Identifying Key Characteristics of Bands for Commercial Deployments and Applications Subcommittee

Final Report and Recommendations

Commerce Spectrum Management Advisory Committee

November 17, 2017

Subcommittee Members:

Paul Anuszkiewicz
Audrey Allison
Donna Bethea-Murphy
Mary Brown
Michael Calabrese
Tom Dombrowsky (Co-Chair)
Carolyn Kahn
Janice Obuchowski
Carl Povelites
Mark Racek
Charla Rath (Co-Chair)
Dennis Roberson
Andrew Roy
Kurt Schaubach
Steve Sharkey
Mariam Sorond
Bryan Tramont
Jennifer Warren

NTIA Liaisons:

Chris Mattingly
Amy Sanders

Overview: The subcommittee was provided five questions to respond to and provide recommendations. Detailed answers have been developed and are contained in the underlying text as well as the full questions delivered by NTIA. An overarching point for determining key characteristics for commercial technology deployment is that the private industry is constantly evolving (both use cases and technology) so that any "key" characteristic may be modified in a dynamic fashion. The subcommittee provides some recommendations for NTIA's consideration below, based on these answers to the questions provided to the Committee.

When drafting these responses, the subcommittee made every effort to capture all commercial industry inputs, such that where "commercial industry" is referenced in responses it is referring to "all" industry represented in the subcommittee, including terrestrial wireless (licensed and unlicensed) and satellite services.

Recommendation 1: The subcommittee recommends that NTIA give consideration to the following key characteristics when reviewing potential new spectrum bands for reallocation or use by the commercial industry: (1) propagation and coverage; (2) capacity; (3) contiguity; (4) international harmonization (scale); and (5) incumbency issues. The subcommittee would note that relative priority for each of these characteristics is likely to vary based on industry and use case.

Recommendation 2: The subcommittee recommends that NTIA make every effort to focus its efforts to identify opportunities for either repurposing or sharing of federal spectrum on bands that are contiguous to existing commercial spectrum uses.

Recommendation 3: The subcommittee recommends that NTIA not attempt to rigidly define low, mid, and high band spectrum bands as this metric is dynamic and ever changing.

Recommendation 4: The subcommittee recommends that NTIA consider directing CSMAC to develop a methodology (rubric) to identify federal bands for potential commercial-federal sharing.

Question 1: From a commercial industry perspective, what are the key characteristics it considers in evaluating the desirability of a particular frequency band as a candidate for licensed (exclusive or shared) and unlicensed spectrum?

Answer: Fundamentally, the key factors when industry looks to evaluate particular spectrum bands are divided into several categories: (1) propagation and coverage; (2) capacity; (3) contiguity; (4) international harmonization (scale); and (5) incumbency issues. Each of these areas is addressed in more detail below. In general, no single spectrum band will meet every requirement for a particular use, given the diversity of industry requirements and use cases. Of note, the industry players will make decisions on the value of a particular frequency range in reliance of these characteristics. Relative priority for each of these characteristics is likely to vary based on industry and use case.

However, it should be understood that this is a dynamic measure as changes in technology and use case requirements will lead to changes by particular parties on what they consider to be a "key" characteristic for a specific spectrum band. For example, a few years ago, there was no consideration in the wireless ecosystem about how to integrate millimeter wave spectrum into LTE networks. That has come about due to advances in technology – both at the radio edge and in the network core. As a result, millimeter wave frequencies, which have been deployed by operational broadband satellite systems around the globe and are planned for further utilization by soon-to-be-launched satellite systems, are being trialed and will commercially launch service by the terrestrial wireless industry in the 2018/2019 timeframe. Both technology capability and probable use cases provide the foundation for evaluating particular bands.

Propagation and Coverage. The physical characteristics associated with a particular spectrum band will dictate its propagation capabilities. The lower in frequency, the larger the wavelength and, accordingly, the more resistant to fading and blocking a spectrum band will be. As such, when looking at use cases (whether for mobile, fixed, satellite, broadcasting, or unlicensed) that require extensive coverage and in-building service, and where maximizing data capacity is not the most critical issue, lower spectrum bands are an optimal choice. In particular, spectrum below 1 GHz has typically been seen as best for terrestrial mobile applications that require greater coverage (both in terms of distance from the base station transmitter as well as external base station to in-building user device). This is necessary because commercial services must deal with extensive limitations in propagation (buildings, terrain, foliage, etc.) that can be best overcome by use of spectrum in lower frequency ranges.

In addition, lower frequencies will allow for less infrastructure to provide the same coverage, presuming that coverage is the primary issue to be dealt with – thereby lowering capital and operational expenditures for these applications. The propagation characteristics of lower frequencies and its resistance to rain fade also make it well suited for high availability satellite applications, especially for services in remote locations. Of course, regardless of the spectrum bands, a single geostationary satellite provides CONUS coverage and three can provide generally global coverage. However, it is important to note that low frequency spectrum, while highly capable for coverage, is limited in its ability to provide capacity since the inverse of strong coverage characteristics is low spectrum reuse. In addition, there is far less spectrum (megahertz) available in the low bands and therefore according to basic Information Theory

(Shannon, et. al), much less data carrying capacity. Mid and high-band spectrum ranges will not have the same propagation characteristics but will have access to more spectrum – and therefore more capability (as discussed below) to provide greater data rates and higher network capacity. Moreover, video – which as a category dominates the utilization of commercial networks – is for the most part viewed indoors, where the limitations related to mid- and high-band propagation characteristics can be a benefit.

Capacity. As discussed above, another key characteristic for spectrum is the capacity that a particular spectrum band can provide. Depending on the use case, propagation and coverage may not be the limiting factor – rather the need for spectrum reuse through base station densification and the need for extensive (i.e. tens of megahertz) blocks of spectrum to provide high data rates and network capacity are more critical. For example, for the streaming of high quality video, industry providers will require access to frequencies that provide sufficient bandwidth to maintain a quality of service expected by consumers. Mid- and high-band spectrum ranges are dramatically larger than those available in low bands and therefore have a greater capability to support broader spectrum blocks, which means that use cases that are not as dependent on coverage and propagation characteristics will place a greater premium on access to higher spectrum ranges.

In the terrestrial mobile industry, coverage (at least in major urban areas) is no longer as important a factor as capacity. This had led to a change in some spectrum valuations to favor mid- and high-band spectrum assets at higher levels than had previously been the case. Satellite parties have broad coverage areas that are provided from a satellite transponder or spot beam and there is a need for extensive capacity when large geographic areas are covered. Unlicensed providers similarly have use cases that require greater capacity. For example, recent efforts have been focused on obtaining significant blocks of 5 GHz spectrum to provide the capacity and data rates consumers demand for home and enterprise Wi-Fi systems. Compared to the 2.4 GHz spectrum the FCC originally identified for unlicensed use, the 5 GHz band has nearly an order of magnitude more bandwidth available.

Contiguity. (This factor is explored in greater detail in the response to Question 2 below.) Another factor when attempting to value a particular frequency band is its proximity to other bands of spectrum currently in commercial use. Spectrum bands that are directly adjacent to similar or complementary uses are more valued than bands that are greatly separated. For a few examples, in the terrestrial mobile industry, the AWS-3 spectrum (1755-1780 MHz paired with 2155-2180 MHz) was more valued as it was directly adjacent to the existing AWS-1 spectrum band (1710-1755 MHz paired with 2110-2155 MHz). Similarly, the unlicensed industry values contiguous blocks of spectrum in the TV White Spaces and the 5 GHz band , and strongly supports the Commission's recent decision identifying for unlicensed use the 64-71 GHz band, which is directly adjacent to the 57-64 GHz band that the Commission previously made available for unlicensed use. The satellite industry also has articulated a need for contiguous 5 GHz blocks of spectrum above 24 GHz to support current broadband systems and enable next generation broadband satellite services currently under development and applied for at the FCC and ITU.

International Harmonization. Spectrum harmonization, which facilitates economies of scale for equipment providers, is also a factor for most services, and especially for satellite services because of the inherently international nature of broadband satellite systems, both geostationary or non-geostationary. If a particular frequency range is available under similar (or the same) technical rules globally, then economies of scale should greatly reduce the costs associated with producing equipment. As a specific example, the 2.4 GHz band (2400-2483.5 MHz) is largely harmonized globally for short-distance unlicensed technologies, such as Wi-Fi or Bluetooth. As such, an equipment vendor can develop and sell the same 2.4 GHz module throughout the world with minimal changes. In addition, it is important to note that harmonization is not limited to requiring that all countries have identical spectrum allocations. The benefits of harmonization can also be derived from "tuning range" solutions covering adjacent or near-adjacent bands in which equipment can be easily reconfigured to operate over multiple bands (i.e., they are within the same tuning range). The tuning range is directly related to the specific frequency – lower frequencies will have smaller tuning ranges and higher frequencies will have higher tuning ranges.

Incumbency Issues. The final characteristic associated with a particular frequency that affects value is the amount and type of incumbent use of the band. A spectrum range that has extensive incompatible incumbent use or that will require difficult sharing requirements to maintain incumbent rights to provide service and innovate will adversely affect the value of the spectrum band. Past spectrum proceedings demonstrate that having a clearly defined process for relocation or well-understood and effective sharing requirements will greatly alleviate the effects of incumbency and reduce risks. For example, the AWS-1 and AWS-3 spectrum bands contained Department of Defense incumbents that either relocated or were protected through a well-defined sharing requirement. Because the relocation process and sharing requirements were well understood, the values of the spectrum rights were not undermined. In contrast, for years there was no equipment available in the WCS band at 2.3 GHz because the protection rights for the incumbent satellite radio providers *in an adjacent band* effectively limited the ability of licensees to use the spectrum. In some cases, effectively addressing incumbency issues may require compromises in terms of some of the other key characteristics identified above, to ensure a balance of important services and maximize the utility of the public spectrum resources.

Question 2: What are the technical and operational impacts of contiguous versus non-contiguous spectrum to satisfy commercial requirements?

Answer: The following statements are taken from interviews from engineering experts in network companies. The background for this answer can be found in Appendix A. There are many commercial technologies, but we have identified three dominant ecosystems for spectrum planning purposes. The answers below are intended to reflect the technical and operational implications of contiguous versus non-contiguous spectrum availability for the IEEE 802.11 family (Wi-Fi, et al), 4G LTE (5G to the extent known), and commercial satellite operations.

In general, there are several themes that are consistent across technologies:

- Systems using contiguous spectrum can be designed to use more channels than two separate tranches of spectrum of the same total size.
- Larger channels provide benefits that smaller channels do not, for example, larger channels produce lower power spectral density or improve geolocation
- Engineering complexity is substantially reduced with contiguous spectrum.
- Broad channels enable the use of technologies that increase data throughput rates.
- While it is possible to aggregate spectrum from different bands, aggregation comes at a cost to performance.

From an engineering perspective, and without respect for incumbency issues or other matters, as the size of the band increases, so do its benefits. Terrestrial technologies are conceived based on building blocks that allow backward compatibility to prior versions. IEEE 802.11, for example, utilizes 20 megahertz building blocks (channelization of 20, 40, 80 or 160 megahertz). LTE technologies generally use 10 megahertz building blocks, although vendor products allow narrower channelization (1, 5 megahertz) to support specific applications that may not need broadband throughput. Similarly, satellite applications rely upon building blocks of spectrum – with the size of the block dependent on use case and service the bandwidth is meant to support. Satellite systems often leverage proprietary protocols to do more with smaller bandwidths, however, the principle that wider frequency bands allow greater bandwidths and improved performance applies equally to the satellite context.

These effects hold true whether the spectrum in question is low band, medium band or high band. However, given the historically high rate of utilization of low band frequencies, it is expected that the benefits of broad swaths of contiguous spectrum will be most evident in mid-band and high-band spectrum.

Question 3: When industry describes its need for low-, medium-, and high-band spectrum, what should we understand to be the definitions for those broad frequency ranges and the rationale for selecting the boundaries between each?

Answer: In general, these definitions are dynamic and subject to change based on use cases and technology evolution. For example, experts believed that 3 GHz was the upper edge of "usable" spectrum for terrestrial mobile services. However, new use cases and technology development have greatly expanded the possible frequencies for terrestrial mobile use – well into the millimeter wave bands (above 24 GHz). By comparison, the satellite industry has for many years made productive use of higher spectrum with High Throughput Satellite (HTS) services that are delivering commercial broadband services throughout the United States.

Benefits of Lower or Higher frequencies:

- *Lower Frequencies.* Generally the "pros" of lower frequencies are that :
    - Better propagation, i.e., the radio waves travel farther.
    - Better in-building penetration (easier to pass through objects such as walls with less attenuation).
- The main "con" is that the ability of the radio waves to travel farther and through objects can be a negative when capacity is the goal (i.e. these characteristics inhibit spectrum reuse)
- *Higher Frequencies.* Generally the "pros" of higher frequencies are that they:
    - Allow for greater capacity by providing more contiguous bandwidth and have fewer incumbency issues.
    - Support frequency reuse because the radio waves do not travel as far as lower frequencies.
- The "con" is that to provide the same amount of coverage as for low band spectrum more infrastructure must be deployed, increasing infrastructure costs.

Evolving definition:

There is little consensus on exactly what constitutes low-, medium, and high-band spectrum. Historically in the terrestrial mobile environment:

- Low-band spectrum was considered spectrum below 1 GHz. These frequency bands were historically described as "beach front property" and thought ideal for terrestrial mobile communications primarily because of the coverage and in-building penetration.
- Mid-band spectrum was between 1 GHz and 2 GHz. This spectrum provided good coverage (2-4 times the number of sites as compared to 850 MHz) and better capacity.
- High-band spectrum was considered that spectrum between 2 GHz and 3 GHz. Frequencies above 3 GHz were for the most part shunned by the CMRS industry.

Trends in the industry have caused requirements to change, particularly the exponential growth in data demand primarily caused by the consumption of video by consumers. Carriers that have coverage spectrum are now looking for spectrum that provides capacity. In parallel, the wireless technology capabilities have continued to improve allowing for low cost operation through this 3

GHz and beyond. As an example, low cost operation in the 5 GHz range for Wi-Fi and now LTE-U / LAA is virtually taken for granted.

Given the lack of consensus and continual evolution of technologies and markets, subdividing the spectrum into more than three bands (high, medium, and low) provides more nuanced insight and in most respects it is more convenient to simply refer to the spectrum in its numeric frequency ranges rather than trying to definitely define major bands such as low, medium and high. However, it is important that US regulatory and policymakers use common references to maximize a common understanding. Rather than classifying particular spectrum bands as “low” “medium” or “high,” it is more useful to speak in terms of the physical characteristics of each band.

If qualitative band definitions are used, the physical characteristics of each spectrum band could be divided conceptually into the following five bands:

Low: 400 MHz–1 GHz or below 1 GHz
Medium-Low: 1–3 GHz
Medium: 3–6 GHz
Medium-High: 6–20 GHz
High: 20–100 GHz or 20–300 GHz or 20 GHz and up

These bands are distinguished from one another by their physical characteristics, notably those associated with radio wave propagation and antenna size/directionality. However, those characteristics change gradually with frequency, with few if any “discontinuities” that would allow easy demarcation of bands. Keeping that in mind, the bands may be characterized as follows:

- The low band (400 MHz–1 GHz or below 1 GHz) is useful for highly reliable, relatively low-data-rate radio links traversing long paths (5 to 50 miles) to for instance handheld mobile phones, mobile satellite terminals, public safety radios, or commercial push-to-talk services having non-directional antennas. Its key advantages are relatively low free-space, foliage, and building-penetration losses, its virtual invulnerability to rain, and the ease with which Doppler shift and frequency drift can be mitigated. Its key disadvantages are shortage of available bandwidth, limited feasibility of directional antennas for beamforming and limited spatial reuse capability for MIMO or site densification. Many mobile antennas start to get inefficient and/or unwieldy below 400 MHz, although VHF and UHF frequencies are widely used by mobile satellite services for two-way data and positioning services, such as Automatic Identification System (AIS) receivers.

- The medium-low band (1–3 GHz) is useful for reliable, medium-data-rate radio links traversing medium-length paths (up to 5 miles) to handheld mobile phones. It has moderate free-space, foliage, and building-penetration losses, and is not particularly affected by rain. It allows somewhat higher degrees of freedom for antenna directionality and spatial reuse, increasing capacity. Site densification by use of small cells is possible. Because of the low power requirements, high-reliability, and ability to use omni-directional antennae, frequencies in this band are used by two-way satellite mobile voice and data services, such as those relied upon by users in military, first responder, energy production, and remote communities.

- The medium band (3–5 GHz) is useful for higher-data-rate radio links traversing shorter paths, or longer paths on which occasional rain outages are considered tolerable. It has relatively high free-space, foliage, and building-penetration losses and is affected only by heavy rain. This band allows considerable antenna directionality and spatial reuse, enabling beamforming and high-order MIMO. This band is better suited for small cell use. Because of their broad coverage and resiliency to rain fade, frequencies in this band are utilized by satellite systems for providing broadcast services in challenging geographies as well as for critical feeder link and tracking, telemetry, and command operations.

- The medium-high band (5–20 GHz) is useful for high-data-rate radio links traversing short line of site paths (less than 5 miles), or longer paths over which frequent rain outages are considered tolerable. It has high free-space, foliage, building-penetration, and rain losses. High spectral efficiency is possible due to increased antenna directionality, low antenna correlation and spatial reuse. This band is primarily suited for small cell use, therefore requiring more infrastructure. In the satellite context, there is extensive use of this band for video delivery, including direct-to-home services, as well as data systems (both direct-to-consumer and for enterprise services).

- Historically, the high band (20–100 GHz or 20–300 GHz or 20 GHz and up) is useful for very-high-data-rate radio links traversing short paths (less than 2 miles) that are either indoors, or on which very frequent rain losses are considered tolerable. It has very high free-space and rain losses. Foliage and buildings are nearly opaque to radio waves in this band. As mentioned earlier, spectrum above 20 GHz is widely deployed in current generation satellite broadband systems operating globally, and these and other millimeter wave frequencies are included in next generation satellite broadband systems already under development. Owing to advances in technology, with extremely directional base station antennas and mobile stations with very high order beamforming and massive MIMO, it is increasingly evident that terrestrial providers will be able to use these frequencies for both fixed and mobile deployments. The FCC said that it would be open to proposals for additional bands above 95 GHz. Another potential upper bound, 300 GHz would bring the range to the top of the millimeter-wave (EHF) band, above which the FCC and ITU have never allocated any frequencies to any service. Leaving the upper bound open is a possibility as well.

The definitions of low-, medium-, and high-band spectrum are very dynamic and will continue to evolve over time. The definitions could continue to develop upward as new technologies and approaches for overcoming some of the physical obstacles are advanced which could, for instance, leverage terahertz communications or free-space optics for some applications.

Question 4: To what extent does the channel bandwidth needed for any given deployment vary depending on whether the deployment is low, medium or high band spectrum?

Answer: The channel bandwidth needed for a given deployment (set of intended applications) does not vary depending on whether the deployment is in low, medium or high band spectrum since technically Shannon's Limit Theorem uniformly applies to any spectrum. Instead, channel bandwidth is normally determined based on spectrum availability (a regulatory issue) and economics (i.e. generally the higher the band, the higher the deployment cost while lower bands have a higher acquisition cost for the spectrum). Those factors in turn drive the set of intended applications that can be supported in the available channel bandwidth. Due to spectrum availability limitations and spectrum acquisition cost constraints, it is unlikely that low and medium band spectrum (independently, or by themselves) would be used to support high data rate 5G applications such as 8K video, VR/AR or any other application that requires >50 Mbps/user. This is the case since an operator's available capacity in low or medium bands would be rapidly exhausted supporting one or a few users.

Mapping spectrum blocks to possible broadband speeds:
(Rough effective real world rate of 7.5 bits/Hz, i.e. current 4G/LTE efficiency levels which will improve to some degree with 5G)

Spectrum block	**Bandwidth supported**
20 MHz	150 Mbps
50 MHz	375 Mbps
100 MHz	750 Mbps

5G applications – estimated required bandwidth

Application	**Bandwidth required**
8K ultra video	50-85 Mbps[1]
VR	50-500 Mbps[2]
AR	100+ Mbps[3]

From the two tables above, we can see that just a few 5G bandwidth intensive app users could exhaust the total bandwidth available in a 20 or 50 MHz spectrum block.

---

[1] https://www.slideshare.net/Sckipio/ultra-hd-requirements

[2] http://www.onlinereporter.com/2016/06/17/arris-gives-us-hint-bandwidth-requirements-vr/

[3] https://www.ietf.org/proceedings/98/slides/slides-98-icnrg-challenges-in-networking-to-support-augmented-reality-and-virtual-reality-cedric-westphal-00.pdf

Low, medium and high band spectrum characteristics (these are representative characteristics that are likely to change over time):

Band	Characteristics
Low	• < 1 GHz • Great propagation – lower cell counts needed to cover a given area • Limited spectrum availability: by definition only 1 GHz available across the entire band • Much of that in use by critical users/applications which require these propagation characteristics (AM/FM radio, public safety uses), or who have historical claims to spectrum (broadcast TV) • **Difficult/economically unfeasible to obtain 50 MHz channels for multiple operators – 20 MHz channels also very challenging** • Low latency applications can be supported, but not high bandwidth • Can support rural broadband, but at limited speeds • Good for low bandwidth IoT applications •
Medium-Low/Medium	• 1 GHz – 6 GHz • Propagation better than high band, but significantly worse than low band • Well suited for high availability satellite applications due to propagation characteristics and resistance to rain fade • **50 MHz and/or 100 MHz channels possible** (3.7 GHz – 4.2 GHz C-Band, if cleared or shared, would provide ten 50 MHz channels or five 100 MHz channels. Sharing 4.2 to 4.4 GHz band with radar altimeters is also technically feasible, but has “safety of life” concerns.) • Fixed wireless broadband could be supported, but new 5G applications (8K video, VR/AR) could quickly exhaust available bandwidth •
Medium-High/High	• > 6 GHz • **Large contiguous spectrum blocks available (100 – 200 or more MHz per channel) for multiple operators** • Gbps speeds/user possible • VR/AR/other low latency, high bandwidth applications can be supported • Propagation is a very significant issue above 6 MHz since transmissions need to be line of sight and even here there are challenges if there is high humidity or if it is raining since water will absorb these signals. • Requires advanced cellular technology to be deployed including beam forming, and massive MIMO, as well as the construction of an ultra-dense cellular network •

Question 5: What commonalities or compatibilities between federal and commercial applications could be exploited to maximize the potential for sharing between federal and non-federal users? These might include, for example, applications that could coexist (technically and/or operationally) or common technologies.

Answer: Spectrum sharing is the "simultaneous" allocation of usage of a specific radio frequency band in a specific geographical area by several independent entities. Spectrum can be shared in several dimensions; time, frequency, space, and sub geography.

Spectrum sharing is usually considered to be either static or dynamic. Sharing approaches span a range of time horizons from long-term to very short-term. In its pure static form, spectrum is shared through specific, defined administrative, technical, and/or market-based mechanisms. Geographic licensing and leasing of spectrum are examples of static sharing. Generally, the mechanisms to effect static spectrum sharing are well understood and need not be explored further.

Dynamic spectrum sharing refers to a range of techniques that permit spectrum to be shared dynamically between users based on priority (e.g., co-primary, primary and secondary, tertiary, etc.) in both spatial and temporal domains. The intent of dynamic spectrum sharing is to be more responsive to user demands to improve spectrum utilization. The degree of dynamism can be low (e.g. Licensed Shared Access or LSA), using databases or coordination portals or high, using spectrum access systems (SAS) or advanced radio technologies including ultra-wideband and multimodal radios.

The potential compatibility for a wireless system to share spectrum depends on several factors including the following:

- The technical capacity for wireless technologies to share spectrum and coexist
- Technical support for cohabitation of spectrum including certified support systems
- Feasibility of upgrading incumbent systems to support spectrum sharing
- Support for operational de-confliction
- Trust between operators / users

Capacity for a System to Share via Deconfliction

For a wireless system to be capable of sharing spectrum, there must be unused spectrum available in time and/or space for sharing. Generally, this holds for systems that have broad spectrum assignment, but relatively sparse or situational usage. Expressed equivalently, good candidates for sharing will show a small number when evaluating the product of the intensity of spectrum use and the extent of spectrum use. Thus, a system that transmits intermittently, but is deployed all over the U.S. can conceivably be as attractive as a sharing candidate as a system that transmits constantly, but with only limited geographic deployments. Note that use extent and use intensity can be measured among multiple dimensions – geospatially, spectrally, temporally – and reduced extent or intensity in use in any of these dimensions can be exploited for spectrum sharing. Also note that within the same dimension, there can be multiple granularities available for measuring use extent and intensity and that finer grained measurements may reveal orders of magnitude more spectrum for sharing than a coarser-grained examination yields.

Similarly, an increased ability of a system to tolerate additional interference makes it a more attractive spectrum sharing partner. First, greater interference margins means that, all else being equal, two disparate systems can operate in closer proximity without regard to the dimensions of spectrum use. Second, increased interference tolerance reduces the risks from transient interference events. But other factors can also increase interference tolerance:

- High performance receivers allow for spectrally closer operation because these receivers can prevent or reject blocking interference from out-of-band signals that would otherwise preclude spectrum sharing.
- The availability of backup channels for control and / or data traffic can allow a system to maintain acceptable operation while transient interference events occur. For instance, LTE systems with both primary and secondary bands of operation can tolerate greater interference in the secondary band as the primary band ensures some continued minimal level of service.
- Support for multiple levels of performance and graceful degradation of performance when transient interference events occur help ensure that the inevitable spectrum sharing errors are not catastrophic.

Third, it is useful to examine if a system's link layer was designed in a way that assumes the presence of other wireless networks under external control. Coordinated MACs (e.g., 802.16h or was done on the DARPA SSPARC program) or distributed polite MACs (e.g., CSMA/CA) can greatly simplify the ease of entry for new systems.

Technical Cohabitation

In addition to spectrum sharing via de-conflicted uses, two systems can also cohabitate – that is to say occupy the same location, time, spectrum, and polarization. For instance, UWB and narrowband systems can classically be used in a cohabitation setting as a cohabitating UWB system appears as a slight increase in noise floor to the narrowband system and the UWB system's spreading gain can similarly reduce the impact of the narrowband system. Likewise, various studies have shown the resilience of LTE systems to low-duty cycle pulsed signals (like radar).

Feasibility of Upgrade to Support Spectrum Sharing

Many legacy systems were not designed for spectrum sharing and thus currently lack the technical capacity for more dynamic forms of spectrum sharing. But legacy systems that can be upgraded to add spectrum sharing technologies are also attractive spectrum sharing targets. Examples of technologies that can be added on to incumbent or new entrant systems include:

- Information sharing systems, such as the Spectrum Access System (SAS), Environmental Sensing Capability (ESC), and occasionally discussed Federal SAS (FSAS)
- Blanking, subcarrier nulling, and fractional frequency reuse and other techniques to control transmissions of both incumbent and new systems at a finer grained level
- Less sophisticated technologies such as shielding

Note that upgrading systems for spectrum sharing can be frustrated by technical limitations (e.g., satellites in orbit), procurement issues (e.g., long technology refresh cycles, systems otherwise planned for deprecation), or the need for continued growth and development in incumbent systems. Any sharing scenarios that propose to freeze potential innovation by incumbent technologies is not desirable, rather an emphasis should be placed on creating incentives for sharing proposals from technologies that allow for mutual growth and development.

Support for Operational Deconfliction

Just because it can be shown that two systems can technically share spectrum with one another, there may be operational reasons that limit sharing compatibility. First, the information needed for sharing may be subject to privacy or security considerations. For instance, sharing troop movements is not allowable for operational security, but without knowledge of their radio locations, their associated wireless systems become poor candidates for sharing. When operational information can be shared, the timeliness and accuracy of the information directly impacts sharing efficiency as lower accuracy and lower timeliness typically imply more conservative sharing mechanisms are required. When communications timeliness is a factor (not unexpected in fine-grained spectrum sharing), operational predictability can overcome the limitations of the coordination channel. At a coarse level, awareness of satellite orbits and ground station locations can help sharing systems predict when a ground station needs protection even if the ground station does not directly convey that information. At a finer-grained level, the predictable rotation of gimbaled radars mean that the times and locations where the radars need protection can be precisely predicted even without information exchange. Finally, when operational information cannot be shared or predicted, it can be observed as is done with the ESC at 3.5 GHz. Note that operational security considerations may also limit the sophistication of coordination, prediction, or observation mechanisms even when deployed (e.g., the ESC uncertainty areas). Technically restricting the direction of operations for new systems can also enhance sharing in several cases.

Trust Between Operators

Ultimately two different network operators or more generally spectrum users will be stymied in sharing if they do not trust each other. This includes trusting that the other operator / user will maintain secure control of their network or equipment and will work diligently and quickly to resolve accidental interference events. Certain technologies, related to network security, auditability, and failsafe mechanisms (e.g., interference resolution processes, and kill switches) can increase trust. Past operator performance in sharing and / or interference resolution can also increase trust thereby making the associated networks more compatible for spectrum sharing. Another way to improve trust is if the interests between the operators are well-aligned. This is largely the situation between commercial terrestrial wireless operators who are generally able to resolve interference issues between their networks without external involvement. Historically, this is the situation between and among both US and foreign satellite operators – commercial and government owned. Commercially, this could be established via some financial arrangement (e.g., leasing to share spectrum) or among federal agencies when missions and therefore interests are closely aligned. Spectrum management authorities can help promote this trust by ensuring that sharing frameworks enable each operator to continue to grow and develop its services, and to continue to offer these services to its relative markets in the public interest.

APPENDIX A

More channels

- Small blocks of spectrum or use of non-contiguous spectrum will limit the maximum channel bandwidth that can be implemented in a system. Depending upon how the available spectrum is configured relative to technology "building blocks," some spectrum could be rendered unusable, narrower channelization may be required, or fewer channels used. If the application requires a wide channel, but the non-contiguous bands are sliced too small, =, it is possible that a single channel may not even fit in the available non-contiguous sub-band.

Benefits of larger channels

- [802.11] As an example of the trade-offs in operations, an 80+80 MHz noncontiguous channel uses half of the transceiver paths (antennas) on each channel, and relative to a single 80 MHz channel, provides no PHY rate increase, less opportunity to beam form, and less channel diversity. As a result, an 80+80 is far less useful than a single 160 MHz wide channel.
- [802.11] Wider channels supported by contiguous spectrum have lower power spectral density, and range/coverage issues are then managed via use of networked APs (i.e., 3 dB less with every doubling of bandwidth) or through operating modes that utilize narrower channels (e.g., 20 MHz wide).
- [LTE] Contiguous spectrum reduces overheads, which improves spectral efficiency (bps/Hz) for better utilization of spectrum.
- [LTE] Contiguous spectrum allows for better use of eNodeB schedulers that leverage channel frequency selectivity to enhance user performance, by scheduling users in sub-bands with better temporary channel properties. This is particularly beneficial in dense urban areas to counter multipath fading.
- [LTE] Contiguous spectrum that allows larger bandwidths provides greater accuracy for infrastructure-based geo-location.
- [Satellite] Contiguous spectrum allows for fewer individual antennae on satellite buses, each of which increases weigh, cost, and complexity on the system.

Reduction in engineering complexity

- [802.11] Contiguous spectrum is an advantage for semiconductor fabrication as it reduces semiconductor complexity.
- [802.11] Contiguous spectrum eases the problems of managing antenna technology and power consumption, which will have different requirements in different bands.
- [802.11] Non-contiguous spectrum doubles the number of band edges and therefore doubles the problem of handling adjacent band interference (unlicensed must accept all interference).
- [802.11] For non-contiguous spectrum that is widely spaced (e.g., 5 GHz/60 GHz), the effective functioning of a voltage control oscillator is more difficult, possibly requiring the addition of multiple VCOs.

- [802.11] Operationally, contiguous spectrum provides an easier approach to managing fast channel changes (e.g., in bands that are encumbered & when the commercial use must avoid those encumbrances, such as governmental radars). The problem of identifying an unencumbered channel and monitoring it are simplified with contiguous spectrum.
- [802.11] In considering non-contiguous bands, or even extremely wide bands of contiguous spectrum, a requirement to notch sub-bands of spectrum (i.e., not operate in a portion of the band) should be taken into account, particularly if there are multiple spectrum sub-bands.
- [LTE] Contiguous spectrum allows larger bandwidth carriers that reduce the need and/or complexity of multi-carrier load balancing.
- [LTE] Contiguous spectrum offers greater flexibility. LTE equipment can be limited by the number of component carriers (CC) that are supported in carrier aggregation. LTE systems can support carrier aggregation (CA) with up to 6 carriers, according to 3GPP standards. When contiguous carriers are aggregated, for example, two 10 MHz contiguous carriers, these can be combined into a single 20 MHz carrier, which now counts as a single carrier component, instead of 2 carrier components.
- [LTE] Contiguous spectrum reduces the complexity and cost of baseband and RF circuitry. In some cases, aggregating very dissimilar bands may trigger the need for additional baseband modems and RF chips.
- [LTE]Contiguous spectrum can decrease antenna complexity and the number of antennas. Aggregation of non-contiguous spectrum can require more antennas.
- [LTE]Contiguous spectrum simplifies the RF front end and lowers cost of base stations and user equipment. Aggregating dissimilar bands requires more RF components (e.g., antennas, power amplifiers, filters, combiners, etc.).
- [Satellite] Non-contiguous spectrum typically means there is a larger frequency range that must be accommodated by the equipment. This results in the following potential impacts to the satellite:
  - additional frequency converter units
  - additional local oscillator frequencies
  - RF hardware units such as LNA's and TWTA's either have to cover a wider band with potentially reduced performance in G/T and EIRP, or a split band design which increases the quantity of these units
  - Antenna Operational bandwidth which will decrease antenna performance and/or increase antenna complexity and count.
  - For digitally processed payloads additional processing bandwidth and unit complexity may be needed
  - For digital beamforming payloads, additional complexity to the processor and payload is required which increases cost. Further, it may exceed the satellite and processor capabilities requiring reduction in performance and service throughput and capacity.
  - Non-contiguous spectrum may require a multiplicity of earth station designs, making gateway locations larger and more complex, and reducing economies of scale on user terminals.

- [Satellite] Non-contiguous spectrum results in more frequency edges which complicates input and output filtering designs impacting cost and performance. In addition, there are potential impacts to out-of-band emissions requirements and coordination. If the non-contiguous bands are separated by critical bands in other services, the satellite communications system may have stringent out-of-band spurious emission requirements that cannot be met or require costly and complex filters which reduce the channel performance.