Challenges and Considerations in Defining Spectrum Efficiency

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***Abstract*— Since spectrum is a precious commodity, knowing how efficiently different technologies and applications use it allows users and operators to make the best decisions on what wireless technology to deploy and in what configuration. Understanding spectrum efficiency can also assist policy makers better decide on how to most effectively allocate spectrum and to whom. Unfortunately, multiple methods exist to measure the efficiency of spectrum use, each with its advantages and disadvantages, and no single measure works for all scenarios. Nevertheless, knowing these measures and their characteristics can lead to wiser decisions about spectrum allocation and deployment**.

***Index Terms*—spectrum, efficient use of spectrum, spectral efficiency**

I. INTRODUCTION

Wireless technology is transforming society, with over six billion people communicating over cellular networks and over a billion using Wi-Fi. Unfortunately only a finite portion of the total electromagnetic spectrum supports radio communication, making it crucial to use this precious resource as efficiently as possible. With a more efficient technology, the same amount of spectrum can deliver greater capacity, either by delivering more bits per second of capacity to each user or by servicing more users. In addition, by knowing how efficiently different applications use spectrum, policy makers can more wisely allocate spectrum and can more easily make decisions such as whether society is best served by spectrum used for television broadcast or for mobile broadband.

One important measure is spectral efficiency, which is the amount of data bandwidth that a specific technology can extract from a certain amount of radio spectrum. As this paper discusses, this measure is extremely useful, but by itself does not fully capture how efficiently spectrum is used, since it does not address another important measure of spectrum efficiency: how readily spectrum can be reused across space. Thus, another measure is to combine spectral efficiency and frequency reuse.

Additional technical measures for gauging spectrum efficiency can be applied, and analyzing more broadly, economic efficiency also plays an important role. The benefits of spectrum to society must also be considered, since not all bits are created equal—for example public safety trumps entertainment.

Finally, emerging policy is increasingly emphasizing spectrum sharing, which under the right circumstances promises to increase efficiency by allowing secondary users to take advantage of underutilized spectrum.

This paper considers the various measures and discusses their strengths and weaknesses. While no single measure applies to all situations, the judicious choice of measure for particular decisions should lead to better outcomes, whether for users, companies, or governments.

II. GENERAL CONCEPTS

Multiple government agencies have studied and reported on the topic of efficient use of spectrum [5] [12-15] [23-25].

One important conclusion is that applicable measures depend on the service. For example, The Commerce Spectrum Management Advisory Committee (CSMAC) states, "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. [5]"

Various factors affect how efficiently spectrum is used, including the type of modulation used, error correction methods, reuse of frequencies across geography, the number of users served, radio performance, and the percentage of time a service is active.

The International Telecommunication Union in ITU-R SM.1046-2 defines the value "Spectrum Utilization Efficiency (SUE) of a radio communication system as a complex parameter: {M, U} [19]. In this equation, M is the useful effect provided by the system and U is the spectrum utilization factor for the system. U is defined as the product of frequency bandwidth, the geometric (geographic) space, and the time denied to other potential users. SUE provides a useful higher-level model for various efficiency measures and is considered in various government efficiency studies [5] [15].

III. TYPES OF RADIO SERVICES

The inherently different usages of spectrum suggest separate measures for different systems. Accordingly, government agencies have developed categories of systems to which they have applied different efficiency metrics. For example, the Federal Communications Commission Technological Advisory Council (FCC TAC) has used six

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categories: two for satellite systems and four for terrestrial systems. These categories include satellite broadcast systems, point-to-point satellite systems, terrestrial broadcast systems, terrestrial personal communication systems, terrestrial point-to-point systems, and terrestrial hybrid systems [15].

IV. Spectral Efficiency and Cellular Systems

One measure of the efficiency of spectrum use is what is called "spectral efficiency," which is measured in bits per second per Hz (bps/Hz). With this value, one can easily calculate the amount of data bandwidth available in a given amount of spectrum. For example, the cellular (terrestrial personal communications system in [15]) technology High Speed Packet Access (HSPA) has approximately 1 bps/Hz of average spectral efficiency in a deployed network [21]. Thus, with a downlink radio carrier of 10 MHz, 10 MHz X 1 bps/Hz = 10 Mbps of aggregate throughput would be available for users. Ignoring some minor scheduling overhead, this amount of capacity translates to a single user with a continuous download speed of 10 Mbps or 10 users each with 1 Mbps.

The spectral efficiency value, however, has multiple challenges. First the value can refer to either peak spectral efficiency or average spectral efficiency. Second, the value is calculated based on complex simulations and is sensitive to a number of underlying assumptions.

Average and peak spectral efficiencies differ because many of today's wireless technologies adapt to the radio environment. With a good quality signal, the radio link can employ higher-order modulation and less forward error correction, thus increasing throughput. For instance, 64 Quadrature Amplitude Modulation (QAM) conveys six bits per radio symbol compared to 16 QAM that conveys 4 bits.

Each modulation scheme produces a certain bit error rate relative to the signal to noise ratio (SNR). The physical layer protocols can correct some of these bits using forward error correction (called coding), but the higher the bit rate, the more coding overhead is needed, and at some point, the link is more efficient with a different modulation scheme. To use spectrum as efficiently as possible, modern radio technologies, including cellular and Wi-Fi, employ multiple combinations of modulation and coding. Fig. 1 shows a simplified example of four scenarios, two with lower-order modulation and two with higher-order modulation, resulting in four values of spectral efficiency, with increasing spectral efficiency as the signal improves.

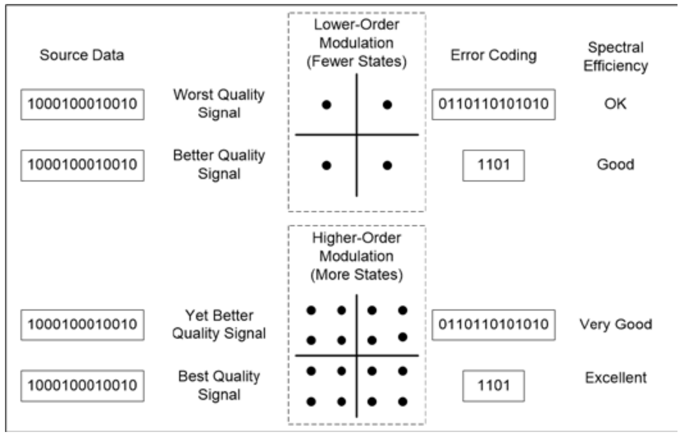

Figure 1. Example of Dynamic Modulation and Coding.

Peak spectral efficiency is determined by the highest throughput a technology can deliver in a given amount of spectrum, occurring with the highest-order modulation scheme available and the least amount of coding.

Of greater utility in assessing how a technology will serve a subscriber base is the average spectral efficiency, which considers the aggregate cell throughput in a deployed configuration of multiple cell sites. Modern cellular technologies such as Code Division Multiple Access 2000 (CDMA2000), HSPA, and Long Term Evolution (LTE), use the same radio carriers in adjacent cells, resulting in significant interference. Therefore most connections operates at a lower bps/Hz value than the peak value.

Engineers develop complex simulations to determine the average spectral efficiency, modeling an actual network with multiple cell sites and devices placed throughout the simulated coverage area. The simulation calculates the level of interference users experience from other users and calculates what modulation and coding each user's device can use. Adding up the throughput of all the users yields the aggregate throughput and produces an average bps/Hz value for the technology.

4G Americas has annually produced spectral efficiency charts through a consensus analysis involving multiple operators, infrastructure vendors, and chipset vendors. Fig. 2 shows the 2013 chart for downlink spectral efficiency comparison of major wide-area wireless technologies [21].

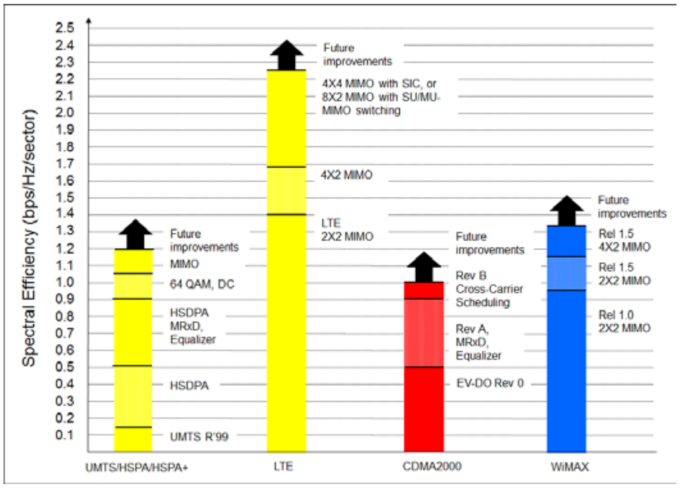

Figure 2: Comparison of Downlink Spectral Efficiency.

Fig. 2 shows that LTE in a typical current deployment (using 2X2 MIMO) has spectral efficiency of 1.4 bps/Hz. Thus, a deployment of 10+10 MHz radio channels would result in 14 Mbps of aggregate downlink per cell sector. Note that the spectral efficiency of a technology is largely independent of the frequency at which it operates, since modulation and coding is the same at different frequencies.

Some of the key assumptions that affect resulting spectral efficiency is the exact mix of stationary versus mobile users and the distance between cell towers. The 4G Americas values are intended to show realistically achievable values in actual deployments. Values cited by other organizations may differ. For example, 3GPP cites a higher value of 1.69 bps/Hz for LTE with cell site spacing of 500 meters and 1.56 bps/Hz with cell site spacing of 1732 meters [1]. The FCC has used a value of 1.36 to 1.5 bps/Hz in some of its spectrum-demand forecasts [13].

Because today's advanced wireless technologies have essentially reached the Shannon Bound, which defines the maximum theoretical efficiency possible relative to noise, future gains in spectral efficiency will be limited; instead smaller cells will play a greater role in increasing capacity [22].

V. Cellular Deployments and Cell Size

In addition to spectral efficiency, an analysis of the capacity of an actual network across a coverage area must also include the number of cell sites. The calculation for network capacity is the capacity of each cell multiplied by the number of cells in a coverage area. The discussion above already explained that the capacity of a cell is the spectral efficiency value times the amount of spectrum used. In most cellular deployments, each base station is divided into three cell sectors. Thus the capacity of a cellular coverage area is: (Spectral efficiency) X (amount of spectrum) X (number of cell sites) X (number of cell sectors/cell site, usually 3).

Considering cell size also allows one to calculate bandwidth/area (bandwidth density), for instance Gbps/sq. km. or bps/sq. m., which provides another important measure of how efficiently an entity has deployed a specific amount of spectrum.

Consistent with this discussion, FCC TAC specifically recommends bps/Hz/sq.km. as the metric for Personal Communications Systems, which takes into account both spectral efficiency (bps/Hz) and deployment density. [15].

The growth in cellular network capacity since the 1980s is much more a function of the growth in the number of cell sites than improvements in the spectral efficiency of the technologies involved. In the U.S., there were 913 cell sites in 1985—at the end of 2012 there were 301,779 [3].

Clearly, the smaller the cell, the greater the bandwidth density, as exhibited by both Wi-Fi and cellular small cells. It could be argued that the best use of cellular spectrum would be to deploy small cells everywhere, but the cost of doing so becomes extremely high, since each small cell needs a physical location with mounting, power, and most significantly, backhaul to the core network. Small cells thus use spectrum efficiently by delivering a large amount of bandwidth, but they are not necessarily economically efficient, which explains why cellular operators are only deploying them selectively in areas of high user concentrations—airports for example.

A broader concept of economic efficiency, which can be defined as the value of the total output relative to the cost of all inputs, is useful because it accounts for costs that technical measures may not [14]. For a cellular network, economic efficiency could be $/bps/Hz/sq. km.

Which measure is then the most important: spectral efficiency, bandwidth density, or economic efficiency? The answer is it depends. An organization determining whether to upgrade to IEEE 802.11ac Wi-Fi from 802.11n might look at the spectral efficiency of each technology, whereas an operator seeking to increase capacity in a stadium might look at bandwidth density to decide between small cells or Wi-Fi.

An analogy is vehicle fuel efficiency. A car with higher fuel economy than another costs less per mile to operate, and certainly less than a truck. But what if the measure is the cost per kilogram transported per mile. The truck would likely be more efficient and a train even more efficient, despite their low miles traveled per gallon of fuel.

VI. White Space Networks

A current debate in policy circles is over white-space networks that exploit unused television channels, and whether more unlicensed spectrum should be allocated to these networks. IEEE has developed two radio-access standards for interoperable equipment in these bands: IEEE802.11af and IEEE 802.22 [17] [18]. The concepts of bandwidth density and economic efficiency provide a means for evaluating the pros and cons of these networks.

Because the frequencies involved are relatively low, signals propagate well and so cells can be quite large, a 10 mile radius for instance [2]. Large cells are economically efficient since fewer cells can cover an area and the infrastructure cost is this relatively low. The resulting data density, however, is relatively low, and thus not necessarily able to service a high density of broadband users. Consequently, while white-space networks may have difficulty competing with densely deployed 4G networks, they may be the perfect solution for under-developed countries, explaining why companies working with white space technology are focusing their white-space efforts on regions of the world such as Africa [16].

VII. Broadcast and Multicast

Concepts of efficiency can also apply to using spectrum for entertainment, since both television and cellular systems can deliver video, the former via broadcasting and the latter via streaming. Digital TV broadcasts use signals with relatively high spectral efficiency, 3.23 bps/Hz, double the 1.4 bps/Hz for LTE [15]. This might make the broadcast system appear twice as efficient as LTE, but remember that the LTE average spectral efficiency value assumes a high-interference environment due to neighboring cells. In contrast, the TV signal assumes virtually no interference on the channel.

In a metro area, the TV signal can propagate across the entire city, whereas the same area might encompass a hundred 4G cells, each with 3 sectors. Although the 4G cells is operating at half the spectral efficiency of the TV channel, there would be 300 times as many separate coverage areas, resulting in the 4G system having 150 times the effective bandwidth density. Fig. 3 depicts a comparison of broadcasting to cellular architecture.

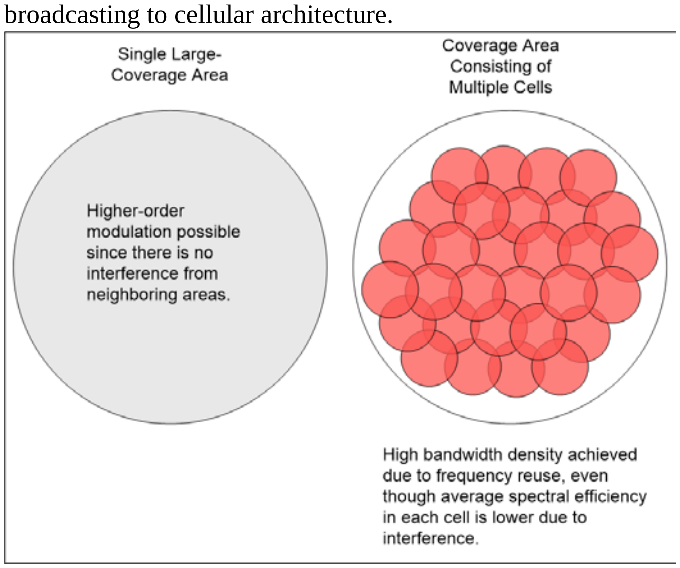

Figure 3: Comparison of TV Broadcasting and Cellular Use of Spectrum.

The broadcasting counterargument would likely be that bandwidth density is not necessarily the appropriate efficiency measure—instead it should be the amount of entertainment delivered to each subscriber relative to the amount of spectrum used.

FCC TAC does in fact propose an alternate measure for terrestrial broadcast systems that accounts for the number of subscribers: information bits per second per Hz of allocated (licensed) spectrum within each common geographic area (bps/Hz) times the average number of users simultaneously served [15].

One question is whether the public is best served by entertainment broadcasting or by on-demand methods via the Internet (such as Netflix and Hulu). This question is not easy to answer, but any analysis might consider that approximately only 20% of homes view TV over the air [20].

Multiple cellular users receiving the same streaming content via a wireless channel can do so more efficiently if each user receives the same stream of bits rather than each user receiving a separate stream. For this reason, cellular technologies have defined multicast services. For example, LTE has a capability called "LTE Evolved Multimedia Broadcast Multicast Service (eMBMS). Although eMBMS has not yet been deployed, it could eventually prove attractive for applications such as sports venues to show replays.

As for how to allocate spectrum between broadcast and mobile broadband, the FCC is resorting to market dynamics and is planning incentive auctions in 2015 that will compensate broadcasters who relinquish 600 MHz spectrum to the cellular industry [11].

VIII. Subscriber Metrics and Quality of Service

The cellular wireless industry has used another efficiency measure: subscribers per MHz of spectrum deployed, which can compare operators or even countries. If country A uses 500 MHz of cellular spectrum to support 10 million subscribers and country B uses the same amount of spectrum to support 100 million subscribers, the temptation might be to conclude that country B uses the spectrum more efficiently—but this is not necessarily correct. Since cellular frequencies are reused from one cell to the next, the amount of spectrum required to cover one dense population area such as a city is the same as covering ten cities or a hundred cities. Hence the country A might simply be a smaller country than country B.

The best means of applying this particular metric would be to compare two operators that are covering the same area. An analysis might show that operator A uses 100 MHz to service 100 million subscribers and a seemingly more efficient operator B uses 80 MHz to service the same area to 120 million subscribers. But another consideration applies—quality of service. If operator B has network congestion with poor service quality, then the operator is not more efficient but may just need more spectrum (or to deploy more cells).

Quality of service also relates to signal quality. A network with fewer cell sites might appear economically more efficient than one with more sites, but if users experience dropped calls or cannot connect at all, then the efficiency advantages are of dubious value.

IX. Spectrum Sharing

Government increasingly is investigating and pursuing spectrum sharing [7] [15] [23] [25]. Spectrum sharing is potentially an important way to use spectrum more efficiently, particularly if a primary licensee only uses spectrum occasionally in time or over a subset of geography, enabling secondary users to take advantage of the spectrum [25]. Limited instances of sharing already exist, for example between Wi-Fi and radar systems at 5 GHz, using a mechanism called Dynamic Frequency Sensing (DFS).

In 2013, CSMAC working groups researched and reported on the feasibility of sharing in specific bands, including the 1755 to 1780 MHz band [4] [6] [8-10].

In the future, estimating the efficiency of a primary system could help determine if the system could be shared.

Once disparate systems share the same spectrum, calculating the resulting efficiency will likely require a combination of the types of metrics discussed above, or new sharing metrics not yet defined.

X. Other Systems

Point-to-point systems differ from cellular systems in that coverage is in beams as opposed to continuous coverage in cellular or broadcast systems. FCC TAC proposes for such systems that the measure be: Information bits per second per Hz of allocated (licensed) spectrum) x (transmitted distance) per square Km of service area) [15].

As for radar systems, unlicensed systems, and terrestrial and satellite receive only observation systems, FCC TAC stated in its report that it had yet to identify and develop suitable spectrum efficiency metrics [15].

XI. Societal Benefits

Ultimately, efficiency assessments must also consider societal benefits. The allocation of D-Block spectrum at 700 MHz to Public Safety for a national broadband network is a case in point. The cell-site (and bandwidth) density of this network will likely be lower than that of commercial networks using the same LTE technology, but the value of the public safety applications is presumably so high that the benefit to society prevails over simply a consideration of how many bits the spectrum can carry.

If the value of an application could be factored in, then the ultimate spectrum efficiency measure would combine the application value with spectral efficiency of the technology used, degree of frequency reuse, and economic efficiency. Unfortunately, no such measure is available or even contemplated, so decision makers must decide which measure is most appropriate for each scenario.

XII. Conclusion

Table 1 summarizes the strengths and weaknesses of the various measures of spectrum use efficiency.

Table 1. Attributes of Various Spectrum Efficiency Measures

Measure	Comment	Weakness
Peak Spectral Efficiency in bps/Hz.	Effective for comparing fastest throughputs available from wireless technologies.	Value sometimes confused with average spectral efficiency. Does not measure aggregate capacity, nor costs, nor degree of frequency reuse.
Average Spectral Efficiency in bps/Hz.	Allows calculation of aggregate capacity in a coverage area. Useful for comparing technologies used for similar applications.	Largely independent of cell size and degree of frequency reuse, so does not address actual network capacity.
bps/Hz/sq. km.	Expands on average spectral efficiency measure (bps/Hz) to take into account degree of frequency reuse.	Does not take deployment costs into account.
Subscribers per MHz.	Provides insight into how many subscribers cellular operators support and provides basis for comparing operators.	Measure is only valid if comparing similar geographical areas and similar subscriber densities.
bps/Hz (in each common geographic area) x (average number of users served)	FCC TAC proposed metric for broadcast systems.	
bps/Hz x (transmitted distance) / (sq. Km. of service area)	FCC TAC proposed metric for point-to-point systems.	
Economic efficiency ($/bps/Hz/sq. km.)	Measures the cost of delivering a service and allows competitive comparison between technologies.	By itself, does not provide insight into data bandwidth that a given amount of spectrum can deliver.
Society benefit.	Allows consideration of non-technical items.	Measure can be subjective.

Although there is no single measure that applies to each scenario, knowing the strengths and of weaknesses of the different measures should lead to wiser decisions on spectrum usage.

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