Before the

FEDERAL COMMUNICATIONS COMMISSION

Washington, DC

In the Matter of

Policies Regarding Mobile Spectrum Holdings

The State of Mobile Wireless Competition

Updating the Spectrum Screen

Comments for Public Knowledge

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1   Qualifications and Disclaimer

I am writing this comment at the request of Public Knowledge, but the opinions expressed are my own. I am a Full Professor at Carnegie Mellon University in the Dept. of Electrical & Computer Engineering and the Dept. of Engineering & Public Policy, and former Associate Director of CMU's Center for Wireless & Broadband Networking. My past government service includes positions at the Federal Communications Commission as Chief Technologist, at the White House as Assistant Director of the Office of Science and Technology Policy, in the House Energy & Commerce Committee as Legislative Fellow, and at USAID as leader of the Telecom Leadership program. My industry positions include Chief Technical Officer of Cyphermint, VTLinx Multimedia, and Proxicast, and member of technical staff at SRI International, AT&T Bell Labs, and Microsoft. I hold a Ph.D. in electrical engineering from Stanford. I am a Fellow of the IEEE, a Fellow of the AAAS, and a member of FCBA and SHPE. I consult on a wide range of technical and policy issues related to information and communications technology.

2   Overview

An effective spectrum screen in the commercial mobile radio services (CMRS) industry must achieve and balance two important objectives. First, the screen should detect when a carrier could have exclusive access to so much spectrum in a region after a proposed merger or acquisition that the carrier's spectrum holdings would give it a substantial competitive advantage that could limit effective competition. In general, market failure can occur when one firm can singlehandedly influence price, such as when one firm can offer a service at a low cost that competitors cannot match. For wireless services, this can happen when these competitors cannot obtain spectrum. To offer comparable services, competitors that are spectrum-starved would be forced to spend considerably more money on infrastructure to serve the given region. Because such a firm can typically only obtain spectrum from the FCC in infrequent auctions or from a small number of firms that are also competitors rather than in an open and fluid market, this becomes an issue for the FCC. An effective spectrum screen will help the FCC determine if the distribution of spectrum in a given market could limit competition in this way.

At the same time, a spectrum screen should be sufficiently flexible to give carriers the ability to pursue different strategies and manage their spectrum portfolios as they see fit within reasonable bounds of market dominance. Regulators should not micromanage spectrum holdings in the name of competition.

To meet these objectives in the long term, the FCC's spectrum screen must treat spectrum assignments differently depending on their frequency band. Creating such a screen is of growing importance. First, the decrease in the number of nationwide carriers underscores the importance of promoting competition. Second, the growing data rates from mobile devices will continue to increase pressure on cellular providers to gain access to large amounts of spectrum, and carriers that cannot obtain spectrum may be unable to compete. Third, and most important for this particular issue, the government's efforts to make enough spectrum available to CMRSs can and probably will lead to a much greater number and

diversity of spectrum bands used for this purpose. The spectrum screen must be a sufficiently versatile instrument to adapt to this new reality.

3   The Unhealthy Fallacy that Spectrum Equals Capacity

It has become commonplace in discussions of spectrum-related issues to confuse the amount of spectrum that a carrier has (presumably measured in MHz or MHz-POPs or MHz-mile[2]) with the amount of data that carrier's network can carry (in GB per month) or the number of people that carrier can serve. For example, it is often stated that if we do not "create" new spectrum bands fast enough to keep up with growing data rates, then capacity will stop increasing, and we will be unable to meet the growing demands of consumers. Although there is certainly good reason to make more spectrum available for broadband wireless communications,[1] the truth is more complicated, because more capacity and more spectrum are not the same thing. The spectrum screen discussion has also been damaged by this common misunderstanding. I will therefore start by putting that argument to rest. A good example of this fallacy within the spectrum screen discussion is the following statement from AT&T.[2]

> "The spectrum screen has always been properly focused on spectrum *capacity*, not nebulous notions of 'value.' … The data-carrying capacity of all spectrum, however, is equal: 20 MHz of AWS spectrum can carry as much wireless broadband data traffic as 20 MHz of 700 MHz spectrum. Accordingly, the spectrum screen must count all spectrum equally; weighting the spectrum on any other basis would produce a grossly distorted picture of the economic impact of a spectrum transaction."

This argument is not unique to AT&T, but it is factually incorrect nevertheless. Actually, the maximum data-carrying capacity of a 20 MHz point-to-point link is generally much greater in the 700 MHz band than in the higher-frequency AWS band, as long as there is no change in distance between transmitter and receiver, antenna gains, transmit power, and interference level.[3] The alleged equivalence of bandwidth and capacity makes even less sense for cellular systems, which is the most relevant case for this NPRM. One cellular system with 20 MHz of spectrum can easily have a much greater data-carrying capacity than a competitor that also has 20 MHz, or even one that has 40 MHz. It is literally the defining principle of a cellular system that the system is made up of cells, and capacity can be increased with no additional bandwidth simply by deploying more cells. The issue is cost; adding a cell may mean spending a half million dollars on a new cell tower.

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[1] Federal Communications Commission, *The National Broadband Plan: Connecting America,* March 2010. http://www.broadband.gov

[2] AT&T, Supplemental Reply Comments of AT&T, in the matter of The State of Mobile Wireless Competition, WT Docket No. 11-186, April 30, 2012, p. 5. http://apps.fcc.gov/ecfs/document/view?id=7021914823

[3] Maximum achievable capacity is 20 MHz * $\log_2 (1 + SINR)$, where SINR = (transmit power) * (transmitter antenna gain) * (receiver antenna gain) * (path loss) / (noise + interference). This path loss fraction depends on frequency, and is generally smaller in the AWS band than the 700 MHz band.

Thus, the real reason why cellular carriers want more bandwidth is not because bandwidth equals capacity, but because a carrier can generally meet its customer's needs at lower infrastructure cost if the carrier gets more bandwidth. *It is this relationship to cost that should be the basis of a spectrum screen and the focus of this NPRM.* For example, if carrier A has 10 MHz of bandwidth in the 700 MHz band and carrier B has 20 MHz at roughly the same frequency, then carrier A will have to spend more money on infrastructure if it wants to match the capacity of carrier B, perhaps by building more cell towers than carrier A, or deploying more sectors per cell, or using advanced technology that gets more bps/Hz. Because of the impact on infrastructure cost, we can conclude that 20 MHz has more *value* than 10 MHz from the same band, and this is reflected in the FCC's current spectrum screen. But if carrier B's 20 MHz was at a higher frequency, e.g. in the AWS band from AT&T's example, would the greater bandwidth still allow carrier B to spend less on infrastructure? As will be discussed in Section 5.1, the answer is sometimes yes and sometimes no. This is not reflected in today's spectrum screen. Moreover, particularly in rural areas, infrastructure cost can be much lower in 20 MHz of 700 MHz spectrum than in 20 MHz of AWS spectrum, so these spectrum licenses do not have equal value, and weighting them equally may produce that "distorted picture of the economic impact of a spectrum transaction" that AT&T is rightly concerned about.

4   Frequency Matters, and This Has Policy Implications

Radio transmissions at different frequencies have different physical properties, and no man-made law or regulation can change this. These differences include the rate at which signals attenuate as they travel through space, the space needed to establish a line-of-sight connection, the ability to pass through objects such as walls, and the types or antennas that are effective. As a result, one cannot say that one frequency is better than another without considering the types of wireless systems to be deployed. One policy implication is that the screen we are developing here should be specifically for terrestrial (i.e. non-satellite) CMRS spectrum holdings, and the same screen may not be directly applicable for other kinds of systems.

Moreover, different spectrum bands may be preferable for different parts of a cellular system. Large-cell coverage, small femtocell hotspots, and wireless backhaul are all likely to be important, but in 2012 and the foreseeable future, it is access to spectrum for wide-area coverage that is likely to be in shortest supply for a carrier that wants to compete in a given market, so that should be the focus of a spectrum screen. This focus will affect analysis. For example, hotspots can more easily be supported at higher frequencies, so if that were the driving use of spectrum, there would be less need for a spectrum screen that considered frequency. However, as of 2011, only 11% of data from mobile-connected devices was being offloaded.[4] It is clear that more wireless traffic must be carried over these short-range connections in the future, but it is likely that cellular carriers will still need some cells that cover larger

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[4] Cisco white paper, *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2011-2016*, Feb. 14, 2012. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.pdf

areas. First, not all communications will occur near a hotspot. Second, some users move while communicating, e.g. from a car, and having larger cells reduces handoffs for these users. Thus, analysis in this comment will focus on large cells.

Note also that the spectrum screen should encourage use of high frequencies for hotspots, as high-frequency bands work well for this purpose and are less useful for supporting large cells. As government agencies seek new and innovative way to make more spectrum available, it is possible that some of that spectrum will be at high frequencies. A screen that forces carriers who make good use of high-frequency spectrum to divest of an equal amount of low-frequency spectrum may actively discourage efficient use of spectrum.

It is conceivable that someday changes in architecture and in the nature of the applications people most want will lead to changes in the type of spectrum carriers most want, although probably not soon. For example, perhaps someday the percentage of traffic that can be offloaded will be so great that demand will not be as great for spectrum that is used in large cells. A policy implication is that the FCC should occasionally review its spectrum screen to determine whether it is still appropriate, perhaps every five to ten years.

5 Defining a *Weighted* Spectrum Screen, and Which Bands to Include

As the number of spectrum bands used for commercial mobile services increases, the FCC will be faced with a dilemma under the current spectrum screen. If higher-frequency bands are excluded entirely from a screen, then a carrier could gain control of a great deal of spectrum that is never considered, plus a significant share of the lower-frequency spectrum, without ever triggering the screen. On the other hand, if all bands are considered and all are treated the same, then a single carrier could completely dominate spectrum under 1 GHz so it is unavailable to competitors without exceeding the spectrum screen. A solution is to weight spectrum by frequency, where *weights reflect the extent to which spectrum at that frequency yields lower costs for the deployment and operation of equipment*. Without loss of generality, we arbitrarily select a *reference frequency f_0*, and define the weight of spectrum at that frequency to be 1. The weighting function $w(f)$ should roughly correspond to the value per MHz of spectrum at a given frequency f divided by the value per MHz at the reference frequency. Thus, if a carrier has a bandwidth of B_i at frequency f_i for different values of i, then the effective size of the carrier's holdings is

$$\sum_{\forall i} w_i(f_i) * B_i$$

The actual value of a spectrum band in facilitating low-cost infrastructure deployment is complex. It depends on frequency and bandwidth. It depends on how the band is fragmented in frequency and geography. It depends on what equipment is available in the band, which depends in turn on the extent to which regulators around the world have allocated the band for the same purpose, and for how long it has been used by CMRSs. It depends on the technical and business strategy of every carrier in the

market. Not only are there too many factors to consider explicitly, but some of them can change rapidly. Thus, a weighting function must provide a reasonable simplification. As the following subsections will show, precisely calculating weights is also nontrivial because the most appropriate weight depends somewhat on circumstances. Some may use this observation to argue against a new weighting function. However, it should not be difficult to come up with a more appropriate weighting function than we have now, which implicitly assigns all frequencies a weight of 1.

The screen should cover bands that are licensed exclusively to CMRSs over reasonably large regions. The screen should not cover unlicensed bands used by carriers, as use of unlicensed bands does not prevent competitors from also using these bands. Nor should the screen cover dynamic secondary access over small timespans and small areas, as might occur under the vision recently proposed by the President's Council of Advisors on Science and Technology (PCAST).[5]

The remainder of this section will
- demonstrate quantitatively that weights should be lower for higher-frequency bands, and
- present methodologies that could prove useful in defining effective weighting functions.

There are two obvious ways to quantify the relative value of spectrum in different in frequency bands: technical analysis based on the physical properties of the spectrum, and economic analysis based on market signals. Each will be discussed in the following subsections.

5.1   Weighting Functions Based On Technical Properties

One important advantage to basing a weighting function on the frequency of spectrum and its physical characteristics is that frequency is an extremely important factor, and the resulting weights can be stable and predictable. Weights would not fluctuate with this week's market activities, or the latest regulatory decision on another continent. Nevertheless, the relationship between frequency and the cost of infrastructure depends on a number of factors, and probably the most important is population density.   As a result, in this section we quantify these effects in three example scenarios corresponding to rural, suburban, and urban regions.

Scenario 1: Rural
For the rural scenario, we quantify the relationship between frequency and infrastructure cost in the case where a CMRS wishes to blanket a region with coverage, and where population density is sufficiently low that the network's data-carrying capacity is not likely to be a problem as long as coverage is good.

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[5] President's Council of Advisors on Science and Technology, *Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, July 2012*.*
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

Cellular infrastructure cost is roughly proportional to the number of towers that must be deployed to cover the region, so cell size is the key. The maximum possible radius of a cell is the maximum distance from cell tower to mobile device at which the signal to interference + noise ratio (SINR) is adequate. This depends on frequency f. Let r be the cell radius at frequency f, and r_0 be the cell radius at the reference frequency f_0. Path loss from the tower to the edge of the largest possible cell is the same, regardless of frequency, and this fact can be used to quantify the relationship between cell size and frequency.

To derive this relationship, we use the Hata Model for path loss in an open area. This is the industry-standard model for regions where there are relatively few obstructions (such as buildings), and where the frequency falls between 200 MHz and 1.5 GHz. We make the simplifying assumption that antenna gain, antenna height, transmit power, and noise are independent of frequency. In this model:

L = 69.55 + 26.16 $\log_{10} f$ − 13.82 $\log_{10} h_B$ - C_H+ [44.9 − 6.55 $\log_{10} h_B$] $\log_{10} d$ − 4.78 $(\log f)^2$ + 18.33 $\log_{10} f$ − 40.94
where
- L is path loss in dB
- f is frequency in MHz
- d is distance from transmitter to receiver in km
- h_B is antenna height in meters
- h_M is height of the mobile antenna in meters
- C_H is 3.2 $(\log_{10}(11.75 \, h_M))^2$ − 4.97

Without loss of generality, we will use 700 MHz as our reference frequency, i.e. $w(700) = 1$. By setting path loss at frequency f and radius r equal to path loss at radius r_0 and frequency $f_0 = 700$ MHz, we find with a bit of math that

$$r = r_0 / 2.911 * 10^{(\log f - 4.654)^2 * 0.1418}$$

For the sake of example, let maximum radius r_0 be 80 km at the reference frequency of 700 MHz.[6] Figure 1 shows how r varies with frequency. We see that frequency has a large effect on cell radius. What matters is the cost per square kilometer served, which is inversely proportional to radius squared. To obtain numerical cost results, we assume that the net present value (NPV) of building a cell tower and operating it every year is one million dollars. We further assume that cells are hexagonal, which means the area of a cell is 2.6 r^2. Figure 2 shows how the resulting cost per square km varies with frequency. Clearly the frequency of a carrier's spectrum has a large impact on its costs. Thus, in this scenario, a carrier would be willing to pay $55 per square km more for spectrum at 700 MHz than it would be willing to pay for spectrum at 1400 MHz.

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[6] There have been reports that LTE technology can support cell sizes of up to 100 km. For example, see Motorola white paper, *TD-LTE: Exciting Alterative, Global Momentum,* 2010.
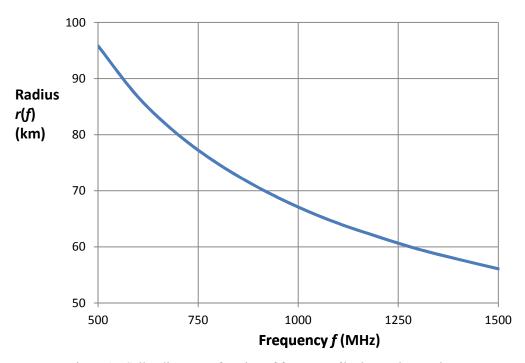http://www.motorola.com/web/Business/Solutions/Industry%20Solutions/Service%20Providers/Network%20Operators/_Documents/_static%20files/TD-LTE%20White%20Paper%20-%20FINAL.pdf

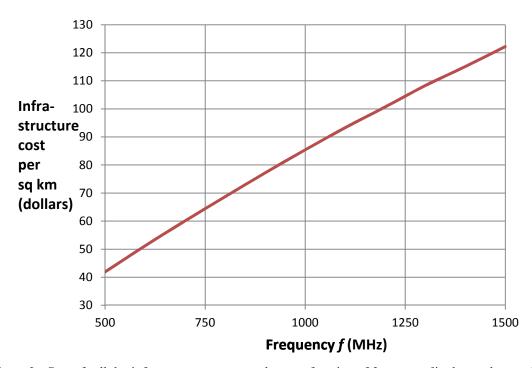Figure 1: Cell radius r as a function of frequency f in the rural scenario

Figure 2: Cost of cellular infrastructure per square km as a function of frequency f in the rural scenario

To observe the impact on spectrum valuations in a specific scenario, consider a carrier that wishes to blanket a rural open area with 10 MHz of spectrum. The population density is 7.4 people per square km, which corresponds to the population density of Idaho as of 2011.[7] If a carrier would pay $1.15 per MHz-POP in this case, which is roughly what was bid in the 2008 auction, this would correspond to spectrum value of $85 per square km. Figure 3 shows how this value changes with frequency.[8] Again, we see that frequency has a large impact on the value of spectrum, as might be reflected in a weighting scheme.
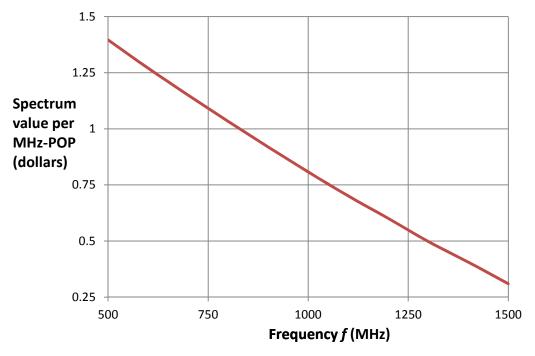

Figure 3: Value of spectrum per MHz-POP as a function of frequency f in the rural scenario

Scenario 2: Dense Urban
In this scenario, a carrier must provide sufficient capacity per square km to meet the needs of a very densely populated city. Cells must be sufficiently small that the number of subscribers in each cell will not require more capacity than a single cell can provide. We assume that to meet this constraint, the cells must be smaller than the maximum possible size even at the highest frequency used by this carrier. In this case, frequency has little impact on the number of towers. There may still be some secondary issues where frequency matters, e.g. building penetration or equipment availability, but the value of a MHz-POP of spectrum when used for this purpose should be roughly the same in all frequency bands used by this carrier.

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[7] *2011 Population Estimates*. United States Census Bureau, Population Division. December 2011.
[8] The low population density in this rural region may cause spectrum valuations to be much lower than $1.15 per MHz-POP. In that case, valuations at all frequencies would be correspondingly lower. The value of spectrum at 1500 MHz might even go negative, which would mean that carriers would rather pay for spectrum at 700 MHz than gain access to spectrum at 1500 MHz for free.

Scenario 3: Suburban

In this example scenario, we assume that a carrier has spectrum in more than one frequency band. Unlike the rural scenario above, to meet the capacity needs of its customers, the carrier must deploy more cells than would be required just to provide coverage everywhere in the lowest-frequency band. Unlike the urban scenario above, to meet the capacity needs of its customers, the carrier need not make its cells so small that they can be entirely covered by a single tower even in the highest-frequency band. In this case, the carrier will use its low-frequency spectrum to serve customers at the edge of the cell, and its high-frequency spectrum for customers near the tower.

Once again, frequency greatly affects the value of spectrum, but in this case, what matters is the data rate that can be supported in different frequency bands rather than coverage. The lowest-frequency band will meet coverage requirements. Higher-frequency bands will be used to meet capacity requirements, and how effectively they can do so depends on frequency. We investigate this effect by determining how data rate changes when frequency is doubled. For example, if doubling frequency causes data rate to drop to 2/3 of its prior value, then we need 3/2 as much of the high-frequency spectrum to offer the same capacity.

To quantify this effect, we assume that data is transferred at the Shannon limit.

$$\text{Data rate} = \text{Bandwidth} * \log_2 (1 + \text{SINR})$$

We further assume that interference + noise is roughly the same at all frequencies, which is reasonable in cases where the maximum radius at the frequencies considered here is well under the actual radius of the cell. Finally, we assume that path loss can be described using another standard Hata model: the model for large cities. For the purposes of this analysis, the most important aspect of the Hata model is that path loss L (when measured in dB) increases with $26.16 \log_{10} f$. More generally:

$$L = 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_B - C_H + [44.9 - 6.55 \log_{10} h_B] \log_{10} d$$

where

- L is path loss in dB
- f is frequency in MHz
- d is distance from transmitter to receiver in km
- h_B is antenna height in meters
- h_M is height of the mobile antenna in meters
- C_H is $3.2 (\log_{10}(11.75 h_M))^2 - 4.97$

We quantify the effect of doubling frequency by examining the ratio of data rate at frequency $2*f$ to data rate at frequency f, which corresponds to $w(2f) / w(f)$ when spectrum is used for this purpose. The ratio $w(2f) / w(f)$ depends on the SINR, or equivalently it depends on what data rates were possible at the lower frequency f. Thus, Figure 4 shows this ratio of data rates as a function of the data rate achievable at frequency f. Near the center of the cell where SINR is high, much higher data rates are possible. In the portion of the cell where 15 bps/Hz[9] is achievable, for example, it is possible to double the frequency and still achieve 83% of the data rate, so the high-frequency spectrum is almost as good.

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[9] Today's LTE can achieve 15 bps/Hz when SINR is high, and future standards will do even better.

For this SINR, $w(2*f) = .83\ w(f)$. However, if the mobile is far enough from the tower that it could only achieve 1 bps/Hz at the lower frequency, then the achievable data rate at the higher frequency is just 22% of that, i.e. $w(2*f) = .22\ w(f)$. Thus, if a small amount of high-frequency spectrum is used to supplement the low-frequency spectrum needed for coverage, that high-frequency spectrum can be used only for devices near the center of the cell, and the high-frequency spectrum is worth almost as much as the low-frequency. On the other hand, if a large part of the cell must be served with high-frequency spectrum, then many of those mobiles using this band will be far from the tower, and the average data rate per MHz at the higher frequency can be well below half that at the lower frequency. As in the rural scenario, we see the value of high-frequency spectrum is much lower, although precisely how much lower depends on a variety of factors.
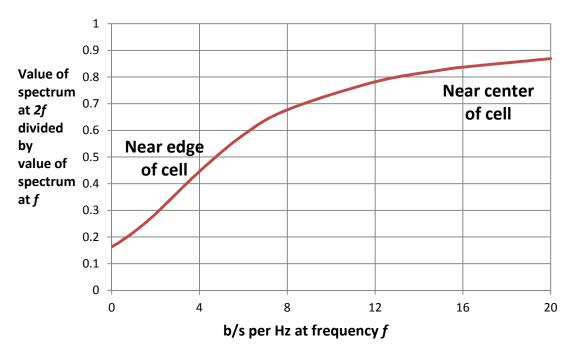

Figure 4: Ratio of the value of spectrum at frequency *2f* to the value of spectrum at frequency f, which equals the ratio of data rate achievable at frequency *2f* to data rate achievable at frequency *f*, as a function of the data rate achievable at frequency *f*.   Suburban scenario

Observations from the Three Scenarios

From the three scenarios above, we observe the following.

- Frequency can dramatically affect infrastructure cost. In some suburban and rural scenarios, doubling frequency can reduce the value of spectrum by much more than a factor of two. This impact of frequency should be reflected in a spectrum screen.
- The most appropriate weighting function depends on a number of technical and environmental factors, including population density. Further work is needed to find a weighting function that represents the best balance.   This should include consideration of frequency bands above 1500 MHz, which are beyond the scope of this comment.

- To meet coverage requirements alone, it is useful to have at least some spectrum in lower-frequency bands, and this low-frequency spectrum might be supplemented effectively with spectrum that is at higher frequencies and therefore less valuable. Thus, a spectrum screen should detect when a carrier thoroughly dominates low-frequency spectrum, regardless of its high-frequency holdings. The current spectrum screen does not do that. This might be addressed by the spectrum shield for spectrum under 1 GHz as proposed in the FCC NPRM. However, the weighting function may also meet this need without adding the second constraint; this depends on the weighting function ultimately chosen.
- Because the screen is applied in one geographic region at a time, and the most appropriate weighting function depends greatly on population density, the FCC might consider different screens for urban, suburban, and rural areas. This would allow the FCC to choose the screen that best fits the region, but it has two major disadvantages that deserve consideration. First, some regions considered in merger reviews may be large enough that they contain a mix of urban, suburban and rural. If so, having multiple screens would only confuse the issue. Second, handsets can typically operate in a limited number of spectrum bands, so there are advantages to using the same spectrum bands in both urban and rural areas, even if the impact on infrastructure cost is different. As long as this is true, there is greater reason to apply the same screen in rural, suburban and urban areas. However, as software-defined radios and perhaps even software radios become more cost-effective over time, the advantages of operating in a small number of bands should recede. The FCC's Technological Advisory Council (TAC)[10] has recently predicted great advances in multiband devices over a five-year period. If these predictions are correct, it will be more reasonable for the FCC to use different spectrum screens in rural and urban areas in perhaps five years when these advances have occurred.

5.2   Weighting Functions Based on Market Signals

An alternative approach to weighting spectrum values is to use market values.   There are advantages to this approach. If there were a highly fluid and transparent market for spectrum suitable for mobile services that is similar to the stock market, then we would have an objective measure of what spectrum is actually worth to the relevant players. However, the spectrum market is quite different from the stock market.

Some have proposed using the winning bids in past auctions to determine the value of spectrum, or valuations that are simple multiples of winning bids. Winning bids provide useful information that should be considered, but they should not be accepted at face value.   The problem is that the value bidders were willing to pay at the time of the auction may be quite different from the value today. Bids do depend on the intrinsic value of the spectrum being auctioned, but they depend on many other

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[10] Federal Communication Commission Technological Advisory Council, Multiband Devices Working Group, Presentation at the FCC on Sept. 24, 2012. http://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting92412/TAC-9-24-12-Presentations.pdf

things as well. These include the level of pent-up demand for spectrum at the time of the auction, the number of carriers in a position to bid at the time of the auction, the interest rates at the time of the auction, the general state of the economy and therefore cellular revenues at the time of the auction, the regulations imposed on the winner which can vary from band to band, the extent to which the band has already been cleared and the cost of clearing it, the extent to which that spectrum band is available internationally which can also change over time, how adjacent spectrum bands are being used at the time of the auction, and more. Basing valuations only on auction bids, which at best are a snapshot of value from a previous era, could therefore introduce significant distortions.

An alternative is to use spectrum values as determined through a secondary market after the auctions. These trades and leases may also produce information that the FCC should consider. The problem here is that the trades and leases are relatively infrequent and the financial details are sufficiently opaque that this also may produce an incomplete and perhaps distorted picture. Moreover, because of these (current) limitations of the spectrum market, overreliance on whatever data does exist may allow carriers to game the system. For example, a carrier may be able to make its holdings at a given frequency to appear less valuable by leasing a small amount of spectrum at that frequency at a price that is well below its market value. Similarly, a carrier may be able to make the holdings of a competitor appear more valuable by paying an inflated price for a small amount of spectrum at the same frequency.

Although there are problems with blindly turning these market signals into weighting functions, there is still much to learn from the signals that are available. For example, one study[11] analyzed auction bids from the U.S., Sweden and Australia, and concluded that spectrum bids do depend on frequency, and if weights were based on their analysis of bids, then the weighting function $w(f)$ might take a form such as this:

$$w(f) = \text{constant} * e^{-0.001\,f}$$

or equivalently

$$w(f) =\ e^{-0.001\,(f-f_0)}$$

where f is frequency in MHz and f_0 is the reference frequency. This work is certainly informative, but based on the small number of data points considered and the high variance, it is not possible to conclude from these results alone whether this is the best weighting function.   Further analysis is needed.

Figure 5 shows the value of spectrum at different frequencies using the above function $w(f)$ for the case where spectrum at 700 MHz is worth $1.15 per MHz-POP. Figure 5 also shows the value of spectrum derived from deployment cost in the rural scenario discussed in Section 5.1, as was also shown in Figure 3. Although calculated in very different ways, the two spectrum value curves are somewhat similar, which is reassuring. The curve based on auction bids decreases more slowly with frequency, but given that the deployment cost estimates were for the rural scenario only and the auction bids apply to areas of all population densities, this difference is reasonable.

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[11] A. Kerans, D. Vo, P. Conder, S. Krusevac, "Pricing of Spectrum Based on Physical Criteria," *Proceedings of IEEE DySPAN,* 2011, pp. 223-230.
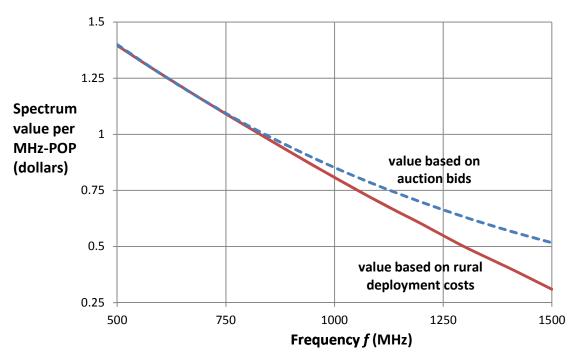
Figure 5: Value of spectrum per MHz-POP as a function of frequency *f* as derived based on
(i) costs in the rural scenario and (ii) auction bids as analyzed by Kerans, Vo, Conder & Krusevac

6   The Relevance of Build-Out

Public Knowledge has previously proposed that spectrum that has not yet been built out be weighted
more heavily.[12] There is reason to consider build-out in the context of a spectrum screen; one sign that
a carrier is building its spectrum holdings not primarily to provide services at low cost but to increase
costs for its competitors is that the carrier will use some of its spectrum inefficiently or not at all.
However, as the previous section shows, devising a weighting function that reasonably reflects the value
of spectrum for reducing infrastructure cost is complicated enough without incorporating another issue
into the calculation. The extent of build-out in a given region might instead be considered a secondary
factor when determining whether a carrier has enough spectrum in that region to undermine effective
competition. Even then, this factor must be considered with care, because spectrum that was
underutilized before a merger may become the focus of build-out after a merger.

With build-out as a separate and secondary factor, the FCC will need a measure of build-out that is easy
to calculate, indicative of whether spectrum is underutilized, and does not require the revelation of
highly proprietary data. This is possible, provided that the FCC collects the appropriate data in the
course of a merger review. A simple but effective approach could focus on number of towers in use,

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[12] Letter from Harold Feld, Legal Director, Public Knowledge, to Marlene Dortch, Secretary, FCC, WT Docket No. 12-
4 (Apr. 30, 2012) at 3.

without revealing exactly where these towers are located, whether they are owned or leased by the carrier, what technology they use, how many subscribers they typically serve or how much data they typically carry. In coverage-limited regions, building more towers typically means extending coverage. In capacity-limited regions, building more towers typically means increasing capacity. Either way, the number of towers is roughly indicative of how the carrier has invested in infrastructure to make greater use of its spectrum holdings.

I would propose that the FCC collect sufficient data to calculate the number of towers per square km in each spectrum band and each region where the spectrum screen is an issue. For example, consider a carrier with a license for 50 MHz in a given band and in a 1000 square km area. If the carrier has deployed 10 towers that use all 50 MHz and 20 towers that use 20 MHz, then the carrier has (10 *50 MHz/50 MHz + 20 * 20 MHz/50 MHz) / 1000 km^2 = .018 towers per km^2 in this 50 MHz.   If this number is considerably lower than can be seen from competitors in the same region or simply low considering other relevant factors, and the carrier is still trying to expand its spectrum holdings, then this could be an indicator that spectrum is being "warehoused."

While potentially useful, this measure must be considered in the context of other factors. Moreover, the definition may change over time as technology evolution may force regulators to change the definition of what constitutes a "tower."

7   Conclusions

The discussion and analysis above offers the following lessons of use to the FCC:
- A spectrum screen is a useful tool when determining whether the spectrum holdings a firm would have after a merger or acquisition would be sufficient to inflate the costs of spectrum-starved rivals, thereby undermining competition.
- There is ample quantitative evidence that the value of spectrum depends on frequency, and that the differences are so great that any spectrum screen that treats all frequency bands the same is inadequate to the task, and will become even more inadequate in the future as CMRSs employ a more diverse set of frequency bands. This is clear both from our quantitative analysis of how the physical properties of spectrum affect infrastructure cost, and from the analysis of market-based measures.
- A spectrum screen could effectively consider the importance of frequency by developing a weighting function based on frequency. Weights should reflect the extent to which spectrum at that frequency yields lower costs for the deployment and operation of equipment. Determining the most appropriate weighting function is not easy, and beyond the scope of this filing. However, this comment demonstrates some of the approaches that the FCC or others might use to determine such a function. In particular, both technical considerations and market data are worth examining. One approach shown here is to quantify the impact of frequency on infrastructure cost under various conditions. This analysis could be extended. Another is to use

price data from spectrum auctions and secondary markets. Weights should not change with every new auction or every new trade, because this would make weights overly dependent on the vagaries of a fluctuating market or even deliberate manipulation by spectrum-holders, but this information can be seriously considered in conjunction with technical analysis.

- The FCC could consider a spectrum screen that is different in areas with different population density, but only if this screen is applied over small enough regions that population density can reasonably be viewed as homogenous.   If so, this approach is likely to become more appropriate in the future, as advances in technology continue to drive down the penalties for supporting many bands in a single mobile device.

- The FCC could consider the extent of build-out as a separate and secondary factor when assessing whether a firm's spectrum holdings would be a threat to competition. A useful measure to consider is the number of towers per square km in each frequency band and region, as defined in Section 6. To use this measure, the FCC must gather sufficient information during a merger review.

- A good screen requires some assumptions about technology, and technology changes over time. Thus, weighting functions and other considerations should be reviewed periodically, perhaps every five to ten years.