plan" in August 2016.

[35] FCC, 20th Mobile Wireless Competition Report (2017), Table II.C.1.

[36] *Id*., Chart II.B.5.

quality and coverage metrics that are used here are positively related to the spectrum HHI in the market, which suggests that the carriers use their substantial spectrum holdings to boost the attractiveness of their wireless offerings.

A. Competitive Advantages of Network Quality and Coverage

Table 4 contains regressions of carrier-specific penetration rates on certain metrics of the carriers' network quality and coverage. These regressions include the same set of controls as the regressions in Tables 2 and 3. As expected, the faster and more reliable is a mobile network, and the broader is the deployment of 4G technology, the more consumers will subscribe. These subscribers could be taken from rival carriers, or they could represent new users of mobile services.

The regression results confirm that carriers' penetration rates are positively related to the quality and coverage of mobile service that they offer to the marketplace. The three quality measures and the two measures of 4G deployment are positively, and (except in one case) statistically significantly, related to the success of mobile carriers.[37] To be specific, a one-point increase in a carrier's Overall, Reliability and Speed scores (which is on a 100-point scale) is associated with an increase of 0.13, 0.12 and 0.06 penetration points in market share, respectively. The first two of these effects are highly statistically significant.

I came to similar conclusions after examining the effect of mobile network coverage on carrier market shares. Those market shares are regressed on two indicators of the extent of deployment of advanced wireless services in the last two columns of Table 4. The regressions show that the percentage of a CMA's land area and the percentage of a CMA's population that are covered by a carrier's 4G network are positively related to market shares. The interpretation of the coefficient on the 4G coverage variable, for instance, is that a 10 percentage point increase in the land area that is covered in the average CMA is associated with about a half percent higher penetration rate and market share for the carrier. These effects are again highly statistically significant.

[37] Presumably, the coverage of 4G technology includes both LTE (Long Term Evolution) standard and non-LTE technologies.

These results cast doubt on claims that increases in subscribers to a wireless network will tend to reduce the speed and reliability of the mobile service for a given amount of spectrum; the cause for this degradation is traffic congestion.[38] On the contrary, results for the second and third models in Table 4 are consistent with a positive correlation between a carrier's subscribership and the speed and reliability that are delivered by its network and its 4G coverage.

B. Use of Spectrum to Support Network Quality and Coverage

In a last set of regressions, I pose the question: What is the relation between the quality and coverage of a carrier's mobile services and its holdings of spectrum. One hypothesis—which is consistent with the conventional concentration-performance paradigm—is that carriers will tend to use spectrum inefficiently as they withhold it from the market (and from their rivals).[39] A frequent corollary of this claim is that spectrum concentration also leads to poorer service quality and diminished product and process innovation. The regression results tell a different story.

The dependent variables in the models in Table 5 are measures of the quality or coverage of specific carrier networks. For each of these models, four controls (along with state and carrier fixed effects) were included to take account of factors that affect the quality and coverage of a carrier's service: the density of radio towers and population, plus land topography and travel time.

The overarching message that is delivered by these regressions is that good quality and broad coverage are positively related to the amount of spectrum that is held by carriers. With only a few exceptions, the quality and coverage indicators are positively related to carrier-level holdings of spectrum: Greater spectrum that is held by a carrier is associated with better quality services and a modernized network. The exceptions occur for spectrum HHIs below 1GHz. In that case, greater concentration in these bands is associated with lower reliability and speed scores, though the effects are not statistically significant. These findings contradict any claims that concentration in spectrum holdings are associated with conduct that results in poor performance: either in terms of the service quality or in terms of innovation.

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[38] *See, e.g.,* Lhost *et al.* (2015).
[39] DOJ *Ex Parte* at 11, and FCC, 2000 Biennial Regulatory Review Spectrum Aggregation Limits for Commercial Mobile Radio Services, WT Docket No. 01-14, Report and Order (2001), ¶ 44 and fn. 148.

VII. POLICY IMPLICATIONS

From the earliest days of the mobile wireless industry the FCC released radio spectrum for commercial use by creating multiple licenses for each band in limited geographic areas, and then assigned those licenses to multiple operators. The FCC followed this strategy when it issued two licenses for each CMA for the original analog cellular service in the 1980s. It did so again when, in the 1990s, it auctioned up to five PCS licenses in each "trading area." The FCC has continued this approach as each new swath of spectrum was released for commercialization.

Nonetheless, regulatory and competition authorities remain concerned that—despite its initial success in inducing entry into the mobile industry—the benefits of this spectrum policy may be reversed over time. By their nature, mergers and acquisitions increase aggregation of spectrum holdings, and direct transfers of spectrum licenses between carriers may do the same. Subsequent auctions also offer an opportunity for incumbents to increase their share of available spectrum.

In response, the FCC has adopted measures that restrict the accumulation of spectrum by incumbents and has attempted to put spectrum in the hands of smaller carriers and new entrants. Some of these rules directly altered the format that governs the spectrum auctions, as when blocks of auctioned spectrum are "set aside" for a specific group of potential bidders.[40] In other cases, a favored class of bidders received a percentage discount off the amount paid if they were to win the auction.[41]

Other measures have been designed to impede or reverse the accumulation of spectrum when licenses change hands. At one time, the FCC placed limits on the bandwidth that one entity could hold in a geographic area.[42] While these "spectrum caps" were phased out years

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[40] *E.g.,* in the recent 600 MHz incentive auctions, the FCC set aside up to a "30MHz reserve" for non-dominant bidders, which meant that less bandwidth was available for large carriers to bid on. *Op. cit.,* Mobile Spectrum Holdings R&O, at ¶ 146.

[41] The (forward) incentive auctions offered bidding credits of 15% or 25% for qualifying small businesses and rural service providers. *See* FCC, Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, GN Docket No. 12-268, Report and Order, 29 FCC Rcd 6567, 6833-47 (2014) at ¶ 475.

[42] The FCC first imposed spectrum caps on Commercial Mobile Radio Services (CMRS) in 1994. FCC, Implementation of Sections 3(n) and 332 of the Communications Act—Regulatory Treatment of Mobile Services, GN Docket No. 93-252, Third Report and Order, 9 FCC Rcd (1994). Subsequently, it placed caps on licensed broadband PCS and Specialized Mobile Radio (SMR) spectrum. Over time it eliminated the various spectrum caps. *See, e.g.,* the phase out of the CRMS cap in 2003, FCC, 2000 Biennial Regulatory Review Spectrum Aggregation Limits for CMRS, WT Docket No. 01-14, Report and Order, 16 FCC Rcd 22668, 22710-11, ¶ 93 (2001).

ago, the Commission still implements a two-part "screen" when reviewing the competitive effects of transactions between mobile service providers – whether as part of a merger or a license transfer. The first part of the screen checks whether the concentration of the parties before and after the transaction (measured by market share HHIs) exceeds certain thresholds in each area (county or CMA). The second part checks whether an entity would own more than one-third of the total spectrum in an area that is "suitable and available" for the provision of mobile telephony/broadband services.[43]

The Commission singles out the aggregation of frequencies below 1GHz and spectrum in rural areas for special attention. On occasion, it has reserved low-band spectrum for bidders that own less than a threshold of low-frequency licenses.[44] When reviewing license transfers, the FCC presumes that an "enhanced factor" exists when some carrier ends up with "one-third or more of suitable and available below-1-GHz spectrum" in which case it more closely scrutinizes the competitive effects of the proposed transaction.[45] In rural markets, the Commission has extended bidding credits to small businesses and rural carriers when auctioning spectrum.[46]

The apparent rationale that underlies these policies is that operators are strictly limited by physical bandwidth of the spectrum licenses, and that unequal distribution of the licenses confer market power on the largest spectrum holders.[47] The estimated inverted-U relationship provides evidence that this proposition does not hold throughout the full range of spectrum concentration. Nor does it support the claims with regard to spectrum concentration in low-frequency bands or in rural areas.

It is possible, of course, that the policies that have been pursued by the FCC and other agencies have held down the degree of spectrum concentration that is observed in the data. The

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[43] *See* FCC, Verizon Wireless-SpectrumCo Order, FCC 12-95 (2012) at ¶ 59 and FCC, Verizon Wireless-ALLTEL Order, 23 FCC Rcd 17473 (2012) at ¶ 54. The FCC has added to, and subtracted from, the suitable and available bands over time. *See, e.g.,* Mobile Spectrum Holdings R&O, ¶¶ 70-134.

[44] As specified in the incentive auctions, entities with less than 45 MHz of sub-1-GHz spectrum in a given service area were eligible to bid on a reserved block up to 30 MHz in size depending on initial spectrum clearing targets. Mobile Spectrum Holdings R&O, at ¶ 146.

[45] Mobile Spectrum Holdings R&O, at ¶¶ 279-289.

[46] For instance, in the recent incentive auctions, 28 rural telephone carriers qualified for a bidding credit of 15%. *See* FCC, Broadcast Television Spectrum Incentive Forward Auction, Attachment A, Qualified Bidders, July 15, 2016.

[47] Concerns over the physical limits of radio spectrum date back at least to the 1927 Radio Act. In the 1929 Congressional hearings on Continuing Power of the Act, Sen. Frederic Sackett (R-KY) stated "The spectrum of these wavelengths—I suppose it is called the spectrum—is very short." Quoted in De Vries & Westling (2017).

relationship that has been estimated in this paper suggests that subscriber penetration, and consumer welfare, would not necessarily be lower in markets that have above-average spectrum concentration.

Competitive concerns that stem from spectrum scarcity become much less relevant as the FCC continues to release substantial amounts of spectrum for mobile wireless use. Recently, the FCC announced its "Spectrum Frontiers" plans that, among other actions, will assign as much as 5 GHz of flexible-use spectrum above 24 GHz for 5G applications in the near future.[48] In fact, the FCC has completed the auction of the first of five millimeter-wave bands located in the 28 GHz range.[49] The bandwidth of this one tranche of spectrum exceeds all of the bands that have been released for mobile wireless use up to the present.[50]

As I emphasized in this paper, radio spectrum, while essential, is by no means the sole factor for successful deployment of mobile wireless services. Other critical factors include the network infrastructure—towers, antennas, base stations, and backhaul—and user devices as well as the technical standards that enable all of the various hardware components to work together. These other factors can be substitutes for, and complements to, radio spectrum.

As an example, cell towers are complements to spectrum because they must be erected throughout the territory in order to provide service. In addition, towers and related equipment such as antenna function as input substitutes for spectrum. A wireless network can carry more voice and data traffic on the same physical bandwidth by placing more towers and antenna in closer proximity so as to take full advantage of spectrum reuse. Other strategies for designing wireless networks – splitting and sharing of cells, distributed and directional antenna systems, and small cell network architecture – also economize on the spectrum that is needed to deliver a given level of service.

Another wireless infrastructure strategy that emerged recently relies on the WiFi access points of wireline broadband networks. An early example is Google's Project Fi mobile service,

[48] This incremental bandwidth will come from licenses to portions of the 24 GHz, 28 GHz, 37 GHz, 39 GHz, and 47 GHz mm-wave bands. *See* FCC, Use of Spectrum Bands Above 24 GHz For Mobile Radio Services, Report and Order and Further Notice of Proposed Rulemaking, 31 FCC Rcd 8014 (10), Aug. 29, 2018.

[49] Aaron Pressman, The FCC Just Wrapped Its First 5G Airwave Auction, Fortune, Jan. 24, 2019.

[50] It is estimated that at this time 715.5 MHz is suitable and available for mobile wireless use. *See* 20th Mobile Wireless Competition Report (2017), Table II.E.1.

which automatically switches between cellular networks (that are leased from Sprint and T-Mobile) and WiFi hot spots—depending on signal strength and transmission speed.[51] More recently, major cable television operators have entered the mobile market by leveraging the WiFi hotspots on their cable networks in combination with cellular networks that are leased from nationwide wireless carriers. One example is Comcast's Xfinity Mobile offering, launched in 2017, that combines the cable company's millions of hotspots with Verizon's nationwide LTE network.[52]

The inverted-U relationship that has been estimated in this paper points to the important role that is played by non-spectrum factors of production and suggests that wireless policies should aim to remove artificial barriers that would otherwise limit carriers' production options. The FCC, in fact, took up this task with a series of recent decisions that attempt to remove state and local impediments to the deployment of wireless infrastructure.[53] These orders require quicker and easier approval of the siting of towers, antennae, base stations, and other wireless equipment, as well as limits on the rights-of-way fees that are charged by local authorities. Reducing impediments of this sort may prove to be more pro-competitive than attempts to equalize spectrum holdings.

Correspondingly, when evaluating wireless transactions or questionable conduct, antitrust authorities should be nuanced in how they take account of spectrum in their competitive analysis. When predicting competitive effects, the agencies are free to explore whichever elements of the mobile ecosystem prove helpful;[54] and unlike the FCC, they do not have a vested interest in the outcomes of past spectrum allocation policies. Furthermore, the trend in competition policy away from reliance on conventional metrics of structural concentration may deter agencies from placing undue weight on spectrum concentration.

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[51] Nick Fox, "Say hi to Fi: A new way to say hello." Official Google Blog (April 22, 2015) at: https://googleblog.blogspot.com/2015/04/project-fi.html

[52] Comcast Introduces Xfinity Mobile: Combining America's Largest, Most Reliable 4G LTE Network and the Largest Wi-Fi Network, Comcast Corp. (Apr. 6, 2017) at https://corporate.comcast.com/news-information/news-feed/comcast-xfinity-mobile

[53] FCC, Accelerating Wireless Broadband Deployment by Removing Barriers to Infrastructure Deployment, Third Report and Order and Declaratory Ruling, WT Docket No. 17-79 (Sep. 26, 2018).

[54] For instance, Sun (2016) has suggested that antitrust authorities should consider efficiencies that are derived from consolidation of base stations when reviewing mergers of mobile operators.

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DATA APPENDIX

This Appendix provides additional detail on the collection and preparation of the dataset that was used for the regression analysis of spectrum concentration and wireless subscription penetration.

Subscription Penetration. Data on wireless connections were collected for each Cellular Market Area (CMA) by the market research firm, Link Analytics, as of the end of 2013 for the four national carriers plus three regional carriers: US Cellular, Leap Wireless, and Metro PCS.[55] There was an eighth residual category for subscribers of all other carriers.

To calculate penetration of wireless services, we start with Census Bureau estimates for 2012 population of each county.[56] These figures include all persons in the CMA regardless of age: including infants and children who are too young to use a cell phone. To approximate better the addressable population, we reduce the CMA population by the Census Bureau's estimates of the percentage of persons who are aged less than 14 years old.

It is not uncommon for consumers to have more than one wireless subscription—whether that is a second cell phone or more a connected tablet. This is one reason why estimates of active SIM cards in a country sometimes exceed its entire population. To adjust for this effect, we use data from the GSM Association's Wireless Intelligence unit, which reported that the average American had 1.51 wireless connections in 2013.[57] Accordingly, each 1.51 connections that are provisioned by a carrier is treated as a single "subscriber."

After these two adjustments to the county population figures, the counties are consolidated into the respective CMAs. Penetration rates for each carrier are then simply the

[55] MetroPCS subscriptions appeared in a separate category even though its acquisition by T-Mobile USA was officially completed in May 2013. It is likely that integration of the networks and customer bases took many months—if not years—to complete.

[56] Estimates of county populations for 2012 were extracted using the Census Bureau's American Factfinder data tool: https://factfinder.census.gov/

[57] *See* GSMA Wireless Intelligence-United States, Data Dashboard (May 14, 2014). London: GSM Association. Available at http://gigaom.com/2012/10/22/the-average-us-subscriber-owns-1-57-mobile-devices/ In this article, GSMA states that U.S. consumers owned 1.57 wireless devices as of 2012. In its other data series, however, GSMA reports that Americans had 1.51 wireless connections—apparently making the distinction that not all wireless devices have an active connection.

number of subscribers (after adjusting for average wireless connections per capita) divided by the estimate of the number of adults (14 years and older). The sum of all carriers gives the overall penetration rate in each market. In a few instances, the penetration rate exceeds 100%. This likely occurs because of discrepancies for the CMA in terms of its actual wireless connections per capita or estimates of the size of its adult population.

Spectrum Metrics. Data were downloaded for radio spectrum holdings for each of the 3,100+ U.S. counties with the use of the FCC's Universal Licensing System ("ULS") for the fourth quarter of 2012.[58] License ownership was recorded for each of six carriers: AT&T, Sprint, T-Mobile, U.S. Cellular, and Verizon Wireless, plus a residual category of all other owners. Licenses that were held by each carrier in the cellular, 700 MHz, PCS, AWS, and WCS spectrum bands were downloaded from the ULS. The ULS reports spectrum holdings at the county level, so these must be aggregated to CMAs to be compatible with the subscribership data.

The ULS ownership records were reformatted, and the names of license owners were mapped to the parent carriers. All spectrum that was not attributed to one of the five carriers in a frequency band was assigned to the "Other" category. Leases to mobile spectrum were not captured. Holdings by partnerships were assigned to the largest license owner when its share exceeded 50%. In cases when two carriers owned portions of a band in the same county, they were assigned a fraction of the band limit in proportion to each one's bandwidth. When the sum of carriers' holdings exceeded the band limit, ownership was allocated in proportion to the carriers' bandwidth holdings.[59] For the SMR spectrum band, Sprint's holdings were taken from its Form 603 filings with the FCC for its consolidation with Clearwire.[60] Spectrum holdings for the BRS/EBS spectrum bands are extracted from the *ex parte* filed in the Sprint/Softbank docket.[61]

[58] Located at: http://wireless.fcc.gov/uls/
[59] In some instances, multiple carriers were assigned the full spectrum holdings in the Cellular A and Cellular B bands. In that case the spectrum limit was divided equally among the license holders.
[60] *See* Description of the Transaction and Public Interest Statement, Exhibit 1, Appendix D, "Sprint Non-2.5 GHz Spectrum." For the SMR band only Sprint's spectrum holdings are considered. https://wireless2.fcc.gov/UlsEntry/attachments/attachmentViewRD.jsp?applType=search&fileKey=61096797&attachmentKey=18313220&attachmentInd=applAttach
[61] I imposed a 55.5 MHz cap on carrier holdings of these BRS bands according to the FCC's determination of how much of this spectrum was usable. The portion of the 55.5 MHz cap that is not held by Sprint is assumed to be held by the residual Other category.

As is typically done for spectrum rights, the bandwidth of holdings (expressed in MHz) was multiplied by county population estimates to make them comparable across CMAs. The resulting amounts, in units of MHz-Pops, were then summed up for each carrier for those counties that comprise each CMA, and the carriers' spectrum shares were computed for each CMA.

The spectrum shares were then used to form the Herfindahl-Hirschman index (HHI) of spectrum concentration for each CMA. This was done for the cellular, SMR, 700 MHz, PCS, AWS, BRS, and WCS mobile spectrum bands. The HHIs were computed taking the "Other" category as though it were a single carrier. Since that category often represented shares of several carriers, the computed spectrum HHI would tend to overstate the extent of spectrum concentration.

In order to address concerns about the unique advantages of low-frequency spectrum, the HHIs for holdings that fall below 1GHz (*i.e.,* cellular, SMR, and 700 MHz bands) were computed. The same was done for spectrum bands that are higher than 1GHz (*i.e.,* the PCS, AWS, BRS, and WCS).

Demand and Cost Shifters. Most of the variables that are used to control for demand for mobile services are derived from estimates that are published by the Census Bureau. Their county-level averages of income, household composition, home ownership and tenancy, and education are aggregated up to the CMA.

Also included were characteristics of the CMA that in other contexts have been known to be strongly related to mobile subscribership, such as average travel time to work[62] and an index of the land topography.[63] To better control for variation in demand conditions, average travel time was computed as a population-weighted average across the counties that make up each CMA. The average land topography was computed by taking the land area-weighted average of the TypoCodes of counties that make up each CMA.

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[62] U.S. Bureau of the Census, American Community Survey, 5-Year Estimates. http://factfinder2.census.gov

[63] The typography code for land surface form topography runs from 1 through 21 as the land surface form runs from "flat plains" to "high mountains." *See* the "Natural Amenities Scale" published by the U.S. Department of Agriculture: http://www.ers.usda.gov/data-products/natural-amenities-scale.aspx#.U0B2fvldWSo

Network Quality and Coverage. Measures were developed using two industry sources that produce indices of technical performance of mobile wireless networks: Mosaik and RootMetrics.

RootMetrics generated a host of technical indicators of voice, data, and text services with the use of a sophisticated collection methodology. Twice per year, measurements were taken for the largest 125 of the Census Bureau's "urbanized areas" (UAs) for the four national mobile carriers. Tests were conducted at all times of the day, inside and outside of buildings, while driving in cars, and at major airports. To perform their tests, RootMetrics used unmodified handsets that were purchased from the carriers. Dozens of metrics were collected in each test that are designed to quantify service reliability (*e.g.*, blocked and dropped calls, establish and maintain a network connection) and speed (*e.g.*, time to connect to an IMAP server, file download and upload times, delay in sending/receiving texts). I use the high-level indices—the Overall, Reliability, and Speed scores—that are weighted averages of the several metrics. Each major carrier received a score on a 100-point scale for each of the 125 urbanized areas. Those areas were imputed to CMAs after determining whether they had counties in common. This matching reduced the sample to about 200 CMAs, which include about 60% of the U.S. population.

Mosaik Solutions reports the coverage of different kinds of wireless network technologies that are deployed by the major carriers. This was done in terms of the size of the land area and the size of the population that can receive the service. I limited the analysis to fourth-generation mobile technologies, including: LTE, HSPA, and WiMAX. When a carrier deployed more than one technology in the same area, I took the one that had the greatest coverage. In addition to the four national carriers, the Mosaik data tracked Leap Wireless and U.S. Cellular.

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FIGURES

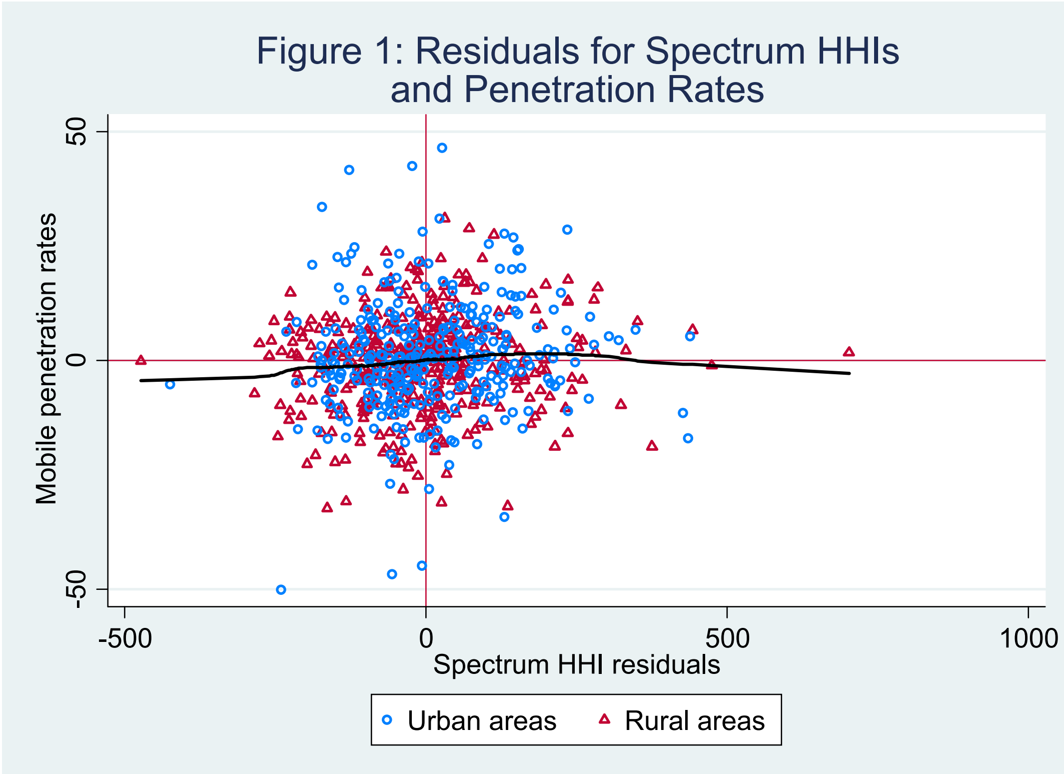
Figure 1: Residuals for Spectrum HHIs
and Penetration Rates
Mobile penetration rates
50
0
-50
-500
0
500
1000
Spectrum HHI residuals
Urban areas
Rural areas

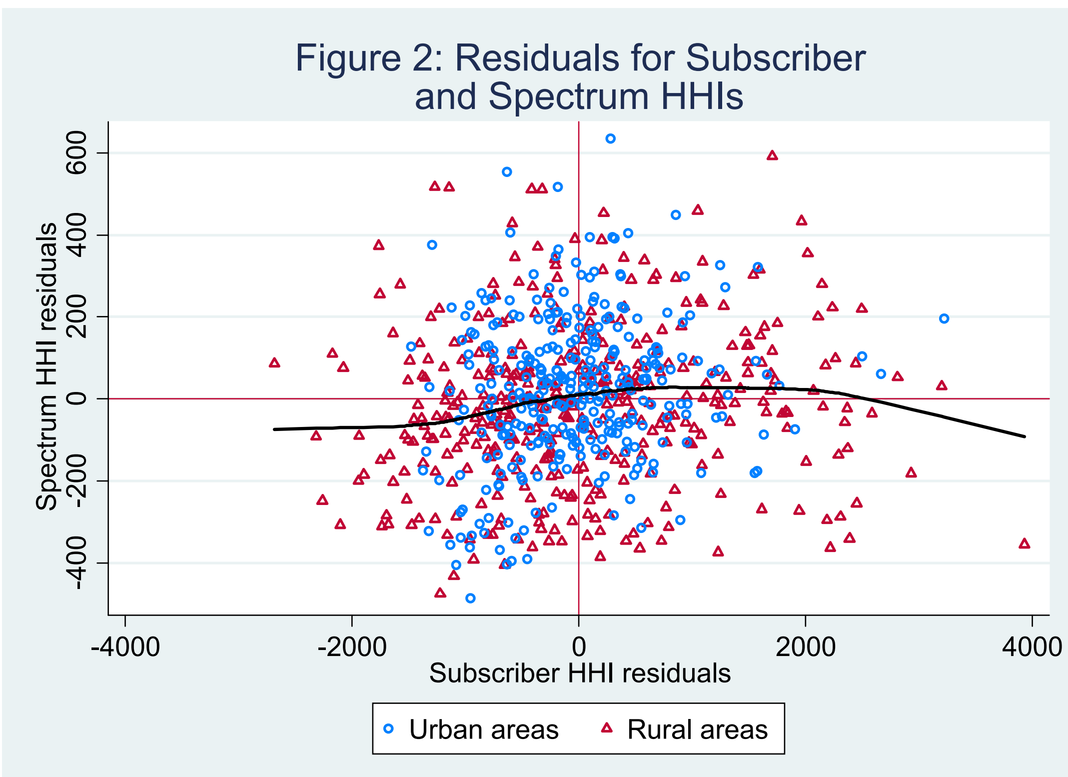
Figure 2: Residuals for Subscriber
and Spectrum HHIs
Spectrum HHI residuals
600
400
200
0
-200
-400
-4000
-2000
0
2000
4000
Subscriber HHI residuals
Urban areas
Rural areas

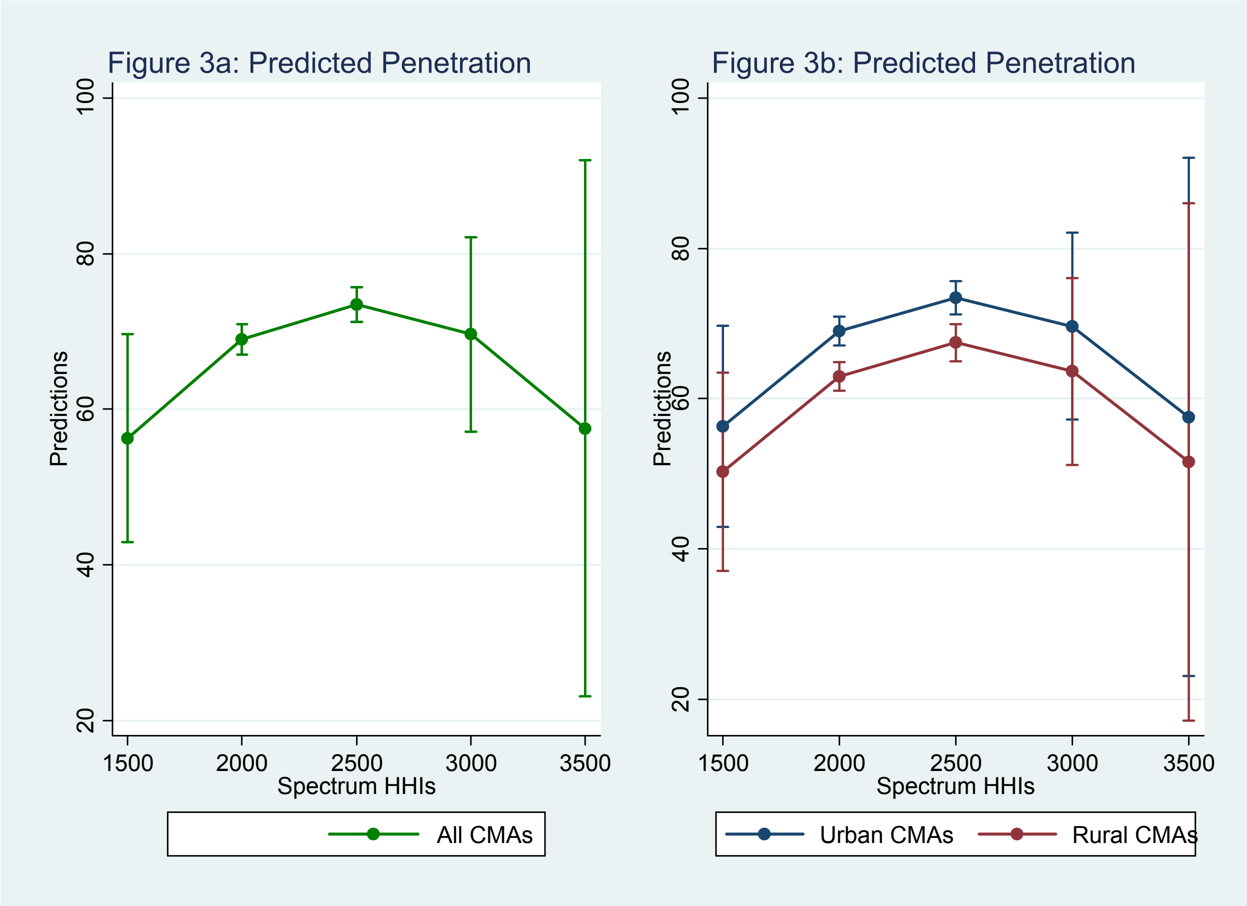
Figure 3a: Predicted Penetration
Predictions
100
80
60
40
20
1500
2000
2500
3000
3500
Spectrum HHIs
All CMAs
Figure 3b: Predicted Penetration
Predictions
100
80
60
40
20
1500
2000
2500
3000
3500
Spectrum HHIs
Urban CMAs
Rural CMAs

TABLES

Table 1: Variable Descriptions and Summary Statistics

Variable	*Description*	*Units*	*Source*	*Mean*	*Min*	*Max*[§]
AllPen	Market mobile penetration rate, end 2013	Subscriptions per 100 adults	U.S. Census Bureau, Link Analytics	71.49	21.01	136.62
Pen	Carrier-specific mobile penetration rate, end 2013	Subscriptions per 100 adults	U.S. Census Bureau, Link Analytics	12.34	0.01	69.91
ShareAll Share<1GHz Share>1GHz	Carrier share of mobile spectrum, all bands and bands below/above 1GHz	Percent	FCC Universal Licensing System, end of 2012	25.21 29.63 23.21	6.55 4.32 7.28	39.51 58.61 42.56
HHIall HHI<1GHz HHI>1GHz	HHI of spectrum holdings of all mobile bands, and below/above 1GHz	0-10,000	FCC Universal Licensing System, end of 2012	2,202 3,054 2,313	1,707 2,090 1,801	3,478 4,689 3,497
IncomePC	Per capita money income in past 12 months, 2008-12	Thousands of 2012 dollars	U.S. Census Bureau	24.29	14.04	49.92
HHsize	Persons per household, 2008-12	Number	U.S. Census Bureau	2.53	2.02	3.69
OwnHome	Percentage of households that own their home, 2008-12	Percent	U.S. Census Bureau	69.9	46.4	84.8
SameHome	Percentage living in same house 1 year & over, 2008-12	Percent	U.S. Census Bureau	84.8	67.4	92.8
HSgrads	Adults age 25+ high school graduate or higher, 2005-12	Percent	U.S. Census Bureau	85.3	61.2	95.4
TravelTime	Mean travel time to work, 2008-12	Minutes	U.S. Census Bureau	22.4	12.2	37.5
TypoCode	Typology of the average land surface form topography	Code 1-21	U.S. Geological Survey's *The National Atlas*	9.3	1	21

PopDensity	Population per square mile	Persons per square mile	U.S. Census Bureau	197.7	0.8	4,433.2
Rural	Indicator of whether PopDensity less than 100	0-1	U.S. Census Bureau	0.55	0	1
TowersDen	Geographic density of cell towers	Towers per square mile	American Tower, SBC Communications	0.04	0.00	0.72
Overall Reliability Speed	Indexes of carrier network quality	0-100	RootMetrics	96.5 97.8 91.6	79.3 82.3 69.1	101.6 99.9 109.5
Area4G Pop4G	4G service coverage by land area and by population	Percent	U.S. Census Bureau, Mosaik	73.0 86.9	0.0 0.0	138.8 103.4
§ - Maximum may exceed 100% due to measurement discrepancies, *e.g.*, land area excludes water covered areas, approximation of adult population.						

Table 2: Regressions of Market Penetration on Spectrum Concentration

Dependent Variable:	Market Penetration	Market Penetration	Market Penetration§		Market Penetration§	
HHIall	0.056		0.013	+0.061		
	(1.27)		(0.21)	(0.83)		
$HHIall^2$	-0.00001		-0.000002	-0.000015		
	(1.09)		(0.12)	(1.19)		
HHI<1GHz		0.005			0.006	-0.012
		(0.49)			(0.32)	(0.58)
$HHI{<}1GHz^2$		-0.000			-0.000001	+0.000002
		(0.47)			(0.40)	(0.64)
HHI>1GHz		0.016			0.028	-0.020
		(0.64)			(0.49)	(0.31)
$HHI{>}1GHz^2$		-0.000			-0.000004	-0.0000002
		(0.31)			(0.33)	(0.03)
Rural			-73.364		34.569	
			(0.92)		(0.45)	
Log(IncomePC)	11.985	13.782	10.871		12.644	
	(2.19)*	(2.59)**	(1.98)*		(2.36)*	
HHsize	5.831	6.302	4.624		4.705	
	(1.23)	(1.32)	(0.98)		(0.99)	
SameHome	1.172	1.208	1.178		1.209	
	(4.62)**	(4.73)**	(4.67)**		(4.76)**	
OwnHome	-0.946	-0.975	-0.963		-1.000	
	(4.86)**	(4.92)**	(5.03)**		(5.10)**	
HSgrads	0.263	0.224	0.223		0.171	
	(1.30)	(1.10)	(1.11)		(0.84)	
Log(TravelTime)	-48.154	-47.238	-45.023		-43.602	
	(11.35)**	(11.06)**	(10.59)**		(10.21)**	
TypoCode	0.040	0.033	0.015		0.014	
	(0.39)	(0.32)	(0.14)		(0.14)	
Log(PopDensity)	4.957	4.986	3.805		3.778	
	(7.79)**	(7.69)**	(4.96)**		(4.87)**	
R^2	0.50	0.50	0.51		0.51	
N	697	697	697		697	
Marginal Effects:						
HHIall	0.0088		0.0077			
	(2.58)**		(2.20)*			
HHI<1GHz		0.0005			0.0003	
		(0.32)			(0.19)	
HHI>1GHz		0.0087			0.0085	
		(3.02)**			(2.95)**	

* $p<0.05$; ** $p<0.01$. Note: Robust t statistics in parentheses. All regressions include a constant term and state fixed effects but the estimates are suppressed. § = rural interaction effects are placed adjacent to the base (*i.e.*, urban) coefficient estimates for HHI spectrum variables.

Table 3: Regression-Adjusted Estimates of Spectrum Concentration Treatment Effects

Treatment Category	*Definition*	*Sample Mean*	*Potential Outcome Mean*§
nHHIall = 0	HHIall < 2,135	67.57	68.71
		[1.007]	[0.959]
nHHIall = 1	2,135 < HHIall < 2,285	74.32	75.61
		[1.082]	[0.950]
nHHIall = 2	2,285 < HHIall	72.60	71.76
		[1.043]	[0.940]

Treatment Estimator	*Contrast*	*ATE*	*ATET*
Without state fixed effects	nHHIall = 1 vs. nHHIall = 0	+6.898	+6.354
		(5.66)**	(4.94)**
	nHHIall = 2 vs. nHHIall = 0	+3.049	+3.377
		(2.47)*	(2.32)*
With state fixed effects	nHHIall = 1 vs. nHHIall = 0	+3.363	+3.528
		(3.29)**	(3.37)**
	nHHIall = 2 vs. nHHIall = 0	+1.672	+1.958
		(2.03)*	(1.76)

* $p<0.05$; ** $p<0.01$. Note: Standard errors in square brackets. Robust Z statistics in parentheses.
§ - Calculated without state fixed effects.

Table 4: Regressions of Carrier Penetration on Network Quality and Coverage

Dependent Variable:	Carrier Penetration	Carrier Penetration	Carrier Penetration	Carrier Penetration	Carrier Penetration
Overall	0.132				
	(2.93)**				
Reliability		0.122			
		(3.54)**			
Speed			0.057		
			(1.47)		
Area4G				0.152	
				(20.28)**	
Pop4G					0.130
					(21.19)**
Log(IncomePC)	2.847	2.809	2.604	2.810	2.940
	(0.93)	(0.93)	(0.90)	(2.02)*	(2.17)*
HHsize	1.627	1.502	1.702	0.021	-0.575
	(0.65)	(0.60)	(0.69)	(0.02)	(0.51)
SameHome	0.153	0.159	0.132	0.301	0.312
	(0.81)	(0.85)	(0.71)	(4.86)**	(5.09)**
OwnHome	-0.261	-0.267	-0.242	-0.230	-0.193
	(2.83)**	(2.87)**	(2.69)**	(4.94)**	(4.30)**
HSgrads	0.132	0.140	0.114	0.012	0.003
	(1.03)	(1.09)	(0.91)	(0.23)	(0.05)
Log(TravelTime)	-9.262	-9.206	-9.000	-10.178	-9.543
	(3.48)**	(3.47)**	(3.44)**	(9.59)**	(9.52)**
TypoCode	0.105	0.099	0.107	0.129	0.045
	(2.33)*	(2.17)*	(2.41)*	(5.29)**	(1.85)
Log(PopDensity)	0.694	0.663	0.818	-0.759	-0.593
	(1.65)	(1.58)	(2.02)*	(4.17)**	(3.46)**
State fixed effects	Yes	Yes	Yes	Yes	Yes
Carrier fixed effects	Yes	Yes	Yes	Yes	Yes
R^2	0.59	0.59	0.59	0.61	0.61
N	817	817	817	3,421	3,411

* p<0.05; ** p<0.01. Note: Robust t stats clustered by CMAs in parentheses. Constant terms are not reported.

Table 5: Regressions of Network Quality and Coverage on Spectrum Holdings

Dependent Variable:	Reliability Score	Speed Score	Reliability Score	Speed Score	4G Land Coverage	4G Land Coverage	4G Pop Coverage	4G Pop Coverage
ShareAll	0.080	0.163			1.646		1.833	
	(1.36)	(2.32)*			(23.49)**		(23.84)**	
Share<1GHz			-0.035	-0.048		0.948		0.948
			(1.59)	(1.50)		(24.05)**		(20.52)**
Share>1GHz			0.104	0.194		0.628		0.824
			(1.86)	(3.68)**		(11.58)**		(13.73)**
TowersDen	-0.136	-1.278	-0.156	-1.310	7.213	7.213	-8.748	-8.658
	(0.05)	(0.35)	(0.06)	(0.36)	(0.86)	(0.86)	(1.28)	(1.27)
Log(TravelTime)	4.958	4.198	5.070	4.382	2.367	2.367	-4.234	-4.240
	(1.91)	(1.53)	(1.95)	(1.60)	(1.08)	(1.08)	(1.70)	(1.70)
TypoCode	-0.060	-0.174	-0.057	-0.169	-0.645	-0.645	-0.252	-0.251
	(1.17)	(2.55)*	(1.12)	(2.50)*	(10.20)**	(10.20)**	(3.27)**	(3.26)**
Log(PopDensity)	0.399	0.260	0.445	0.337	7.863	7.863	9.566	9.559
	(1.13)	(0.70)	(1.27)	(0.89)	(21.62)**	(21.61)**	(25.89)**	(25.89)**
State fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Carrier fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.55	0.72	0.55	0.73	0.74	0.75	0.71	0.72
N	820	820	820	820	4,182	4,182	4,162	4,162

* $p<0.05$; ** $p<0.01$ Note: Robust t stats in parentheses. Constant terms are not reported.