

Spectrum Valuation: implications for sharing and secondary markets

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TPRC46 Abstract¹

How much is electromagnetic spectrum worth? Appropriate metrics and methodologies for valuing spectrum help policymakers, network operators, service providers, and end-users in planning wireless-related investment and in ensuring that spectrum resources are used efficiently. Secondary markets have often served to provide publicly observable, market-based valuation metrics, but in the case of spectrum, these are under-developed and segmented, limiting the availability and comparability of market transactions as indicators of spectrum value. Furthermore, the continued growth in wireless services and networks of all types and further advances in wireless technologies enabling more dynamic and granular spectrum sharing are transforming the supply and demand conditions for RF spectrum.

Today, the most common metric for valuing spectrum resources is \$/MHz-POP, derived from dividing the value of a spectrum transaction by the total population in the coverage area of the license times the bandwidth (in MHz). Traditionally, spectrum value has been observed in spectrum auctions, M&A transactions involving the transfer of spectrum usage rights, or from infrequent secondary market activity. This was a viable approach when the fungibility of spectrum resources was limited by technical, market, and regulatory factors that constrained the commodification of highly differentiated spectrum resources and limited the potential for dynamically reallocating, substituting and transferring spectrum rights via markets.

With increased opportunities for spectrum sharing, the transition to 5G, smaller cell architectures, and the emergence of IoT, new spectrum usage patterns are arising and enabling more granular, multi-dimensional, virtualized spectrum management (in terms of frequency, location, time, etc.). In a world of increasing spectrum sharing, dynamic spectrum access, and commercial applications of higher frequencies for wireless service, \$/MHz-POP may be an increasingly noisy indicator of spectrum value.

In this paper, we consider how changing technology, markets and policy are enabling the commoditization of spectrum resources and explore what that implies for traditional spectrum value metrics that are used to project auction proceeds and value spectrum transactions.

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1. Introduction

How much is electromagnetic spectrum worth? Today's wireless environment is defined by the transition to 5G, the emergence of IoT, and rapidly increasing demand for data. These new trends are impacting how we use, access and define rights over spectrum. It is unclear to what extent current and legacy spectrum valuation methods and metrics still apply. Spectrum sharing, dynamic spectrum access, smaller cell architectures, and commercial applications of higher frequencies for wireless service may also be making the most commonly cited metric for spectrum value, \$/MHz-POP, an increasingly noisy indicator of spectrum value. Many of the traditional drivers of spectrum value may be less relevant in light of new technologies, while new factors are emerging as we push the frontiers of spectrum access. Even factors that remain relevant may have new implications. Consequently, fundamental changes in wireless services and networks suggest a need to reconsider the relevance of \$/MHz-POP as a spectrum valuation metric.

Current trends indicate that the future is shared spectrum, which poses challenges to spectrum valuation. As a thought experiment, let us consider the value of a Priority Access License (PAL) in the emergent Citizens Band Radio Service (CBRS).³ Here, licenses are time limited and are only valid when the incumbent is not present. The measure of \$/MHz-POP must be discounted by some factor in order to account for the incumbent's use, which is unknown and potentially unknowable for national security reasons. Alternatively, with the movement to small cells that may make use of millimeter wave spectrum in the 5G future, a measure of MHz will be increasingly inappropriate for accounting for the much larger bandwidths that will be associated with millimeter wave licenses.

Our objective in this paper is to consider the different aspects that enter (or should enter) in the spectrum value equation given recent trends in spectrum sharing and the development of secondary spectrum markets. To this end, we begin by exploring various factors that affect spectrum value and the valuation methods that are currently used. This allows us to set the stage for taking a more predictive approach towards defining spectrum value in more technically advanced settings, the economic implications these entail and the regulatory changes these may require. In this manner, we expect that this work will permit us to shed light on how economic measures should adapt to the continuous evolution of the technology that dictates novel spectrum-based services.

The balance of this paper is organized into four sections. In Section 2, we review the challenges for valuing spectrum resources, identifying why metrics for valuation are important, the factors that impact spectrum valuation, and the earlier literature and methods used to value spectrum. In Section 3, we discuss several key trends in the wireless technology and markets that are rendering the valuation challenge more complex and moving us toward a potential future world in which Spectrum-as-a-Service may be more appropriate. In Section 4, we discuss the role of secondary spectrum markets in enabling such a world and highlight some of the policy options that could facilitate the emergence and maturation of such markets. Section 5 offers concluding remarks.

³ The CBRS is being defined in the 3.5Ghz band (see <https://www.fcc.gov/wireless/bureau-divisions/broadband-division/35-ghz-band/35-ghz-band-citizens-broadband-radio>).

2. Spectrum Value

Radio frequency spectrum derives its value from how it is used. Spectrum is an input in the means of production, and its value is derived from the value of the products and services that are produced by using the spectrum. Spectrum is a national resource that is managed by the government on behalf of the public interest. It is a renewable resource in that the quantity of spectrum is constant, although the capacity of the spectrum (the range and number of potential uses and users that the spectrum can sustain) has been increasing with the evolving state of wireless technologies, markets, and regulatory policies. The challenge of spectrum management is to maximize the total usage-value realized from our spectrum resources over time.

In a world where all spectrum use is centrally administered (the ideal of Command and Control (C&C)),⁴ an ideal administrator would assign spectrum usage rights so as to realize the highest social (total) value over time. In an uncertain, changing world with imperfect and asymmetric information and multiple stakeholders pursuing their conflicting private interests, achieving this idealized goal of perfect C&C administration is impossible.

Consequently, the actual management of spectrum has been decentralized and delegated to separate regulatory authorities and management regimes that have evolved over time. In the U.S., responsibility for managing spectrum resources is divided between the FCC (for commercial use spectrum) and the NTIA (for federal government use spectrum). In the case of the FCC, there has been an on-going decades-long trend toward transitioning away from C&C style management frameworks (in which government administrators play a more direct role in determining how spectrum is used) toward market-based management frameworks.⁵ More recently, policymakers have looked toward options for similarly transitioning government-use spectrum toward more market-responsive management.⁶

Prices play a key role in markets, signaling the value or opportunity cost of resources to market participants, allowing them to make better informed decisions about resource use. Better market information on the price or market value of spectrum contributes to increased market efficiency and can help ensure that spectrum resources are directed to their highest-value uses over time. In an idealized world, spectrum might trade on the basis of efficient market pricing as a commodity via liquid, low-transaction-cost, competitive secondary markets. This would be the extreme counterpoint to the idealized C&C administrator model hypothesized earlier. Like the idealized

⁴ The Command & Control (C&C) terminology was used as short-hand to characterize the administrative management of spectrum usage, isolated from market forces (see FCC (2002)). The C&C characterization applies perhaps best to Federal spectrum usage since even when spectrum rights were administratively assigned to commercial users (e.g., broadcast licenses in the past), those commercial users and their spectrum usage were still subject to market forces. Analogously, one may argue that even Federal users are not immune from market forces and so it is not appropriate to view spectrum management as a dichotomous choice between administrative government control versus market-based control, but rather as a continuum of spectrum management choices wherein government regulations continue to play a part in all regime frameworks, but with a changing role.

⁵ See FCC (2002) or Robyn (2014).

⁶ See PCAST (2012).

C&C model, however, a world in which spectrum traded like a homogeneous commodity is also impossible.

Although this idealized market outcome is not feasible, the confluence of evolving technical, market, and policy forces offer the potential to make spectrum resources more commodity-like, which has the potential to enhance spectrum allocative, productive, and dynamic efficiency. The emergence of more liquid, lower transaction-cost, and competitive secondary markets for spectrum resources would be key enablers and outcomes of spectrum resources becoming commodified. The emergence of secondary markets is itself an outcome of an important complementary enabling development – the increased reliance on dynamic sharing of spectrum, wherein spectrum is shared not just among users of a single network (as occurs within cellular and WiFi networking already) but across users, uses, and networks (as may occur when non-affiliated users transfer differentiated bundles of usage rights via mature secondary markets).

The efficiency of spectrum management depends on the ability to reallocate spectrum resources to higher value users, uses, and (lower-cost) technologies as market and technical conditions change. Administrative or market-based spectrum assignments that do not change over time, even if efficient at the original time of assignment, are unlikely to remain socially optimal over time. In a world in which spectrum usage or assignments cannot change and opportunities to substitute across rights bundles are limited, the benefits and need for consistent spectrum valuation metrics is much less. It is only with increased opportunities to change or transfer bundles of usage rights among stakeholders on a more granular and dynamic basis that the need for consistent pricing or spectrum valuation metrics becomes more important, as we will explain further below.

In the balance of this section, we explain some of the reasons why spectrum is not easily commodified and hence, why seeking a single commodity price or value metric that is applicable across very different bundles of usage rights is difficult if not infeasible. Although spectrum rights are becoming increasingly substitutable as a consequence of technical and market supply and demand trends and regulatory reforms, it is important to understand why spectrum usage rights will remain, at best, imperfect substitutes. We conclude the discussion with a review of prior efforts to estimate the dollar value of spectrum.

2.1. Factors differentiating spectrum resources

In the following sub-sections, we review key reasons why different bundles of spectrum access rights are valued differently and will remain, at best, imperfect substitutes.

2.1.1. Physics

The physics of radio-frequency propagation provides the first factor that explains why spectrum resources are imperfect substitutes. Electromagnetic spectrum is a multidimensional resource. Matheson and Morris (2012) characterize spectrum as a seven-dimensional *electrospace*.⁷ The

⁷ The capacity of spectrum is interference limited and interference occurs at the receiver when it is incapable of disambiguating its intended signal from the noise of other transmissions in the spectrum. Conceptually, a perfect receiver could separate signals that differed along any of seven possible dimensions: frequency, time, spatial location (x-y-z location), or direction of travel (azimuth, elevation angle). The existing state

physics of electromagnetic propagation make certain "regions" of electrospace more desirable for particular economically valuable applications: different frequency bands offer different coverage/capacity tradeoffs, options for antenna design (e.g., size, directionality), network architecture choices (e.g., cell size), etcetera. For example, lower frequency bands have better non-line-of-sight (NLOS) propagation characteristics, which make them better at penetrating buildings and less susceptible to attenuation from natural factors. This makes lower frequency spectrum attractive for providing ubiquitous coverage, although at the expense of antenna size and capacity.⁸ Hence, historically, lower frequency bands have been preferred for commercial services as these allow coverage to be maximized with relatively fewer access points (or base stations).⁹

As demand increases in denser population, higher use areas, higher frequencies have become more valuable assets, as these can more easily provide the additional capacity needed by existing service providers. Propagation losses at higher frequencies are often offset by the use of directional antennas, which, also allow for greater spatial sharing. These opportunities have prompted a shift towards millimeter wave spectrum and small cells.¹⁰ Nevertheless, there are still physical limitations to consider. For instance, the limited coverage area of these spectrum bands and their high susceptibility to obstacles and interference, make these bands useful for enhancing localized access opportunities instead of maximizing coverage.¹¹

2.1.2. Technology state of the art

The state of the art and commercial availability at scale of new wireless technologies is another important factor that impacts the value of different bundles of spectrum usage rights. Although the physics of spectrum propagation do not change, new technology makes it feasible to support valuable uses across a wider range of spectrum bands, thereby rendering different frequency spectrum closer (if still imperfect) substitutes in many networking contexts. For example, cellular services operate globally on a wide range of frequency bands, and most cell phones are capable of some degree of frequency agility that allows mobile services to roam across frequencies and provider networks.

Historically, radio hardware and types of services were closely coupled because of limited link budgets and the need to more tightly customize the value chain to make it work. This was especially challenging in early analog systems. With the rise of MIMO, cognitive radio and SDR

of wireless technology and networking limits the capabilities of receivers to separate signals, thereby limiting the realizable capacity of spectrum. For further discussion, see Matheson and Morris (2012).

⁸ Lower frequency antennas are larger and there is less frequency available for a given bandwidth, so band allocations are smaller for lower frequency spectrum.

⁹ Additionally, digital processing of wireless signals is easier with lower frequency spectrum because lower sampling rates are required to digitize the signals. As digital processors have become faster and less expensive, higher frequency spectrum has become easier to use.

¹⁰ Small cells are low power (20 to 100mW), limited range (no more than 100m) wireless base station[s] or Access Point[s] ("AP") offering variable data rates (from 10-100Mbps or higher). For further discussion, see Lehr & Oliver (2014).

¹¹ From a broader coverage perspective, significant investments would be required to match spectrum access opportunities provided by lower bands.

capabilities, digital signal processing and a host of other technologies, it has become easier to manage and implement applications in multiple frequency bands. In turn, the rise of spread spectrum technologies, improved antenna designs, among others, allowed for more fine-grained, multidimensional receiver designs.

Technology now exists to unbundle applications from frequencies (e.g., network and resource virtualization), to aggregate frequencies and potentially manage waveforms on a case-by-case basis (in real time with communicating cognitive radios, supplemented by control channels). For example, current LTE standards support dynamic channel selection, channel aggregation, cooperative networks, multi-radio hand-sets, and other capabilities that allow heterogeneous spectrum resources to be used to support applications.

As technology reduces the advantages of operating in particular frequency bands by providing work-arounds to physical differences, it has expanded the range of usable frequencies (reducing spectrum scarcity by expanding the extrinsic margin) and increased the substitutability of adjacent frequencies. This is reflected in the availability of hardware, and increasingly software, that makes radios and their services more frequency agile.

2.1.3. Policy and Regulatory Legacies

The value of spectrum usage rights depends, in part, on the license arrangements, as these constrain the services to be provided and the business models to be employed. This limits spectrum substitutability and the potential to allow markets to reallocate spectrum usage toward higher-value uses.

While technological advances may have increased spectrum substitutability, the potential to substitute or reallocate spectrum resources has been limited by the regulatory framework. Historically, C&C regulation narrowly dictated the applications and technologies that could be employed in the use of different spectrum resources.¹² For example, broadcast spectrum was reserved for use by high-power, television broadcasting stations until relatively recently, precluding the use of such spectrum for mobile broadband applications. With the transition to the allocation of exclusive-licensed, flexible-use spectrum for mobile telephony and the introduction of unlicensed (commons) usage models, significant progress has been made toward enabling market-based spectrum resource assignment.¹³ More generally, the nature of the regulatory

¹² This is typically referred to as spectrum *allocation*. Market-based methods are generally applied to the problem of spectrum *assignment*, which involves the determination of which user gets which rights in a particular time and location.

¹³ In debates over spectrum management regimes, there have been disagreements over whether unlicensed spectrum allocations represent a market-based approach, or whether the only true market-based approach is based on (exclusively) licensed spectrum. The debate hinged on whether unlicensed spectrum (characterized as a spectrum commons) should be viewed as a property rights regime in so far as the rights to use the spectrum were shared by all compliant users, the terms under which the sharing was regulated were set by government regulations (Part 15 rules), and the spectrum was not amenable to market-based trading of the rights. This was in contrast to licensed spectrum which was often accompanied with a property right allowing licensees to exclude other users, and in some cases allowing the licensee to sell the license via a secondary market transaction, thereby giving the licenses an aspect of private property with its

framework governing different spectrum bands, wireless uses and usage models has had a significant impact on the value of spectrum resources and their potential to be imperfect substitutes.

Increasing flexible spectrum access opportunities has been the driving force for regulatory reforms for some time. These efforts confirm the readiness to continue the shift from a C&C model to more market-oriented and resource sharing methods. This transition has been challenging and slowed by shifting technologies and the presence of incumbent systems. New resource use and sharing methods have necessitated rethinking the allocation of spectrum rights bundles along the continuum between the exclusive-use and commons extremes.¹⁴ These bundles of rights are also subject to legacy rights assignments to incumbents that remain associated with particular bands due to past regulatory decisions and investments. This adds to the complexity of the resulting bundles of rights, as we now face intricate rights systems (i.e., a ‘patchwork of legal rights’).

2.1.4. Markets and Incumbency

The growth of demand for spectrum resources, maturity of the market and diversity of participants varies greatly across wireless markets, which has a significant impact on spectrum valuation. For spectrum to be reallocated to a higher value use, incumbent users need to be relocated and the strategic interests of incumbent and new users need to be reconciled. The relevant challenges are band and context dependent. For example, over-the-air TV operates in the 600MHz band due to legacy technology and architecture that relies on high-power, large-cell broadcast networks that need to be cleared out of the spectrum before it can be used by mobile broadband networks. Alternatively, any consideration of repurposing unlicensed Wi-Fi spectrum would confront a tragedy of the anti-commons if attempted,¹⁵ and eliminating exclusivity on LTE licensed spectrum would confront resistance from incumbents who would be likely to resist the perceived expropriation of their usage rights.

2.1.5. Other Factors

In addition to the basic physics and the state of technology, regulations and markets, a number of other factors impact the value of spectrum resources.

attendant economic implications (e.g., strong incentives to internalize the costs and benefits of using the resource efficiently). More recent analyses have recognized that both unlicensed and licensed are property rights regimes which are subject to different government regulations (so neither is purely market-based) that provide expanded scope for market competition to determine how spectrum resources are used (relative to prior regimes characterized as C&C). With licensed spectrum, the role for market forces is more direct and most saliently demonstrated in the competition among cellular network operators. With unlicensed spectrum, the market forces play out through competition among wireless equipment makers and through the usage decisions of unlicensed users which include both end-users and network operators, and as we discuss further below, increasingly cellular network operators. For a discussion of these debates, see for example, Hazlett (1998), Faulhaber and Farber (2002), or Lehr (2009).

¹⁴ For a discussion of emergent rights relationships, see Weiss et al. (2015). For a discussion of how rights bundles may arise in spectrum sharing scenarios, Cui, Gomez & Weiss (2014).

¹⁵ The Tragedy of the Anticommons arises when the rights to use a resource are too widely distributed or fragmented, resulting in a coordination breakdown if an attempt is made to move the resource to another rights model.

Whether spectrum is paired or harmonized are additional factors that can affect spectrum value. Because most mobile operators rely on paired spectrum (one channel for upstream and one for downstream transmissions), exclusive licenses for paired spectrum are valued higher than for unpaired spectrum. However, the growth in asymmetric traffic flows (primarily driven by the increased need to support video traffic flowing downstream to subscriber handsets) and expanded capabilities to support time-division multiplexing of wireless signals are reducing reliance on paired spectrum, and may be expected to limit the price premium associated with paired resources.

Similarly, spectrum that is internationally harmonized is more valuable since it facilitates international roaming and supports a lower cost ecosystem, reducing deployment costs. Radio equipment providers are more inclined to provide equipment for harmonized spectrum because of the larger addressable market it implies.

The emergence of software defined radio (SDR) and cognitive radio (CR) technologies have reduced the relative benefits of using harmonized or paired spectrum, since SDR/CR allow waveforms to be adjusted to accommodate differences in frequencies. Such technologies also make it easier to customize hardware/software and spectrum management on a more granular, dynamic basis (e.g., customization in time, location, frequency, etc.).

Finally, it is important to remember that the geographic location where spectrum resources are to be used impacts the demand for service and the costs of deploying wireless infrastructure and network operations. The terrain, foliage, weather, and presence of potential spectrum users can impact spectrum and wireless networking requirements, and hence has a significant impact on spectrum value. Also, spectrum needs to be available where the demand for wireless communications is located. Thus, 10MHz of spectrum in New Mexico is valued differently than the same 10MHz of spectrum in Manhattan or Maine, and spectrum rights in New Mexico are not substitutes for spectrum rights in New York. When spectrum is able to be assigned on a more granular basis, this will contribute to the potential for increased variation in pricing for spectrum resources on a more granular basis. This may offset the forces of flexibility that might otherwise be driving spectrum values toward less differentiated pricing (valuation).

2.1.6. Summing up

The physics of RF propagation, legacy regulations, incumbent resistance, and other factors render spectrum imperfect substitutes; however the growth of market demand (increasing demand for capacity spectrum, relative to coverage spectrum), the development of more frequency-agile radio networks, and the transition to more market-friendly spectrum management frameworks has increased options for viewing spectrum in different bands as substitutes and the benefits from reallocating spectrum rights to higher value uses.

This simultaneously increases the need for better spectrum valuation or "pricing" metrics and the complexity of the challenges associated with developing such metrics. If spectrum were fully commodifiable (i.e., capable of being rendered as perfect substitutes), then we might hope that market forces would assert the economic "law of one price," rendering objective spectrum valuation easier. Unfortunately, as discussed above, while technical and market trends have increased opportunities to substitute among spectrum resources (i.e., rendered spectrum more

commodity-like), this process remains far from complete today and spectrum resources will remain imperfect substitutes indefinitely.

To evaluate the benefits, for welfare maximization and to individual stakeholders, of reallocating spectrum resources, spectrum markets need better spectrum pricing information with which to value spectrum resources. When spectrum is shared, the total value of the spectrum is the cumulative value to all uses.¹⁶ This fundamental principle—that spectrum value is derived from the benefits of services deployed—holds for all spectrum, regardless of service, whether the spectrum is licensed, licensed by rule, or unlicensed.

For licensed spectrum, we can observe the prices at which licenses trade at auction, via secondary market leases, or via M&A transactions. The availability of such transaction data makes it easier to quantify the economic value of licensed spectrum. Estimating the value of unlicensed spectrum is more challenging since the value must be inferred from the value of the goods and services that make use of the unlicensed spectrum.¹⁷ Although unlicensed spectrum cannot be purchased (and hence there is no observed total transaction value), it is incorrect to infer that there is no private opportunity cost or price associated with its use by end-users or wireless network operators.¹⁸

When we observe the price at which an exclusive-use spectrum license trades, we do not observe its total value to society, but rather the value to the acquiring licensee. It is the present value of future profits associated with specific rights to deploy on exclusive spectrum. Economists often think of this as the economic rents associated with a specific spectrum assignment.¹⁹ The total value of the spectrum to society may be estimated by adding the consumer surplus generated by the services provided by the licensee (which is the difference between the consumers' willingness to pay and what they actually pay for the services).²⁰

Furthermore, the value that a particular stakeholder may place on spectrum depends on that individual's perspective. One might be interested in the total value to society or the economy that may be derived from the use of spectrum. For example, Hazlett, Munoz, and Avanzini (2012)

¹⁶ For a detailed discussion of the sources of spectrum value in the context of spectrum sharing see Bazelon and McHenry (2014). Also, see Forge, Horvitz & Blackman (2012).

¹⁷ As an example of economic value added by unlicensed spectrum see Katz (2014).

¹⁸ Operating in unlicensed spectrum exposes users to the risk of congestion from other users, which imposes a cost that may be viewed as stochastically variable spectrum capacity. While different in detail, that is not fundamentally different from the stochastically variable capacity that the holder of an exclusive spectrum license has when having to contend with dead spots due to leaves or buildings. In both cases, spectrum availability is uncertain and that uncertainty factors into the valuation equation that different users will use in valuing alternative portfolios of spectrum rights.

¹⁹ For a detailed discussion of economic rents and the value of spectrum licenses see Bazelon and McHenry (2013).

²⁰ Nonetheless, since the total consumer welfare is greater than the potential economic activity, we consider it beyond the scope of this paper. For a discussion of the consumer welfare generated by licensed spectrum, see Bazelon and McHenry (2015). Additionally, there is also the social value of wireless services enabled by federal spectrum use. While the value of these services—and the spectrum that enables them—is undeniable, they are outside of the scope of this paper.

developed order of magnitude comparisons of U.S. wireless service revenues and the associated consumer surplus generated by the almost 200MHz allocated to cellular operators in 2009 (\$301-\$364B) to the total auction proceeds from 1994-2009 (\$53 billion), leading them to conclude that the value created by spectrum usage vastly exceeds the realized transaction value from spectrum auctions. This is hardly surprising but the focus of Hazlett et al. (2012) was not to value the spectrum directly, but to infer how the value generated by the spectrum is impacted by the mechanism used to allocate the spectrum.

When looking across countries, Hazlett & Munoz (2009) conclude that auctions that focus on getting the spectrum into the hands of the most efficient operators (rather than those designed to capture spectrum rents as general government revenues or assign spectrum via beauty contests or lotteries) generate significantly more value for the economy, and hence are to be preferred. In a similar theme, Hazlett (2005) has argued that exclusive, flexible-use licensed spectrum, with its strong incentives for the licensees to use the spectrum efficiently, produces an order-of-magnitude higher total value for society than does spectrum allocated for unlicensed uses. However, the comparison is misleading because whereas the cellular industry revenues provide a monetary estimate of the value associated with using cellular spectrum, there is no comparable data available for unlicensed use. Countering Hazlett's argument, Thanki (2012) estimates that the combined economic value to the U.S. economy contributed by a subset of the applications associated with users of unlicensed spectrum is several times larger than Hazlett's estimates.²¹

2.2. Estimating the value of commercial spectrum licenses

In practice, observing the value of spectrum licenses is challenging for several reasons. The profitability of a spectrum license, as with most assets, is often not directly observable. Spectrum value estimates are generally based on existing market transactions. However, the paucity of market transactions and significant variability in the characteristics of individual specific spectrum licenses is not generally observable to practitioners.

As with any asset, there are several potential ways to estimate value: (1) analyze transaction data to determine market values for different spectrum bundles; (2) develop a general equilibrium model of supply and demand to estimate a market equilibrium price for spectrum; (3) build a cost model to estimate net profits from the band; (4) infer value of spectrum indirectly from changes in value of another asset (e.g., market value of firm varying with event that is directly related to spectrum value); or (5) a hybrid approach of the above. With respect to spectrum; however, each of these approaches is complicated due to the lack of transactional data and the complexity of modeling costs or revenues from any given service. As the complexity of networks increases with 5G, applying any of these approaches is likely to become even more challenging.

Most valuations of spectrum allocated as flexible use licensed or intended for wireless broadband have relied on a normalized metric that converts transaction values for different bundles of

²¹ Other examples of dueling estimates of the economic value created by the use of spectrum for licensed or unlicensed spectrum are provided by Cooper (2012); Deloitte (2014), Lewin, Marks and Nicoletti (2013); Milgrom, Levin & Eilat (2011); Thanki (2009), and Ofcom (2006).

spectrum rights into a normalized spectrum "price" metric (i.e., \$/MHz-POP).²² The \$/MHz-POP price metric is computed by dividing the total value of a spectrum transaction, in dollars, by a normalized quantity metric – the number of megahertz (MHz) included in the license times the population (POP) in the license coverage area.²³

The \$/MHz-POP metric captures several of the key features that go into determining the private value of the spectrum rights that may be transferred via a spectrum transaction. The larger the frequency range, the larger the "quantity" of spectrum included in the transaction, which is a rough proxy for capacity. The larger the geographic area, the larger the potential market that the spectrum covers in geo-space. However, that tends to be less important in terms of sizing a market's revenue-generating potential than the population included in the coverage area of the license territory.

Among the benefits of this metric has been its comparability across spectrum transactions, frequency bands, geographic areas, time, and a host of other characteristics. With specific adjustments for the unique characteristics of a spectrum license, the \$/MHz-POP value of any wireless broadband spectrum license could be estimated, compared to other bands, or converted to the total license value.

Spectrum valuation approaches often leverage the \$/MHz-POP metric in order to compare spectrum values across individual licenses and estimate the value of unique licenses. For example, suppose one knows the \$/MHz-POP "price" of a spectrum transaction for a specific licensed area. By using historical auction results to estimate the relative spectrum value between the known license area and a target estimation area, one can estimate the implied market price of any other license within the same band. Likewise, by converting a transaction to the average \$/MHz-price for an entire band, one can estimate the value of other bands based on the unique characteristics of the two bands.

Researchers have also used this metric as the basis for econometric modeling, by converting the value of each license to \$/MHz-POP. For example, Connolly et al. (2018) and Wallsten (2016) provide two recent studies that used data from the U.S. spectrum auctions since 1996 to econometrically estimate the value of licensed spectrum. The results are highly complementary with Wallsten (2016) using data for all 69,000 licenses that were auctioned in the 80 auctions that took place from 1996 through 2011. Connolly et al. (2018) focuses on a smaller subset of the licenses (about 7,000) that were awarded from 1996 through 2015 for use by mobile applications. In both cases, the economists provide hedonic econometric estimates showing how the license prices varied with a range of factors. The authors convert the transaction data to \$/MHz-POP prices to normalize the observed transactional data on a common, comparable basis.

Wallsten (2016) finds that licenses with more MHz are more valuable, but not on a \$/MHz basis, which seems surprising and may be due to unobserved factors (e.g., lower frequency spectrum which is also typically associated with smaller MHz licenses earning a significant premium relative

²² The \$/MHz-POP metric is specific to mobile broadband licenses. Broadcast licenses, for example, are typically valued based on license or population.

²³ That is, if one views the value of the transaction as "P times Q" then to compute P you divide PQ by Q, where Q is the normalized quantity metric.

to higher frequency spectrum licenses). Both Wallsten (2016) and Connolly et al. (2018) find that licenses with higher POP are more valuable, which is logical since licenses covering more POP signal larger addressable market demand potential. Connolly et al. (2018) also find that value increases with median income and POP density, which further accentuates the demand potential. Both studies find that paired spectrum is more valuable than unpaired, which reflects the legacy bias of mobile network technologies to use separate channels for upstream and downstream traffic between the handsets and the cellular base stations. Wallsten (2016) also finds that policy uncertainty lowers license values, whereas increased flexibility increases license values. The fact that CMRS licenses, which are flexible, are more valuable is a point noted in the various papers by Hazlett cited earlier and is further emphasized in Connolly et al. (2018). Both studies find that spectrum value increased over time as markets for wireless services and applications expanded and demand soared.

An interesting point noted by Connolly et al. (2018) is that the discount associated with higher frequency spectrum has decreased as a consequence of technological advances that make using such spectrum less costly²⁴ and demand for additional, less-crowded spectrum has increased. Finally, Wallsten (2016) finds that license prices (measured as \$/MHz-POP) are higher for smaller territory licenses, which challenged prior presumptions that larger area licenses are more valuable. Both of these results are encouraging for the 5G future because of the expected transition toward smaller cells and expanded use of higher-frequency spectrum.

In addition to evaluating the transaction data provided by auctions, Wallsten (2016) also examines data on secondary market spectrum trading associated with mergers and acquisitions and spectrum deals reported in the trade press. Wallsten finds this data complements that auction data, but tends to be of lower quality. Unfortunately, the publicly reported data is not always sufficiently detailed to allow one to infer the full terms of the transaction. Additionally, many of the deals involve non-spectrum assets as well, so isolating the spectrum values becomes problematic.

Another approach to valuing spectrum is to focus on modeling the costs of using alternative spectrum resources. Many of these studies are based on engineering cost models of building wireless networks using particular cellular resources. Most of these studies do not directly address the question of how changing the spectrum resources would impact overall costs, but to the extent they enable such calculations they can contribute to estimating the opportunity cost (value) of different spectrum resources. Examples of studies that have estimated the costs of building wireless networks with different spectrum resources include Oughton and Frias (2017), who provide a detailed cost-model for building out 5G small cell infrastructure across the UK; Frias et al. (2017) who consider the total cost of ownership of different portfolios of spectrum assets; Johansson et al. (2007), who model the costs of supporting heterogeneous wireless networks; and Bouras et al. (2015), who model the costs of dense cell deployments. Gomez and Weiss (2013) offer one of the few papers to examine how different technical features may limit spectrum substitutability, thereby reducing the fungibility of different spectrum rights.

²⁴ For example, widespread commercialization of MIMO techniques and more intelligent antenna designs facilitates using higher-frequency spectrum.

Nonetheless, this metric cannot capture the variety of critical market factors that are just as important as the number of megahertz and the covered population. All of these factors make spectrum un-commodity or un-widget-like. In this way, the "MHz-POP" approach offers a very imperfect quality-adjusted way to account for the "quantity" or the bundle of spectrum associated with different spectrum transactions. Although these complicating factors have always been considered by participants engaged in spectrum transactions, the compelling need of business planners, policymakers, investors, market analysts, and academic researchers for a simple, comparable price metric has ensured that the price metric, \$/MHz-POP, remains in common use. As the complicating factors, however, become more complex and difficult to account for in basic valuation strategies, the comparability and meaning of the metric becomes more strained.

Perhaps more critically, however, recent market trends discussed further below suggest that comparability across bandwidths and populations is increasingly challenging. Spectrum sharing across frequencies and time, dynamic spectrum access and the focus on millimeter wave spectrum suggests that the MHz are no longer comparable across spectrum bands. Likewise, geographic and temporal spectrum sharing, combined with increased focus on small cells in high capacity areas makes even estimating the relevant population challenging.

3. Market and Technical Trends Impacting How Spectrum is Valued

In Section 2.1, we presented different factors that impact spectrum valuation and in section 2.2, reviewed existing methods for valuing spectrum resources, including methods that focused on transactional data associated with commercial-use licensed spectrum. In what follows, we explore market and technical trends that are shaping the current telecom environment, and how these are impacting the way in which spectrum may be valued, and contributing to the need for new valuation metrics.

3.1. Spectrum Sharing is the only feasible future

The future of spectrum use, at the extensive and intensive margin, will have to include sharing. The chimera of clean, exclusive use spectrum is increasingly elusive, as most spectrum resources become shared. Consequently, the dichotomy between exclusive-use and shared spectrum becomes more nuanced. These nuances are translated into different definitions of property rights, which are assembled into rights bundles that address the needs of different services and adapt to the requirements of incumbents and new entrants.

Initial sharing schemes clearly defined priorities and rights (e.g., tiered-sharing schemes deployed for CMRS and TVWS); however, as more complex sharing and rights arrangements emerge (including those relying on smart-spectrum contracts enabled by technologies like blockchain (see Weiss et.al. (2018))), we may find even more diversified rights regimes with reduced priorities or obligations to share.

As more factors affect the definition of rights, their value becomes more context-dependent. To be able to assess whether the value of A is greater than B, we would need to calculate the marginal values of A and B with respect to all the variables affecting the valuation of these assets. Consequently, the calculation of the value of the widely varying bundles of rights remains a challenge that needs to be addressed.

Along these lines, the underlying value of the resulting bundles of rights is continuously created through technologies that turn these bundles into marketable services and allow for the development of enforcement mechanisms that render these rights meaningful (see Weiss et al. (2012)), by ensuring quality of service, resource availability and access conditions for incumbents and service providers.

In summary, more nuanced rights make a cost/benefit analysis more complex, hence posing challenges towards properly defining the value of specific resources. The underlying goal is to navigate through this "rights' patchwork" and still be able to assemble resources that can satisfy different types of services. We expect technical approaches such as channel aggregation (provided by LTE) and resource/network virtualization to help in this process by reducing transaction and search costs.²⁵ Additionally, technology should continue to evolve to make it possible to identify sharing opportunities (i.e., white spaces) and detect violations in more constrained and variable settings.

The use of the \$/MHz-POP metric for evaluating the value of licensed spectrum, and in particular, the value of exclusive/flexible use spectrum licenses for mobile broadband made sense in a world where most of the network providers were relying on licensed spectrum. The \$/MHz-POP estimates from auctions or other secondary market transactions could be tweaked using factor adjustments (as suggested by Wallsten, 2016, or Bazelon and McHenry, 2014) to derive comparable estimates for potential private value of licenses for substitute rights bundles.

Furthermore, from a policy perspective, the distinction between spectrum license economic value and total value to the spectrum user was less important. Policymakers expected total value to rise with spectrum license value, so as long as the allocations of licensed spectrum (principally via competitive auctions) were generally maximizing spectrum license value, then that would also result in the maximization of total value.

Finally, earlier spectrum frequency allocations were more closely aligned with particular markets (by usage, technology, and business model), rendering transactions across heterogeneous frequency bands (rights bundles) either impossible or less likely (e.g, broadcast spectrum traded as broadcast licenses and PCS spectrum traded as cellular licenses). In this world, opportunities for substitutability or transactions involving the transfer of rights bundles across licensing frameworks (e.g., exclusive/flexible use licenses v. unlicensed), frequencies (mid-band or lower-frequencies), and demand scenarios (broadcast or government-use spectrum being transferred via market transactions to mobile broadband use) were more limited. Consequently, stakeholders had less need for consistent pricing or valuation metrics to compare very different spectrum rights bundles.

As wireless network operators expand the portfolio of services they seek to offer and increasingly make use of unlicensed or shared spectrum (with more limited exclusivity rights), \$/MHz-POP estimates, derived from commercial license transaction data, offer a less reliable basis for valuing

²⁵ In section 3, we take a deeper look into different technical scenarios and how they affect spectrum valuation.

the economic and social value of spectrum. As spectrum users contemplate deploying services that will make use of a mix of complementary spectrum resources across diverse frequency bands (where the ability to substitute is more difficult and requires substantially greater complementary investments in non-spectrum infrastructure to accomplish) and regulatory regimes (e.g., mixing licensed and unlicensed), operators will need a valuation metric that accounts for the value added.

Furthermore, with the emergence of new usage models (e.g., Internet of Things devices that may value coverage over capacity and may have more limited spectrum agility, or new types of specialized MVNOs or wireless operators that wish to rely on dynamically-available on-demand spectrum), valuation metrics that presume relatively long-lived licenses (which have been typical of mobile licensing) may be less applicable.

This suggests that we need to clearly distinguish between two separate shortfalls of the \$/MHz-POP metric: (1) With spectrum sharing, DSA and millimeter wave, the \$/MHz-POP is an increasingly imprecise unit of measure to estimate spectrum license value; and (2) as we continue to share more spectrum and rely more on unlicensed spectrum, policymakers need to be thinking about how to quantify this total value to ensure we continue to put spectrum to its highest and best use.

3.2. Technologies Impacting Spectrum Value

With the transition to 5G underway and 6G on the horizon, our expectations have significantly risen as to what these technologies will enable. Behind the scenes, there are a series of technical measures that need to be taken into account, which include the design and adoption of small-cell networks, the utilization of millimeter-wave spectrum, enhanced spectrum management capabilities, among others. Taken together, these emergent technologies are expanding the universe of spectrum usage rights bundles that need to be valued and simultaneously making it feasible to substitute more flexibly across rights bundles and opening up opportunities for more granular and differentiated pricing of different rights bundles. These conflicting trends are increasing the need for better valuation metrics at the same time that they are making acquiring such metrics more challenging. In the following sub-sections, we explore how these technical factors impact the valuation of spectrum.

3.2.1. Millimeter-Wave Spectrum

Meeting the need for the order-of-magnitude improvements in performance promised by 5G will require greatly expanding the capacity of existing mobile broadband networks. Part of this need is expected to come from exploiting frequency bands above 10GHz. These bands have particular physical characteristics, which may bring new factors into the valuation equation. First, because these bands have only recently begun to attract commercial interest, we can expect the value of these bands to increase in value as prospects for their usefulness in delivering valuable wireless services increases. Second, however, prospects for using millimeter wave (mmW) spectrum are constrained by the physical characteristics of these bands. For instance, their propagation characteristics make their coverage area rather small, which would require a larger investment in hardware to obtain the same coverage as lower frequencies. Although this increases infrastructure

costs for providing coverage, it also makes it possible to reuse spectrum more aggressively with a reduced risk for interference from adjacent cells.²⁶

If we take population density into account, higher frequency spectrum is less likely to be cost-effectively deployed in low density areas. This suggests that the relative value of high frequency spectrum in rural areas, compared to urban areas, will be even lower.

Another difference is that mmW spectrum is much less scarce and channels are expected to be allocated with larger bandwidths and across wider frequency ranges. This makes comparing them on a per-MHz basis less useful.

Future spectrum valuation should reflect a more granular analysis of areas that will be deployed for specific frequencies. This may be achieved through a spectrum fungibility analysis where factors of concern are compared, such as coverage, capacity, etc. (see Gomez and Weiss (2013)).

Finally, as we move to building systems in the mmW band, the propagation characteristics imply that, in practice, the rights bundle for spectrum use will be increasingly tied to real estate ownership of base station sites. Building a seamless, geographically diverse service will likely require spectrum and radio resource sharing to a degree that we have not seen before. For example, neutral host providers are expected to emerge in venues (e.g., stadiums, airports, shopping malls, campuses) that will provide spectrum facilities infrastructure (antennas, wired backhaul, power, and other non-spectrum network assets) in local areas that may be shared by multiple network operators (see Lehr (2017)).

3.2.2. Small-cell Networks

One of the trends in the last decade has been the rise of so-called small-cell networks. Splitting larger cells into multiple smaller (lower power) cells facilitates the spatial reuse of spectrum, thereby allowing spectrum resources to be utilized more intensively. Additionally, smaller cell architectures make it easier to make use of different spectrum assets since NLOS and distance-propagation issues are less important. Finally, lower power provides benefits for mobile devices in terms of energy savings.

When the cells become smaller, the spectrum used is a smaller fraction of the total cost of deploying an access point, and other factors loom larger in terms of determining the spectrum efficiency. For example, the spectral efficiency is very sensitive to the placement/orientation of base stations so operators deploying small cells will need to trade-off the increased cost savings realized from user-deployed small cells versus professional installation against the likely losses in spectral efficiency (see Chapin & Lehr (2011), Lehr & Oliver (2014)).

In the context of 5G and the use of millimeter wave spectrum, small-cell networks naturally arise. It is clear that 5G networks would require an extensive spectrum sharing mechanism in every direction, as its objective is to support various degrees of requirements which include throughput,

²⁶ For a more detailed discussion, refer to <https://www.rcrwireless.com/20160815/fundamentals/mmwave-5g-tag31-tag99>

quality of service, type and quality of devices, among others. Thus, it is expected that these networks should allow for seamless co-existence and collaboration of mobile and wireless systems, which according to researchers, will require collective efforts through open frameworks.²⁷

To achieve its small-cell and dynamic network objectives, 5G should exploit the limited interference stemming from the use of shorter wavelengths. Notable examples include providing opportunities for more efficient spectrum reuse and the possibility to address coverage issues with local, dynamically available licenses.

3.2.3. Dynamic Spectrum Management Capabilities

Different spectrum sharing arrangements raise different rights enforcement challenges. If spectrum is to be traded more dynamically via robust secondary markets,²⁸ with spectrum users entering and leaving local markets on a more dynamic basis, better capabilities to track and enforce rights assignments will be needed. Frequently updated maps of transmission opportunities or white spaces will be needed to allow users to identify and assess the value of alternative rights bundles, and to contract for available spectrum resources. Big data analytic techniques, artificial intelligence, and softwarization²⁹ methods are likely to be used to enhance current management techniques and develop novel ones. These methods may help us leverage existing historical information on spectrum use patterns in order to develop a more fine-grained, real-time optimization of spectrum co-existence options. This would permit spectrum users to identify spectrum allocation (or white space) opportunities on a more granular basis, expanding the range of secondary market activity that could be supported.

New management systems such as the Spectrum Access System (SAS) that is being developed and deployed to manage the three-tiered spectrum sharing framework being adopted for the 3.5GHz CBRS band should be capable of leveraging opportunities emerging from the aforementioned analysis techniques. This would also support efforts to forecast future spectrum access trends that may enhance upcoming sharing proposal schemes.

²⁷ For a more detailed discussion, refer to: <http://theinstitute.ieee.org/ieee-roundup/blogs/blog/the-softwarization-of-telecommunications-systems>

²⁸ As we explain further below, secondary markets may exist across a range of time, location, and rights contexts. For example, there may be markets for long-term transfer of usage rights where buyers expect to retain the spectrum acquired for the long term, potentially until the end of the license term. There may also be real-time markets in which users acquire spectrum rights on a temporary basis with the rights reverting to the license holder who may be a band manager. There may be band-specific or geo-location specific secondary markets, or markets focused on specific classes of applications or wireless network services (that bundle spectrum as part of their market offering).

²⁹ Softwarization methods include Software Defined Networks, Network Function Virtualization and cloud computing. These methods promote to utilize software solutions instead of hardware improvements, which are expected to impact all stages of network development. For more information, please refer to: <http://theinstitute.ieee.org/ieee-roundup/blogs/blog/the-softwarization-of-telecommunications-systems>

4. Valuing Spectrum in a Shared Future

Future spectrum use is likely to involve the use of "spectrum as a service" (see Doyle et al. (2014), Cramton & Doyle (2017)) and opportunities for the deployment of more robust secondary markets. Reinforcing the idea that the value of spectrum stems from the services provided with it, and with the help of technologies that enhance the flexible use of spectrum, we expect spectrum to be increasingly detached from specific and unique services. In turn, this gives place for the development of secondary spectrum markets where spectrum buyers can access spectrum resources that fit a wide variety of possible services.

This still doesn't solve the spectrum valuation problem. We have argued above that the \$/MHz-POP measure of valuation is becoming increasingly noisy for all but the highest-level purposes. This measure combines a metric addressing spectrum supply (MHz) and a metric addressing potential demand (POP). As we have argued above, the economic value of the supply part depends on many factors, such as system architecture, technology, frequency band, geography, etc. The demand part (POP) represents relatively homogenous users scattered over a sufficiently large geographic area (SMSA). In fact, systems support heterogeneous uses and users whose demand can vary substantially over relatively small geographic areas and by time of day/month/year.

Thus, as we previously argued, we expect that valuation will be affected by a broad range of factors. Rather than simply criticize existing approaches, we must consider what attributes a more useful, less noisy valuation metric might have. To develop this, we consider factors predominantly related to demand separately from those predominantly related to supply.

4.1. Demand-related factors

We consider demand as user requirements for wireless information transfer. Users, here, are point sources that send and/or receive packets of digital information.³⁰ The statistical characterization of the transmitted packets may be independent of the received packets. These point sources may be arranged geographically in many ways: associated with other infrastructures (e.g., roads, stadiums, airports), in other areas of economic production (e.g., sensors in factories). We expect "hot zones" of traffic to exist within an SMSA.

One way of engineering a communication system is to dimension the system for a prescribed quality of service (e.g., dropped calls, blocked calls, packet delay, etc.). This kind of engineering process would seek to discover the location, timing, and intensity of the hot zones in an area and build a system to support them. This would lead to a potentially wide variation in system architecture and, hence, spectrum valuation within an SMSA.

Note that not all wireless applications transmit packets. For example, broadcast systems have a single point source and many receivers through the service area. Likewise, sensor networks may transmit only and not receive. These transmissions are often considered to be at low levels of

³⁰ In discussing the demand for spectrum and characterizing it as involving the exchanging of packets, we do not mean to focus solely on two-way communication applications, but also include wireless sensing applications which may rely to differing degrees on the sending versus receipt of wireless signals (e.g., radio telescopes and radar applications).

transmission power, requiring a widely distributed infrastructure to receive and aggregate these signals.

The traffic demand of the point sources is dependent on underlying social and economic activity, of course. We do not argue for including such a characterization in a valuation schema; but, it is also true that this complex context for wireless communications means that we should not assume that all transmissions are equally valuable.

4.2. Supply-related factors

As we have argued above, the mechanisms for providing wireless connectivity and capacity are substantially dependent on factors such as system architecture, the frequency band in use, governance of sharing arrangements, etc. When we can no longer assume "clean" radio bands, i.e., when radio bands are shared, the meaning of "MHz" as a capacity measure becomes ambiguous. It would certainly be possible to adjust the MHz measure by the average utilization, but it is quite conceivable (e.g., in mm-wave systems) that sharing is highly localized, so that adjustment may also be noisy.

In a shared future, wireless capacity may be provided in a variety of ways. One of the leading approaches in the near term is using a database system to mediate sharing. This approach is in place for the TV White Spaces, and the CBRS proposes the use of a SAS as well. In particular, the SAS allows for two tiers of commercial sharing (Priority Access and General Access) with incumbent users. PAL license fees may provide a sense of the dynamics of valuation in shared spectrum since their durations are relatively short.

Another approach considers a more generalized virtualization of spectrum and radio resources (Doyle et.al., 2014). These environments feature increasingly complex bundles of resources, and hence rights, that need to be assembled. Thus, we need a mechanism that can efficiently match supply and demand. Navigating the rights system can result in an onerous task that could signify an additional market entry barrier. A successful shared future requires mechanisms that can aid small and big participants to offer/obtain resources that fit the services of interest. One approach would be to develop auction mechanisms that best fit these market scenarios (probably at a high computational cost).

Another approach could be to include a specialized entity (or 'middleman') that can serve this purpose. In Gomez M.M. (2017), the author explores the creation of such an entity, referred to as 'virtual network builder,' whose duty is to match available spectrum supply with the market demand (stemming from service providers) in a secondary spectrum market. This network builder serves multiple purposes, a critical one being to leverage its knowledge of the market to assemble adequate bundles of resources for current and new market entrants. In this way, providers who have limited knowledge of the market can have similar opportunities as more experienced ones. In general terms, having an entity with knowledge of the market can increase the opportunities for resource suppliers and buyers alike, as we may be driving away from thin markets where a one-to-one mapping of demand and supply is required. Additionally, having a source that can keep track of the fluctuations of prices paid for resources can serve to consistently analyze how the value of the spectrum resources changes and how that is influenced by the services provided by

the spectrum buyers. Of course, such a system would work if there is sufficient competition among middlemen.

4.3. Toward alternative valuation measures

As we move toward a world of more heterogeneous shared spectrum use (in terms of spectrum resources, users, uses, and networks), expanded valuation metrics will be needed to adjust more effectively for supply and demand differences.

For example, as POP becomes a less useful proxy for anticipated demand, we may find a measure like Mbps/km² to provide a more useful measure of demand, since it speaks to density of usage more directly. Such a measure would bundle in the data-layer communications capability of the network, and hence would further blur the boundaries between the spectrum resources used and the technology selected to enable the spectrum use. While some such measure may provide a better way to normalize for market demand, it would likely also pose challenges for how to control for differences across higher-layer network architectures and applications (e.g., are the Mbps traffic one-way or bi-directional, is the traffic real-time or cacheable).³¹ We suggest such a metric to highlight the need for the research and analyst community to think more expansively about potential valuation strategies and metrics.

Typically, spatial variations are addressed by pixelating a geographic area. Pixelation itself has factors that need to be addressed (e.g., are pixels defined based on uniform area, uniform demand or uniform supply?) that are beyond the scope of this paper. A broad measure of value for a region (e.g. an SMSA) would require a sensible aggregation of the pixels in the area, a process that might better lend itself to a statistical description rather than a single number (e.g., average valuation, peak valuation).

Focusing primarily on the economic value of licensed spectrum fails to capture the increased use of unlicensed spectrum, and the emergence of new models for spectrum access as underlays (UWB), overlays (TVWS), or new multi-tiered sharing models (CBRS) renders it increasingly inappropriate to price spectrum usage rights using a common \$/MHz-POP price. From a social perspective, this approach leads to an unfair assessment of social value when comparing spectrum used by cellular provider networks to spectrum used by Wi-Fi networks. As noted earlier, cellular spectrum is mostly exclusively licensed, and its value is imputed via the revenues earned from the sale of cellular service. Imputing the value of Wi-Fi spectrum is more difficult because it is typically not monetized in service revenues. These problems can lead policymakers to false conclusions about the relative contributions to social value of exclusively licensed versus unlicensed spectrum.³²

³¹ For example, these are the sorts of distinctions that may matter if the traffic is entertainment video as opposed to video-conferencing.

³² As we discuss further below, supporters of unlicensed have argued that this has biased policymaking toward preferring allocations to exclusively-licensed spectrum. Regardless of the position on takes on debates over whether additional spectrum should be unlicensed or licensed, the lack of comparable valuation metrics complicates decision-making and confuses the debate.

Moreover, the wide-spread practice of off-loading cellular traffic to Wi-Fi and the prospect of LTE use of unlicensed spectrum demonstrates that from an end-user and service provider perspective, spectrum is increasingly being regarded as substitutable. However, the relative scarcity of exclusive-use spectrum and its value in enabling network operators exert stronger control over the quality of service that can be provided via the spectrum, may tend to increase the private value of licensed spectrum. At the same time, the average value of a bundle of spectrum resources (high and low frequency, licensed and unlicensed) may either go up or down depending on aggregate supply and demand conditions.

4.4. Secondary markets and spectrum valuation

The same trends that are driving increased demand toward more dynamic access to heterogeneous spectrum resources are making it increasingly important that we evolve efficient secondary markets for transacting spectrum.

This is due, in large part, because it is generally acknowledged that the only way we can meet the growing demand for spectrum usage rights to support all of the different wireless networks, technologies, and end-users that want such rights is by sharing spectrum more intensively among heterogeneous users, uses, and networks. Increasingly, the technology and market ecosystem are emerging to render spectrum with heterogeneous quality (in terms of its RF characteristics, regulatory license-terms, and business usage cases/models) increasingly substitutable and complementary.³³ This increases the social cost of failing to reallocate spectrum on a more dynamic basis to its most efficient uses. As discussed earlier, while auctions are appropriately viewed as important tools for enabling markets to play a larger role in spectrum management, and when appropriately designed, can help ensure that spectrum is directed to the licensees with the highest private usage values (which also ought to correspond to the highest social usage values if downstream markets are also efficient), this assignment only applies as long as the market valuations at the time of the auction apply. Over time, changes in markets and technology will cause valuations to alter, opening the potential that auction assignments are no longer optimal. It is in such situations that secondary markets will become increasingly important.

At this point, it is unclear precisely how or which secondary markets will evolve to be of greatest importance. In an idealized vision of perfect secondary markets, spectrum buyers and sellers could come together and buy and sell spectrum rights in liquid, efficient markets, akin to those that exist to trade commodities like oil, hog bellies, or silver. To the extent this occurs, we expect bundles of spectrum rights to transact more like commodity goods or widgets, although the pricing may vary significantly by local context (measured in time duration of access rights, precise location, and other attributes). The epitome of such a model was captured by the academics and

³³ Having heterogeneous spectrum assets and networks that are increasingly spectrum agile allows operators greater flexibility in mix-and-matching spectrum resources to the needs of specific situations. This allows operators to exploit the relative differences in spectrum usefulness when that is desirable (complementary) or to offset those differences when the spectrum resources need to act as substitutes. Thus spectrum is never purely capacity or coverage spectrum, but can be either or both, as needed.

policymakers that investigated models for spectrum sharing based on Spectrum Usage Rights (SUR).³⁴

Many of the participants in such markets are actually producers or buyers of the commodities, but there are also market speculators and intermediaries. There are also financial derivatives (futures, options, and more complicated securities) that are based on commodity markets. Collectively, these give rise to a complex matrix of market price data associated with the various transactions. Were such markets to exist in spectrum, we would have lots of spectrum valuation data, and users of spectrum would just need to look to the market prices to infer the market value for spectrum.

While highly liquid markets already exist for real commodities and their financial derivatives for many goods and services, secondary spectrum markets are very far from that ideal and they are unlikely to get there any time in the foreseeable future due to the inherent limitations in spectrum commodification identified earlier.³⁵ Nevertheless, enabling expanding options for secondary market spectrum trading is important to facilitate the transition to more efficient spectrum management regimes and greater sharing among heterogeneous network operators. With better secondary markets, market forces could be used to re-partition or assemble rights bundles that more closely match market conditions.

The promotion of secondary markets and the focus on spectrum valuation metrics are linked because a challenge in getting to liquid secondary markets is the lack of potential buyers and sellers of rights, which in turn, is due in part to the lack of a consensus on how spectrum should be valued. Better publicly available information on spectrum prices (which more active secondary market transaction data would provide) would contribute to a greater consensus on how to value spectrum and would promote greater trust on secondary markets. Would-be buyers and sellers are more inclined to rely on secondary markets for off-loading excess spectrum resources or for acquiring additional resources if they can be confident that the markets are fair and competitive (i.e., free from hold-up risks). As secondary markets evolve and become more liquid (on both the demand and the supply side), they will provide a stream of useful spectrum pricing data that will contribute to reinforcing the liquidity and efficiency of those markets. In this sense, better valuation and pricing data will contribute to the development of secondary spectrum markets and the development of those markets will enhance collective spectrum valuation capabilities.

³⁴ In 2006, the UK regulator, Ofcom, launched a consultation to define Spectrum User Rights (SURs) that could provide the basis for a regulatory-implemented, technically-neutral property rights regime that would allow rights holders to trade interference-protected spectrum rights (see Ofcom (2006), "Spectrum Usage Rights: Final Report," UK Ofcom, 1721/TNR/ES/1, February 10, 2006, available at <https://www.ofcom.org.uk/consultations-and-statements/category-1/sur>). For further discussions of what might be possible in the way of technical approaches to defining spectrum rights bundles, see Matheson, Robert, and Adele C. Morris. "The technical basis for spectrum rights: Policies to enhance market efficiency." *Telecommunications Policy* 36.9 (2012): 783-792 or Doyle, L., Kibilda, J., Forde, T.K. and DaSilva, L., 2014. Spectrum without bounds, networks without borders. *Proceedings of the IEEE*, 102(3), pp.351-365.

³⁵ Mayo and Wallsten (2010) documented the role of nascent spectrum secondary markets for spectrum.

5. Conclusions and Future Research Directions

Spectrum derives its value from how it is used. Appropriate metrics to value spectrum resources are needed to allow wireless users, network providers and policymakers to make informed decisions about how best to allocate spectrum usage rights and direct investment in wireless infrastructure and services.

Historically, opportunities to trade and transfer spectrum usage rights were limited by technology, markets, and regulatory policies. With changing technology and market conditions, barriers to reallocating and transferring spectrum rights has impeded efforts to ensure scarce spectrum resources are directed to their highest value uses. Although policymakers have made significant progress toward transitioning from legacy C&C style spectrum management toward market-based spectrum management, further progress is needed. The emergence of robust secondary markets would help address this issue, but an impediment to their emergence is the lack of good data on the value of spectrum that would allow wireless users to assess the relative value of spectrum and facilitate the pricing of trades in spectrum resources.

Historically, the most commonly used metric for comparing the value of spectrum has been the \$/MHz-POP metric, which has been used to summarize data from auctions and secondary market transactions, principally associated with mobile broadband licenses. In this paper, we have argued that this popular metric of spectrum value has become less useful over time as technology, services and spectrum allocation and assignment approaches have changed.

With increased reliance on shared spectrum and business models based on mixing licensed and unlicensed spectrum, the \$/MHz-POP data based on transactions for exclusively-licensed spectrum will prove less useful for valuing more complicated spectrum rights bundles. The emergence of IoT, 5G, millimeter wave technology and smarter networks and devices are increasing both the demand for and the capabilities of wireless networks to utilize spectrum on a more granular and dynamic basis. The intensifying demand for spectrum usage rights is for all types of uses from all types of users. This includes increased demand for communications and sensing applications, commercial and government users, and legacy and new networks. These capabilities and shifting demand priorities are increasing the need for secondary markets to effect the requisite rights transfers, but the emergence of such markets are hampered by the lack of appropriate valuation metrics.

As shared spectrum becomes a dominant feature of spectrum assignment and use in the future, we expect that spectrum resources will become increasingly detached from specific services and users, enabling heterogeneous users and uses to share spectrum more intensively. As services become more flexible, bundles of rights may become more complex, further complicating the challenge of assessing the value of the underlying spectrum resources. In consequence, we expect there to be multiple spectrum valuation metrics, but consensus on a limited set of valuation methods will help support more robust spectrum secondary markets.

Although market and technology trends are making spectrum more commodity-like, allowing increased substitution of spectrum resources in different frequency bands, there are inherent limits to spectrum substitutability that will persist even in the long term. Nearer term, and during the ongoing transition toward increased reliance on market forces, spectrum substitutability will be

further limited by the need to accommodate diverse wireless architectures with heterogeneous spectrum requirements (e.g., legacy v. new radios, lower v. higher frequency, local v. large coverage area, macro-cell v. small cell, etc.), usage models (e.g., commercial v. government, low v. high bit rate, communications v. sensing, etc.) and regulatory regimes (e.g., exclusive v. shared, on-demand v. long-term-licensed, cooperative v. non-cooperative sharing, etc.). Identifying the right bundle of spectrum resources will remain highly context dependent (e.g., dependent on the users' business model, local market and technology context, and RF environment), necessitating adjusting spectrum values for multiple factors. We have identified many of these factors and discussed qualitatively how emerging supply and demand trends are affecting spectrum valuation and opportunities for substitution.

While we feel confident in concluding that the overall challenge for valuing spectrum is getting more complex but also more important, we do not feel confident in predicting whether average spectrum prices or the variance in value by location, time of day, or level of interference protection will increase or decrease. On one hand, the increased spectrum agility of emerging wireless networks is expanding the supply of spectrum on the intrinsic (e.g., by allowing more dynamic and finer-grained allocation to support higher levels of simultaneous spectrum utilization by diverse users and uses) and extrinsic (e.g., by opening new higher frequency resources in the millimeter wave bands to commercial use) margins. On the other hand, demand for wireless access from all sorts of users and networks continues to grow rapidly.

Going forward, we need more empirical research across the entire frequency domain on how shifting spectrum usage models are impacting the costs of wireless networking, demand for wireless services, and value creation associated with using our scarce spectrum resources. We also need further work on designing institutional frameworks, contracting mechanisms, and enforcement models for supporting the development of robust, competitive secondary markets to allow market forces greater scope to reallocate spectrum resources efficiently. This may include developing standardized contracts for spectrum resource bundles. Moreover, collecting and publishing data on rights assignments and transaction pricing, much of which may be generated by robust secondary markets will be important and will help promote the development of such markets.

6. References

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