COMMERCE SPECTRUM MANAGEMENT ADVISORY COMMITTEE
(CSMAC)

WORKING GROUP 1

DEFINITIONS OF EFFICIENCY IN SPECTRUM USE

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When Marconi conducted the first radio transmissions in 1895, the energy from his spark gap transmitter occupied the entire usable radio spectrum. The first transatlantic transmission in 1901, which blanketed an area of over a hundred million square miles, was capable of sending as little as one bit every 6 seconds. In fact, only a single such transmission could be accommodated on the surface of the earth using that technology. It is now possible to conduct a million voice conversations, or equivalent data exchanges, in the usable radio spectrum in one location. Furthermore, cellular systems today allow the radio spectrum to be reused 50 times or more within the boundaries of a single large city. Of course, the demand for access to spectrum and the types of applications has also exploded and it has become a critical resource to be effectively managed by governments worldwide.

There is a strong need for the U.S. government to manage spectrum in as effective a manner as possible so as to optimize the overall utility of this important resource, while at the same time meeting important and increasing U.S. Government mission requirements that can only be accomplished through the use of spectrum resources. One critical aspect of spectrum management is the efficiency of its assignment and use. Unfortunately, it is not possible to establish a uniform metric for spectrum use efficiency that encompasses the wide range of services and uses for which spectrum is needed. As an extreme example, comparing cellular voice systems with military radar systems is unlikely to produce a useful mutual comparison. Spectrum efficiency determinations for federal operations require an analysis that involves both technical and subjective considerations. Thus, to address efficiency a taxonomy of spectrum uses is identified and efficiency within each class of use is considered separately. Beyond simple efficiency metrics, the actual optimal use of spectrum also relates to the effectiveness with which the spectrum meets the actual user or mission requirements. In some cases efficiency may become subservient to usage-based considerations. For example, when safety or mission assurance requirements are involved, users may well choose to sacrifice some level of efficiency in exchange for increased reliability or access.

DEFINING SPECTRAL EFFICIENCY

Before one can discuss possible metrics for spectral efficiency it is important actually specify what one is interested in attempting to measure based on the intended purpose of the measurement. For example, one could be interested in Technical Spectral Efficiency which would consider the theoretical capacity of the wireless components to carry traffic using the least amount of spectrum. This would be somewhat different from a notion of Operational Spectral Efficiency which would measure the practical efficiency of a system under operational conditions. The difference between technical and operation SE can be seen by considering an LMR system designed to provide coverage for a given area. A very dense, multi-site, trunked LMR system would provide maximum technical SE. However, the operational SE would include planned or measured traffic loading, and it might show that the system capacity greatly exceeded the expected needs of the coverage area. Thus for a given operational situation, the “improvements” in technical efficiency of one system over another might not be significant. One could also define a notion of Allocational Spectral Efficiency that measures traffic over the actually allocated spectrum. This was described in a recent Korean paper, ”Frequency Use Status Investigation and Spectrum Utilization Metric” from ISART 2008. This notion would handle the problem of how well the band allocations match the demand for the respective services. It makes no sense to build systems with higher SE, if that change merely means that more frequencies in the allocated band remain completely unused. This factor is intended especially to motivate the spectrum manager to make better use of all frequencies, instead of only requiring efficient practices from the users.

Beyond understanding the purpose of measuring the system efficiency we should also note that there are somewhat different modes of wireless communications which may demand different efficiency considerations. These will factor into the taxonomy that we use in analyzing spectral efficiency. Wireless systems can be used in a **transport** mode where data is moved across a region without providing any local services. This mode of use puts a premium on point to point communication. Wireless **access** systems on the other hand provide local services without net transport of data across a region. In such systems, access capacity to the served users is paramount. Systems may also be **coverage** oriented systems in which a minimal amount of access service is provided across a defined coverage area. This corresponds, for example, to many public safety systems where excess access capacity may not be useful unless a minimal service level is provided universally within an area. Of course, systems may exhibit combinations of these modes which further complicates making efficiency evaluations of them. For example, LMR systems are often used to simultaneously provide transport, access, and coverage modes. In some cases, a given service typically is used in a single mode (PCS = access mode, point-to-point = transport mode, etc.). In other cases, the multiple modes make it difficult to calculate a single number for the efficiency of a system, since the various modes have different functions and dimensional units. Therefore, the respective values of the multiple modes cannot be made generally fungible, and calculations will provide answers that inherently are “apples and oranges.”

TAXONOMY OF USE

Once we understand what sort of efficiency measure we are interested in and something about the service modes, we also need to be able to compare systems that have enough in common to indeed be comparable. To facilitate this, we break spectrum use into the following classes:

1. Broadcast systems: For broadcast systems there is a tradeoff between intended coverage areas and independent usage. E.g., satellite systems may achieve large coverage areas but if the signal is intended as a local signal then much of the coverage may be effectively wasted. Conversely, if large coverage is desired then land based broadcast systems may need to operate multiple frequencies with the same information content to avoid interference issues. Broadcast systems provide multiple data sets that are individually selectable by the many recipients. This

may allow a definition of efficiency based on the number of independent data sets that are available per MHz.

2. Personal Communications Systems: This is perhaps the easiest class of systems for which to define efficiency and the one for which the discussion is most often had. Data rate per bandwidth or voice calls per bandwidth are the common norms.
3. Point to point directional systems: For this category one can assume highly directional systems. Efficiency here is thus a function of both the data rates achievable over a link of a given bandwidth and the ability to operate multiple independent links on the same frequency in close proximity.
4. Non-communication transmitter/receivers: This category encompasses radar systems which provide a wide range of important functions not only for national security purposes but also for safety of life, e.g. air traffic control and severe weather warning.
5. Satellite Systems: This category is noteworthy because of the extremely broad geographical impact of the systems which makes defining their efficiency challenging. In particular, they may see large differences in technical efficiency metrics versus operational ones given their potential to provide broad area coverage even to sparse users communities.
6. Passive listeners: This category is primarily astronomical, space surveillance and remote sensing, and weather uses. While efficiency for this class may sound like an odd concept, one can certainly ask whether spectrum set aside for such activities can be localized to specific areas where detectors are, or whether some such activities might be best placed in space.
7. Short range uses: This category includes a variety of relatively low power short range uses for which limited interference issues are assumed due to the power and range constraints. Included in this are communications systems like Bluetooth and WiFi and other emerging utility systems like short range anti-collision automotive radars. Various proposed multi-hop ad hoc systems for sensors or personal communications should also be considered in this category.

SURVEYING ACTUAL FREQUENCY ASSIGNMENTS AND USE

Any discussion of spectral efficiency relies upon the existence of an accurate and maintained survey of actual frequency use by the various frequency holders. Clearly the simplest way to increase efficiency in the global sense is to locate unused or severely underused frequency bands and reassign them to functions that will actually utilize them. Such an exercise must, of course, take into account essential applications that may not be required on a constant basis. For the purposes of discussions of efficiency we assume that to the extent practicable this is already being done and that the government tracks such information. In addition to actual assignments, each band should be tracked for use distribution over geographic regions of use, times of use, density of transmissions. Since the main concern of this paper is technical aspects of efficiency we will not further address the reallocation of unused or underused bands.

General Observations About Efficiency

The determination of spectrum efficiency is not a simple matter and requires a multi-dimensional analysis involving technical and subjective considerations. An analysis based on a single parameter such as bit/sec/hertz will lead to erroneous conclusions for non-commercial communications systems and, in government systems used for non-communication applications, to misleading and misinterpreted results. Simply stated the objective of any spectrum policy should be to maximize the utility and benefit of the radio spectrum which is a broader objective than just technical efficiency. In some situations application requirements may cause the traditional notion of spectrum efficiency to be subservient to usage-based considerations.

For communication systems any discussion of spectrum efficiency must take into account the amount of spectrum utilized, the area covered, the amount of information transmitted, and the time the spectrum is in use. For example, one could use more spectrum uniformly over a large area to transmit a given amount of information to a set of receivers or one could use less spectrum repetitively via a cellular scheme to transmit the same amount of total information to the receivers. One could use 256 QAM to transmit information over a given bandwidth over a small interval of time or possibly use QPSK to transmit information continuously. Which of these is more efficient may depend upon meeting the intended user requirements. One also needs to decide in defining efficiency how to compare unicast and multicast information. E.g., using an apparently lower efficiency broadcast mechanism to reach a group of users who want to receive the information using a single spectrum allotment may actually be more efficient than using a more efficient modulation scheme that requires the information to be transmitted on separate channels to reach the same user set. Efficiency of the total system may also be improved by utilizing systems that take advantage of gaps in use within one system to opportunistically communicate information for users not part of the system being studied. That is, so-called cognitive radio schemes might increase efficiency even if efficiency as seen by one band owner is not changed. The point of this discussion is not that a particular approach is likely to be more or less efficient than another but rather that efficiency is ultimately the result of considering the totality of messages being sent to achieve all the communications desired across all users in a given (ultimately infinite) time window divided by the amount of spectrum used to achieve this. It should be clear that actually computing such a value, let alone optimizing it, is impossible.

Military communication systems, and possibly other public safety ones, have additional operational requirements, well beyond those placed on commercial/civilian systems, such as resistance to jamming and additional coding for security purposes. Although some of the techniques utilized may reduce spectrum efficiency, the capabilities provided are essential to mission success and safety of life.

Some Relevant History from Personal Communications

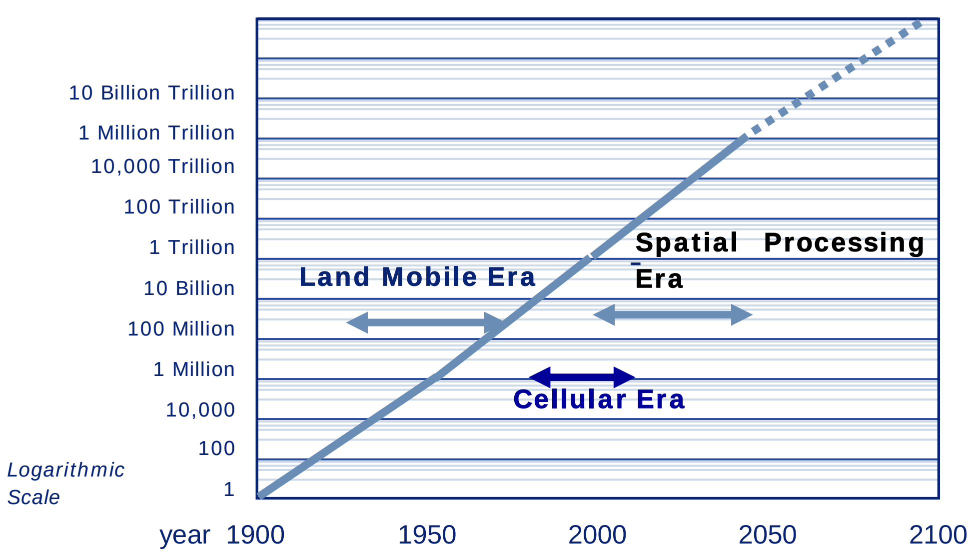
Perhaps the most illustrative example in changes in efficiency has been personal communications so it is useful to understand what the history of that segment can tell us about efficiency issues. The spectral efficiency of a personal communications air interface may be defined as the maximum capacity of that air interface to carry bits of information per second normalized to the magnitude of the spectrum. A better term would be "spectral capacity". A possible measure of spectral capacity for personal communication systems might be bits per second per Hertz per sector in a fully loaded practical implementation. The measure of bits per second per hertz is straightforward and objective. The terms "fully loaded" and "practical" are subject to interpretation, so much so that even approximate measures are difficult and quarrelsome.

A less contentious approximation of the relative spectral efficiency of personal communications systems during the period from the advent of personal radio communications to the present that is less precise but more informative can be derived as follows:

1. Establish a standard message, i.e., a number of bits representing a voice conversation or a data message.
2. Estimate the available spectrum using the best technology available at various times during the period from the advent of personal radio communications to the present.
3. Select a large enough coverage area to accommodate the concept of geographic re-use (say, the entire surface area of the earth).
4. Estimate the geographic re-use potential of technologies existing at times in the period under consideration.

5. Estimate the total number of standard messages that can be accommodated over the selected coverage area using the entire available spectrum, with the maximum possible geographic re-use.

A set of results of such calculations are depicted in this chart:



On average, effective spectral capacity for communications has doubled every 30 months for the past 110 years. The effectiveness of spectrum utilization in personal communications has improved by a factor of about a trillion since 1901. Focusing on the most recent period, it improved a million times since 1948. Of that million-times improvement since 1950, only roughly 15 times was the result of being able to use more spectrum (3 GHz, today vs. 150 MHz, in 1948) while the rest of the capacity increase came from how the available spectrum was is used. About 5 times was from using frequency division, that is, the ability to divide the radio spectrum into narrower slices (25-kHz channels vs. 120-kHz channels), and about 10 times through the use of improved modulation techniques. Most of the million times improvement since 1948 was the result of geographic sharing. Re-use began on a continental basis, then by country and city sized areas. Cellular technology introduced hand-off and reduced coverage, over many years, to areas a kilometer or less in radius.

General-purpose digital services have invisibly facilitated much of the above recent improvement in spectrum capacity by allowing a single system to provide almost any desired type of service, in contrast to past practices of building a myriad of special-purpose systems that each provided a single service. This means that a single efficient small-cell infrastructure can take advantage of large economies of scale, as well as effortlessly "sandwiching" in many of the previous low-duty-cycle special-purpose services. Thus, a single general-purpose cell phone can provide world-wide voice (person-to-person or multi-person broadcast), data, email, graphics and photos, TV and radio, real-time weather radar plots, emergency E9-1-1, and location-dependent information. This suggests that modern SE metrics can be realistically generalized in terms of bits/s instead of voice channels, video channels, etc. (Many special-purpose state and local government functions (e.g., public safety) have just begun to notice this effect.)

Although the chart depicts linear change, improvements actually occurred in spurts, stimulated by market imperatives (i.e., land mobile) or by government requirements (cellular). The potential to achieve further improvement through modulation methods, time division, or extending the upper limits of spectrum use has been almost exhausted. Geographic sharing, in the form of MAS (multi-antenna signal processing – also known as "smart antenna, MIMO, adaptive arrays, etc.), however, has the potential to extend the improvements well into the future.

Broadcast System Efficiency

For broadcast systems efficiency can be defined in terms of the served audience per amount of utilized spectrum. For a national audience, a single frequency assignment carried everywhere may well be most efficient, thus favoring systems such as satellite. For a localized but dense audience localized reuse of spectrum may provide the most audience coverage per bandwidth, thus favoring traditional land based broadcast. For a sparse audience, some combination of broadcast with unicast within a more cellular arrangement might actually prove the most efficient.

ITU-R SM.1046-2 “Definition of Spectrum Use and Efficiency of a Radio System” defines the Spectrum Utilization Efficiency, SUE, (or Spectrum Efficiency as a shortened term) of a radiocommunication system by the complex parameter:

$$SUE = \{M, U\} \quad (1)$$

where:

M: is the useful effect obtained with the system in question; and

U: is the spectrum utilization factor for that system.

The measure of spectrum utilization – spectrum utilization factor, *U*, is defined as the product of the frequency bandwidth, the geometric (geographic) space, and the time denied to other potential users:

$$U = B \cdot S \cdot T \quad (2)$$

where:

B: frequency bandwidth

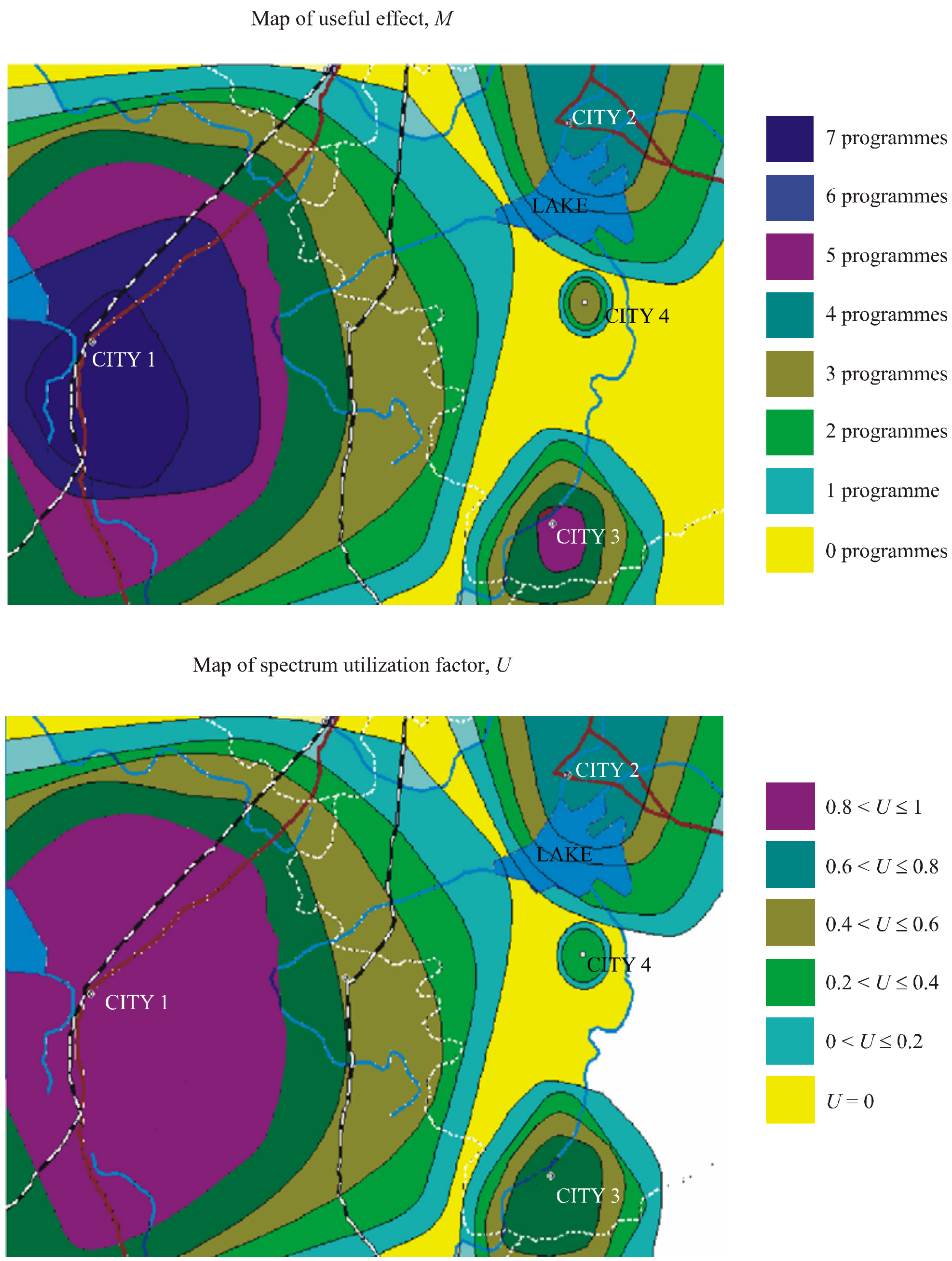
S: geometric space (usually area) and

T: time.

The useful effect (M) of a television broadcast is determined by the number of users (population) able to receive the broadcast. The useful effect of a television broadcasting system would vary with the population density in different parts of the geographical area in question and the number of television programs that can be received.

Spectrum utilization is determined by considering what limitations existing TV stations impose on its utilization by new stations. For a TV station situated at the centre of area element *i*, this may be the total number of TV channels that are denied in that area element due to considerations of EMC with existing TV stations, K_i, or it may be the proportion: $U_i = \frac{K_i}{K}$, where *K* is the total number of TV channels. It is considered that EMC conditions are not met in a given TV channel if the harmful interference generated by one or more of the existing TV transmitters prevents the normal operation of receivers working with the new TV transmitter, or if the new TV transmitter, transmitting signals at the frequency of that channel, creates unacceptable interference for receivers in communication with the existing television transmitters, including those which are operating in some other TV channels.

ITU-R SM.1046-2 provides details on how to assess the Spectral Efficiency for broadcasting systems. The results of the assessment may be presented in the form of a geographical map showing the values of useful effect and spectrum utilization factor across the area in question (see an example in the Figure below), or by calculating the average value for the whole area (in the example, Spectral Efficiency SUE= (M = 3.2 TV programs, U =0.4)). The spectral efficiency of sound broadcasting systems can be similarly derived.



Generalized indicator: SUE = (M = 3.2 programmes, U = 0.4)

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PERSONAL COMMUNICATIONS SYSTEMS

For personal communications we can define spectral efficiency as: Bits per second per Hertz per unit area, in a fully loaded system for a given quality of service. Note that this is oriented toward a land based system but a satellite based system of this sort can be thought of where the satellite represents the “site”. One problem with even this reasonable sounding definition is that it still must assume what an acceptable bit error rate might be (quality of service) and what an acceptable coverage level might be (since there is a relationship between coverage and levels of interference or frequency reuse).

As an example of the difficulty with these definitions consider that bits per second per Hz as a basic measure would suggest that higher degrees of modulation would always yield more efficiency (i.e., 128QAM is much more efficient than BPSK). However, frequency reuse is also impacted in multi-cell systems by interference and such that higher order modulation might require lower channel reuse thus yielding lower efficiency in the multi cell environment. One can go to smaller cell sizes to increase the metric of bps/Hz/area and thus appear to get higher efficiency but this also misses the impact of cost related to increased numbers of cells.

The above notwithstanding, we can define efficiency pragmatically for this class of system using equation (1) by fixing a target cell size and computing for that cell size a net bps/Hz/area value over a sufficiently large area to encompass full frequency reuse of all assigned channels.

POINT TO POINT SYSTEMS

These systems have efficiency considerations that are similar to the previous category. Improved modulation schemes can achieve better use of an assigned band. Thus a simple bits/hertz metric can be a useful indicator. In addition, as point to point systems, higher directionality of the systems can mitigate interference among nearby installations.

Using equation (1) from ITU-R SM.1046-2, the useful effect M of a point to point (p-p) system needs to be derived for analogue and digital systems. The reference for determination of the useful effect of an analog system could be simply assumed as being the number of transmitted voice channels. However, in p-p systems, it is also interesting to consider the total distance over which the information is transmitted. For digital systems, the useful effect can be measured by the transmission rate, multiplied by the total distance over which the information is transmitted. The spectrum utilization factor U for a p-p system can be determined using equation (2).

More details on the above parameters as well as examples of calculation of Spectral Efficiency for point to point systems can be found in ITU-R SM.1046-2. Results may also be expressed using the metric of number of voice channels/Hz/km for analogue p-p systems and bps/Hz/km for digital p-p systems.

RADAR SYSTEMS

Radar systems perform a variety of important functions for numerous Federal agencies, including DoD (all services), Coast Guard, DHS, FAA, NASA and NOAA. These systems operate in bands allocated to the Radiolocation service. Radars can be fixed or transportable and can operate on ships, aircraft, missiles, land vehicles or on a space platform as part of national security/defense missions, such as missile defense, advanced naval systems and advanced airborne early warning systems. In addition to the national security functions, radars are also heavily embedded in the national weather infrastructure, e.g. severe weather early warning capability, air traffic control safety and science applications. Since 9/11, there has been an increased reliance on information observed and provided by radar systems within the United States. We should note that it is likely that in the United States the specific air traffic management radar systems used uniquely for cooperating aircraft for location and navigation purposes will see a reduced role as alternative systems such as GPS plus ADS-B are introduced. However, for addressing non-cooperative and potential threat targets, radars will remain vital.

Technical characteristics of radar systems are closely related to the operational requirements of its mission. Some of the key technical parameters that govern radar performance are operating frequencies, bandwidth and waveform modulation. The propagation characteristics of a frequency band are key to accomplishing specific radar missions which vary from accurate wind measurement for wind profiler radars to requirement for long-range search and surveillance. The bandwidth over which a radar operates and the type of waveform modulation employed impact the radars ability to counter electronic attack and electromagnetic interference as well as determining target resolution. In addition these parameters are key to cooperative operation of multiple radars within the same bandwidth.

Unlike other radio services, such as non-critical communications systems, that may have a commercial spectrum-based alternative, to fulfill their mission, radars do not. Moreover, commonly applied efficiency measures, such as bits/Hz/sec, for PCS types of services are not appropriate for radars. Among its shortcomings, these efficiency measures do not provide the ability to factor in the criticality of the function/mission that is using the spectrum or determine the utility of the information provided. Hence, the spectrum efficiency of a radar system can only be compared to the spectrum efficiency of a different radar of similar capabilities. The spectrum efficiency of a radar can’t be directly compared to the spectrum efficiency of a communications device.

It is noted that radar systems have implemented many new technologies since its first introduction 60+ years ago. The evolution of technologies includes use of solid state transmitters to replace traditional radar transmitter devices, such as magnetrons, and improved signal processing techniques. Solid state transmitters have increased radar reliability and allowed for more flexibility in using different types of waveforms. Improvements on the receiver side, such as advances in signal processing and improved microprocessors, have resulted in radars that provide increased information, such as improved target resolution, in the same amount of bandwidth. Since, spectrum efficiency should be a goal for all systems using radio frequencies and in order to promote and ensure spectrum efficiency for radars NTIA has adopted Radar Spectrum Engineering Criteria (RSEC) which is contained in Section 5.5 of the NTIA Manual. The RSEC criteria focus almost exclusively on minimizing the amount of unwanted radar signal energy radiated at adjacent frequencies, which is important to enabling greater flexibility in adjacent band uses. These criteria are reviewed and updated on a regular basis to promote adoption of more advanced radar technology in future operations through newly developed technologies, e.g. improvements in spectral roll-off.

SATELLITE SYSTEMS

Satellites provide services around the world to governments, emergency responders, the media, industry and consumers alike. Satellite systems operate under several radiocommunication services classifications. Fixed-Satellite, Broadcast-Satellite and Mobile-Satellite radiocommunciation services are the most commonly used for commercial applications, although the US Global Positioning System (GPS), which is operated in the Radionavigation satellite service, is used for many commercial and personal applications, in addition to critical Federal operations.

Satellites can inherently offer coverage to a large portion of the earth providing instant infrastructure to countries or large geographical areas. Should efficiency be measured solely by the size of the area covered, geostationary satellites would clearly be considered a highly efficient means of providing coverage-mode communications and broadcast services. Additionally satellites provide great mobility for users over large geographical areas. It is noted that satellite systems can be deployed in many different orbital constellations, including LEO, MEO, GEO and HEO, each providing a unique set of capabilities, from less delay time, larger coverage area or improved angle of arrival, to meet the operator's business and services approach.

Over the past few decades satellite communications have improved in four distinct areas. First, advances in digital modulation, transmission protocols and error correction techniques have significantly improved satellite throughput. Second, satellite manufacturing has improved as well, with better spacecraft antennas and higher power amplifiers allowing higher RF power levels to be transmitted. Next, earth station technology has evolved allowing much smaller and cheaper stations to outperform larger older stations. Finally, larger launchers have also yielded benefit to the satellite communication industry by allowing significant increases in the size of the satellite, which in turn allows more channels to be accommodated on a spacecraft.

Like most communication services, satellite services initially relied on analog transmissions to deliver services, which limited the overall capacity that a system could provide. As a representative example, one studio quality, video signal transmitted using frequency modulation required an entire 36 MHz satellite channel. Now, through the use of various digital encoding and compression techniques, it is possible to transmit five video programs using the same bandwidth. To accomplish these results, various techniques are used to compress the video signal down to a manageable data rate. The information stream is then combined with powerful error correction codes which enable the use of modulators that can transmit multiple bits of information with every symbol (e.g. 8-ary and 16-ary PSK). When all these modulation and coding techniques are combined, satellite carriers become highly efficient at carrying high data rates over wide areas. These techniques are continuously being refined as developments occur in modulation and coding technology.

The satellites being used by operators today are much more efficient than were the first communication satellites or even satellites launched only a few years ago. Antennas have evolved from small Yagi antennas with a few dB of gain to precisely developed parabolic reflector systems that provide gains in the range of 30 to 35 dBi. New active phased array antennas enable on-demand beam steering, beam shaping, e.g. spot beams, and hopping resulting in optimum utilization of spectrum through frequency re-use. Additionally, satellite amplifiers are much more powerful, linear and efficient. Coupling the improved amplifier with flexible communication payloads that allow beam to beam power sharing and frequency agility furthers optimizes use of power and spectrum resources. All these improvements have allowed higher power levels to be transmitted towards the earth, and as a consequence for some applications, large earth stations can now be replaced by much smaller terminals, including handheld and other consumer devices.

Earth station technology and manufacturing methods have also improved significantly in the past 30 years. Large antennas have been replaced by smaller ones as manufacturing methods have improved. New manufacturing methods allow for better reflector surfaces and RF component performance at dramatically reduced prices. While the first earth stations required cryogenically cooled receivers, similar performance is now available with solid state, low noise amplifiers which can be manufactured for a few dollars. As a result of this product evolution, the first available 2.4 meter VSAT's which cost upward of approximately $50,000 a piece and operated at a data rate of 9.6 kbps have been replaced by 74 cm terminals that can operate at 5 Mbps for a cost of approximately $300.

Lastly, development of launch vehicle systems with increasingly greater payload lift capability has also contributed to improved satellite efficiency. While the first GSO communication satellites weighed a few hundred kg, current satellites can weigh above 6000 kg. The ability of more powerful boosters to launch even the heaviest satellites maximizes the number of channels that can be accommodated on the spacecraft, thereby dramatically increasing the throughput of a single satellite.

Continued advances in satellite technology have allowed the satellite industry to provide greater overall capacity, achieve a higher level of frequency reuse and share spectrum with other satellite networks. A representative example is that early satellite networks with regional coverage delivered approximately 2 Gbps in 500 MHz of spectrum where today utilizing the advances outlined above satellites can provide more than 100 Gbps in 500 MHz spectrum yielding a 50X improvement in efficiency since satellites became a private industry two decades ago. From a consumer stand point, the most clear examples of these improvements is the rapid growth of the delivery of High Definition TV programming over satellites and the advent of smaller consumer devices that are widely deployed today. Additionally, the international nature of satellite services requires complex spectrum coordination on multiple levels. Satellite operators are required under international rules and treaties to coordinate with each other, through their respective administrations, consistent with domestic and international allocations and treaty requirements. Associated with these procedures are international milestones, and in the case of the US domestic milestones, that ensure satellite spectrum is used in an efficient manner.

Passive Listeners

This class of use is not directly subject to a notion of spectrum efficiency because it is assigned based on non-economic considerations to allow uses that have high societal value such as radio astronomy. It is important to first understand that the selection of specific frequency bands required for passive listeners depends on what is being measured. While the efficiency of the listening mission itself may not be a definable metric, the amount of spectrum used (the frequency range, the guard band size, the geographic area, and the time duration) can be determined. ("Used" in this instance means that that transmissions by communications or other systems are not allowed.) The impact of the required "reserved" spectrum on other users can then be measured and potentially optimized to increase overall efficiency at some cost.

For example, a radio astronomy system could use an expensive, low sidelobe, directive antenna or it could use a conventional design, directive antenna. The first option is more expensive, but would have higher spectrum efficiency than the second option. This is because the second option would require all communications transmitters to be geographically separated at a further distance from the radio astronomy system compared to the first option.

SHORT RANGE SYSTEMS

This category includes a number of relatively new short range communications systems such as WiFi (IEEE 802.11 family) and Bluetooth, as well as potentially other ad hoc systems oriented to deployments of sensors and the like. This set of applications has been the focus of extreme levels of commercial investment over the last decade that has resulted in rapid improvements of data rates and system capacities (e.g., 802.11b to 802.11n standards having over a 20x improvement in less than 10 years). Much of the macro efficiency of these systems comes from the high degrees of frequency reuse due to the short range nature of the systems. Micro efficiency of these systems can be evaluated in traditional bits/second/hertz over an area terms.

COGNITIVE SYSTEMS

In addition to considering the efficiency of various classes of radio systems in isolation there is also the possibility of taking a broader look at cross application efficiencies through a regime of cognitive adaptive spectrum use. If such a scheme can be made to work, then it is likely that efficiency of spectrum use will greatly increase since unused portions can be put to use on an opportunistic basis. This would increase (assuming an unlimited demand load) the amount of communications taking place. A regulatory regime would be required to allow this to happen in an orderly manner. For example, such a regime might provide priority access of a frequency band to a first user (e.g., government user) and secondary access of the same frequency band to a second user (e.g., civilian user), provided that the second user has demonstrated to the satisfaction of the NTIA and/or the FCC that the frequency band may be used opportunistically on an interference-free basis. Such a regulatory regime could provide incentive for industry, government, and academic researchers to develop/perfect cognitive radio algorithms that will make the approach feasible, leading to a significant increase in spectrum utilization and thus efficiency. DARPA has already conducted significant work in this area under its XG program, and continued work in this area should be encouraged as a long term path toward increased efficacy of spectrum use. A simplistic version of this has already been used between radar systems and short range license exempt data communications in opening the 5GHz bands for use by wireless LAN devices.

CONCLUSIONS

It is at best difficult to make general statements about spectral efficiency since so much is related to detailed mission requirements and the various types of use. However, some conclusions can be reached:

1. Users should be required to compare existing and proposed systems to other alternative ones within the same section of the taxonomy to justify the effectiveness of the specific system in meeting the mission goals while occupying a minimal resource footprint. It is important to realize in doing this that a narrow interpretation of efficiency may not capture larger efficiency gains available through the macro level sharing of systems among multiple Federal and non-Federal users.

2. For at least the classes of personal communications systems, broadcast systems, and point to point systems, objective metrics of spectral efficiency do exist and should be used in the context of other mission requirements to assess proposed systems.

3. Further research should be supported to define and improve efficiency metrics for other classes of systems. This should include definitions of types of efficiency relevant to the various categories of use as well as into the metrics for each type.

4. It would be useful to catalog Federal uses of spectrum against the taxonomy above to either validate the utility of this taxonomy or to improve it as necessary. It would also be useful to conduct an approximate evaluation of comparative spectrum efficiency of existing systems (e.g., are federal systems generally less efficient than non-federal systems).

5. Continued research into cognitive systems should be undertaken to look for opportunities to harvest more spectrum uses opportunistically, particularly for uses where the primary mission requirements generate very intermittent use of the assigned bands.

6. Given the general improvements in spectral efficiencies that are accruing from modern equipment, the single greatest improvement in efficiency may often come from sharing of systems and the spectrum they occupy between multiple Federal and/or non-Federal users.