A 53-Year History of Spectrum Efficiency Studies and Recommended Future Directions

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report series

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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ABBREVIATIONS AND SYMBOLS

AM   amplitude modulated

ARSR   air route surveillance radar

ASR   airport surveillance radar

ATC   air traffic control

AWS   advanced wireless service

CARSR   common air route surveillance radar

CBRS   Citizens Broadband Radio Service (CBRS)

CDMA   code division multiple access

CONUS   Continental United States

CCIR   Consultative Committee International Radio

CFR   Code of Federal Regulations

CMMI   Capability Maturity Model Integration

CSELT   Centro Studie Laboratori Telecomunicazioni

CSMAC   Commerce Spectrum Management Advisory Committee

DFS   dynamic frequency selection

DoD   Department of Defense

DoT   Department of Transportation

EIA   Electronics Industry Association

EMC   electromagnetic compatibility

FAA   Federal Aviation Administration

FCC   Federal Communications Commission

FDR   frequency dependent rejection

FRC   Federal Radio Commission

FM   frequency modulation

IEEE   Institute of Electrical and Electronics Engineers

IF   intermediate frequency

IMT   International Mobile Telecommunications (4G or 4.5G)

IoT   Internet of Things

IRAC   Interdepartment Radio Advisory Committee

ITS   Institute for Telecommunication Sciences

ITU-R   International Telecommunications Union Radiocommunication Sector

JTAC	Joint Technical Advisory Committee (of the IEEE)
LMR	land mobile radio
LRR	long range radar
NTIA	National Telecommunications and Information Administration
OMB	Office of Management and Budget
OOB	out of band
OoBE	out of band emissions
OSM	Office of Spectrum Management
OT	Office of Telecommunications
OTP	Office of Telecommunications Policy
PODAF	power flux density over an area in a frequency band
PSD	power spectral density
RF	radio frequency
RSEC	radar spectrum engineering criteria
SDC	software defined control
SE	spectrum efficiency
SEMT	spectrum efficiency metrics tool
SEWG	Spectrum Efficiency Working Group
SFA	Sachs Freeman Associates
SS	spread spectrum
SUE	spectrum use (or utilization) efficiency
SUM	spectrum use measure
TDMA	time domain multiple access
TIA	Telecommunications Industry Association
TSB-88-B	Telecommunications Systems Bulletin 88-B
TSC	Technical Subcommittee (of the IRAC)
U-NII	unlicensed national information infrastructure
USP	United States and Possessions
VSA	vector signal analyzer
VSG	vector signal generator
WC	weighting coefficient
WG	working group
WRC	World Radio Conference

EXECUTIVE SUMMARY

Spectrum is a limited resource upon which the world makes continually increasing demands. It is therefore natural and compelling to study the efficiency with which radio systems use spectrum. Such studies may be used to understand the extent to which radio spectrum may be better utilized by future systems, as well as how better allocation and sharing decisions may be made by spectrum engineers and managers for existing systems.

Formal spectrum efficiency studies began over half a century ago in 1964. Since then, dozens of studies, analyses, and reports involving a few hundred researchers have been published on the topic. In this report, we have mined the most significant of these previous studies for fundamental insights and points of broad consensus that other researchers have developed over the years.

A review of the historic spectrum efficiency literature shows that there is broad consensus on fundamental spectrum efficiency metrics, focused on increasing productive spectrum use and reducing spectrum blocking. There is also broad consensus that spectrum efficiency metrics are best used to compare similar radio systems or to optimize the deployment of radio systems within a frequency band.

Historically, spectrum efficiency studies have mostly focused on terrestrial fixed services and more recently on terrestrial mobile services; substantially less work has been done with regard to radio systems in other services. Although spectrum efficiency has improved for all radio systems over the years, it is evident that these studies have played a role in accelerating the introduction of more spectrum-efficient systems.

The second part of this report builds on lessons learned from the previous studies. Using those lessons learned, it recommends directions for possible future work. Possible approaches for constructing future efficiency metrics are laid out. We discuss the problem of how to include radio systems' potential for sharing spectrum with both similar and different systems (e.g., for mobile and cellular radios to share spectrum with other mobile systems and with non-mobile systems). This discussion is presented within the framework of how sharing may be assessed in spectrum efficiency studies. Effectiveness and cost are important additional aspects of spectrum use, but these topics are beyond the scope of this spectrum efficiency study.

We recommend that future spectrum efficiency (SE) studies, including those in which SE metrics will be developed, should be informed by the results of this detailed literature review. Chief among our recommendations are:

1) Only similar systems delivering like service to users should be compared to each other for SE metrical purposes.

2) SE metrics and comparisons should be relative, not absolute.

3) Band-dependent SE should compare similar radio systems operating in those bands.

4) Recent technical innovations should be significantly included in future SE studies and metrical development. These include software defined control (SDC) of transmitters and receivers that can take advantage of intelligence about local environments; smart or intelligent antenna designs including electronic beam steering and gain control; and dynamically controlled frequency agility. Such technical features have barely been considered in many past studies, because they have only recently become widely available.

5) Receiver selectivity characteristics are just as important for spectrum blocking as transmitter out of band (OoB) and spurious characteristics. Future SE studies and SE metrical development need to focus equally receivers and transmitters.

Recent technological developments make possible widespread implementation of smart transmitters and receivers. This will produce more opportunities for spectrum sharing than ever before. Spectrum sharing can be based on dynamically controlled systems that respond to their local environments. Spectrum sharing is barely addressed in many earlier SE studies because of technology limitations, but can now be implemented in field-deployed radio systems. The time is right to re-consider SE of many systems and to carefully examine new SE software tools and metrics that can take advantage of new technologies.

NTIA's Office of Spectrum Management (OSM) and Institute for Telecommunication Sciences (ITS) have been leaders in the field of SE studies for the last half-century. Their work has led, amongst other successes, to the implementation of:

- Trunked radio system use by many agencies

- SE factors as criteria for new agency radio systems

- Dynamic frequency selection (DFS) technology for spectrum sharing at 5 GHz.

We recommend that OSM and ITS should undertake further SE studies and SE metrics. This will permit the US to take advantage of the new opportunities for sharing that new technologies are making possible.

ACKNOWLEDGMENTS

A 53-YEAR HISTORY OF SPECTRUM EFFICIENCY STUDIES AND RECOMMENDED FUTURE DIRECTIONS

Frank H. Sanders, Kristen E. Davis, and Keith D. Gremban[1]

Spectrum is a limited resource upon which the world makes continually increasing demands. It is therefore natural and compelling to study the efficiency with which radio systems use spectrum. Spectrum efficiency studies reveal how future systems can make better use of radio spectrum, and allow spectrum engineers and managers to make better allocation and sharing decisions. This report provides a 53-year historical review of previous domestic and international spectrum efficiency studies. Based on this review, we recommend possible future spectrum efficiency work to extend the state of knowledge in this area.

1. INTRODUCTION

Radio spectrum is a limited but infinitely renewable resource that is available only in limited amounts of frequency bandwidth during any given time interval and within any given volume of space. Spectrum availability is always limited because, as we will explain in this report, every transmitter that radiates (and in many cases, every transmitter that has been given *administrative permission* to radiate) blocks some set of possible receivers from successful operation across some amount of frequency bandwidth, space, and time. Conversely (and this important point is often missed or neglected), *every receiver* that admits radio energy (or, again, has been given administrative permission to admit, e.g., radio astronomy receivers) *prevents some possible set of transmitters from operating*. The particular technical characteristics of transmitters and receivers, and of radio wave propagation in any given environment, determine the extent to which transmitters and receivers deny each other the use of spectrum in the frequency, space, and time domains. *This mutual cross-blocking of transmitters by receivers and receivers by transmitters is the cause of spectrum resource limitations.*

This report provides a 53-year historical review of previous domestic and international spectrum efficiency studies. Based on this review, we recommend possible future spectrum efficiency work to extend the state of knowledge in this area. To close, NTIA/ITS experts provide their insights on SE metric construction.

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Before we begin, let us set the stage by clarifying a few terms, introducing *spectrum utilization* and *spectrum efficiency metrics*, and presenting our vision for the future of spectrum efficiency.

1.1 Terminology

In this report, the term "frequency bandwidth" means a center frequency of a radio signal *combined with* the associated bandwidth of the same signal; the term denotes the quantities of frequency and bandwidth as a single entity or parameter. This term is obscure today but as we shall see it was historically developed for spectrum efficiency studies. It is still a useful term within the context of this field of study.

In the context of spectrum utilization discussions, blocking has historically been taken to be more administrative than physical in nature. That is, *computed blocking* based on radio propagation models has been considered to drive the availability of *assignments* that give operators legal permission to operate radio systems with specified characteristics at specified locations, and sometimes only for specified times (e.g., AM broadcast radio daytime-only assignments). As discussed in this report, however, modern dynamic spectrum access (DSA) based radio systems are beginning to make blocking a physically real characteristic between and among multiple radio systems that are sharing spectrum with each other in given areas and time periods.

As will be developed further in this report, the dimensions of frequency bandwidth, space, and time are only a shorthand description of the full set of spectrum utilization and efficiency parameters that are described by the *electrospace* concept of spectrum usage.

1.2 Spectrum Utilization and Spectrum Efficiency Metrics

Spectrum utilization is the *quantified extent* to which *useful information* is conveyed through transmitters and receivers via the use of frequency bandwidth, space and time. Spectrum utilization involves the use of transmitters and receivers which block or limit use of spectrum by other receivers and transmitters. Thus, any spectrum utilization inevitably causes some *quantifiable amount* of spectrum blocking.

Note that spectrum blocking is not interference. Spectrum blocking is built into rules to prevent interference from occurring. This concept is described further in Section 2.3.2. Because any spectrum utilization by any user blocks (i.e., denies or limits) spectrum utilization for other users, it is both obvious and compelling to study the extent to which spectrum could be more utilized by users in general by understanding the extent to which such blocking can be reduced. The *ratio* of the amount of useful information transferred through a radio link, system, or network to the *amount of blocking* caused by that same information transfer is the *spectrum use (or utilization) efficiency* (SUE) of that system or network. This ratio is also referred to as *spectrum efficiency* (SE). In this report, we will use the shorthand for this ratio, SE, where SE = (useful information transferred in a radio link)/(blocking of other radios by that link).

The numerator in the SE ratio can typically be computed in terms of binary digits (bits) transferred per unit time;[2] it is usually an absolute quantity. The blocking denominator, however, can be (as we shall see) computed in at least three ways:

1) In absolute terms as a comparison to a theoretical minimum blocking amount

2) As a comparison between the blocking of a real-world radio system and an arbitrary reference radio system

3) As a comparison of the blocking between two real-world radio systems

So blocking, and hence any overall SE ratio that includes the blocking term, can be either relative or absolute. But since SE ratios only make sense to the extent that they allow *comparisons* between similar systems or else between a given system and a theoretical construct (say, against a theoretical maximum SE), all SE results are in some sense always relative.

To put it another way, SE can in principle be an arbitrary number (say, 225) that is compared to another arbitrary number (1032). Such pairs of SEs can be compared as the ratio of their arbitrary values (here, 225/1032). Alternatively, every SE can be referenced to a theoretical limit that can itself be normalized to unity; in this case all SEs would always be valued between 0 and 1. But even both cases SE values will ultimately be compared between systems. SEs, even when stated in absolute terms, are always *effectively* relative because comparisons must always be made between pairs of them.

SE is a numerical quantification; it is a *metric*. In this report we propose constructions for this metric based on the possible characteristics of radio systems. Once delivered, SE metrics are to be used over the course of possible future work.

1.3 Future Goals and Objectives

Having defined our terms, let us state the problem to be addressed in possible future SE work:

- Take into account the results of past and present SE studies and recommendations

- Consider currently available and likely near-future radio technologies that might affect the SE of radio systems (including the potential of some systems for spectrum sharing)

- Develop an approach for determining the SE of any given radio system, so that the relative SE metrics of any two similar radio systems can be compared to each other

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[2] This quantity can be adapted to radar systems by considering the information-equivalent value of their space searches per unit time. For example, all empty cubic meters found in each scan are considered to be zeros and all occupied cubic meters are set to ones.

By similar, we mean the same type of data transmitted and received on the same type of radio link. For example, digital data sent and received on a point-to-point microwave link should only be compared to other data sent on other microwave links.

SE metrics should be realistic, understandable by non-specialists, and implementable for applicable radio systems and band efficiency studies. Implementations might include software tools.

Possible future SE work may include the development of SE metrics for a variety of radio services. That work would not include the economics of implementing various SE approaches, and their impacts on mission effectiveness (how well or how efficiently a radio system works).

SE metrics should be developed in forms that allow application to specific types of radio systems and services. These metrics need to be acceptable to Federal government agencies for all types of radio systems and band uses that might be addressed. Stakeholders include Federal and non-Federal spectrum managers, engineers, and procurement personnel. SE metrics and criteria will help procurement personnel select better radio systems for their agencies. The SE metrics should be sufficiently detailed to be of use in comparing similar types of radio systems and band usage to each other, while being simple enough to be applied by stakeholders.

Any SE-metrical analyses should be consider SE-related information from other stakeholder Federal agencies. This information would include the technical characteristics and requirements of those agencies' relevant spectrum systems.

2. HISTORICAL REVIEW OF SPECTRUM EFFICIENCY STUDIES

This section presents a 53-year historical review of previous domestic and international spectrum efficiency studies. We begin with a table that sets up a linear chronology of SE studies. We then switch to prose and do not follow a purely linear timeline. Section 2.2 establishes the technical-historical context. Sections 2.3 and 2.4 dive into a dissection of different technical approaches, and how each relates to prior work or sets the stage for following work. We close in Section 2.5 by summarizing the results of these SE studies and presenting the most important lessons that we have drawn from them.

2.1 Spectrum Efficiency and Related Studies Documents Summary

Table 1 lists the 35 SE studies that are described in this report. This list, although not exhaustive of the available SE literature, shows both the earliest published studies and some of the most significant studies in the field to date. In this table, we establish a linear chronology of SE studies, identify the significant SE researchers, and acknowledge the organizations that sponsored this research. We summarize each publication with a minimum of technical detail and minimal references to other work.

Sections 2.2 through 2.4 expand upon Table 1 to provide the full historical context. In other words, the Table 1 "Brief Summary" column is a condensed and less thought-provoking version of the subsequent prose. This redundancy is intended to allow someone to see 53 years of spectrum efficiency studies at a glance. Table 1 also serves as a quick reference, to hasten literature searches. We recommend that readers at least familiarize themselves with the chronology of events and the sponsoring organizations before proceeding to Section 2.2.

Table 1. SE and SE-Related Studies Addressed in this Report

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Joint Technical Advisory Committee of the IEEE[3] (JTAC)	"Radio Spectrum Utilization" [1]	1964	One of the earliest referenceable documents addressing the topic of SE. Identifies frequency, bandwidth, and physical space as fundamental dimensions of spectrum-space utilization.
Gifford (General Electric)	"EMC Revisited— 1966" [2]	1966	Another early referenceable document in which parameters of frequency, bandwidth, space, and time are explicitly identified as components of spectrum utilization and as parameters for possible future SE metrics. PODAF is introduced to describe a parameter combination of POwer flux Density over Area within a Frequency bandwidth for spectrum utilization.

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[3] Institute of Electrical and Electronics Engineers

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Cohn, et al (JTAC)	"Spectrum Engineering: The Key to Progress" [3]	1968	Proposes the concept of *denial of spectrum to other users* as a core concept in SE considerations. Discusses SE as an explicit metric to be somehow computed. Proposes general forms for SE metrics. Recognizes explicitly that receivers as well as transmitters cause spectrum blocking.
Hinchman (Office of Telecommunications Policy Division, Institute for Telecommunication Sciences (OTP/ITS))	"Use and Management of Electrospace: A New Concept of the Radio Resource" [4]	1969	Introduces the electrospace concept for potentially computing SE metrics. Partitions radio signals into an eight-dimensional matrix of three occupied spatial dimensions plus frequency, time, power, polarization, and direction of propagation. Expands the PODAF parameters; Ewing and Berry [7] and Berry [11] later make use of this work.
Rostow (ed.) for (President's Task Force on Communications Policy)	"The Use and Management of the Electromagnetic Spectrum" [5]	1969	Identifies spectrum "wastelands" which exist because frequency managers implicitly grant reception rights to receivers by rejecting applications for transmitters that would interfere with them. First known acknowledgement of receiver blocking as a spectrum utilization factor in a policy document.
Vinogradov (Moscow Electrical Engineering Institute of Communications)	"A Criterion for Estimating the Efficiency of Radio Frequency Spectrum Utilization" [6]	1973	The work has unique structure and development relative to all other citations in this table; it appears to have been developed independently of other works cited here. Proposes a 14 parameter SE metric that is fundamentally the ratio of useful data throughput to amount of electrospace occupied by any radio link. Seems to be the first instance of an SE parameter that considers blocking (or not) based on signal modulation.
Ewing and Berry (OT/ITS)	"Metrics for Spectrum-Space Usage" [7]	1973	Arguably the most significant single document in the early SE literature. This is the first U.S. government publication to propose explicit SE metrics as its primary topic. Cites practical objections to the use of "ideal" systems for SE metrics. Proposes three SE metrics, which include transmitter and receiver characteristics and antenna radiation patterns.
Colavito (Società Italiana per l'Esercizio Telefonica)	"On the Efficiency of the Radio Spectrum Utilization in Fixed and Mobile Communication Systems" [8]	1974	First attempt to apply an SE metric to the laydown designs of land mobile radio (LMR) and fixed service (point-to-point microwave) radio systems. Develops his own metric without reference to other works cited in this table. Proposed SE metric uses ratio of characteristics of an idealized radio system to the actual values of an existing system. Discusses possible future extension of his work to the benefits of smaller LMR base station coverage areas (cells).
Hatfield Office of Telecommunications Policy (NTIA/OTP) (1975); Office of Telecommunications (NTIA/OT) (1977)	"Measures of Spectral Efficiency in Land Mobile Radio" [9] and [10]	1975 and 1977	Proposes the use of data erlangs per unit time per unit bandwidth per unit area as an SE metric for LMR systems. This version of an SE metric is much simpler than other metrics in the literature and is easier to actually compute and use. Discusses some of the subtleties of determining actual data rates and true occupied bandwidths for LMR systems. Concludes that smaller LMR cells are much more spectrally efficient than larger cells.

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Berry (NTIA/ITS)	"Spectrum Metrics and Spectrum Efficiency: Proposed Definitions" [11]	1977	An expanded and more formal version of Berry [7]. The same three metrics are described, again with pros and cons presented for each. Argues for metrics that are not necessarily technically perfect but which are good enough for spectrum managers and engineers to use to compare systems, suggesting that in being simplified they have a better chance of being used by non-specialists. Argues against using idealized systems as metric references. Proposes the development of specialized metrics for specific services such as broadcasting, fixed (point to point), and radar.
Berry and Haakinson (NTIA/ITS) Sponsored by Federal Communications Commission (FCC)	"Spectrum Efficiency for Multiple Independent Spread-Spectrum Land Mobile Radio Systems" [12]	1978	Compares the SE of wideband, time-division multiple access (TDMA) spread spectrum (SS) LMR systems to conventional narrowband LMR. Shows less SE for SS modulation than for conventional frequency modulation (FM). Proposes *overlaying* SS systems on conventional LMR bands to improve the overall SE—an early example of improving SE through spectrum sharing. Demonstrates the substantial complexity that occurs when all the subtleties of real radio systems have to be taken into account for realistic SE determinations.
Moreno Centro Studi e Laboratori Telecomunicazioni S.p.A. (CSELT)	"Spectrum Utilization in a Digital Radio-Relay Network" [13]	1982	Uses general expressions for SE to examine the SE of a specific type of radio system. Describes a methodology for evaluating the amount of radio spectrum used by a node in a broadband radio communication network, on the basis of general criteria and definitions for spectrum use and efficiency. Concludes that SE is highly dependent on the modulation technique for the radio system, and that much work is required to transform general SE expressions into SE formulas for specific radio system.
Cronin and Berry (NTIA/ITS)	"The Effect of Bandwidth and Interference Rejection on the Spectrum Efficiency of Land Mobile Radio Systems" [14]	1983	Compares the relative spectrum efficiency of two generic (wideband and narrowband) LMR systems. In most cases the narrowband systems use less spectrum than the wideband systems even though the narrowband systems require greater protection from cochannel interference. This paper demonstrates again the extent to which general-purpose SE expressions have to be modified before they can be applied to particular types of radio systems.
Consultative Committee International Radio (CCIR)	CCIR Report 662-2, "Definition of Spectrum Use and Efficiency" [15]	1986	This is the first internationally agreed upon definition for spectrum use and efficiency. CCIR sets forth a basic SE metric that is the ratio of "useful result obtained from the radio equipment" to the product of bandwidth, space, and time. The general expression is modified for specific application to various kinds of point-to-point microwave networks.

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Cohn Sachs/Freeman Associates (SFA) under contract with the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC)	"Methodology for Determining Spectrum Efficiency" [16]	1986	Expands the SE concept to the overall efficiency of entire radio bands. The recommended SE metrics still look the same as before: throughput divided by the product of denied bandwidth, space, and time. The only new feature is that the SEs are to be computed relative to an idealized reference radio system. The concept is to compare SEs of one service to those of another service via a single dimensionless number between 0 and 1 computed for each service.
Berry, Chang, Frazier, Levy and Sussman (NTIA/ITS and NTIA/OSM)	"Application of the Technical Spectrum Efficiency Factor (TSEF) to the Fixed Service in Three Frequency Bands" [17]	1986	Describes NTIA work toward SE metric tools (software). Applies an absolute SE coefficient to the fixed service in the frequency range of 947 MHz to 40 GHz. Provides SE term definitions; a general formula for a technical spectrum efficiency factor (TSEF) that evaluates fixed-service SE in the given spectrum range; a computer model; and analyses of three government fixed radio systems in the range of 7.1 to 8.5 GHz.
Mayher, et al (NTIA/OSM) and NTIA/ITS)	"The SUM Data Base: A New Measure of Spectrum Use" [18]	1988	Describes a new tool developed by NTIA for analyzing SE of services, as referenced in Cohn [16]. The report describes a new Spectrum Use Measure (SUM) data base which joins the technical properties of radio spectrum to geography. This allows for the quantification, measurement, and graphic display of how the nation's spectrum resource was being utilized.
Hinkle and Farrar (NTIA/OSM)	"Spectrum Conservation Techniques for Fixed Microwave Systems" [19]	1989	Identifies SE techniques for the fixed service (point-to-point microwave links). Develops a reference microwave system for use in SE metrics. Concludes that the entire complement of all system characteristics must be taken into account (e.g., antennas, RF filters, IF filters, spurious emission levels). Only by taking all such factors into account can the true blocking in bandwidth, space, and time be determined. This requires SE metrics that are carefully crafted on a system-by-system basis.
CCIR	CCIR Report 662-3, "Definition of Spectrum Use and Efficiency" [20]	1990	An updated version of previous CCIR Report 662-2 [15]. Definitions remain essentially unchanged.
Cohen, et al (NTIA/OSM and NTIA/ITS)	"Land Mobile Spectrum Efficiency: A Plan for Federal Government Agencies to Use More Spectrum-Efficient Technologies" [21]	1993	Analyzes Federal LMR infrastructure with respect to SE and cost effectiveness. Summarizes Federal LMR requirements and techniques. Explains and quantifies the benefits of rechannelization, trunking, and other technical methods to improve spectrum utilization. Recommends methods to introduce cost effectiveness. This report is important because it encourages Federal agencies to achieve more efficient spectrum use on an entire service basis rather than just a radio system-by-system basis.

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Matheson (NTIA/ITS)	"A Survey of Relative Spectrum Efficiency of Mobile Voice Communication Systems" [22]	1994	Uses simplified SE definitions to compare the SEs of several mobile radio systems. Compares analog FM dispatch radio to a variety of contemporary systems and near-term deployments. The calculations show a ratio of 1:1 million between the most efficient and least efficient of the systems considered. Demonstrates how to compare and optimize SE for an entire class of systems that all provide the same basic service.
International Telecommunications Union, Radiocommunication Sector (ITU-R)	ITU-R Rec. SM.1046-2: "Definition of Spectrum Use and Efficiency of a Radio System" [23]	2006	This ITU-R Recommendation provides internationally agreed upon SE terms and definitions. It discusses not just how to use SE metrics, but how to *not* use SE metrics. For example, comparisons of SE should be performed only between similar types of radio systems providing similar radiocommunication services.
Joiner, et al (NTIA/OSM)	"Assessment of Federal and Non-Federal Land Mobile Radio Frequency Assignment Methodologies" [24]	2007	Describes how the frequency assignment process influences spectrum efficiency in Federal LMR spectrum bands.
Cai, et al (NTIA/OSM and NTIA/ITS)	"Assessment of Alternative Future Federal Land Mobile Radio Systems" [25]	2008	Evaluates the efficiency of Federal spectrum use in a congested band (162–174 MHz) and area (Washington, DC). This report compares spectrum resources used by several alternative LMR system architectures employing trunked radio technology to the spectrum resources used by conventional LMR systems.
ITU-R	ITU-R Rep. M.2134: "Requirements Related to Technical Performance for IMT-Advanced Radio Interfaces" [26]	2008	Applies SE metrics to International Mobile Telecommunications (IMT) Advanced radio systems, which are also known as 4G and 4.5G. This report uses an SE metric that is the ratio of all data running through all cells in a network to the product of the network's time, channel bandwidth, and physical cell blocking.
Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 1 (WG-1)	"Definitions of Efficiency in Spectrum Use" [27]	2008	Applies the ITU-R SM.1046-2 SE metric [23] to broadcasting, personal communications systems (PCS), point-to-point, radar, satellite systems, "passive listeners," short range systems such as Wi-Fi (IEEE 802.11) and cognitive systems. Expands upon the conclusion that only similar systems should be compared for SE.
FCC	"Spectrum Efficiency Metrics" [28]	2011	Studies two broad classes of systems (satellite and terrestrial). Proposes SE metrics for six sub-classes (satellite broadcast systems, point-to-point satellite systems, terrestrial broadcast systems, terrestrial personal communication systems, terrestrial point-to-point systems, and terrestrial hybrid systems). Discusses the challenges associated with the development and usage of SE metrics. Provides sample calculations.

Author(s) and Sponsoring Organization	Title	Year	Brief Summary
Rysavy (Rysavy Research)	"Challenges and Considerations in Defining Spectrum Efficiency" [29]	2014	Analyzes CSMAC, FCC, and ITU-R documents to provide a broad survey of contemporary SE metrics calculations and assessments for various types of radio systems. Discusses the concept of peak versus average SE. Spectrum sharing is addressed in the context of SE studies.
ITU-R	ITU-R Rec. 2083–0: IMT Vision: "Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond" [30]	2015	This Recommendation addresses the SE of future IMT communication systems. ITU-R Rec. 2083-0 contains no new material on SE metrics, which are to be computed on the basis of data throughput per cell. The SE problem is only noted as a rote calculation in this document.
NTIA/OSM	"Manual of Regulations and Procedures for Federal Radio Frequency Management" [31]	2015	This manual, colloquially known as the "NTIA Red Book" contains numerous technical regulatory requirements for Federal radio systems. These requirements for transmitters, and receivers (including antennas) are intended to reduce spectrum blocking and thereby improve and promote SE for all Federal radio systems. A prime example is the Radar Spectrum Engineering Criteria (RSEC) that require radar transmitters and receivers to meet numerous criteria to reduce their blocking of other spectrum systems, and hence improve their SE characteristics.
NTIA/OSM	"Quantitative Assessments of Spectrum Usage" [32]	2016	Provides quantitative assessments of existing use of 960 megahertz of spectrum in five bands between 1300 MHz and 3550 MHz. The assessments are presented as an intermediate step for potential future sharing and repurposing of the subject bands. The report does not directly address the topic of SE but does identify spectrum sharing as a method for improving SE.
International Telecommunications Union, Radiocommunication Sector (ITU-R)	ITU-R Rec. SM.1046-3: "Definition of Spectrum Use and Efficiency of a Radio System" [33]	2017	An updated version of previous ITU-R Rec. SM.1046-2 [23].
ITU-R	ITU-R Report M.2410-0: "Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interface(s)" [34]	2017	This ITU-R Report calls out, in detail and at length, specific approaches and procedures for calculating SE metrics (both peak and average SE) for future IMT-2020 radios.

2.2 Technical-Historical Prologue to Spectrum Efficiency Studies

This discussion is provided in the same sequence as the chronological development of SE-related literature. We follow this chronology because SE studies have themselves evolved and following this progression is an excellent way to understand the current state of SE studies and metrics. As shown in the examination below, there is little or no controversy regarding the general form of SE metrics for the terrestrial broadcasting, mobile, and fixed services. But considerable difficulties seem to invariably appear in the application of such generalized SE metrics to specific applications, particular radio systems and services.

In a half-century of SE studies, no one-size-fits-all SE implementation has been found. Indeed, as described below, many of those researchers have concluded that no single-fit SE metric will ever be found. SE metrics are easier to write down as simple equations than they are to apply to radio systems and services with messy individual idiosyncrasies. An example is the need to calculate the percentage of users per unit time and area who are receiving acceptable-level service. With that said, many radio systems have nevertheless been successfully analyzed for SE, with sometimes counterintuitive results. All SE studies seek to compare one radio system to another—and only similar radio systems at that. Unlike systems seem to not be compared in the literature, for reasons that will be discussed below. Some of the literature in fact specifically warns against comparing unlike systems for SE as an illogical exercise. And, as we shall also see, lacunae exist for SE metrics that might be applied to most services other than (stated most broadly) broadcasting, mobile, and fixed.

With this background, we begin the examination of SE metric development and application. The first radio regulatory law in the U.S., the Radio Act of 1912, was spurred by the Titanic disaster. The Titanic's radio had been installed primarily to allow passengers to send personal messages and conduct stock market transactions. During the sinking, the ship's two radio operators stayed at their stations transmitting calls for assistance until the radio room went underwater. Their calls were received by a number of ships that were too far away to reach the scene until the next morning. There was a nearer ship that was just beyond visual range of the Titanic and which could have reached the scene of the sinking soon enough to rescue survivors who were dying in the frigid water. But its radio had been shut down for the night before Titanic's distress calls began to be sent. Consequently it did not respond when a timely arrival might have saved numerous lives. The Radio Act was inspired when this fact was publicized by Congressional hearings on the tragedy. The Radio Act created a requirement, still in force with the International Maritime Organization, that ships at sea must maintain 24-hour radio coverage.

The Radio Act of 1912 was signed into law four months after the sinking, in August of that year. This Act required commercially operated radio stations to obtain licenses of operation from what was then the Department of Commerce and Labor. The Radio Act of 1912 established some technical requirements including specifications for station frequencies (which were not allowed to go above 1.495 MHz). It included what would now be read as an SE requirement: "In all circumstances, except in case of signals or radiograms relating to vessels in distress, all stations

shall use the minimum amount of energy necessary to carry out any communication desired."[4] An exception to this SE requirement was made for vessels in distress, which were directed as follows: "When sending distress signals, the transmitter of a station on shipboard may be tuned in such a manner as to create a maximum of interference with a maximum of radiation."[5] This was regulatory use of non-efficiency to maximize the reception of distress calls.

The Radio Act of 1927 superseded the Radio Act of 1912. It removed most radio regulatory control from the Department of Commerce[6] and created the Federal Radio Commission (FRC) to regulate radio use instead. The modern era of radio regulation began with the Communications Act of 1934 which superseded the 1927 Act and transferred most radio regulatory authority to the successor of the FRC, the Federal Communications Commission (FCC).

Prior to the 1934 creation of the FCC, broadcasters competed for listeners by engaging in "power wars" [7, pg. 6] in which they continually increased their transmitters' radiated power levels. In doing so, they gained listeners for themselves while blocking other stations from reaching the same listeners. Since the amount of blocking is inversely proportional to SE (as described below), the pre-regulation broadcasters were in fact serving their own interests in reaching more listeners by reducing their radio systems' SE. This was especially true at night when signals in the amplitude modulated (AM) radio broadcasting band at about 1 MHz propagated (as they still do) across continental distances.

While reduction in SE by boosting transmitter power was in the interest of individual AM broadcasters, it was not in the overall national interest that the radio resource should be used that way; the broadcasting "power wars" of the 1920s and 1930s led to the 1934 establishment of modern, comprehensive government regulation of the radio spectrum by the FCC to "end the chaos" [7, pg. 6]. Seen from the perspective of our own time, after a half-century of subsequent SE engineering discussions and studies, a motivating factor in the establishment of the FCC was the need to arrest declining SE in AM broadcasting so that the nation's radio resource could be better utilized.[7]

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[4] Sixty-Second Congress, Session II, Chapter 287, "An Act to Regulate Radio Communication," Regulation XIV. http://legisworks.org/sal/37/stats/STATUTE-37-Pg302b.pdf. The Act also required large ships to maintain radio operators on duty at all times, and to henceforth use the then-new SOS call for distress signals.

[5] Ibid, Regulation VII.

[6] The Commerce Department retained the independent Interdepartment Advisory Committee on Radio Broadcasting, which was later renamed the Interdepartment Radio Advisory Committee (IRAC). This committee was established in 1922 to provide a cooperative method for Federal agencies to resolve spectrum use issues amongst themselves. The IRAC is today the longest-standing Federal committee; it celebrated its 2000th meeting in May 2017.

[7] Even in recent years the broadcasting service has continued to impel efficiency innovations through the 700 MHz auction and by making use of so-called white space between broadcast channels. The 2017 Incentive Auction is another example of repurposing television broadcasting spectrum to higher-valued use.

2.3 Early Spectrum Efficiency Studies

2.3.1 Laying the Groundwork for Dedicated Spectrum Efficiency Studies

Although SE was addressed intuitively as a regulatory issue beginning in the 1930s, it was not until the 1960s that engineers began to explicitly concern themselves with radio spectrum occupancy in terms of quantifiable metrics for utilization and efficiency. As shown in Table 1, the earliest published SE-related material dates from the mid-1960s. The first documents in this study area did not discuss SE per se. Rather, the first reports, those of JTAC in 1964 [1] and Gifford in 1966 [2], discuss metrics for spectrum utilization without discussing the efficiency of that utilization. Both of these documents identify frequency bandwidth, space, and time as the fundamental elements of spectrum utilization—a contribution that has stood the test time, as these parameters are still regarded as keystones of SE metrics today. In [2], a somewhat more sophisticated metric is introduced, the power flux density over an area within a frequency bandwidth (PODAF). The acronym never caught on but the concept has survived.

The next significant report addressing this topic, by Cohn in 1968 [3], moves a significant step forward by considering SE as a metric to be determined, and by further proposing that *denial of spectrum to other users* should be at the core of the SE concept. For the first time, spectrum efficiency is identified as an explicit metric to be somehow computed. SE is proposed to be the ratio of spectrum space used by an ideal system to the spectrum space used by a system that is to be evaluated. The "spectrum space" in this metric is defined to be product of the amount of bandwidth, time, and physical volume that a radio system denies to others. This document recognizes explicitly that receivers as well as transmitters cause spectrum blocking. In the early and mid-1970s, Ewing and Berry [7] build their work on this foundation.

In 1969Hinchman [4] introduces the electrospace concept for potentially computing, quantitatively, the use of radio spectrum. Hinchman proposes to partition radio signals into an eight-dimensional matrix of three spatial dimensions plus frequency, time, power, polarization, and direction of propagation. He never uses the word "efficiency," but he does explain that much what he calls the "radio resource" goes unused not because of actual blocking but because of weaknesses in the systems by which radio assignments are provided, resulting in overly conservative estimates of the amount of blocking that *could* occur if any given assignment were used. He expands the PODAF parameters and says that the resource could be better used if a full accounting were made of the actual transmitter and receiver occupancy of electrospace. Ewing and Berry [7] and Berry [11] later make use of this work, and his expanded set of parameters are still used in SE studies and analyses.

In the same year Hinchman published, the government released a policy document [5] (with no endorsement from the White House [35], [36]). This policy document contained recommendations for future radio spectrum management. The document obliquely addresses SE, identifying spectrum "wastelands" which exist because frequency managers implicitly grant reception rights to receivers by rejecting applications for transmitters that would interfere with them. This is the first known acknowledgement in a policy document of receiver blocking as a spectrum utilization factor. Although this document's recommendations were never acted upon,

Congress would in later years explicitly (and repeatedly) request that both FCC and NTIA study SE for existing and future systems.

2.3.2 First Dedicated Spectrum Efficiency Studies

Four years later, in 1973, a pair of important SE papers were published independently of each other and with no apparent knowledge by the respective authors of each other's work. The first of these was by Vinogradov [6]. Citing no references (implying work in somewhat of a vacuum), and with an independent development, he proposes a 14-parameter SE metric. This metric is fundamentally the ratio of useful data throughput to the amount of electrospace occupied by any radio link. Vinogradov's electrospace parameters are somewhat unique for that time, including, e.g., the lengths of radio links and their modulations. His proposal seems to be the first instance where blocking (or not) based on signal modulation is considered as an SE parameter. The technical "quality" of transmitters and receivers and their antennas is also included in this metric, similar to Berry's later discussion of the same. This work is later cited along with Ewing and Berry 1973 [7], Berry 1977 [11] and Colavito 1974 [8] as a reference in the development of the first CCIR SE definition.

The other important paper of 1973, Ewing and Berry [7], is the first U.S. government publication proposing explicit metrics for SE as its primary subject; as such, it may have had greater impact on the field in the U.S. than Vinogradov's work. It builds on and significantly extends earlier work by Gifford 1966 [2], Cohn 1968 [3], Hinchman 1969 [4], and others. This is arguably the most important paper to that date and still one of the more fundamental and important papers in the field. Firstly this is because Ewing and Berry precisely and explicitly call out transmitter and receiver blocking (Figure 1) as being the foundation of spectrum use limitation and they show that the two classes of equipment have equal impact.

Secondly, they go on to actually build three possible metrics and present pros and cons for each. For each of the metrics, they develop mathematical measures for the spectrum spaces used (blocked) by transmitters and receivers, designated M_T and M_R, respectively. All three of the metrics are fundamentally based on blocking of frequency bandwidth, time, and space, and include transmitter and receiver characteristics and antenna radiation patterns. All subsequent metrics in the SE field have been in one way or another outgrowths of these metrics, so they are worth consideration. The following three metric descriptions are paraphrased from [7].

The first metric, "*situation specific denial*," evaluates competition for space among existing systems. *Situation specific denial* is the volume of spectrum space that a system denies to competing systems. The authors develop a detailed set of equations and provide a method for computing the *situation specific denial* between any given set of receivers and transmitters. This metric computes the exact interaction between any two exactly specified real-world radio systems. Its value varies with time, as variations inevitably occur in the operation of all transmitters and receivers. In the words of the authors, its value is "not persistent." They find this feature to be undesirable for a spectrum metric. They point out, however, that this metric has the advantage of being realistic in terms of potential interference between any two existing systems: it accurately computes the product of bandwidth, area, and time denied by any one radio system to competing radio systems. But it is time-variable between any two particular systems and
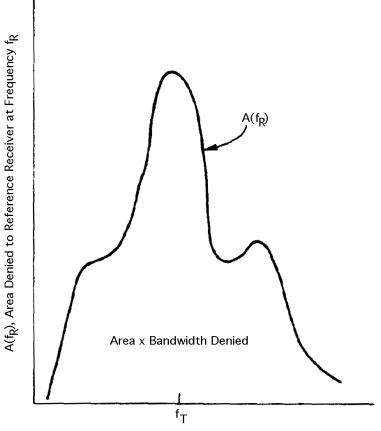
14

moreover its value changes with the introduction of new systems that are more or less susceptible to interference than the original system that was evaluated. As the authors go on to point out, this metric may lack rigor because the values computed might depend on the completeness of particular knowledge of competing systems. A related problem is that the value of the metric may be dominated by a single system that might be unimportant or rare.

The second metric, "*uniform denial,*" uses an idealized reference system as a benchmark. *Uniform denial* is the volume of the spectrum space denied by a transmitter or receiver to an *idealized reference* receiver (or transmitter). Once the reference is chosen, this measure depends only on the characteristics of a particular station that is being evaluated. The uniform metric eliminates some of the shortcomings of the *situation specific denial* metric by substituting reference receivers and transmitters for actual competing systems. It is therefore thought by the authors to be more objective and time-invariant. The main objection to this metric, they state, is the apparent arbitrariness of the specifications of some parameters of the putative reference systems. Idealized reference systems, they comment, can seem unrealistic considering the wide range of systems in use in some regions of the spectrum-space.

The third metric, "*autonomous denial,*" depends only on characteristics of the transmitters and receivers of the system being considered. The two previous metrics depend on knowing or computing the transmission loss between stations. Transmission loss can only generally be known statistically; it varies with terrain, climate, geography, and so forth. The *autonomous denial* metric avoids this problem because it does not use transmission loss between stations. Its values depend only on the characteristics of radio stations (receivers or transmitters) which are denying spectrum, time, and space to others.

For the *autonomous denial* metric, M_T and M_R are given as normalized values that only depend on characteristics of the transmitter and receiver equipment. They derive $M_T = (\tau \cdot P) \cdot \sqrt{g_T}$, where P is transmitter power in a bandwidth, τ is time blocked and g_T is maximum transmitter antenna gain. Similarly, for receivers the derived measure is $M_R = (\tau/Q)/\sqrt{g_R}$ where Q is the receiver selectivity (inversely analogous to transmitter power) and g_R is maximum receiver antenna gain.

The most important aspects of this metric are the emission and admission characteristics of the transmitters and receivers being considered. Such a simple measure is especially appealing, the authors comment, if it is proportional to the amount of spectrum space denied. *Autonomous denial* is claimed to be objective and time-invariant while requiring no arbitrary reference standards. Nor, the authors say, does transmission loss need to be known to compute it. Moreover, it is supposed to be proportional to spectrum-space denied for the important special case when transmission loss is approximately that of free space and only two spatial dimensions are considered, as is the case for many spectrum blocking scenarios.

Figure 1. Blocking of a receiver by a transmitter, Figure 6 from [7]. Transmitters are shown to be analogously blocked by receivers.

When defining *autonomous denial*, the authors take transmitter use to be directly proportional to emission power spectral density; the more energy radiated, the more the radio resource is used (blocked). Receiver use is taken to be inversely proportional to the protection power spectral density. For a receiver, the larger the protection power spectral density, the less the receiver is "protected," hence the amount of spectrum used (blocked) is less.

Autonomous denial has the advantage of being defined for individual transmitters and receivers, but there is the possibility that a system will have multiple receivers or transmitters whose blocked spectrum spaces happen to overlap. In that case, the sum of the metrics for several overlapping stations will *not* be proportional to the total space denied. The solution to the overlap problem for this generalized metric is not obvious, the authors state, since they do not deal directly with space denied anywhere in their calculations. So, despite the appealing simplicity of the metric, and its independence from arbitrary choices such as idealized reference stations, the authors state that they "cannot recommend it at this time." They found it impractical or impossible to generally know or compute the overlaps between station coverages at the time of publication (1973). (This is a problem that was to some extent solved in later decades, when more computational power became available. For example, expanded computing power was used

to minimize coverage overlaps of newly established digital television broadcasting stations at the turn of the 21st century.)

Ewing and Berry's 1973 paper [7], along with Vinogradov's study [6], mark the first dedicated effort to determine spectrum use metrics and lay the foundation for all subsequent work in the field of SE. The next year, Colavito [8] made the first published application of an SE metric to the laydown designs of land mobile radio (LMR) and fixed service (point-to-point microwave) radio systems. Colavito presents his own metric without reference to other works cited in Table 1. His proposed SE metric uses the ratio of the characteristics of an idealized radio system to the values of an existing system. Parameters used in his SE metric are occupied bandwidth, space, and time, consistent with the parameters of earlier studies. He uses antenna radiation patterns to help evaluate blocking (or not) of the subject radio systems. He discusses possible future extension of his work to space communication services. Based on application of his SE metric, Colavito argues for the use of small(er) LMR base station coverage areas (cells) to shrink frequency re-use distances in crowded areas and improve SE for such systems in general.

Hatfield [9] and [10] in 1975 and 1977 proposes the use of voice communication data (erlangs) per unit time per unit bandwidth per unit area as an SE metric for LMR systems. His version of an SE metric is much simpler than other metrics in the literature, but is arguably easier to actually compute and use. Hatfield discusses at length some of the subtleties of determining true data rates and true occupied bandwidths for LMR systems (as opposed to theoretical or specified data rates and occupancy bandwidths). Like Colavito [8], Hatfield concludes that smaller LMR cells are at least ten times more spectrally efficient than larger cells.[8] This work was published twice, once as a conference paper and then again as an IEEE paper, in 1975 and 1977.

In 1977, Berry published a more formal development and presentation of his 1973 work with Ewing. This article [11] proposes the same three metrics as in [7], again with pros and cons presented for each. Berry argues for practical metrics that are not necessarily technically perfect but which are good enough for spectrum managers and engineers to use to compare radio systems, suggesting that in being simplified they have a better chance of being used and understood by non-specialists. This is consistent with the approach of Colavito [8] and Hatfield [9], [10]. Berry suggests that the generalized metrics that he is proposing can be modified into a set of specialized metrics that can be applied individually to services including broadcasting, fixed (point to point), and radar.

Berry argues against using idealized systems as SE metric references, because idealized radios are more difficult to implement theoretically while offering no operational advantages over other approaches in which like radios are compared to like radios with nothing idealized. This argument could be phrased as: if one computes (a/r) and (b/r), where "r" is the reference quantity, this is the same as knowing and computing a/b straightaway without the need to have brought some arbitrary reference quantity "r" into the computations in the first place. One could counter-argue that it might be useful to know the individual reference ratios for academic

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[8] Reducing cell size is not, however, a degree of freedom that Federal agencies ordinarily have when they deploy LMR systems. They use their LMR networks to maximize coverage with a strictly limited amount of infrastructure (e.g., a limited number of base stations).

purposes, but lacking the existence of any actual system "*r,*" what exactly is the point of knowing how any quantity compares directly to "*r*"?[9]

2.3.3 Earliest Applications of Spectrum Efficiency Metrics

The next year, Berry and Haakinson [12] compare the computed SE of wideband, time-division multiple access (TDMA) spread spectrum (SS) LMR systems to conventional narrowband LMR. This is an applied SE study that has a much different flavor than the earlier papers by Ewing and Berry [7]. It is more like Colavito [8]. This may be because, as we shall see for every other applied SE study, the actual computation of the SE of any given system seems to inevitably involve special tailoring to take into account the particular idiosyncrasies of every particular radio system. Running the "near-far" problem through repeated computer simulations, Berry and Haakinson show less SE for SS modulation than for conventional frequency modulation (FM).[10] This is partly due to the fact that the SS systems have to use separate frequencies for uplinks and downlinks. (The putative SE advantage of the SS systems is processing gain. But the SE metrical value is shown to be inversely proportional to the cube root of the processing gain—not enough, as it turns out, to be an improvement on the SE of conventional LMR systems.) However, the authors comment that *overlaying* SS systems on conventional LMR bands could be feasible and could show total overall improvement in SE through such sharing. Berry and Haakinson [12] calculate that such systems could share spectrum without interfering with each other, if properly deployed.

This is a remarkable early example of improvement in SE through spectrum sharing. It is casually presented at the end of the paper with very little comment, and there seems to be no indication that anyone pursued their suggestion—an example of an idea that was so far ahead of its time that it went nowhere. Overall, this paper demonstrates the substantial complexity that occurs when all the subtleties of real radio systems have to be taken into account for realistic SE determinations (including, e.g., calculations of percentages of time that adequate service is available with adequate reliability to particular numbers of users).

Four years later, Moreno [13] provides another study in which general SE expressions are used to examine and potentially improve the SE of a specific type of terrestrial mobile radio system. He describes a methodology for evaluating the amount of radio spectrum used by a node in a broadband radio communication network, on the basis of general criteria and definitions for spectrum use and efficiency. Moreno draws on earlier work by JTAC [1], Vinogradov [6], Ewing and Berry [7], and Berry [11] for his fundamental assumptions and basic SE expressions.

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[9] Paraphrasing and expanding on remarks by Berry, the fuel efficiency of any given automobile could in principle be compared to the best possible dimensionless efficiency, ε, of a theoretically optimal heat engine, where $0 < \varepsilon < 1$. But since practically no consumers know thermodynamic theory (just as, Berry notes, practically no radio regulators or consumers will ever know anything about SE metrical theory), and since in the end all consumers must needs compare one available automobile model to another existing model, why compare actual automobile efficiencies to theoretical ε when each model can be compared directly to every other model without inserting the needless intermediate step of comparison to a non-existent, theoretically "perfect" model?

[10] Note, too, that SS systems can use modulations (e.g., code division multiple access (CDMA) and frequency hopping) to accommodate more users.

Moreno shows that SE is highly dependent on modulation technique for the type of radio system he examines, which is a novel observation in the field at that time. Moreno echoes the comment made by Berry and Haakinson [12] that for systems using different modulations much work is required to transform relatively simple and seemingly straightforward general SE expressions into specific SE formulations that can be applied to compare particular types of radio systems to each other. This is a recurring theme in SE studies: *it is far easier to sketch a metric than it is to apply it to any real radio system.*

In the next year, 1983, Berry and Cronin [14] compare the relative spectrum efficiencies of two generic (wideband and narrowband) LMR systems. In this analysis, spectrum utilization is related to transmitter bandwidth, receiver interference rejection characteristics, transmitter locations, frequency assignment techniques and other real-world deployment characteristics. A curve-fit equation estimates the amount of spectrum needed to assign frequencies to transmitters of both types when they are randomly located in an area. Spectrum utilization when transmitters are located at preferred sites (e.g., tall building rooftops) or clustered near city centers is examined. In most cases the narrowband systems are found to use (block) less spectrum than the wideband systems even though the narrowband systems require greater protection from cochannel interference. This paper demonstrates yet again the extent to which general-purpose SE expressions have to be modified before they can be applied to particular types of radio systems.

2.4 Later Spectrum Efficiency Studies

2.4.1 First Internationally Agreed Spectrum Efficiency Metric and Multi-Agency Work

In 1986, more than a decade after early work was published in the field, the CCIR published the first internationally agreed upon definition for spectrum utilization and efficiency [15]. Drawing on the work of Gifford [2], JTAC [1], Vinogradov [6], Ewing and Berry [7], Colavito [8], Berry [11], and some others, CCIR sets forth in [15] a basic SE metric that is the ratio of "useful result obtained from the radio equipment" to the product of blocked or denied bandwidth, space and time. The CCIR document goes on to show how this definition might be applied to real-world radio systems by modifying the general expression for the specific application of point-to-point microwave networks. This definition is still fundamentally in effect today in updated successors such as [33].

Cohn, of Sachs-Freeman Associates, was subsequently contracted by the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC) to study, develop and report on several SE topics for Federal Agency radio systems [16]. His 1986 report: 1) recommends a method of determining SE of radio systems in general; 2) recommends a method of determining the efficiency of band use when a number of systems occupy a given geographic area and frequency band; and 3) provides a definition of band efficiency. Cohn's work expands the concept of radio system efficiency to the concept of overall efficiency of use of entire radio bands. The plan at that time was for NTIA, as the regulator of spectrum use for Federal agencies, to then apply the recommended SE metrics to determine the distribution of SE values for various Federal fixed systems and bands in at least one government fixed service-band. Berry, through the TSC, subsequently develops at ITS in Boulder a computer program

(now a software tool) for NTIA to use with the Government Master File of Frequency Assignments (GMF) to provide this distribution. Cohn's recommended SE metric in [16] is consistent with the recently developed CCIR definition: throughput divided by the product of denied frequency bandwidth, space, and time.

2.4.2 Absolute Versus Relative Spectrum Efficiency in the TSC-Sponsored Metric

A feature of [16] is that the proposed SEs are all to be computed relative to an idealized reference radio system. This is directly contrary to the approach that Berry [11] recommends, where he argues for solely relative SE metric evaluations. Cohn advocates the use of absolute references in order to be able to compare SE of one radio service to another via a single dimensionless number ε ranging between 0 and 1, to be computed for systems in every radio service. To return to Berry's earlier analogy with automobile mileage comparisons [11], an absolute efficiency metric would be implemented so that the relative mileage efficiencies of *all transportation systems* could be compared: Aircraft to ships to railroads to automobiles, and so forth. While an automobile-to-automobile comparison requires only an automobile-tailored relative metric, which is what Berry argues for, comparisons among *all* types of transportation systems can only be implemented in any practical manner by first establishing the absolute efficiency of every transportation mode relative to the dimensionless efficiency value, ε. Then, all transportation systems are ranked against each other via their "ε" value.

The question that any inter-system SE comparison approach begs is, Why would anyone seek to do this? Comparing automobile efficiency to aircraft efficiency could be seen as pointless or illogical, unless there is some motivation or goal to replace, say, aircraft with automobiles or *vice versa*. In the radio context, the question becomes, Why would it be necessary or desirable to compare the SE of mobile radios to, say, radars, point-to-point microwave links, or space communications? Unlike the transportation-system analogy, these radio systems do not even have the same basic missions; they provide totally different services to their users. One type of radio service can never, by definition, replace another (e.g., there can be no LMR-based replacement for radar nor any cellular mobile network replacement for space communications). So why try to compare them in the first place? Furthermore, they all have individual spectrum needs that are driven by their individual technical idiosyncrasies and band requirements, including band-specific propagation requirements conforming to their mission requirements (e.g., 4000 nmi propagation required for long-range space search radars but only distances of a few hundred feet required or even desired for some types of cellular networks). Indeed, as we shall see, a number of subsequent documents such as ITU-R SM.1046-2 [23] will specifically caution against using SE metrics for inter-service comparisons.

2.4.3 SE Metrics Applied to Operational Radio Systems

Also in 1986, Berry et al. [17] propose an new SE metric and apply it to three actual, operational government fixed-service (point-to-point microwave) systems. This NTIA report responds to an Executive Order (12046) and a follow-on Department of Commerce Order (10-10) instructing NTIA to work with the FCC to take steps toward implementing SE metrics as part of a larger goal of ensuring efficient and effective use of the spectrum.

The working goal is to develop a tool that applies an absolute SE coefficient (between 0 and 1) to the fixed service in the frequency range of 947 MHz to 40 GHz. In this case, the tool is a combination of an analytical algorithm for a technical spectrum efficiency factor (TSEF) and a computer program that implemented that algorithm for real-world fixed radio systems. The report describes four tasks that were accomplished:

- A quantitative definition for terms connected with "efficient spectrum use"

- A method of application and a general formula for a TSEF that evaluates fixed-service SE in the given spectrum range

- A computer model (written in FORTRAN) that evaluates the TSEF of selected fixed systems

- Results from that computer model that analyze three specific government fixed radio systems in the range of 7.1 to 8.5 GHz.

Although the TSEF in [17] is defined as absolute (0–1), the authors use the most efficient of the three systems as a reference system and compare the other two systems to that one. Thus the ostensibly absolute TSEF is rendered, in effect, into a relative SE factor.

While [17] notes some usefulness for the TSEF, several limitations are flagged. Chief among these are the combination of the need to identify reference systems in such studies with the dearth of information needed to identify and quantify such reference systems. This includes lack of sufficient data in ordinary spectrum assignment listings such as the GMF. SE studies ordinarily require detailed engineering data for radio systems, e.g., detailed receiver frequency-response curves. Such data are not usually available for radio systems (i.e., are not found in radio technical specification sheets provided by vendors) and may not even be in those vendors' engineering-design repositories. Berry et al. [17] imply, but do not say explicitly, that identifying, defining, and using adequate reference systems may be a barrier to further implementation of such a metric.[11]

The effort required to design and implement the TSEF for the three microwave systems was substantial; there are 124 descriptive and technical content pages in [17], excluding preliminary pages and references. Even today, the approach that the authors take in this study might be used as a tutorial for others who seek to design and implement SE metrics. It can likewise be taken as a caution about the difficulty and complexity of such studies and implementations.

NTIA continued to pursue substantial SE studies of actual band usage through the rest of the 1980s, the only organization anywhere that seems to have done so. In 1988 NTIA issued a report [18] describing a new tool developed by NTIA for analyzing SE of services, as had been

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[11] Consider for instance this statement on page 2-2 of [17]: "The specification of a reference system that accomplishes the same mission as the evaluated system and uses minimum spectrum resources requires specific knowledge of the system's communications and performance requirements. Therefore, a realistic effort to establish reference systems for an automated application of the TSEF necessitates making assumptions about the systems. This will have a significant effect [*read as adverse effect in this context–FHS*] on the accuracy of the TSEF calculation."

proposed in the Cohn 1986 report for the TSC [16]. The NTIA report by Mayher, et al [18], describes a new Spectrum Use Measure (SUM) data base which joined the technical properties of radio spectrum to geography. This allows for the quantification, measurement, and graphic display of how the nation's spectrum resource was actually being utilized, at least insofar as database information would indicate. Further development of the SUM data base was expected to lead to better spectrum management and promote more efficient and effective use of radio spectrum. The computer program development for [18] was led by Berry at NTIA/ITS.

A year later, Hinkle and Farrar continued the ambitious NTIA SE effort by publishing report [19], which identifies spectrum conservation techniques for fixed-service point-to-point microwave links. (Spectrum conservation is essentially the same as SE.) Antennas, signal modulations, signal processing, power amplifier characteristics and radio frequency (RF) filtering are all examined. This inclusion of several applied characteristics of radio systems had been recommended by Vinogradov [6], Ewing and Berry [7], and Berry [11].

Farrar [19] develops a reference microwave system for use in SE metrics. (This follows the recommendation of Cohn [16] and Berry's actual implementation example in the body of [17]—but contradicts Berry's first recommendation [11] and his stated goal in the introduction to [17]). SE metrics based on the then-recent 1986 CCIR Report 662-2 [15] are applied via a custom-written computer program. The authors conclude that, if the SE of a radio system is to be completely understood and quantified, *the entire complement of all system characteristics including (but not necessarily limited to) antennas, RF filters, IF filters, signal modulation and processing, transmitter power, link length or cell size, out-of-band emission levels, and spurious emission levels must all be taken into account*. Only by taking all such factors into account can the true blocking in bandwidth, space, and time be determined. In other words, it is concluded, SE metrics must be carefully crafted on a system-by-system basis.

Once again, this report illustrates the contrast between the ease of sketching an SE metric and the often substantial difficulty of implementing it. Farrar [19] also illustrates the extent to which every service, and sometimes every individual radio system, needs to have an SE metric especially crafted for it. The results of [19] reinforced an identical conclusion in [17]. Both highlight, in a negative fashion, the ordinary lack of availability of the highly detailed and system-specific engineering information needed for good implementation of realistic SE metrics.

The next year sees an updated CCIR SE definition document issued, CCIR Report 662-3 [20]. The definition is substantially the same as that issued in 1986 [15].

In 1990 NTIA continued its SE program by analyzing the then-current Federal LMR infrastructure with respect to both SE and cost effectiveness in a report written by Cohen (not to be confused with Cohn), et al [21]. This appears to be the first time that economic analysis is performed in this sort of study. This report documents analysis methods along with results, conclusions, and an implementation plan. The report examines in detail, and summarizes, Federal LMR requirements and techniques such as simplex, repeater, trunking, cellular, and then-emerging wireless technologies. The benefits of rechannelization, trunking, and other technical methods to improve spectrum utilization are explained and their SE advantages are quantified.

Methods to introduce cost effectiveness are also introduced. One of these methods exploits the economy of scale provided by large networks. For example, agencies could reduce costs by replacing small individual networks with a large shared network. Policy and regulatory methods that NTIA could use to implement the plan include Federal agency use of commercial vendor services whenever feasible, and the use of shared radio communication systems among government agencies (e.g., shared trunked radio networks among agencies and commercially procured trunked services from vendors).

Cohen et al. [21] is important because it shows that SE can be improved not just by focusing on individual radio systems, but by examining the SE that accrues when agencies move away from using individual smaller, dedicated radio networks and instead share single larger radio networks and procure radio network services from commercial vendors. Thus, this report encourages Federal agencies to achieve more efficient spectrum use on an entire service basis rather than just a radio system-by-system basis.

In 1994, Matheson [22] uses simplified SE definitions to compare the SEs of several types of mobile radio systems. The use of simplified SE definitions echoes Ewing and Berry's 1973 [7] and Berry's 1977 [11] comments that overly complicated SE metrics may be arguably more technically accurate but will never be implemented if they are overly complex. A variety of systems then in use and proposed for then-near-term deployment are compared to analog FM dispatch radio. Matheson's calculations show a ratio of 1:1 million between the most efficient and least efficient of the types of systems considered. This report is an example of how SE comparisons can be made between various technologies if they are closely related to one another and all provide the same basic service. As with Cohen et al [21], this is not a system-by-system approach to SE but rather a recommendation for how to achieve better SE in an entire class of radio service.

2.4.4 Current ITU-R Spectrum Efficiency Definition Published

In May 2006 SE definitions were added to ITU-R Rec. SM.1046 [23]. The current version of this Recommendation ([33]) continues to be the internationally agreed upon SE definition document. This Recommendation discusses not just how to use SE metrics, but how *not* to use them. Recommendations in [23] include:

- The bandwidth-space-time domain should be the basis for spectrum utilization metrics (the same as has been the case since the beginnings of these studies a half century ago)

- The basis for calculating SE should be the determination of the "useful effect" obtained by the radio systems through the utilization of the spectrum, with some examples of how to do this provided in the Recommendation Annexes

- *Relative* SE metrics should be used to compare similar radio systems

- *Comparisons of SE should be performed only between similar types of radio systems providing identical radiocommunication services.*

ITU-R Rec. SM.1046-2 states: "Values for spectrum use efficiency (SUE) could be computed for

several different systems and could indeed be compared to obtain the relative efficiencies of the systems. Such comparisons, however, will have to be conducted with caution. For example, the SUEs computed for a land mobile radio system and a radar system are very different. The information transfer rate, receivers, and transmitters in these two systems are so different that the two SUEs are not commensurate. It would not be particularly useful to try to compare them. Hence, *the comparison of spectrum efficiency should be only done between similar types of systems and which provide identical radiocommunication services*." (Emphasis added.)

Subsequent ITU-R documents [26], [30], and [34] demonstrate the application to radio communication network design. The first of these, ITU-R Report M.2134 [26], applies SE metrics to International Mobile Telecommunications (IMT, same as 4G or 4.5G) advanced radio systems. It uses an SE metric that is the ratio of all data running through all cells in a network to the product of the network's time, channel bandwidth, and physical cell blocking. The next, ITU-R Rec. 2083 [30], calls out, in detail and at length, specific approaches and procedures for calculating SE metrics (both peak and average SE) for future IMT-2020 radios. The use of SE metrics in these publications indicates the maturity that SE studies have achieved, at least for mobile radio systems; they are now performed routinely for new mobile radio system designs and services prior to deployment. The third document, ITU-R Report M.2410 [34], calls out, in detail and at length, specific approaches and procedures for calculating SE metrics (both peak and average SE) for future IMT-2020 radios.

2.4.5 Recent Notable Spectrum Efficiency-Related Published Works

NTIA has continued its SE work in recent years with a related pair of reports [24], [25] that examine SE approaches and practices in Federal LMR bands. A third report [32] addresses current usage in five bands between 1300 and 3550 MHz, with the goal of identifying possibilities for future sharing as a way toward more efficient spectrum use in some or all of those bands.

The first of these reports, Joiner et al. [24], describes how the frequency assignment process influences spectrum efficiency in Federal LMR spectrum bands. It concludes that better frequency re-use, and hence improved SE of LMR band usage, can be achieved among Federal systems by implementing a revised version of the then-current frequency assignment analysis algorithm (the algorithm itself being based on interference analysis between frequency requests in the assignment process). Joiner et al. [24] recommend that NTIA and other Federal agencies use an interference-assessment methodology for frequency assignments that is based on the Telecommunications Industry Association (TIA) Telecommunications Systems Bulletin 88-B (TSB-88-B). The use of TSB-88 is now an available option in frequency assignment menus used by NTIA and some other Federal agencies.

The second report in the pair, Cai et al. [25], evaluates the efficiency of Federal spectrum use in a particular, congested LMR band (162–174 MHz) in a densely populated area (Washington, DC). Cai et al. [25] compare spectrum resources used by several alternative trunked LMR system architectures to the spectrum resources used by conventional LMR systems. Three different trunking architectures are studied as scenarios within a 100-mile radius coverage area centered on Washington, DC. GMF assignment data and ITS-derived channel occupancy measurement

results are combined to determine traffic levels in erlangs within each base station service area. Those traffic levels in turn are used to determine the amount of spectrum needed by the trunking systems.

Cai et al. [25] conclude that trunked LMR systems will normally use less spectrum than conventional LMR. It notes that trunking radio system SE grows with scale: the SE of trunked LMR systems increases with the number of users. In other words, it says that greater Federal agency participation in, and use of, trunked radio systems will result in more spectrum-efficient overall use of LMR spectrum. The authors further conclude that the details of trunked-LMR base station frequency-use design are critically important in reaching the full spectrum-usage potential of these systems.

The third recent notable report, [32], examines current spectrum usage in 960 megahertz of spectrum in five bands that are allocated for Federal use: 1300-1390 MHz, 1675-1695 MHz, 2700-2900 MHz, 2900-3100 MHz, and 3100-3550 MHz. To estimate this usage, NTIA gathered technical characteristics of radio systems with assignments in the bands and obtained estimates from system users of how much of the time their systems produced spectrum occupancy. These data are then used to provide approximations of the extent to which each system uses its assigned spectrum and the extent of geographic coverage of this usage. The cumulative total of each Federal agency's radio band usage by all radio systems across all frequencies is provided as the "quantitative assessment" for each of the five bands that are reviewed. Results for multiple agencies are aggregated where applicable. NTIA also reports in [32] on agency estimates for projected increases, if any, in their spectrum usage needs in the bands under study. Where possible, non-Federal spectrum is identified which could be used to help fulfill agency missions.

For each of the bands, the basic study approach of [32] is as follows. Transmit station and receive station technical characteristics (called elements) are gathered, including frequency, necessary bandwidth, station class, location, power (of transmitters), antenna height, and antenna gain. Using these data, contours are computed for both transmitters and receivers. These contours are surface areas where specified power spectral density (PSD) thresholds are equaled or exceeded for transmitters and receivers. With the PSD contours computed, the percentage of population impacted and the percentage of geographic availability are computed within those contours. Finally, working in units of 5 MHz at a time, the frequency usage, geographic usage, and estimated time usage is described for each of the bands. Total spectrum usage is estimated based on aggregation of the spectrum usage contours. Frequency usage is described in terms of the number of frequency assignments that fall within each 5 MHz band segment. Geographic usage is described in terms of the percentage of the population impacted by the transmit and receive station spectrum usage contours and the percentage of the geographic area that is not covered by spectrum usage contours. The time usage is described using agency-provided estimates for the times that stations are actually used to perform their missions.

NTIA report [32] concludes with summaries for each of the five bands under study. Each of these band summaries includes: the total estimated current spectrum usage; projections for future spectrum usage; identification (or not) of possible future Federal access to non-Federal spectrum for performance of agency missions; and risks to agency missions that might be posed by future changes in band usage. Although this report does not specifically address SE as a topic, it may be

used to improve SE in the subject bands by encouraging more sharing in these bands in the future between Federal and non-Federal radio systems.

On a broader level, CSMAC has recently published a study document [27] that qualitatively discusses applications of the ITU-R SE metric [23] to the following services: broadcasting, personal communications systems (PCS), point-to-point, radar, satellite systems, "passive listeners," short range systems such as Wi-Fi___33 (IEEE 802.11), and cognitive systems. CSMAC report [27] echoes ITU-R Rec. SM.1046-2 [23] in saying that only similar systems should be compared for SE. The CSMAC report specifically comments: "The spectrum efficiency of a radar cannot be directly compared to the spectrum efficiency of a communications device."

And it goes further in its conclusions: "Users should be required to compare existing and proposed systems to other alternative ones *within the same section of the taxonomy* (emphasis added) to justify the effectiveness of the specific system in meeting the mission goals while occupying a minimal resource footprint."

In parallel with CSMAC the FCC has issued a working group (WG) whitepaper [28] on SE that divides all radio spectrum use into two broad classes of systems: Satellite and Terrestrial. Within those two broad categories, the WG focuses its analyses on six system classes: Satellite Broadcast, Point-to-Point Satellite, Terrestrial Broadcast, Terrestrial Personal Communication, Terrestrial Point-to-Point, and Terrestrial Hybrid. SE metrics are proposed for each. The challenges associated with the development and usage of SE metrics are discussed and sample calculations for each SE metric are supplied.

In 2014, an independent researcher, Rysavy, published [29] his own analysis of recent CSMAC, FCC, and ITU-R documents. Rysavy [29] provides a broad survey of the current state-of-the-art in SE metrics calculations and assessments for various types of radio systems. The concept of peak versus average SE is discussed. Spectrum sharing is addressed in the context of SE studies: "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." This discussion of spectrum sharing as it relates to SE is novel, and may lay the groundwork for substantial work yet to be performed at the nexus of radio system sharing and earlier SE metric development.

2.4.6 Spectrum Efficiency Requirements in the NTIA Manual and Code of Federal Regulations

NTIA issues and maintains a living document, the "Manual of Regulations and Procedures for Federal Radio Frequency Management" [31]. This NTIA Manual contains technical regulatory requirements for Federal radio systems. These requirements are for transmitters, receivers, and antennas. These requirements are intended to reduce spectrum blocking and thereby improve and promote SE for all Federal radio systems. A prime example of SE requirements in the NTIA Manual are the Radar Spectrum Engineering Criteria (RSEC). These require radar transmitters and receivers to meet numerous criteria to reduce their blocking of other radar systems and hence improve their SE characteristics. Federal system characteristics addressed in the NTIA Manual requirements such as the RSEC include (but are not limited to): receiver passband selectivity;

carefully tailored transmitter emission limits that include regulatory masks for out-of-band emissions (OoBE), spurious emissions, and harmonic emissions; and antenna performance requirements.

The FCC promulgates its own SE requirements through radio rules and regulations in the Code of Federal Regulations (CFR) and related documents. Like the NTIA Manual, the bulk of these rules and regulations is intended to reduce blocking amongst radio systems within the same radio service.

2.5 Summary of Spectrum Efficiency Studies

This section summarizes the results of previous SE studies and presents the most important lessons that we have drawn from these.

2.5.1 Points of Consensus on Spectrum Efficiency Metrics

The literature shows that there is broad consensus on fundamental SE metrics. From the earliest publications onward, it has been universally agreed that the quest for minimization of spectrum blocking must be the starting point for all SE studies. Furthermore, the ratio of effective or productive spectrum use to the product of blocked frequency bandwidth, space, and time has been and continues to be universally agreed upon (i.e., [33]) as the basic SE metric for all radio systems.

There has been some disagreement historically as to whether all SE metrics should be strictly relative (allowing only comparison of one system to another), versus whether radio systems being evaluated should be compared to some kind of ideal, reference radio system. The question has not been definitively settled, but in recent years a large degree of consensus has been reached. The consensus is as follows. Only radio systems that are highly similar to each other, and that provide identical services to their users should be compared directly to each other via SE metrics and in SE studies, as stated explicitly and forcefully in [33] and [27]. It is illogical and unproductive to compare unlike radio systems to each other in SE studies.

There seems to a broad trend toward evaluating SE of a frequency band, rather than (or in addition to) evaluating system-specific radio SEs. This is seen in [18]–[20], [22], [27], [28], and [37]. The idea is to synchronize or harmonize radio technologies in entire given bands to achieve the best possible SE across multi-band swaths of radio spectrum.

2.5.2 Maturity of Spectrum Efficiency Metric Application for Two Radio Services

SE metrics have reached maturity for some services and are being routinely implemented in bands used by terrestrial mobile services, as demonstrated by [26], [30], and [34]. The terrestrial fixed service (point-to-point microwave) has historically seen extensive SE study and metrical application as demonstrated in [18]–[20], although not so much SE work seems to have been done for this service in recent years.

A common thread running through all published SE studies for the last half-century has been that it is far easier to define SE metrics than it is to apply them. Every specific application seems to require carefully crafted tailoring to take into account all of the vagaries and idiosyncrasies of each type of radio system and service. This difficulty arguably tends to reduce the number and scope of SE studies that are performed.

2.5.3 Lack of Spectrum Efficiency Metric Application in Other Radio Services

The literature seems to lack studies showing effective calculation or implementation of SE metrics for services other than terrestrial mobile and terrestrial fixed. We do not know whether these *lacunae* are due to a perceived lack of need for SE application for other services, or whether application of SE metrics has perhaps been attempted but then abandoned for other services due to possible difficulties of application. There may be some truth to both possibilities.

2.5.4 Summary of Practical Effectiveness of Spectrum Efficiency Studies

SE examinations have had a positive impact on the radio services. Published studies have improved SE in the terrestrial mobile communications and fixed service bands, including:

- Implementation of more spectrum-efficient signal modulations to optimize use of bandwidth and reduce or minimize bandwidth blocking[12]

- A trend toward smaller cell sizes with concomitantly shorter frequency-reuse distances in the private sector (but not in resource-limited Federal network deployments)

- A trend toward more use of trunked and cellular-style radio systems by Federal agencies and less use of conventional LMR networks; more sharing of larger radio networks and less use of smaller, agency-dedicated radio networks

- More use by government agencies of commercial radio services on larger radio networks, where feasible

(The last three points are especially put forth in [25].)

For services where published SE studies are lacking (e.g. radar), SE has nevertheless tended to improve via regulatory action. For example, the requirements of the NTIA RSEC limits for Federal radars have been tightened progressively for the last 40 years with the development of, for instance, newer emission masks such as RSEC D and E. These require steeper roll-off curves for OoBE and substantially lower (tighter) limits on spurious and harmonic emission levels than required by earlier RSEC emission mask limits.

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[12] With the caveat that more spectrally efficient modulation schemes are typically more susceptible to interference. This can make them less able to share spectrum, that outcome in turn representing a relative *decrease* in SE.

2.5.5 Recent and Recommended Future Innovations in SE Studies

In recent years it has become common to assess both peak and average SE for radio systems (as performed, e.g., in [34]). This is due to recognition that many modern radio systems have significantly different peak versus average emissions, and consequently produce peak and average blocking levels that differ significantly from each other. This recent innovation has been incorporated easily into SE calculations, to judge by recent publications such as [30] and [34].

An innovation that has scarcely been mentioned in the literature and is just beginning to be considered from a utilization and SE perspective [29] is how SE is (or rather, how it ought to be) related to spectrum sharing, and how various types of spectrum sharing should be analyzed for SE. This gap should perhaps be surprising since the trend toward new uses of spectrum bands has in recent years moved decidedly away from dedicated services on a band basis and has moved instead toward band sharing between unlike services. Current examples include ongoing spectrum sharing between Dynamic Frequency Selection (DFS) unlicensed national information infrastructure (U-NII) radios and 5 GHz radars; near-term sharing between new Citizens Broadband Radio Service (CBRS) terrestrial communication networks (plus possibly Internet of Things (IoT)) radios and radars at 3.5 GHz; near-term sharing between new terrestrial mobile communications network uplinks and space communication meteorological satellite (METSAT) downlinks in the 1695–1710 MHz spectrum; near-term sharing between new advanced wireless service version 3 (AWS-3) networks and telemetry links in the same part of the spectrum; and possible future sharing between various new radio systems and existing radars and telemetry links at 1.3 GHz. The days seem to be over when new services obtained exclusive placement in bands while pre-existing legacy systems were shifted to other bands. From this point forward, it appears that new services in bands will ordinarily share with legacy systems, the so-called incumbents. This being the case, the implications of radio spectrum sharing for utilization efficiency need to be thoroughly examined in new SE studies.

Since SE is inversely proportional to radio blocking, and since sharing reduces or eliminates blocking between systems and perhaps even between services, sharing clearly needs to somehow be factored into some sort of improved SE estimates for the systems that implement it. However, sharing (or sharing potential) is not obviously inherent in the characteristics of any given radio system. It is a function of at least two radio systems or services considered jointly. We recommend that an SE study program thoroughly address the SE implications of band sharing. In particular, we recommend that methods be developed in a new study for the quantitative inclusion of spectrum sharing in future SE metrics.

2.5.6 Chief Lessons Drawn from Previous SE Studies

The chief lessons that we draw from previous SE studies are:

1) Only similar systems delivering like service to users should be compared to each other for SE metrical purposes.

2) SE metrics and comparisons should be relative, not absolute.

3) To the extent that band-dependent SE is examined, it should be via comparisons between similar radio systems operating in those bands.

4) Technical features that have only recently become widely available should be significantly included in future SE studies and metrical development. These include SDC of transmitters and receivers that can take advantage of intelligence about local environments; smart or intelligent antenna designs including electronic beam steering and gain control; and dynamically controlled frequency agility.

5) Receiver characteristics are just as important in terms of spectrum blocking as are those of transmitters. Receiver selectivity characteristics are just as important as transmitter OoB and spurious characteristics. Future SE studies and SE metrical development need to maintain as much focus on receivers as on transmitters.

3. RECOMMENDED FUTURE SPECTRUM EFFICIENCY APPROACHES

The assessment of SE in the presence of sharing between systems and services in entire bands needs to be readdressed. Increasing demands for access to radio frequency spectrum have renewed high-level national interest in improving the efficiency of Federal Government spectrum usage and providing more overall spectrum access for both Federal and non-Federal entities. Numerous SE studies by the Federal Government, industry, academia, the CCIR, and ITU-R over the past five decades ([1]–[34]) have attempted to describe and quantify SE and related metrics. As described above, the results of these studies have been implemented to varying degrees. As the references show, little work has been done on the basics of SE over the last two decades (with the exception of several reports published by OSM and ITS addressing LMR SE). Also as noted above, *lacunae* exist in the application of SE metrics for numerous radio services and SE comparisons should only be made between similar types of radio systems.

To enable Federal agencies to improve their spectrum-use efficiency, technical SE metrics need to be accepted by both the Federal and non-Federal spectrum management communities. A comprehensive review and assessment of characteristics of spectrum-dependent systems, and spectrum management practices and policies is necessary to establish an acceptable set of SE criteria in these communities in the U.S. The review particularly needs to focus on new SE methods and metrics that may be applied to Federal spectrum use. It should also include an examination of the efficiency of new and emerging technologies that might offer efficiency improvements. As noted above, this needs to include spectrum sharing as an important new component.

A set of versatile spectrum efficiency metrics should be developed with implementations for specified types of radio systems and bands that are cost-effective and practical for regulatory implementation by Federal spectrum users. Specific SE metrics need to be developed that can be applied to technical standards for radio systems used by Federal agencies.

We recognize that SE metrics occupy only one axis of a radio system three-space for efficiency, mission effectiveness, [13] and cost. Ultimately all three components must be considered for all radio systems, as it is entirely possible to design and develop radio systems with high SE but which might be either impractically costly to implement or not very mission-effective. However, the recommendations we make here for future SE study approaches do not address any aspects of cost or effectiveness.

3.1 Recommended Future SE Tasking

In Table 2 we recommend possible future SE work. This work should be performed on the basis of radio system types and bands. The recommended tasks take into account factors that include availability of information to develop SE methods and metrics, and ongoing efforts by other Federal agencies to perform similar work. OSM, ITS, and other Federal agencies and

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[13] Effectiveness is defined here as the extent to which spectrum resources satisfy overall user requirements.

stakeholders should collaborate in the effort on an ongoing basis to ensure that all relevant information is considered and to avoid duplication of efforts.

Table 2. Recommended Future SE Analysis Tasking.

Radiocommuni-cation Service	Representative Federal Systems	Study Focus	Spectrum Bands
Radiolocation	Long-range air traffic control and defense radars	Band packing for existing and next-generation long-range radar (LRR) air traffic control (ATC) and defense radars.	1215–1390 MHz
Radiolocation Meteorological Aids	Short-range airport surveillance (ASR), Next Generation Weather Radar (NEXRAD), weather & future long-range radars	Band packing improvement for existing ASR & weather radars and future long-range radars (frequency separations versus distance separations).	2700–3100 MHz
Mobile	Conventional and trunked mobile radio technology	Spectrum efficiency among existing mobile radio systems, and in comparison to possible future mobile radio systems. Study to determine if FirstNet can satisfy Federal mobile voice and data communication requirements. Determine what FirstNet would have to include in its network design going forward to satisfy Federal mobile voice and data communication requirements.	200 MHz–6 GHz mobile bands
Radiolocation	Military land, ship, and airborne radar systems	Band packing; sharing using database and/or spectrum sensing techniques (e.g., Citizens Broadband Radio Service in 3550-3650 MHz band); developing sharing approach with airborne systems.	3100–3550 MHz
Fixed Fixed-Satellite	Fixed satellite service (FSS) and point-to-point (PtP) systems	Band packing improvements for FSS and PtP systems Bi-directional sharing with non-Federal PtP systems.	1.4–31 GHz FSS and PtP bands

3.2 Recommended Overall Approach

All tasking outlined in Table 2 should include:

- For each study area, a detailed proposal including the elements below.

- Collaboration with Federal agencies to identify approaches for achieving improved spectrum efficiencies, including agency information pertinent to previous work relating to those agencies' respective radio systems and services.

- Publication of a technical report containing the following elements:

- An overview of the SE work that has been undertaken
- A thorough review of available literature for previous SE study results
- Analysis of previous SE study results
- Recommendations for new directions for SE metrics as needed for application to existing and future Federal government radio systems and services

- Analysis of the SE improvements that are effective and viable for tightened receiver technical standards.

- Analysis of SE methodology as it relates to Office of Management and Budget (OMB) Circular A-11, Section 31.12,[14] to determine practicality and effectiveness in implementation.

- Close coordination with other Federal agencies on the progress of work efforts, including concurrence with those agencies on study results as efforts progress. The mechanism for this coordination should be OSM's chair position on the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC).

- Development of SE software tools that can be used to implement new SE approaches. These tools should be designed to be used in connection with the NTIA Manual and OMB Circular A-11.

3.3 Recommended Scale of Spectrum Usage in a Future SE Studies

As we have seen in the literature review, there has been a trend over the years to move the focus of SE studies from the smaller scales of individual radio systems and networks toward larger-scale studies of overall band usage and efficiency (e.g., [32]). We recommend that this trend continue to be followed, looking more at band SE than at individual system SE. This recommendation comes with the cautionary note that only like radio systems and services in various bands should be compared to each other. We also note that, in order to examine large-scale band usage and efficiency, the detailed individual technical characteristics of all of the systems that use any band must be taken into account.

3.4 Recommended Types of Spectrum Efficiency Consumers to be Addressed

Going all the way back to remarks by Hinchman [4] (1969), Ewing and Berry [7] (1973), Hatfield [9], [10] (1975 and 1977), and Berry [11] (1977), developers of SE metrics and studies have been concerned with striking a balance between studies and approaches that are sufficiently

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[14] Executive Office of The President Office of Management and Budget Circular A-11 Preparation and Submission of Budget Estimates provides guidance to all Executive departments and establishments on budget preparation and execution. Section 31.12 directs agencies to include in the development of their budget justifications for procurement of major radio spectrum-dependent communications-electronics systems consideration of the economic value of the spectrum being used and of the spectrum efficiency of the system being procured. A methodology is given to evaluate relative spectrum efficiency when considering alternatives for procuring systems.

accurate and detailed to yield useful results, but not so overly technical and complicated as to discourage the use of the SE models that have been developed. The need to strike this balance is as critical now as it has ever been. We recommend that future SE studies should address two levels of SE consumers. These would be 1) high-level spectrum managers and planners and 2) acquisition planners and specialists.

For spectrum managers and planners, SE work should provide guidance on future directions that can be pursued to achieve better overall SE performance on a band-by-band and service-by-service basis, including guidance on how to assess potential for spectrum sharing among systems in future spectrum band allocation plans.

For acquisition planners and specialists, SE studies should provide guidance including software tools that can be used to help compare alternative types of radio systems that may be under consideration for acquisition. This work should be targeted toward applicability in acquisitions of Government-owned equipment under guidelines such as those in OMB Circular A-11.

3.5 Absolute Versus Relative Spectrum Efficiency Metric Deliverables

Based on review of the existing SE literature, we recommend against development of SE metrics that are absolute or that are based on comparison of radio systems to absolute or idealized reference systems. Our reasons have been stated above. It is sufficient to reiterate here that any SE metric ultimately results in a comparison between two alternative radio systems. There is no use in using reference systems as intermediaries in such comparisons. We also note again that, following the existing guidance in the literature including from ITU-R and CSMAC, we recommend only making SE comparisons between like types of radio systems that deliver like services to their users.

4.   CONSTRUCTION OF TECHNICAL SE METRICS

This section provides advice from NTIA/ITS experts on SE metric construction. As the SE literature shows, it is fairly easy to write SE metrics and not at all easy to implement them for individual radio systems and services. ITU-R Rec. SM.1046 [33] provides a starting point, in the form of guidance for the basics of SE metric construction. We recommend that future SE studies follow that guidance.

When it comes to constructing actual SE assessments for systems and services, including on the basis of service bands, we anticipate that the following radio system parameters will be used in future SE metrics:

- Transmitter power and power control

- Transmitter frequency agility and multi-band operational features

- Transmitter bandwidth

- Transmitter modulation

- Transmitter pulse width and pulse repetition rate (i.e., duty cycle) for pulsed systems

- Transmitter out-of-band, spurious and harmonic emissions

- Transmitter antenna configurations and performance

- Transmitter software defined control

- Transmitter dynamic control for spectrum sharing

- Receiver overload characteristics

- Receiver bandwidth

- Receiver sensitivity

- Receiver agility

- Receiver interference rejection capabilities

- Receiver antenna performance

- Receiver software defined control including factors of location awareness, environmental sensing and database information

Sections 4.1 and 4.2 describe these transmitter and receiver parameters, respectively. The remainder of this section provide feedback on other topics, such as metric scope, spectrum sharing, weighting coefficients, and software development.

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4.1 Transmitter Parameters to be Considered in SE Metrics

Transmitters and receivers play equivalent roles in blocking spectrum and reducing SE. Transmitter and receiver characteristics that will likely be included in SE metric development are described below.

4.1.1 Transmitter Power and Power Control

Transmitter power blocks other users; lower power tends to be associated with less blocking and higher SE, if all other factors are held constant. Power control can be an important factor in overall SE and should be accounted for in future SE metric development.

4.1.2 Transmitter Frequency Agility and Multi-Band Operational Features

Frequency agility is the ability to change frequencies in response to varying conditions within a radio system and in response to external radio-environmental factors. Frequency agility can improve SE. Some systems can operate in more than one radio band, changing bands to avoid interference to some receiver systems. Multi-band operational options can improve SE and need to be included in future SE metric development.

4.1.3 Transmitter Bandwidth

Bandwidth is a primary blocking factor in the accepted definition of spectrum efficiency. Narrower bandwidths are generally preferred for better SE. But many modern systems require substantial bandwidths to operate. Within these wide bandwidths, however, there are opportunities to operate at low duty cycles and in relatively narrow resource blocks that may allow more users to share in time-dependent overlays. Future SE metric development should take into account these opportunities for wider-bandwidth radio systems.

4.1.4 Transmitter Modulation

Modulation is related to but not the same as bandwidth; modulation should be an important consideration in any SE metric. Although some modulation schemes may be ostensibly more efficient than others, there can be an inverse relationship between the SE of a modulation scheme and the robustness of the modulation to interference. This inverse relationship can mean that a more efficient modulation scheme requires a higher transmitted power level to mitigate or prevent interference, which tends to then lower SE. The trade-offs associated with the selection of modulation should be addressed in future SE metric development.

4.1.5 Transmitter Pulse Width and Pulse Repetition Rate (Duty Cycle) for Pulsed Systems

Pulsed systems (usually radars but sometimes beacons) use combinations of pulse width and pulse repetition rate; the ratio of pulse width to pulse repetition rate is called duty cycle. Lower duty cycles tend to share better with other radios than higher duty cycles. But a dominant design

trend in recent years has been to use higher duty cycles because solid state transmitters cannot manage their mission requirements very well with low duty cycle transmissions; old-style, high-power tube transmitters that use lower duty cycles can often share spectrum better than their newer solid state counterparts. Examination of duty cycle factors should be a feature of future SE metric development.

4.1.6 Transmitter Out-of-Band, Spurious and Harmonic Emissions

In information theory, bandwidth is whatever channel width is needed to push a certain amount of data on a per-unit-time basis. This definition can be (and is) applied to radio systems. But SE should address more than just data bandwidth. It must also address how much bandwidth is pre-empted by one system before another system (or even another channel in the *same* system) can use another, adjacent channel. That bandwidth is not really related to Shannon's limit, or at least it is only loosely related. This is the out-of-band and spurious-emission bandwidth of a radio system. While this is not often found as a reported characteristic of most radio systems, it can be a key factor in determining the SE of any given radio system. Harmonic emissions likewise play a role in SE.

It is extremely important to understand that OoB, spurious, and harmonic emission levels are not the same as regulatory mask limits placed on those levels. Most radio systems' OoB, spurious, and harmonic levels are well below (often tens of decibels) *lower* than the applicable mask limits. Thus mask limits should not be used in SE studies. *Actual* OoB, spurious, and harmonic levels need to be determined and used in future SE metric development wherever possible.

4.1.7 Transmitter Antenna Configurations and Performance

Tighter antenna beams with higher gain levels tend to be associated with better SE. Electronically formed and steered antenna patterns may provide more SE than static antenna patterns. Accurate characterization of antenna patterns should be an important part of future SE metric development.

4.1.8 Transmitter Software Defined Control

Software defined control (SDC) of transmitters may allow for dynamic modifications of transmitter configurations which may in turn improve the SE of transmitters. SDC of transmitter modes can play an important role in better sharing between radio systems and should be included in future SE metric development wherever it is applicable.

4.1.9 Transmitter Dynamic Control for Spectrum Sharing

SE metrics have traditionally included factors such as bandwidth per user per unit area served. They have also included factors for channel-to-channel bandwidth (e.g., how narrow can the communication channels be, and how closely can the channels be spaced from one to the next). But in this era, an entirely new factor needs to be considered: the potential for sharing (or not) between different types of systems. It is conceivable, for example, that a System A that is in

some sense highly spectrum efficient does not share, or does not share well, with another type of system, System B. So System A itself does an excellent job of using spectrum, but it demands an exclusive or near-exclusive spectrum allocation for itself in order to do so. Consider, however, that a third system, System C, is comparatively less efficient than System A, but that Systems B and C can share well with each other. They do not demand exclusive spectrum allocations or assignments for themselves, as each shares with the other. How, we ask, are we to consider the efficiency of System A (high when considered for itself, stand-alone, but having little or no sharing potential), to Systems B and C, each less efficient individually but which share well with each other? This question of how to account for dynamic control in spectrum sharing between different sorts of radio systems needs to be addressed in future SE metric development.

4.2 Receiver Parameters to be Considered in SE Metrics

Receivers are equally important to transmitters for SE assessments. Most transmitter characteristics that should be assessed in SE studies are mirrored by analogous (or inversely analogous) receiver SE characteristics. These are described below.

4.2.1 Receiver Overload Characteristics

Every receiver overloads at some input power level. Lower overload thresholds may be associated with less SE. The overload characteristics (such as 1 dB compression and ultimate dynamic saturation power levels) should be assessed for all receivers in future SE studies. Since these often are not known, they may need to be determined through measurement campaigns that support future SE metric development.

4.2.2 Receiver Bandwidth

In elementary electrical engineering theory, receiver bandwidths should be matched to transmitter bandwidths for optimal SE operation. However, there are cases in which receiver bandwidths must substantially exceed the ostensible requirement of a given modulation. An example is a receiver that must achieve excellent phase characteristics; doing so requires that sharp, brick-wall filtering must not be used, and that receiver bandwidth must exceed that of the signal being received. Such characteristics and requirements should be assessed, reported, and used in future SE metric development.

4.2.3 Receiver Sensitivity

Receiver sensitivity is the closeness to which receiver noise approaches the theoretical limits imposed by the laws of thermodynamics. While high sensitivity (a close approach to a thermodynamic limit) is ordinarily considered a good thing in radio design, it can also cause undesired signals and noise to adversely affect receiver design at relatively low received power levels. (But note that sometimes the receiver sensitivity is not of so much concern as is the ratio of desired signal power to a receiver's inherent internal noise level.) Receiver sensitivity is a crucially important factor in knowing at what levels harmful interference from undesired signals and noise will occur. This may in many cases need to be measured as it is not always known for

all receiver systems. In any event, this parameter needs to be characterized for all subject receivers in the course of development of future SE metrics.

4.2.4 Receiver Frequency Agility

Receiver frequency agility should mirror transmitter agility; more agility is associated with higher SE. Capabilities for frequency agility should be included for every radio system in the development of future SE metrics.

4.2.5 Receiver Interference Rejection Capabilities

Receiver RF front end and intermediate frequency (IF) response curves can significantly affect interference resistance and therefore SE. Unfortunately these response curves are not ordinarily available for many, perhaps most, radio receivers. Actual response curves should be used wherever possible in future SE metric development.

4.2.6 Receiver Adjacent Channel Filtering and Rejection Characteristics

Up to a point, the better (tighter) a receiver's adjacent channel filtering and rejection characteristics are, the better its SE. But there have been cases in which narrower-bandwidth receiver performance (e.g., 12.5 kHz LMR channels being superseded by 6.25 kHz channels) has provided illusory SE benefits because the adjacent-channel rejection of such radios was so poor that the radios' actual channelization implementation had to be confined to a channel spacing of 12.5 kHz. So, while this parameter should be included in future SE metric development, it should not be included at its face value. It should be included along with a de-rating factor of unity or more (e.g., a de-rating factor of 1.8 multiplied by the channel width) to reflect the actual channel spacing that can be achieved.

4.2.7 Receiver Antenna Performance

The higher the gain (directionality) of receiver antennas, the better a system's SE usually is. Electronic beam forming and steering to track transmitted signals can provide better SE, although at the cost of more system complexity. Electronically controlled beam steering and gain control can significantly improve the SE of receivers by providing for more gain on desired signals while rejecting energy from unwanted signals and noise. Future SE metrics should include factors accounting for antenna beam forming and performance, and should account for the advantages of electronic antenna beam control.

4.2.8 Receiver Software Defined Control Including Factors of Location Awareness, Environmental Sensing and Database Information

SDC of receivers can allow for dynamically controlled configuration modifications which may improve the SE of transmitters. This feature of some modern receivers may hold great potential for improved SE. There are two fundamental SDC environments to consider: Sharing between

radios and services in which both sides of the sharing arrangement use SDC, versus sharing in which only one side of the sharing uses SDC radios. The first case would be applicable to bands in which there are no legacy systems and the sharing engineering is being done from the ground up. The second case, which is more likely to generally occur, is one in which legacy systems that do not have SDC features are to share with newer systems that do have SDC. In this more common situation, the SDC features of the newer radios can be used to allow them to work around the legacy systems in the same band. In both cases, SDC may include factors of location awareness, environmental sensing, and database information. Future SE metrics should prominently consider the use of SDC as a factor, especially for sharing scenarios.

4.3 Ratio-Based Structure of SE Metrics

For all of the reasons stated above, we recommend that SE metrics in future studies should be constructed as comparisons that are to be made between two real-world radio systems at a time. Comparisons should only be made between similar types of radio systems delivering like services to their users, per recommendations in documents and studies such as [23] and [27].

4.4 SE Metrics for Systems with Minimal (or No) Deployment in the United States

We recognize that the U.S. government procures and deploys numerous, and sometimes quite large, radio systems that are deployed minimally or not at all within the Continental United Sates (CONUS), Alaska, Hawaii, and Possessions. To the extent that these systems are deployed within the United States and Possessions (USP), they are largely or entirely confined to test and training facilities. We see limited utility in including these systems in future SE studies; we recommend that such systems should not ordinarily be included in future SE work.

4.5 Incorporation of Potential for Spectrum Sharing (or Lack Thereof) in SE Metrics

As noted above, it is extremely important that spectrum sharing capabilities and/or potential be included in future SE metrics. Exactly how this should be done is a large uncertainty; it will likely be the largest risk factor for future SE metric development. But successful inclusion of spectrum sharing potential in future SE metrics can also provide the largest payoffs in the entire effort.

4.6 The Role of Weighting Coefficients in SE Metrics

Weighting coefficients (WCs) are numbers that are made up by study organizers to try to emphasize certain features of radio systems at the expense of other features. WCs pose a problem to the objectivity of ostensibly objective studies, including SE metrics development efforts, because they allow the people who are implementing them to arbitrarily select features that they "like" at the expense of other factors that they do not like so much. And even if all people who looked at an SE metric under development were to agree that one feature were more important than another feature (unlikely as that would be), how can any feature of a radio system be objectively given a particular WC of, say, 1.85 versus 1.84 or 0.94 or 0.28? The answer is that such weighting cannot ever truly be objective; WCs create an appearance of objectivity (because

they are numbers) while being inherently non-objective (because their basis is always suspect). We note further that WCs have been used little or not at all in the major studies of the last 53 years that are cited in this report. We speculate that the authors of those past studies have been well aware of the problems posed by WCs. This being the case, we recommend that WCs be avoided in the development of future SE metrics.

4.7 Scorecard-Type SE Metrics

In a scorecard approach to SE, radio systems are given point scores for various features or lack thereof. The points are added to provide an overall system score, and like systems are then compared to each other based on their comparative scores. Scorecard factors ordinarily include non-technical factors of mission effectiveness and the economics of radio system implementations. As far as we can tell, based on our 53-year literature survey, scorecard approaches to SE metrics have not been formally reviewed.

Scorecards pose exactly the same problems for the objectivity of SE studies as do WCs. Like WCs, scorecards depend upon the opinions of the people who make them up and implement them. They use numbers and mathematics to try to sustain an illusion of objectivity when their basis is anything but. Furthermore, if any future SE study is supposed to be restricted to SE assessments only, then a scorecard approach to SE metrics would be precluded. In any event, the lack of reviewed literature for scorecards and their inherent subjectivity makes them unsuitable for inclusion in the development of future SE metrics.

4.8 Recommended Methodology for Converting SE Metrics into Software Tools

Complexity in possible future SE metrics should be implemented in software, which we will refer to as Spectrum Efficiency Metrics Tool (SEMT). A well-engineered software package would assist engineers in specifying system parameters, computing complex formulas, and visualizing results for SE metrics. As future SE metrics might be developed, parallel work paths should develop software to support and automate SE metric computations. There is significant precedent for this approach in previous SE studies. We recommend the SEMT software development progress with the following three elements.

First, adopt a flexible, incremental, and iterative approach. Rather than planning software work from beginning to end in significant detail, recognize that changes are inevitable. SEMT software should be developed as a series of iterations. Each of these should include analysis, design, coding, and test phases. These should culminate in incremental releases of working software. Detailed planning should be done for intermediate iterations, while more distant iterations should only be sketched. As the understanding of SE metrical problems evolves, changes can be incorporated into future plans and future releases.

Second, encourage efficient communication between stakeholders and the SEMT development team. One key to successful SEMT development is regular communication between stakeholders and the software development team. Discovery sessions should be held in the initial stages of each iteration in order for stakeholders and the development team to reach a shared understanding of project needs.

Third, regularly release interim software and collect stakeholder feedback. Users and stakeholders should be provided with working intermediate versions of the SEMT. The stakeholder role is to evaluate the intermediate software and provide feedback to the software team of issues and potential enhancements. The frequency of the release/feedback cycle should be agreed upon between stakeholders and the SEMT development team.

5. SUMMARY OF RECOMMENDATIONS FOR FUTURE SE STUDIES

Future SE studies, including those in which SE metrics will be developed, should be informed by the results of the detailed review of the last half-century of SE literature presented in this report. Chief among these are:

- Only similar systems delivering like service to users should be compared to each other for SE metrical purposes.

- SE metrics and comparisons should be relative, not absolute.

- To the extent that band-dependent SE is examined it should be via comparisons between similar radio systems operating in those bands.

- Technical features that have barely been considered in many past studies, because they have only recently become widely available, should be significantly included in future SE studies and metrical development. These include SDC of transmitters and receivers that can take advantage of intelligence about local environments; smart or intelligent antenna designs including electronic beam steering and gain control; and dynamically controlled frequency agility.

- Receiver characteristics are just as important in terms of spectrum blocking as are those of transmitters. Continued awareness of this must be reflected in future SE studies and SE metrical development. Receiver selectivity characteristics are just as important as transmitter OoB and spurious characteristics. Future SE work needs to maintain as much focus on receivers as on transmitters.

Recent technological developments allow for widespread implementation of smart transmitters and receivers. This can make for more opportunities for spectrum sharing than ever before. Spectrum sharing can be based on dynamically controlled systems that respond to their local environments. Spectrum sharing is barely addressed in earlier SE studies because of technology limitations, but can now be implemented in field-deployed radio systems. Now the time is right to re-consider SE of many systems and to examine carefully some new SE implementations and metrics that can take advantage of technologies that are just becoming available.

NTIA's Office of Spectrum Management (OSM) and Institute for Telecommunication Sciences (ITS) have been leaders in the field of SE studies for the last half-century. Their work has led, amongst other successes, to the implementation of trunked radio system use by many agencies; the capability for agencies to implement and use SE factors as criteria for their new radio systems; and the implementation of DFS technology for spectrum sharing at 5 GHz. We recommend that OSM and ITS should undertake further SE studies and SE metrics with an eye to taking advantage of the new opportunities for sharing that new technologies are making possible.

6. REFERENCES

[1] Joint Technical Advisory Committee (JTAC) of the Institute of Electrical and Electronics Engineers Inc. (IEEE) and Electronics Industry Association (EIA), "Radio Spectrum Utilization." 1964.

[2] Gifford, R. P., "EMC Revisited—1966," IEEE Transactions on Electromagnetic Compatibility, EMC -8, pp. 123-129. Sep. 1966.

[3] Cohn, S., editor for JTAC, "Spectrum Engineering: The Key to Progress." Mar. 1968.

[4] Hinchman, W. R., "Use and Management of Electrospace: A New Concept of the Radio Resource," IEEE Conference on Communication, Conference Record (IEEE NY), 1969.

[5] Rostow, E. (ed.), for President's Task Force on Communications Policy, "The Use and Management of the Electromagnetic Spectrum," Staff Paper 7, Clearing House for Federal Scientific and Technical Information, PB 184421, Washington, DC, Jun. 1969.

[6] Vinogradov, N. V., "A criterion for estimating the efficiency of radio frequency spectrum utilization," " Telecommun. Radio Eng., vol. 28/29, pp. 37-42, Dec. 1974.

[7] Ewing, D. R. and L. A. Berry, "Metrics for Spectrum-Space Usage," OT Report 73-24, Office of Telecommunications Policy Support Division, Office of Telecommunications, Boulder, CO, U.S. Dept. of Commerce, Nov. 1973.
https://www.its.bldrdoc.gov/publications/3174.aspx

[8] Colavito, C., "On the efficiency of the radio frequency spectrum utilization in fixed and mobile communication systems," Alta Frequenza, vol. XLIII, pp. 640-651, Sep. 1974.

[9] Hatfield, D. N., "Measures of spectral efficiency in land mobile radio," IEEE Vehicular Technology Group Conference Record, pp. 23–26, 1975.

[10] Hatfield, Dale N., "Measures of spectral efficiency in land mobile radio," IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-19, No. 3, pp. 266–268, Aug. 1977.

[11] Berry, L. A., "Spectrum metrics and spectrum efficiency: proposed definitions," IEEE Trans. on Electromagnetic Compatibility, vol. EMC-19, no. 3, pp. 254-260, Aug. 1977.

[12] Berry, L. A., and E. J. Haakinson, "Spectrum Efficiency for Multiple Independent Spread-Spectrum Land Mobile Radio Systems," NTIA Report 78-11, NTIA/ITS, U.S. Dept. of Commerce, Boulder, Colorado, Nov. 1978.
https://www.its.bldrdoc.gov/publications/1919.aspx

[13] Moreno, L. "Spectrum utilization in a digital radio-relay network," IEEE Trans. on Electromagnetic Compatibility, vol. EMC-24, no. 1, pp. 40-45, Feb. 1982.

[14] Cronin, D. H. and L. A. Berry, "The Effect of Bandwidth and Interference Rejection on the Spectrum Efficiency of Land Mobile Radio Systems," NTIA Report 83-139, NTIA/ITS,

U.S. Dept. of Commerce, Boulder, CO, Dec. 1983.
https://www.its.bldrdoc.gov/publications/2140.aspx.

[15] Consultative Committee International Radio (CCIR), "Definition of Spectrum Use and Efficiency," CCIR Report 662-2, pp. 1-14. *In*: Recommendations and Reports of the CCIR 1986, vol. 1: Spectrum Utilization and Monitoring, XVIth Plenary Assembly, Dubrovnik, 1986. Published Geneva 1986.

[16] Cohn, S. I., editor for Sachs/Freeman Associates, "Methodology for Determining Spectrum Efficiency," Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC) Document Number TSC-2026/1-1. 4. 9, via TSC Purchase Order 43–SANT503717, 1401 McCormick Dr., Landover, MD, 1986.

[17] Berry, L.A. et al., "Application of the Technical Spectrum Efficiency Factor (TSEF) to the Fixed Service in Three Frequency Bands," NTIA Technical Memorandum TM-86-115, NTIA/ITS, U.S. Dept. of Commerce, Boulder, CO, Sep. 1986.
https://www.its.bldrdoc.gov/publications/2109.aspx.

[18] Mayher, R. J., R. H. Haines, S. E. Litts, L. A. Berry and G. F. Hurt, "The SUM Data Base: A New Measure of Spectrum Use," NTIA Technical Report TR-Report 88-236, NTIA/OSM and NTIA/ITS, U.S. Dept. of Commerce, Annapolis, MD, Aug. 1988.
https://www.its.bldrdoc.gov/publications/2260.aspx.

[19] Hinkle, R. J. and A. Farrar, "Spectrum Conservation Techniques for Fixed Microwave Systems," NTIA Technical Report TR-89-243, NTIA/OSM, U.S. Dept. of Commerce, Annapolis, MD, May 1989. https://www.its.bldrdoc.gov/publications/2267.aspx.

[20] CCIR, "Definition of Spectrum Use and Efficiency," CCIR Report 662-3, Geneva, 1990.

[21] Cohen, D. J., P. C. Roosa, R. J. Matheson, D. E. Kitzmiller and G. M. Patrick, "Land Mobile Spectrum Efficiency: A Plan for Federal Government Agencies to Use More Spectrum-Efficient Technologies," NTIA Technical Report TR-93-300, NTIA, U.S. Dept. of Commerce, Annapolis, MD, Oct. 1993. https://www.its.bldrdoc.gov/publications/2326.aspx.

[22] R. J. Matheson, "A Survey of Relative Spectrum Efficiency of Mobile Voice Communication Systems," NTIA Report 94-311, NTIA/ITS, U.S. Dept. of Commerce, Boulder, CO, Jul. 1994. https://www.its.bldrdoc.gov/publications/2338.aspx.

[23] International Telecommunications Union Radiocommunication Sector (ITU-R), "Definition of Spectrum Use and Efficiency of a Radio System," Recommendation ITU-R SM.1046-2, Geneva, May 2006.

[24] Joiner, B., A. Paul, K. Cai and E. F. Drocella Jr., "Assessment of Federal and Non-Federal Land Mobile Radio Frequency Assignment Methodologies," NTIA Technical Report TR-07-447, NTIA/OSM, U.S. Dept. of Commerce, Washington, DC, May 2007.
https://www.its.bldrdoc.gov/publications/2484.aspx.

[25] Cai, K., B. Joiner, R. J. Matheson, E. F. Drocella Jr., G. M. Patrick and D. S. Anderson, "Assessment of Alternative Future Federal Land Mobile Radio Systems," NTIA Technical Report TR-08-451, NTIA/OSM and NTIA/ITS, U.S. Dept. of Commerce, Washington, DC, Dec. 2007 https://www.its.bldrdoc.gov/publications/2488.aspx.

[26] ITU-R, "Requirements Related to Technical Performance for IMT-Advanced Radio Interfaces," Report ITU-R M.2134, Geneva, 2008.

[27] Commerce Spectrum Management Advisory Committee, Working Group 1 (CSMAC WG-1), "Definitions of Efficiency in Spectrum Use," October 2008.

[28] Federal Communications Commission (FCC) Technological Advisory Council, Sharing Work Group, "Spectrum Efficiency Metrics," FCC Whitepaper, Washington, DC, Sep. 2011. https://www.fcc.gov/oet/tac/2011.

[29] P. Rysavy, "Challenges and considerations in defining spectrum efficiency," Proc. of the IEEE, vol. 102, issue 3, pp. 386-92, Mar. 2014.

[30] ITU-R, "IMT Vision: Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," ITU-R Recommendation 2083-0, Geneva, Sep. 2015.

[31] "Manual of Regulations and Procedures for Federal Radio Frequency Management," NTIA/OSM, U.S. Dept. of Commerce, Washington, DC, Sep. 2015 revision of May 2013 edition. https://www.ntia.doc.gov/page/2011/manual-regulations-and-procedures-federal-radio-frequency-management-redbook.

[32] NTIA, "Quantitative Assessments of Spectrum Usage," U.S. Dept. of Commerce, Nov. 2016. https://www.ntia.doc.gov/report/2016/quantitative-assessments-spectrum-usage.

[33] International Telecommunications Union Radiocommunication Sector (ITU-R), "Definition of Spectrum Use and Efficiency of a Radio System," Recommendation ITU-R SM.1046-3, Geneva, Sep. 2017.

[34] ITU-R, "Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interfaces," Report ITU-R M.2410-0, Geneva, Nov. 2017. https://www.itu.int/pub/R-REP-M.2410-2017.

[35] Samuelson, R.J., "Communications policy plans finally released," The Washington Post, 21 May 1969.

[36] Broadcasting Magazine, "Task force study finally reaches Hill," 26 May 1969.

[37] Federal Communications Commission (FCC) Spectrum Policy Task Force: Report of the Spectrum Efficiency Working Group (SEWG). Washington, DC, 15 Nov. 2002. https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf.

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Spectrum is a limited resource upon which the world makes continually increasing demands. It is therefore natural and compelling to study the efficiency with which radio systems use spectrum. Such studies may be used to understand the extent to which radio spectrum may be better utilized by future systems, as well as how better allocation and sharing decisions may be made by spectrum engineers and managers for existing systems. This report provides a 53-year historical review of previous domestic and international spectrum efficiency studies. Based on this review, we recommend possible future spectrum efficiency work to extend the state of knowledge in this area. A recommended approach for future efficiency studies and metrical development is laid out. We recommend that OSM and ITS, which have both been leaders in past SE studies, should undertake new SE work based on technological developments that have only become available for widespread implementation in field-deployed radio systems. The problem of how to include radio systems' potential for sharing spectrum with both similar and different systems (e.g., for mobile and cellular radios to share spectrum with other mobile systems and with non-mobile systems) is discussed within the framework of how sharing potential may be assessed. Effectiveness and cost are important additional aspects of spectrum use, but these topics are beyond the scope of this spectrum efficiency study.

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