Spectrum Metrics and Spectrum Efficiency: Proposed Definitions

LESLIE A. BERRY

Abstract—**A spectrum metric—a unit of measure of spectrum-space use—is defined and used to define a measure of spectrum efficiency as the ratio of communications output to spectrum-space input. It is shown that this efficiency measure is easier to compute than another candidate, and gives the same relative result. Several examples of the application of this measure are given. Implications of a definition of spectrum efficiency are mentioned.**

I. INTRODUCTION

SPECTRUM efficiency is much discussed. For example, the Office of Telecommunications Policy (OTP) was commissioned to (among other things) "help attain coordinated and efficient use of the electromagnetic spectrum" [1]. The Joint Technical Advisory Committee was tasked in 1964 to "recommend ··· procedures that would ··· increase the effective and efficient use of the radio spectrum" [2], and numerous Federal Communications Commission (FCC) Dockets include spectrum efficiency as an important consideration.

But there is no generally accepted definition of spectrum efficiency, or measure of spectrum efficiency. The International Radio Consultative Committee (CCIR) has called for such a definition [3], and it is likely that one will be adopted at the next Plenary Assembly. If a definition is adopted, present CCIR recommendations, and even International Radio Regulations, may be changed to call for "maximum spectrum efficiency," rather than for minimum necessary bandwidth as they now do. Even if international considerations are disregarded, a measure of spectrum efficiency could be used by U.S. frequency managers and regulators to compare the relative efficiency of different proposals, and even to set minimum standards of spectrum efficiency. It is therefore important that the definition be realistic and computable.

Several definitions have been proposed [4]-[12]. Some of these are for specific applications; others are generally applicable; but all can be cast in one of two general forms. One form is the ratio of the communications output to the spectrum space used to produce the output, which will be called the output/input efficiency. The other form is the ratio of the spectrum space used by an "ideal" system to the spectrum space actually used, which will be called the ideal/input efficiency.

In Section III B it will be shown that the two forms always give the same *relative* result, and that the output/input measure is easier to compute. However, a measure of the spectrum-space input must be defined first, and this is done in Section II.

Manuscript received February 9, 1977.

The author is with the Office of Telecommunications, Institute for Telecommunication Sciences, U.S. Department of Commerce, Boulder, CO 80302. (303) 499-1000.

II. DEFINING A METRIC FOR SPECTRUM-SPACE USE

A. The Components of Spectrum Space

It is generally, but not universally, agreed that the components of spectrum space should be radio-frequency bandwidth, physical space (such as area or volume), and time [4]-[11]. There have been suggestions that other quantities, such as polarization and modulation, are also dimensions of spectrum space [13]. The argument for including these quantities is that systems using values of the parameters that are "orthogonal" or nearly orthogonal do not interfere with each other. For example, horizontally polarized antennas do not respond well to vertically polarized radio waves. However most of these proposed quantities such as polarization and modulation, do not fit well into a metric for spectrum space. So they will be excluded from the proposed measure of *spectrum-space* use, although their influence will show up in the measure of *spectrum efficiency.*

The physical space included in the definition of the spectrum-space metric will depend on the service that is involved. For many terrestrial services such as broadcasting and land mobile, the space of interest is two dimensional, and area is used as a factor as proposed by Gifford [4] and Powers [5], for example. The critical physical space for geostationary satellites is a line—the geostationary orbit. So measures of spectrum space for this service usually include degrees of arc (a linear metric) in the product [10], [14], [15]. In some cases, the relevant physical space is volume [16], and for point-to-point services it may be angle around a pivitol point.

The importance of the dimension of time varies with the service. Many services operate continuously with analog modulation (for example, point-to-point microwave, some broadcasting, navigation services) so the time factor is a constant. In other services, such as land-mobile radio, time sharing is of vital importance to efficient spectrum use.

It is proposed that the spectrum metric—the unit of measure of spectrum-space use—be defined as the product

(bandwidth) × (relevant physical space) × (time)

that is denied to other potential users.

B. "Used" means "Denied to others"

The area around a transmitter in which a usable reliable signal can be received is almost always smaller than the area in which the same transmitter can cause unacceptable interference. For purposes of spectrum management and efficiency, it is clearly the area that is denied to other potential users that is important. This is the area that is related to spectrum saturation. Similarly, it is the bandwidth and time that are *denied* to other users that is critical in frequency assignment [2], [7].

There are two ways in which these dimensions can be denied. The space is ***physically denied*** if it is filled with sufficient power to interfere with other proposed operations. This is the denial of interest to spectrum engineering [2], [7]. In Section C, definitions of a spectrum metric based on physical denial are developed.

Frequently, the spectrum space is *administratively denied* [7]. That is, frequency managers make rules or frequency assignments denying space to other users even if that space is not filled with interfering radiation. Administrative denial is sometimes a practical upper bond to physical denial imposed to account for the statistical variability of radio system performance and to make management of the spectrum simpler. In other cases, administrative denial is related to the spectrum space used by the receiver, also covered in Section C.

C. The Complementary Nature of Spectrum-Space Use by Receivers and Transmitters[1]

Traditionally, radio transmitters have been considered the users of the spectrum resource. They use the spectrum space by filling some portion of it with radio power—so much power that receivers of other systems cannot operate in certain locations, times, and frequencies because of unacceptable interference. Notice that the transmitter denies the space to *receivers* only. The mere fact that the space contains power in no way prevents another transmitter from emitting power into the same location; that is, the transmitter does not deny operation of another transmitter (unless the coupled strength is so great that improper transmitter operation, e.g., intermodulation, occurs).

On the other hand, receivers use spectrum space because they deny it to transmitters. The mere physical operation of the receiver interferes with no one (except as it inadvertently acts as a transmitter or power source). Even then, the space used physically is small. However, the authorities deny licenses to transmitters in an attempt to guarantee interference-free reception. The protection may be in space (separation distance, coordination distance), in frequency (guard bands), or even in time (in the United States, some MF broadcasting stations are limited to daylight operation). This denial constitutes "use" of the space by the receiver, and is closely related to administrative denial. The radio astronomy bands are a familiar example of the recognition of receiver use of the spectrum space.

Thus receiver and transmitter usage of the spectrum resource results in complementary denial: transmitters deny use of a time-frequency-geographic region to receivers wishing to receive another signal, and a protected receiver denies a time-frequency-geographic region to transmitters whose operation would interfere with it. An obvious way to incorporate these facts into a unit of measure of spectrum space is to partition the resource into two spaces—the transmitter space and the receiver space—and define dual units to measure the usage of each space. For administrative simplicity, the two units can be recombined into a single measure of system use.

[1] Sections C and D are consensed from [7].

D. Calculation of Physical Denial

For the purpose of calculating its spectrum use, a transmitter can be characterized by its location in geography and frequency, and by its *emission power density function* $\epsilon(\phi, f; f_T)$ which has the units W/Hz. This function shows the spectral power density at frequency f radiated in the azimuthal direction ϕ, when the transmitter is tuned to frequency f_T. (Area will be used as the physical space in this development.)

In most practical problems the power density emission function of the transmitter can be approximately separated into the product of a function of frequency and a function of azimuth

$$\epsilon(\phi, f; f_T) \sim p(f; f_T) g_T(\phi) \tag{1}$$

where $p(f; f_T)$ is the spectral power density at the antenna terminals, and $g_T(\phi)$ is the transmitting antenna gain function (at its normal design frequency).[2] The function $p(f; f_T)$ includes all power emitted, including spurious emissions and transmitter noise.

Similarly, a receiver can be characterized by its location and its *admission function* $\alpha(\phi', f; f_R)$, which is the fraction of the power density at frequency f arriving from direction ϕ, that will reach the demodulator of a receiver tuned to frequency f_R. It has no units.

The receiver admission function can be approximately separated

$$\alpha(\phi', f; f_R) \sim \frac{g_R(\phi')}{g(f; f_R)} \tag{2}$$

where $q(f; f_R)$ is the selectivity function of the receiver, and $g_R(\phi')$ is the receiver antenna gain pattern.

Much of the power emitted by the transmitter does not reach the receiver. The difference between emitted power and received power is the basic transmission loss—defined to be the loss between isotropic antennas, and denoted by $l(f, d)$ where d is the distance between the transmitter and receiver [17]. It is assumed here that $l(f, d)$ represents the basic transmission loss for average conditions for the frequency of interest.

A general expression for the power coupling between a

[2] *Editor's Note:* This assumption appears reasonable in the vicinity of the carrier frequency, but may result in substantial error at harmonic and other spurious frequencies far removed from the carrier.

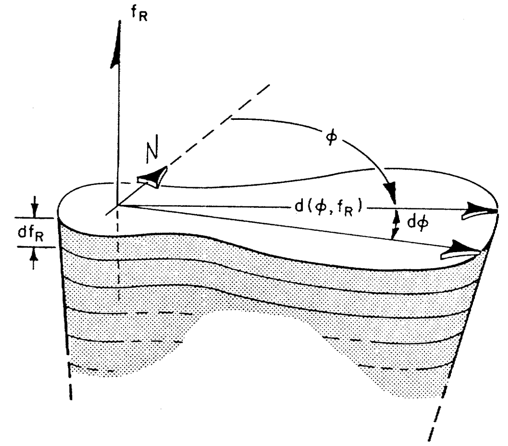

Fig. 1. Representation of the (bandwidth X area) volume denied to a receiver by a transmitter with a directional antenna.

transmitter T and a receiver R is

$$P = \int_0^\infty \left[\frac{\epsilon(\phi, f; f_T)}{l(f, d)} \right] [\alpha(\phi', f; f_R)] \, df$$

$$\sim g_T(\phi) g_R(\phi') \int_0^\infty \frac{p(f; f_T)}{l(f, d) g(f; f_R)} \, df (W) \tag{3}$$

In this equation, ϕ is the azimuth angle from T to R and ϕ' is the azimuth angle from R to T. On a flat surface, $\phi' = \phi + \pi$. The first factor in brackets is the spectral power density arriving at the receiver having suffered basic transmission loss $l(f, d)$. The second factor in brackets is the fraction of that power density admitted by the receiver so that the product is the spectral power density received. Integration over all frequencies with nonzero power density yields the total received power, P.

Suppose now that transmitter T and receiver R are not in the same system, so that there is a potential for interference. For any receiver there is some threshold amount of power in an unwanted signal that will interfere with acceptable reception of the wanted signal. Denote this threshold power level of receiver R by P_R.

By setting $P = P_R$, and assuming that all characteristics of the transmitter and receiver are fixed, (3) can be used to determine the minimum noninterfering separation $d = d(\phi, f_R)$ of T and R.

1) The Situation-Specific Denial Metric: Often, only a few types of systems compete for assignments in a particular frequency band and geographic region. The spectrum space that a system denies to each competing system can be calculated and is called the *situation-specific* metric. The combined spectrum space that a system denies to all competing systems is the measure of its spectrum-space usage.

The transmitter is characterized by its spectral density function $p(f; f_T)$ and its antenna pattern $g_T(\phi)$. Suppose the typical receiver R in a competing system has selectively function $q(f; f_R)$, antenna pattern $q_R(\phi')$, and interfering power threshold P_R. Solve (3) for $d(\phi, f_R)$, the minimum noninterfering distance separation in direction ϕ from T for a receiver tuned to frequency f_R. Fig. 1 is a plot of $d(\phi, f_R)$ for an illustrative transmitter with a directional antenna. It can be seen from Fig. 1 that the geographical area that T denies R is given by

$$A(f_R) = \int_0^{2\pi} 1/2 \, d^2(\phi, f_R) \, d\phi. \tag{4}$$

The spectrum-space "volume" used at frequency f_R is $A(f_R) df_R$ (see Fig. 1). The denied areas for each frequency f_R can be computed and the resulting incremental volumes are summed. The result multiplied by τ_T (the time the transmitter operates) is the situation-specific metric M_T for the spectrum space used by transmitter T

$$M_T = \tau_T \int_0^\infty A(f_R) \, df_R$$

$$= \tau_T \int_0^\infty \int_0^{2\pi} 1/2 \, d^2(\phi, f_R) \, d\phi \, df_R \tag{5}$$

where $d = d(\phi, f_R)$ satisfies (3).

Similarly, the spectrum space denied to a transmitter by a receiver R operating τ_R h/day is

$$M_R = \tau_R \int_0^\infty \int_0^{2\pi} 1/2 \, d^2(\phi', f_T) \, d\phi' \, df_T \tag{6}$$

where $d = d(\phi', f_T)$ must satisfy (3) for the admission function of the evaluated receiver and the emission function of the denied transmitter.

Formally, the only difference between the metrics M_R and M_T is the interchange of admission and emission functions, but it is likely that the numerical values are different. At any rate, the space measured is different; receiver space is denied to transmitters and transmitter space is denied to receivers.

2) The Uniform Denial Metric: The numerical value of the situation-specific metric depends on the relative locations and specific emission and admission characteristics of the competing systems. Thus the value for a fixed system could be changed by the introduction of a new system in the same band or area. The *uniform metric* avoids this undesirable feature by using idealized reference transmitters and/or receivers. Spectrum space *used* is now considered to be the spectrum space *denied* to such *reference receivers* and *transmitters.* Equations (5) and (6) are still used to define the uniform metrics; however, (3) now has simplified forms.

For the transmitter metric, define an idealized "probe" receiver which has an isotropic loss-free antenna ($g_R(\phi') = 1$), and a perfect narrow selectivity function, so that $q(f; f_R) = 1$ if $f_R - b/2 \leqslant f \leqslant f_R + b/2$ and $q(f; f_R) = \infty$ otherwise. The bandwidth of the reference receiver b is chosen small enough that the spectral density $p(f; f_T)$ of the transmitters is essentially constant over it.

With these assumptions on the referenced receiver, the power coupling (3) becomes

$$P_R = g_T(\phi) p(f_R; f_T) b / l(f_R, d) \tag{7}$$

where P_R is the interference power threshold of the reference receiver. Recall that (7) must be solved for $d = d(\phi, f_R)$ to evaluate (5) for the transmitter metric.

The power threshold P_R of the reference receiver in (7) is somewhat arbitrary. However, it may logically be related to the average ambient noise power density since this is the power that would "use" the space in the absence of any system. Specifically, choose P_R/b to be the average ambient noise power density [18], [19].

An analogous definition can be made of the space denied to a reference transmitter by a particular receiver R. In this case, assume that the reference transmitter has an isotropic antenna ($g_I(\phi) = 1$), and a perfect narrow spectral density function. Specifically, $p(f, f_T) = 0$ unless $f_t - b/2 \leqslant f \leqslant f_T + b/2$, and with this interval $p(f, fT) = P_T/b$, where P_T is the emitted power of the reference transmitter.

With these assumptions (3) becomes

$$P_R = \frac{P_T g_R(\phi')}{g(f_T; f_R) l(f_T, d)} \tag{8}$$

where P_R is the interference threshold of the evaluated receiver. Again, (8) must be solved for $d = d(\phi', f_T)$ to evaluate (6) for the uniform metric for receiver R.

Equation (8) shows, explicitly, what is intuitively obvious—that the space denied by a receiver to a transmitter depends on the power P_T emitted by the reference transmitter. In this case there is no "natural" reference level to use as there was in the case of a reference receiver, so the choice will have to be arbitrary.

For many applications, the desired information is the amount of spectrum space used by a receiver *relative* to the spectrum space used by other receivers. It can be shown [7] that if the transmission loss $l(f, d)$ is proportional to a power of distance d, then the *relative* value of the uniform metric is independent of the choice of P_T. This condition holds for free-space loss which is proportional to d^2 (for frequency fixed) and for some other cases. However, in general, even the relative value of the spectrum space used by receivers depends on the choice of P_T, because loss near the earth's surface is not proportional to a power of d for all distances. Thus the "best" choice for P_T remains an open question. Once a choice has been made, however, this measure of spectrum-space use depends only on the characteristics of the evaluated receiver, including its power threshold.

3) Simple Metric for Idealized Transmitters and Receivers: The uniform metric for a transmitter assumes that the reference receiver has a rectangular bandpass (i.e., selectively function). Similarly, the uniform metric for a receiver assumes that the reference transmitter has a rectangular power spectral density function. In both cases the emission (or admission) function of the *evaluated* equipment (transmitter or receiver) is arbitrary; it does not need to be "rectangular".

Suppose, on the other hand, that a transmitter has a perfect power spectral density function of bandwidth B. Then, the uniform metric $M_T = \tau_T B A(f_T)$ where $A(f_T)$ is the area (4) denied to a competing receiver with tuned frequency $f_R = f_T$ [7]. Analogously, if we want to evaluate the metric for a receiver with a perfect rectangular bandpass of bandwidth B, then the uniform metric is $M_R = \tau_R B A(f_R)$ where $A(f_R)$ is the area denied to a competing transmitter. That is, the uniform metric reduces to a simple (time) (area) (bandwidth) product for "perfect" equipment characteristics.

The metrics above measure the amount of spectrum space denied by *individual* transmitters and receivers. If a system has, say, multiple receivers and the spectrum-space volumes denied by these receivers overlap, then the amount of spectrum used by the system is not simply the sum of use by its component parts. Rather, it should be the union of spectrum-space volume denied, and the measure of system use should be less than the sum of the use of component receivers. An analogous situation may occur with a system having transmitters. (See [7] for examples.)

E. Final Choice of Metric Spectrum Efficiency Definition

The idea incorporated in the situation-specific metric are often used in electromagnetic compatibility and spectrum engineering analyses because they accurately describe the interactions in a real situation. However, for ease in extending the metric to a definition of spectrum efficiency, it is recommended that the simplification commonly used in frequency allocation and assignment be adopted. This simplification required defining a bandwidth-area-time product in which each factor is an upper bound (usually a conservative upper bound) of the factors that would be computed by using the simplified metric in Section D-3, and taking the union of spectrum space used by all transmitters and receivers in the link, system, or aggregate systems being evaluated.

III. DEFINING A MEASURE OF SPECTRUM EFFICIENCY[3]

The concept of quantifying efficiency by the ratio of desired output to valued input is familiar to people in all walks of life. A current example is a measure of personal transportation efficiency: miles/gallon. This example illustrates several features of generally accepted measures of efficiency. The numerator is the desired output of interest—even though it may not represent the entire output or system function. The denominator is a measure of the critical input to produce the output. Notice that the numerator and denominator need not be the same kind of quantity, and that the units of the resultant ratio may not make "sense"—the units of miles/gallon turn out to be inverse area.

This measure of efficiency, which does not include all of the technical detail that an engineer might want, is useful because it communicates desired significant information to the nonengineer—to the consumer, the policy maker, and the government regulator. To be valuable and accepted, a measure of spectrum efficiency also should be understood and usable by nonengineers—by the lawyers, economists, and nonspecialists who make final decisions about spectrum use in the International Telecommunication Union (ITU); and in the United States, the FCC, and the OTP.

[3] Some of this section appeared in [20].

A measure of spectrum efficiency that has these characteristics would be the general form

$$\frac{\text{communications achieved}}{\text{spectrum space used}} \tag{9}$$

or more generally (to accommodate radar, navigation systems, radio control, etc.)

$$\frac{\text{information delivered}}{\text{spectrum space used}}. \tag{10}$$

The nature and units of the numerator will depend on the type of service provided. The denominator was discussed in Section II.

A. Examples of Input/Output Measure of Spectrum Efficiency

Engineers addressing practical problems of interest to them have defined input/output ratios naturally. A notable example is the measure of "orbit utilization efficiency," defined by CCIR Study Group 4 in 1974, for the geostationary satellite service [10], and still under study [15]. For digital modulation, they defined efficiency as

$$\frac{\text{bit rate}}{\text{(RF bandwidth)(orbit arc in degrees)}}. \tag{11}$$

Since bit rate is bits/s, (11) can be written

$$\frac{\text{bits}}{\text{(RF bandwidth)(orbit arc)(time)}}. \tag{12}$$

This is precisely the form recommended for the output/input efficiency measure in (9). The numerator is the amount of information transferred (measured in bits), and the denominator is the product of bandwidth, time, and geometric space. In this case, the critical geometric space is the geostationary orbital arc—a line.

For analog communications satellites, the orbit utilization was defined to be

$$\frac{\text{information bandwidth}}{\text{(bandwidth)(orbit arc)}}.$$

In this case the information delivered is not quantified. Instead, the surrogate quantity, information bandwidth, is used because it is proportional to the potential rate of information transfer. This example illustrates one of the practical compromises that can be made in implementing the general form of the definition.

In a study aimed at maximizing the utility of microwave point-to-point networks in a dense urban environment, Tillotson, Ruthroff, and Prabhu [6] defined the "communication capacity" as

$$\frac{\text{(no. of usable channels)(channel information bandwidth)}}{\text{(radio bandwidth required)}}.$$

They specified the number of *usuable* channels (instead of the number of channels) because they were calculating the amount of information delivered in the presence of interference, and only usable channels deliver information. Thus the numerator is analogous to the one defined by the CCIR [10]—it represents the communications capacity assuming that all channels are carrying information. However, the denominator contains only one dimension of the resource used—bandwidth. Their model has a fixed geographic area with a fixed (but quasi-random network) crossing it; and they apparently assumed full-time denial by the network. This latter assumption is true for many, but not all, applications.

More recently, Hatfield [11] reviewed measures of spectral efficiency proposed for comparing land-mobile radio systems and concluded that the most useful definition of spectral efficiency is

$$\text{erlangs/MHz/mi}^2.$$

Since an erlang is a measure of traffic per unit time, this ratio can be rewritten

$$\frac{\text{traffic}}{\text{(bandwidth)(area)(time)}}$$

which is precisely the output/input ratio for spectrum efficiency (9).

Starting with the general form in (9), but not including time as a factor, Vinogradov [16] developed an explicit formula for the spectrum efficiency for a point-to-point radio link. Considerations used to derive the formula include the antenna gains and sidelobe power, the transmitter power and emission bandwidth, polarization, receiver sensitivity, and path length.

B. Another Candidate: The Ideal Measure of Efficiency

One proposed definition of "spectrum efficiency" has the form [2], [9]

$$\frac{\text{spectrum space used by an ``ideal'' system}}{\text{spectrum space used by the system being evaluated}}.$$

The denominator of this ratio is intended to be the same as the denominator of the output/input ratio; namely, the product of bandwidth, geometric space, and time denied to other users. The numerator is the product of the same three factors that an "ideal" or "perfect" system performing the same function would deny to other users.

The "ideal" measure conforms to the traditional engineering concept of efficiency—a dimensionless number between 0 and 1. However, to nonspecialists it may have a parochial flavor—a preoccupation with conserving spectrum space as an end in itself. Returning to the miles/gallon analogy, would consumers want to replace the miles/gallon measure with one which compared the amount of fuel used by an "ideal" automobile with the amount used by a particular model? Such a measure does allow ranking of different systems, but gives no guidance as to what the customer gets for his input of gasoline. Since many decisions which impact spectrum use are made by nonspecialists (for example, by congressmen, FCC commissioners, and ITU delegates) it is advantageous to have a measure of spectrum efficiency that they intuitively grasp.

Other advantages of the output/input ratio are that it is less subjective, takes fewer steps to compute, and gives the same relative answer as the ideal measure of spectrum efficiency. For example, suppose that the spectrum efficiency of a point-to-point microwave link must be computed. The link must carry a fixed number of telephone circuits m miles a given percentage of the time. This is the "output" which is the numerator of the output/input efficiency ratio: X circuit miles for p percent of the time. To complete the calculation of the efficiency, the spectrum space used (bandwidth $\times$ area $\times$ time) the link denied to other users must be computed. Although this calculation is not trivial, it is not necessary for the present comparison because both measures have exactly the same denominator. Thus the input/output measure of spectrum efficiency is computed.

Now consided the calculation of the ideal efficiency measure. The calculation of the denominator is the same as before. Also the output (X circuit miles with reliability p) must still be specified, else how can the ideal system be determined? And what is the amount of spectrum space used by the "ideal system?" The transmission could be via coaxial cable or by waveguide which would use almost zero spectrum space. Is this the ideal system? Or the system could use antennas with very narrow main beams and very low sidelobes. What is the pattern of the "ideal" antenna? Other parameters which would reduce the required spectrum space would have to be specified; e.g., receiver noise figure, modulation index, and modulation type. The necessity of answering these questions makes the "ideal" measure of spectrum efficiency difficult to compute and somewhat subjective. In practice, the ideal system is usually abandoned, and replaced by some other reference system [9].

If the purpose of a measure of spectrum efficiency is to compare systems, then nothing is gained from the additional difficulty of computing the ideal/input measure, because both measures give the same relative result. Let C stand for the output specified in the example above (X circuit miles with reliability p). Suppose system A uses S_A spectrum space to provide the output, system B uses S_B spectrum space to do it, and an ideal system uses S_I spectrum space. The ideal efficiency measure for system A is S_I/S_A, and for system B it is S_I/S_B. Then system A is

$$\frac{S_I/S_A}{S_I/S_B} = S_B/S_A \tag{13}$$

times more efficient than system B. Using the output/input measure, the efficiency for system A is C/S_A and for system B it is C/S_B. Using this measure system A is

$$\frac{C/S_A}{C/S_B} = S_B/S_A \tag{14}$$

times better than system B, which is the same result obtained before.

IV. CONCLUDING REMARKS

A spectrum efficiency measure of the form (communications achieved)/(spectrum space used) is advocated in this paper because

- it will be better understood by nonspecialists who make or, at least, influence decisions about use of the spectrum resource;
- it is easier to calculate and less subjective than another candidate, the ideal/input measure.

Its potential practicality has been illustrated by examples of its use by engineers concerned with particular real-world problems. It should be further tested by converting the general form into specific definitions for many more applications such as broadcasting, point-to-point microwave links, and radar. This should not be considered to be merely an academic exercise because the CCIR will probably adopt some definition of spectrum efficiency soon. The resulting change in international regulations will impact radio system planners, designers, and operators.

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Spectrum Utilization Problems

SERGE S. SVIRIDENKO, SENIOR MEMBER, IEEE

Abstract—**This paper discusses various spectrum utilization problems, including the efficiency of spectrum use considered from the standpoint of communication theory. Mathematical modeling for spectrum efficiency is discussed for linear and nonlinear receiver models. Sharing problems between satellite and terrestrial relay systems are mentioned, and various solutions are discussed.**

INTRODUCTION

THE radio-frequency spectrum is a range of frequencies used for wireless transmission of information from one place to another.

Although the problem of radio-frequency spectrum utilization has existed ever since electromagnetic waves were discovered, the spectrum remains one of the least evaluated natural resources despite the amount of study which it has been given [1]-[38]. (These references are general in their scope.)

At the present time, radio communications of all kinds are expanding on a colossal scale and radio spectrum requirements are increasing, accordingly. Spectrum congestion has made it necessary to study the possibilities of sharing among the various radio technical systems [11], [27], [31]-[33].

At the national level, the spectrum is used for the management of industry and national resources, defense and security forces, broadcasting, radio communications, meteorology, astronomy, space research, and other purposes. The role of the spectrum in the international exchange of information needs no further elucidation here. It is clear that the significance of the spectrum is not only technical but also economic and social [14], [19], [25], [34].

Manuscript received July 21, 1977.
The author is with the International Radio Consultative Committee (CCIR), International Telecommunication Union, Geneva 20, Switzerland.

Despite protracted efforts made at an international level, frequency allocation is not yet based on stringent technical criteria, due mainly to the difficulties involved in selecting such criteria.

Guidelines for the use of the spectrum are laid down in the Radio Regulations [8], which define the organizational and technical conditions governing the sharing of frequency bands by individual radio services, specify standards for radio emission parameters, etc. The Radio Regulations cover the following services: fixed, mobile, broadcasting, radionavigation, radioastronomy, standard frequency and time signals, radio amateur, and various types of space service [9].

EFFICIENCY OF SPECTRUM USE

The efficiency of spectrum utilization depends, as is well known [1], [3], [5], [6], [34], on such parameters as radiated power, bandwidth, service area, length of transmission, signal waveform, antenna pattern, class of interference and type of noise, the threshold level of the receiver decision element, the cost of the equipment used, and the methods of frequency planning.

In order to evaluate the efficiency of spectrum utilization it is necessary to have technical criteria for its quantization and measurement. These should be practicable and objective and should take account of the statistical nature of system parameters and the dual nature of the use of the spectrum, for both transmission and reception.

Besides having criteria for the quantitative measurement of spectrum utilization, it will be useful to have criteria for the economic analysis of the spectrum as a resource [11], [14]-[19].

For a long time, bandwidth has been the preeminent factor considered to represent spectrum occupancy, even though