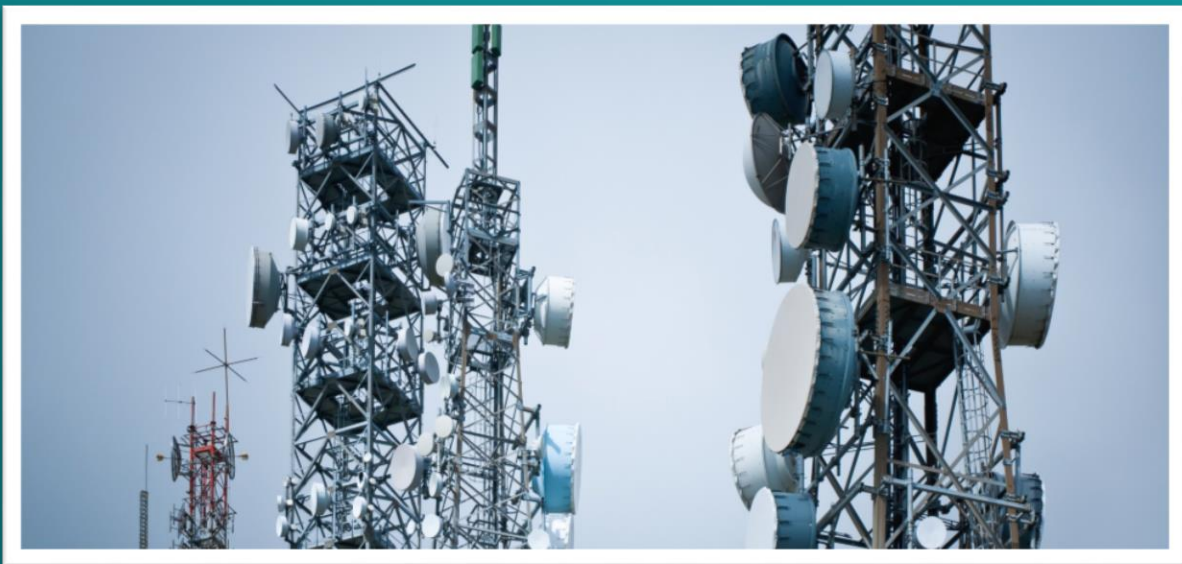


SPECTRUM EFFICIENCY MEASUREMENT

Definitions and considerations to be observed
for its application in Mexico



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The Spectrum Engineering and Technical Studies Bureau and the Engineering and Technology Bureau define the concept of *spectrum efficiency* as well as the means for its measurement, called *Spectrum Efficiency Integral Measurement (SEIM)*, which will be mandatory for all concessionaires. However, since the SEIM considers economic, social and regulatory aspects, this study seeks the involvement of the industry, the academy and society in the analysis of the elements to be included in the SEIM.

To this purpose, this research displays an integrated view of *spectrum efficiency*, from the analysis of the state of the art, to further define the *spectrum efficiency* as will be adopted by the IFT. Later, the SEIM concept and its component sub-metrics are defined; finally, those technical and regulatory premises involved in the compliance of the spectrum efficiency metrics by concessionaires are analyzed.

The content of this research and the opinions expressed on it does not reflect a definitive statement by the Governing Board of the IFT regardless certain regulation, guidelines or normativity. The only purpose of this research is to give context to the questions given in the Participation Form of the “Public Consultation for Integration to collect useful information for the design of Spectrum Efficiency Metrics”.



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PREAMBLE

- 1 The radio spectrum (hereinafter the “spectrum”) is a limited natural resource holding a high economic and social value, with a growing demand. Its demand is so high, as well as the diversification of its applications (mobile telephone, mobile broadband, security communications, Internet of Things, satellite communications, etc.), that nowadays its utilization has a transverse impact in practically all aspects of human activity.
- 2 In this sense, the Radio Regulations, instrument by which the Member Countries¹ of the International Telecommunication Union (hereinafter, the “ITU”) regulate radio services, indicates in its preamble the following:

*“0.2 Members shall endeavor to limit the number of frequencies and the spectrum used to the minimum essential to provide in a satisfactory manner the necessary services. To that end, **they shall endeavor to apply the latest technical advances as soon as possible** [...]*

*0.3 In using frequency bands for radio services, Members shall bear in mind **that radio frequencies and any associated orbits**, including the geostationary-satellite orbit are limited natural resources and that **they must be used rationally, efficiently and economically**, in conformity with the provisions of these Regulations [...]*

0.5 With a view to fulfilling the purposes of the International Telecommunication Union set out in Article 1 of the Constitution, these Regulations have the following objectives: [...]

*0.6 **to facilitate equitable access to and rational use of the natural resources of the radio-frequency spectrum and the geostationary-satellite orbit; [...]***

*0.9 **to facilitate the efficient and effective operation of all radiocommunication services;**”²*

(Emphasis added).

- 3 In this line of thought, one of the objectives of regulators³ is to maximize the social benefit from the exploitation of the radio spectrum. Consequently, the radio spectrum shall be managed by regulators in a rational manner and being watchful at all times that such resource is not wasted by the concessionaires⁴. It is therefore necessary to have mechanisms for the regulators to identify not only the degree of utilization of the spectrum by the concessionaires but also how *beneficial* is this utilization to society.
- 4 However, various factors have a direct influence on the degree to which concessionaires may take maximum advantage of their authorized spectrum. These factors include physical propagation properties of some frequency bands over others to provide a certain radiocommunication service; technical characteristics of the deployed networks (antennae,

¹ International Telecommunications Union member countries referred in the Radio Regulations only as “Members”.

² ITU, *Radio Regulations. Articles*, Switzerland, International Telecommunication Union, Vol. I, 2016, p. 3.

³ Those entities or agencies in each country in charge of the management of the radio spectrum.

⁴ Individual or legal entity holding a concession granting the right to use, leverage or exploit frequency bands of the radio spectrum or orbital resources, in the terms and modes established by the Federal Telecommunications and Broadcasting Law.

transmitters, receivers, media access techniques, technology, etc.), and the regulatory conditions under which the holders of the spectrum are enabled to provide their services.

- 5 In this context, a possible mechanism to verify the use of the radio spectrum is through the application of *Spectrum Efficiency Metrics* (hereinafter "SEM"). Generally, the SEM are composed of formulae to obtain numerical indicators that evaluate how efficiently the concessionaires use the spectrum in relation with the radiocommunication services they provide. But, how is *efficiency* defined in reference to the radio spectrum? How to measure *spectrum efficiency*? Which parameters shall be considered in the metrics? How should the result of the metrics be parametrized?
- 6 So, this document is intended to offer an integrated view of spectrum efficiency from the analysis of the state of the art, to further propose a definition of spectrum efficiency and analyze those technical and regulatory premises that shall be observed for its implementation in Mexico.

ACRONYMS

Cofetel	Federal Telecommunications Commission
DOF	Federal Official Gazette
DTT	Digital Terrestrial Television
EEM	Economic Efficiency Metric
GoS	Grade of Service
IEEE	Institute of Electrical and Electronics Engineers
IFT	Federal Telecommunications Institute
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
LFTR	Federal Law on Telecommunications and Broadcasting
LTE	Long Term Evolution
MVNO	Mobile Virtual Network Operator
PNER	National Radio Spectrum Program
QM	Quality Metric
SE	Spectrum Efficiency
SEIM	Spectrum Efficiency Integral Metric
SEM	Spectrum Efficiency Metric
SPTF	Spectrum Policy Task Force
SUE	Spectrum Utilization Effectiveness
T-RSEM	Technical-Regulatory Spectrum Efficiency Metric
UER	Radio Spectrum Unit
WMC	Wholesale Mobile Concessionaire

GLOSSARY

Coding	Action performed by the transmitter consisting of the conversion of the information signal into signs, symbols, letters, numbers, etc. to be received and understood by the receiver.
Data compression	Reduction in the number of bits used to represent one or more pieces of data.
Directivity	Characteristic of an antenna that indicates the concentration of the radiation emitted by the transmitting antenna in a certain direction, or emphasis of the radiation received by a transmitter antenna from a certain direction.
Erlang	Unit of traffic density in a telecommunications system.
Geostationary satellite	A satellite with a circular and direct orbit located on the Earth's equatorial plane and with a revolution period equal to the Earth's rotation period. Therefore, the relative position of the satellite remains fixed in relation with a fixed point on the surface of the Earth.
International Mobile Telecommunications	Generic term to designate mobile broadband services around the world.
Internet of Things	Global infrastructure of the information society that allows the provision of advanced services by interconnection to objects (either physical or virtual) thanks to the interoperability of information technologies and current and future communications.
LTE	Long Term Evolution Technology used to deploy 4G networks. This technology makes full usage of the Internet protocol for all services (data and voice) and the connections between all the points in its network.
Media access technique	Technique used to access and share the same transmission media between two or more radiocommunication devices.
Mobile broadband	High capacity access service that allows the provision of diverse convergent mobile services through a reliable network infrastructure, regardless of the technologies used.
Mobile Virtual Network Operator	Concessionaire or authorized party who provides sales or resales mobile services or capacities previously contracted with a wholesale mobile concessionaire.

Modulation	Process applied to change one or more properties of a transport frequency proportionally to the information signal.
Multiplexing	Transmission of information from one or more sources to one or more destinations over the same propagation medium. Although transmission is done over the same medium, it does not necessarily occur at the same time or occupies the same bandwidth.
Multiprogramming	Distribution of more than one programming channel over the same broadcasting transmission channel.
Orthogonal use of frequencies	Digital modulation technique that transmits information over various transport frequencies, which are orthogonal to each other. This orthogonal feature means that at the maximum intensity point of one transport, the others have null intensity.
Radio Spectrum	Space that allows the propagation, without any artificial guidance, of electromagnetic waves with frequency bands conventionally fixed below 3,000 GHz.
Radiocommunication services	Service implying the transmission, emission or reception of radio waves for specific telecommunications purposes.
Signal fading	A reduction in a signal's power or energy due to losses during its propagation.
Thermal noise	Noise generated by thermal disturbance of the electrons in a conductor. Also known as white or Johnson noise.
Wholesale Mobile Concessionaire	Holder of a commercial use concession that allows the provision of mobile services and who offers wholesale mobile telecommunications services.

I. BACKGROUND OF THE SPECTRAL EFFICIENCY METRICS PROJECT

1.1 The radio spectrum in Mexico. Study and actions. More and better spectrum for Broadband.

- 7 On early 2013, the now extinct Federal Telecommunications Commission (Cofetel), to provide inputs for compliance with objectives 41 (Trunking Telecommunications network) and 44 (Competition in telephone and data services) of the “Pact for Mexico”⁵, published a study called “*THE RADIO SPECTRUM IN MEXICO. STUDY AND ACTIONS. More and better spectrum for Broadband*” (hereinafter the “Study”). Broadly, the Study analyzed more than 600 MHz identifiable as IMT (*International Mobile Telecommunications*) and was able to identify 124 MHz additional spectrum below the 4 GHz band which may be feasible to provide broadband services; making special emphasis on those bands identified as IMT by the ITU.
- 8 In this context, part of the Study sought to exemplify in a simple way the use of the spectrum by the concessionaires, referred to their number of users and the granted amount of spectrum. This way, “intensity of use” was defined, and was measured by dividing the number of users by the amount of spectrum (users/MHz) for each concessionaire.
- 9 In addition, the Study included a basic analysis on the “*Efficient Use of the Spectrum*”, as well as a proposed action to “*Design and Implement a Methodology to Estimate Spectrum Efficiency*”, where it concluded as follows:

“Current situation

- *Efficiency in the use of the spectrum is not a concept that has an established metric.*
- *Some assigned spectrum bands show low use intensity.*
- *In some cases, spectrum assignments have led to a speculative element seeking to rise the resource’s prices.*
- *No obligation is currently set for the regulated parties for an efficient use of their assigned or granted spectrum.*

Issue

- *There is no methodology or minimum criteria to measure the degree of efficiency in the use of spectrum bands.*
- *No guidelines, criteria or procedures exist to measure the degree of efficiency in the use of the spectrum.*
- *No relevant international experience has been found related to the application of methods to determine the spectrum efficiency of bands in use.*
- *Since a methodology is not available, the economic and social affectations caused by an inefficient use of the spectrum are unknown.*

⁵ Presidency of the Republic, “Pact for Mexico”, Mexico, 2012. Recovered on February 15, 2012, available at: <http://pactopormexico.org/PACTO-POR-MEXICO-25.pdf>

- Nowadays, the authorities of the sector do not have regulating instruments to establish obligations on the regulated parties for the efficient use of the spectrum resources”⁶.

10 Under this analysis, the Study proposes seven actions that may solve the issue, as follows:

“Proposed actions

1. Make a study that collects international experience on the determination of methods to evaluate efficiency in the use of the spectrum.
2. Make studies aimed at the development of methodologies and the obtention of metrics on the efficient use of the spectrum.
3. Based on those studies, define a methodology to measure spectrum efficiency, applicable to Mexico, considering the specific characteristics of the domestic telecommunications sector.
4. Formally define the methodology to be adopted for its application to spectrum efficiency measurement processes.
5. Regular execution of the mechanisms and procedures by which the degree of efficiency in the use of the spectrum will be measured.
6. Adapt equipment and applications used by the National Monitoring Network for the technical execution of the measurements related to the spectrum efficiency methodology.
7. Issuance of the general provisions to define the conditions, guidelines and applicability under which measurements will be taken, reports will be issued and corrections will be made to improve efficiency in the use of the spectrum”⁷.

11 It shall be noted that the Study never defined the term “spectrum efficiency” but did aim at a reorganization of the spectrum to introduce new radiocommunication services and new technologies (rebanding).

1.2 Mexican legislation and regulations on Spectrum Efficiency

1.2.1 The Mexican Constitution.

12 On June 11, 2013 the “Executive Order amending and supplementing various provisions of articles 6, 7, 27, 28, 73, 78, 94 and 105 of the Political Constitution of the Mexican United States”, by which the Federal Institute of Telecommunications (IFT or the “Institute”) is created, was published in the Federal Official Gazette (“DOF”). In this sense, Article 28 of the Constitution stipulates that:

“Monopolies, monopolistic practices [...] are forbidden in the Mexican United States

*The Federal Telecommunications Institute is an independent agency, with legal capacity and assets, whose purpose is the **efficient development of broadcasting and telecommunications**, in accordance with the Constitution and in the terms set by law. The*

⁶ Cofetel, “THE RADIO SPECTRUM IN MEXICO. STUDY AND ACTIONS. More and better spectrum for Broadband”, *Federal Telecommunications Institute*, Mexico, 2013. Recovered on February 15, 2012, available at: <http://www.ift.org.mx/sites/default/files/contenidogeneral/espectro-radioelectrico/el-espectro-radioel-ctrico-en-mexico.estudio-y-acciones-final-consulta.pdf>

⁷ Idem.

IFT is in charge of the regulation, promotion and supervision of the use and exploitation of the radio spectrum, networks and the provision of broadcasting and telecommunications services [...].

(Emphasis added).

1.2.2 Federal Telecommunications and Broadcasting Law

13 Therefore, on July 14, 2014 the Federal Telecommunications and Broadcasting Law (LFTR) was published in the DOF. It shall be noted that this Law does not include a concrete definition of the *efficient use of the spectrum* or *spectrum efficiency*. However, it does provide for the development and promotion of an efficient use of the radio spectrum as well as the efficient provision of telecommunications and broadcasting services under a collective understanding of the word *efficiency*.

14 This is stressed by **Article 54** of the LFTR, which indicates that:

"The radio spectrum and orbital resources are National public domain assets, held and managed by the State [...]

On managing the spectrum, the Institute shall seek to attain the following general objectives for the users' benefit: [...]

IV. The effective use and protection of the spectrum [...]"

15 Relating to the SEM, subject herein, the LFTR indicates the following in its Title Second, Chapter I, Section I "About the Authority of the Institute and its Composition":

"Article 15. To exercise its authority, the Institute is empowered to: [...]

XLVIII. Establish the mandatory *spectrum efficiency metrics* as well as the measurement methodologies to allow their quantification".

(Emphasis added).

16 Also, in Title Fifteenth, Penalties, a sanction was considered for any holder of the spectrum who does not comply with the established spectrum efficiency levels. So, Chapter II on Telecommunications and Broadcasting establishes that:

"Article 298. Breach of the provisions of this Law and its regulations, will be penalized by the Institute in accordance with the following: [...]

D) A fine equivalent to 2.01% to 6% of the concessionaire's or the authorized party's revenue for: [...]

VII. Failing to comply with the efficiency levels of use of the radio spectrum established by the Institute".

(Emphasis added).

1.2.3 National Radio Spectrum Program

- 17 The Constitutional Amendment on the subject of Telecommunications (the “Amendment”), published in the DOF on June 11, 2013⁸, considered among its main objectives to allow access to information and communications technologies, including broadband, to the population, as well as to establish competition and free access conditions for telecommunications and broadcasting services. This way, a larger number of users would be allowed access to such services, under better quality and pricing terms.
- 18 Consistent with this, and considering the relevance of the radio spectrum for the provision of telecommunications and broadcasting services, article seventeenth transitory of the Amendment established that, within the framework of the National Democratic Planning System, the Federal Executive should include in the National Development Program and the corresponding sectoral, institutional and special programs, a National Radio Spectrum Program (PNER, for its acronym in Spanish), which would establish two working programs: one for the 700 MHz and 2.5 GHz frequency bands, and another to reorganize the spectrum to radio and television stations.
- 19 So, on September 29, 2017, the Ministry of Communications and Transport published the PNER in the DOF⁹. Within the elements included in the PNER, the general objectives with their corresponding strategies and lines of action were included. The lines of action are associated to the development and implementation of market mechanisms to promote an optimum assignment of the spectrum and to guarantee the competition process and free access. Therefore, Objective 3 states the following:

Objective 3	
<i>Develop actions to determine and encourage an efficient use of the radio spectrum in the country.</i>	
<i>Description</i>	<p><i>The radio spectrum is a scarce resource and, consequently, it is necessary that the corresponding public policies and regulations seek a more efficient use of such resource.</i></p> <p><i>Since an efficient use of the spectrum involves diverse approaches, this objective states the preparation and execution of diverse strategies and lines of action to determine the degree of efficiency in the use of the radio spectrum, as well as to develop measures to reorganize the spectrum.</i></p>

<i>Strategy 3.1. Evaluate the efficient use of the radio spectrum.</i>	
<i>Action Lines</i>	
<i>3.1.1.</i>	<i>Prepare mandatory spectrum efficiency metrics.</i>
<i>3.1.2.</i>	<i>Prepare measurement methodologies to allow the application of spectrum efficiency metrics.</i>

⁸ Further information is available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5301941&fecha=11/06/2013

⁹ “National Radio Spectrum Program 2017-2018”, available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5498528&fecha=26/09/2017

1.3 Comments

- 20 Even when *spectrum efficiency* has been discussed in Mexico for some time (from the final stages of the now extinct Cofetel to this day in the IFT), and how it may impact the development of telecommunications and broadcasting, **to this date no precise definition of “spectrum efficiency” exists for its concrete meaning**, even by the ITU.
- 21 In addition, as indicated in item 2.2.2, the LFTR mentions the terms *efficiency* and *effectiveness* as equivalent for the case of the radio spectrum and, reading carefully, it may be interpreted that the efficiency/effectiveness is composed of different factors such as service quality, technical implementations within telecommunications and broadcasting networks and economic competition aspects, among others.
- 22 Additionally, it is expected that the existence of SEM will not only be part of a regulatory framework to promote an efficient use of the spectrum, but that its compliance will have an impact on the holders of the spectrum. In this sense, Article 298 of the LFTR mentions a sanction on those concessionaires who do not comply with the spectrum efficiency *levels* established by the Institute.
- 23 It may therefore be established that:
1. No definition of *spectrum efficiency* exists, even internationally.
 2. To evaluate *spectrum efficiency*, it is necessary to consider various factors, since it may be addressed from diverse scopes: economical, regulatory and technical.
 3. *Spectrum efficiency* shall be measurable, so that certain parameters may be applied to define “levels” and so comply with Article 298 of the LFTR.
 4. In addition to item 3, breach of spectrum efficiency levels causes an administrative sanction.
- 24 As may be noted, not having a definition of *spectrum efficiency*, prevents the existence of “metrics” to quantify it. As a consequence, the following section analyzes the state of the art on the definitions of *spectrum efficiency* and the implications associated to its measurement, which have been prepared by different involved agents such as the industry, the academy, international agencies and regulators.

II. STATE OF THE ART ON SPECTRAL EFFICIENCY

- 25 At the early sixties, the impact of *spectrum efficiency* on the use and exploitation of the spectrum, on both holders and end users, was being discussed in international conferences or scientific journals. At that time the first definitions or rather approximations to what should be (or should include) the spectrum efficiency began to appear; such ideas have remained to these days. Therefore, this chapter shows the state of the art on the definitions of spectrum efficiency, as well as a general view of the diverse approaches to define the metrics that have been conceptualized to quantify *efficiency*.
- 26 It shall be noted that various research articles address the concept of *spectrum efficiency*, but focused only on specific technical aspects, for example, *efficiency* between signal coding techniques, *efficiency* in antennae radiation patterns, *efficiency* on thermal noise in transmission systems, and *efficiency* between multiplexing techniques, among others. In short, there are uncountable *efficiencies* which, generally speaking, seek to “show” how some method, technique or technology is better than another one. So, although these *efficiencies* somehow impact *spectrum efficiency*, none of them is able to unify those factors that should be involved in the definition of parameters for *spectrum efficiency*. Therefore, the state of the art indicated here does not consider those isolated definitions of *efficiency*.

2.1 Institute of Electrical and Electronics Engineers: IEEE

- 27 The digital library of the IEEE¹⁰ includes two key articles that are the conceptual columns for the intents to define *spectrum efficiency* and its measurement. The first document that refers in a *unified* manner to *spectrum efficiency* was published in 1976 by Leslie A. Berry and is called “*Output Oriented Measures of Spectrum Efficiency*”¹¹. Later, in 1992, Shila Heeralall published an article called “*Discussion of Spectrum Efficiency and Factors that Affect it*”¹².
- 28 Although these articles may be deemed as “obsolete” due to the dates when they were written, the concepts and formulae proposed in them do not expire regardless of technological progress attained to this date. Such is the case that later articles resume this work to go deeper into the formulae proposed in both articles without adding any innovation. Therefore, the contents of both articles are addressed and explained below, as well as their author’s conclusions.

2.1.1 “Output Oriented Measures of Spectrum Efficiency”, Leslie A. Berry

- 29 This document is aimed at the proposal of a definition of efficiency, as well as to establish procedures to increase effectiveness and an *efficient use of the spectrum*. So, the article

¹⁰ The Institute of Electrical and Electronics Engineers, better known as the IEEE, is a worldwide association of engineers aimed at standardization and the development of technologies for the benefit of humanity and, in an effort to disseminate technological developments. This institute has a digital library known as the IEEE Xplore Digital Library, famous around the globe for its prestige and professionalism, available at: <http://ieeexplore.ieee.org/Xplore/home.jsp>

¹¹ Berry, Leslie A., “Output Oriented Measures of Spectrum Efficiency”, *IEEE 1976 International Symposium in Electromagnetic Compatibility*, United States, 1976, pp. 1-3.

¹² Heeralall, Shila, “Discussion of spectrum efficiency and the factors that affect it”, *1992 IEEE International Conference in Selected Topics in Wireless Communications*, Canada, 1992, pp. 413-416.

proposes to measure spectrum efficiency seen as an *output/input rate* of any telecommunications system and makes a comparison with another (homologous) type of *efficiency* measurement, which is the *ideal/input ratio*. Although this document does not precisely define *spectrum efficiency*, it does establish it through these ratios, which are explained below.

2.1.1.1 The definition of the “output/input ratio” formula

30 In the *output/input* ratio, the numerator is the product obtained as output from a telecommunications system and the denominator is the factor (or factors) used to generate the output. Generally, it may be represented as follows:

$$\frac{\text{delivered information}}{\text{spectrum space}}$$

where the “*space spectrum*” is the generally the product of three factors: the *amount of used spectrum*, the *geographic area* “covered” by this spectrum and the *time* of utilization. This formula is so versatile that it may be adapted for different types of radiocommunication services, of which the following four are exemplified in said article:

Service	Formula
Services via geostationary satellite with digital modulations	$\frac{\text{bits}}{(\text{bandwidth})(\text{orbital arc})(\text{time})}$
Analog communications satellite	$\frac{\text{data bandwidth}}{(\text{bandwidth})(\text{orbital arc})}$
Microwave point-to-point networks	$\frac{(\text{no. of channels used})(\text{data channel bandwidth})}{(\text{required bandwidth})}$
Mobile radio systems	$\frac{\text{traffic}}{(\text{bandwidth})(\text{area})(\text{time})}$

2.1.1.2 About the *ideal/input ratio* formula

31 Relating to this formula, another type of definition of *special efficiency* exists, the *ideal/input ratio*, expressed as follows:

$$\frac{\text{space spectrum of an ideal system}}{\text{space spectrum of the evaluated system}}$$

where the denominator is the same as in the *output/input ratio* and the numerator has the same factors as the denominator but obtained from an “ideal” or “perfect” system.

32 So, the author argues that:

“Suppose that the spectrum efficiency of a point-to-point microwave link needs to be computed. The link shall carry a fixed number of telephone circuits to *m* miles a determined percentage of time. The previous sentence constitutes the “output”, which is the numerator in the output / input efficiency ratio [...]

Now consider the calculation of the ideal efficiency measurement [...] How can the ideal system be determined? **And what is the amount of spectrum space used by an "ideal system"?** The transmission could be via coaxial cable or by waveguide which would use almost zero spectrum space. Is this the ideal system? Or the system could use antennas with very narrow main beams and very low side lobes. What is the pattern of the "ideal" antenna? Other parameters which would reduce the required spectrum space would have to be specified; e.g., receiver noise figure, modulation index, and modulation type. **It is the necessity of answering these questions that make the "ideal" measure of spectrum efficiency difficult to compute and somewhat subjective**¹³.

(Emphasis added).

- 33 Later, in 1977, Leslie A. Berry published another article titled "Spectrum Metrics and Spectrum Efficiency: Proposed Definitions"¹⁴, where the author resumes the definition of *output/input ratio* to quantify the *spectrum efficiency*, as in her previous article. However, although this article may seem identical to the previous one, its added value is that the *output/input ratio* is characterized as a *metric* to compare *efficiency* between telecommunications systems. Also, the author reaffirms that considering a metric that includes "ideal" parameters would make the computation of the metrics more difficult and would make it look "subjective".

2.1.1.3 "Spectrum Utilization Problems", Serge S. Sviridenko

- 34 As in 1977, and within the same publication as Leslie A. Berry's article, Serge S. Sviridenko's article "Spectrum Utilization Problems"¹⁵ was published, analyzing and discussing diverse problems on the utilization of the spectrum, including an *efficient use of the spectrum*. Although this article does not define or propose the concept of *spectrum efficiency*, or anything related to a measurement to quantify efficiency, it does highlight that *spectrum efficiency* shall not be considered as an "exclusive" matter of technique or technology, but that it involves other factors such as economic factors. In this context, Serge arguments that:

*"At the national level, the spectrum is used for the management of industry and national resources, defense and security forces, broadcasting, radiocommunications, meteorology, astronomy, space research, and other purposes. The role of the spectrum in the international exchange of information needs no further elucidation here. It is clear that the significance of the spectrum is not only technical but also economic and social"*¹⁶.

(Emphasis added).

- 35 So, the evaluation of an efficient use of the spectrum not only depends on technical factors (as may be suspected initially) but it impacts other aspects of great importance such as

¹³ Berry, Leslie A., "Output Oriented Measures of Spectrum Efficiency", *IEEE 1976 International Symposium in Electromagnetic Compatibility*, United States, 1976, pp. 1-3.

¹⁴ Berry, Leslie A., "Spectrum Metrics and Spectrum Efficiency: Proposed Definitions", *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-19, no. 3, United States, 1977, pp. 254-260.

¹⁵ Sviridenko, Serge S., "Spectrum Utilization Problems", *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-19, no. 3, Switzerland, 1977, pp. 260-265.

¹⁶ *Idem*.

economic and social. Therefore, the evaluation of the efficiency in the use of the spectrum should, in principle, go further than technical factors:

"In order to evaluate the efficiency in the use of the spectrum, it is necessary to have technical criteria for its quantification and measurement..."

*Besides having criteria for the quantitative measurement of the utilization of the spectrum, it would be useful to **have criteria for the economic analysis of the spectrum** as a resource"¹⁷.*

(Emphasis added).

2.1.2. Discussion of spectrum efficiency and the factors that affect it, Shila Heeralall

- 36 The first objective of this document is to "develop a unified method of assessing spectrum efficiency (Erlangs/km²/Mhz) for any system, and to discuss the basic opportunities for improving it". The second objective is to "consider practical systems: identify some of the main parameters and factors that affect spectrum efficiency and discuss their weight against other system requirements". It shall be noted that the article's language is mainly technical, meaning that the indicated concepts imply an advanced knowledge in telecommunications. Therefore, this section only seeks to address the main findings indicated by the author, not going any deeper into specifics.
- 37 The article does not define *spectrum efficiency* explicitly but describes it through an equation. It defines *spectrum efficiency* as the product of three main components: *time*, *space* and *frequency* which are expressed in terms of traffic density, area of coverage and utilized spectrum, respectively, as follows:

"Spectrum efficiency, 'Eff.total'. is the product of three components. These three components are: time efficiency 'Eff.time', space efficiency, 'Eff.space', and frequency efficiency, 'Eff.freq':"¹⁸

$$Eff_{total} = Eff_{time} * Eff_{space} * Eff_{freq}$$

[...]

$$Eff_{total} = \frac{\text{Erlangs/cell}}{\text{cell area} * \text{available spectrum}}$$

Where:

- Erlangs/cell = amount of traffic in one mobile telephone cell, in Erlangs.
- cell area = geographic coverage area of the cell, in km²
- available spectrum = amount of spectrum configured in the cell, in MHz.

- 38 The formula indicates that spectrum efficiency is represented by *Eff_{total}*, which is inversely proportional to the area of the cell and amount of available spectrum, and directly proportional

¹⁷ Sviridenko, Serge S., "Spectrum Utilization Problems", *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-19, no. 3, Switzerland, 1977, pp. 260-265.

¹⁸ Heeralall, Shila, "Discussion of spectrum efficiency and the factors that affect it", *1992 IEEE International Conference in Selected Topics in Wireless Communications*, Canada, 1992, pp. 413-416.

to the amount of traffic supported by the cell. So, it is possible to observe that *spectrum efficiency* may be increased or diminished introducing variations in those factors.

- 39 It shall be mentioned that, although the author focuses the *spectrum efficiency* formula on the mobile cellular service, the concept of *spectrum efficiency* subject to any modification whatsoever when applied to other telecommunications or broadcasting services. This is because the technical considerations behind the formula (service geographic area, implemented amount of spectrum and total traffic in the network) are present in most radiocommunications services.

2.1.2.1 Parameters to increase spectrum efficiency

- 40 This equation indicates that, since Eff_{total} is the product of space, time and frequency efficiencies, it is possible to increase Eff_{total} by modifying any of these parameters, for example:

- To increase Eff_{time} :
Using dynamic channel assignment, which would allow to increase their quantity in the cell without prejudice to the previously assigned amount of spectrum. Therefore, the amount of traffic in the cell is increased.
- To increase Eff_{freq} :
Diminishing the amount of spectrum by using better coding, modulation and data compression techniques.
- To increase Eff_{space} :
Diminishing the frequency reutilization distance between the cells.

2.1.2.2 Main factors and parameters affecting spectrum efficiency

- 41 Although upon a first general understanding it may be observed that spectrum efficiency may be improved, the implementation of enhancements may lead to secondary impacts on other factors and even on other efficiencies. For example, on implementing better compression techniques in audio signals, a higher number of signals may transmit over a certain bandwidth; however, this causes a reduction in the quality of the audio due to the small amount of bandwidth dedicated to transmitting the signals.

- 42 The article mentions the following factors that affect spectrum efficiency:

- the number of channels available for a specific region,
- signal fading,
- the features of the environment (terrain),
- carrier - interference ratio,
- interference due to coverage overlaps,
- non-homogeneous traffic between cells,
- the characteristics of the antennae,
- power control,

- non-continuous transmissions,
- cellular patterns selection,
- the size of the system or network, and
- the number of times that the frequencies are reused.

2.1.2.3 The author's comments

43 As a conclusion, the article mentions the following:

*"In a more general way, many trade-offs are necessary in system design [...] low cost, small size, lightweight terminals, reliability, universality, evolvability. They may influence the choice of spectrum efficiency enhancement techniques or other system design aspects or even impose simplicity. Enhancements should not impose costly sophistications and undesired trade-offs [...] Ideally they [enhancements] should be options that service providers can buy only when needed"*¹⁹.

(Emphasis added).

44 In other words, spectrum efficiency is a consequence of the concessionaire's technological improvements on its network infrastructure, according to its business plan, and not as a regulatory imperative.

2.2 International Telecommunications Union Rec. ITU-R SM.1046 "Definition of spectrum use and efficiency of a radio system"

45 To "ensure the rational, equitable, efficient and economical use of the radiofrequency spectrum by all radiocommunication services" and considering that "that there is a need for defining the degree and efficiency of spectrum use, as a tool for comparison and analysis for assessing the gains achieved with new or improved technologies, particularly by administrations in the national long-term planning of spectrum utilization and the development of radiocommunications", the ITU published in 1994 its first Recommendation ITU-R SM.1046-3 "Definition of spectrum use and efficiency of a radio system"²⁰(the "Recommendation").

46 This recommendation includes three concepts as key pieces: *the spectrum utilization factor, the spectrum utilization effectiveness (SUE) and the relative spectrum utilization efficiency*, which are based on the IEEE articles mentioned above. Then, it is to be expected that the definition of *spectrum efficiency* proposed in the recommendation, maintains the *space spectrum* concept.

2.2.1 Spectrum utilization factor

47 Since an efficient use of the spectrum is attained (among other methods) by technical implementations, for example, the directivity of the antenna, geographic separation,

¹⁹ Heeralall, Shila, "Discussion of spectrum efficiency and the factors that affect it", 1992 IEEE International Conference in Selected Topics in Wireless Communications, Canada, 1992, pp. 413-416.

²⁰ ITU-R, "Recommendation ITU-R SM.1046-3 (09/2017). Definition of spectrum use and efficiency of a radio system", Series SM Spectrum Management, Switzerland, 2006. Recovered on February 15, 2018, available at: https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1046-3-201709-!!!PDF-E.pdf

frequency sharing or orthogonal use of frequencies and time sharing, the measure (factor) of spectrum use “U” is defined as “the product of the frequency bandwidth by the geometric (geographic) space by the time denied²¹ to other potential users”, as defined below:

$$U = B \cdot S \cdot T$$

Where²²:

B: bandwidth.

S: geometric space (usually, the surface); it may be a volume, a line, or an angular sector surrounding some point. The amount of space depends on the power spectrum density.

T: time.

2.2.2 Efficiency in the use of the spectrum

- 48 The efficiency in the use of the spectrum, or *spectrum efficiency*, of a radiocommunication system may be understood as a relation between the useful effect and the utilization factor of the spectrum, which is given by the following expression:

$$EUE = \frac{M}{U} = \frac{M}{B \cdot S \cdot T}$$

Where:

M: useful effect obtained with the intended radiocommunications equipment.

U: utilization factor the spectrum with such system.

2.2.3 Relative efficiency of the utilization of the spectrum

- 49 It is possible to compare spectrum efficiencies between two similar telecommunications systems (which provide the same services) from the efficiency of a “standard” system to be used as comparison base. The preceding is defined as *relative efficiency* and is defined from the following expression:

$$ERE = \frac{EUE_r}{EUE_p}$$

Where:

RSE: relative spectrum efficiency, this is, the ration between the SUE.

SUE_p: spectrum use efficiency of a *standard* system.

SUE_r: spectrum use efficiency of an actual system.

²¹ It may be expressed also as the time during which the channel is in use.

²² The Recommendation does not specifically mention the units of the utilization factor formula. So, the selection of the units for the coefficients is up to whoever applies it, for example, establishing the bandwidth in MHz, geometric space in square kilometers and time in days.

50 In this case, an adequate model of the standard system would be the theoretically most efficient, easily defined and understood, or the one deemed as an industry standard. In case the selected standard system is the one theoretically most efficient, the ERE's value would fall between 0 and 1.

51 This being said, the Recommendation suggests the following:

1. *“that, as a basic concept, the composite bandwidth-space-time domain should be used as a measure of spectrum utilization – the “spectrum utilization factor” [...] for transmitting and receiving radio equipment;*
2. *that the basis for calculating spectrum utilization efficiency (SUE), or spectrum efficiency in short, should be the determination of the useful effect obtained by the radio systems through the utilization of the spectrum and the spectrum utilization factor[...]*
3. *that the basic concept of relative spectrum efficiency [...] should be used to compare spectrum efficiencies between radio systems;*
4. *that any comparison of spectrum efficiencies should be performed only between similar types of radio systems providing identical radiocommunication services [...]*
5. *that in determining the spectrum efficiency, the interactions of various radio systems and networks within a particular electromagnetic environment should be considered”²³.*

52 However, the Recommendation contrasts the following, relating to what shall be considered to evaluate spectrum efficiency.

“[...] values for 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, the 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. It would be beneficial to conduct the comparison of the spectrum efficiency or utilization of the same system over time to see if there is any improvement in the specific area under study.

It should also be noted that although spectrum efficiency is an important factor, because it allows the maximum amount of service to be derived from the radio spectrum, it is not the only factor to be considered. Other factors to be included in the selection of a technology or a system include the cost, the availability of equipment, the compatibility with existing equipment and techniques, the reliability of the system, and operational factors”²⁴.

(Emphasis added).

²³ ITU-R, “Recommendation ITU-R SM.1046-3 (09/2017). Definition of spectrum use and efficiency of a radio system”, Series SM Spectrum Management, Switzerland, 2006. Recovered on February 15, 2018, available at: https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1046-3-201709-!!!PDF-E.pdf

²⁴ Idem.

2.3 FCC Spectrum Regulation Task Force Spectrum Efficiency Working Group Report

- 53 At an international level, agencies in charge of the regulation of the Spectrum have said little about *spectrum efficiency* and its quantification methods, and much less a public statement exists from Administrations about the adoption of regulations to evaluate radiocommunication services' spectrum efficiency. It shall be noted that promoting an efficient use of the spectrum (arising from a collective understanding of the word *efficiency*) is not the same as a concrete definition of *spectrum efficiency* and the establishment of a methodology to quantify, evaluate and compare the spectrum efficiency of radiocommunication services.
- 54 In the United States of America, the Spectrum Policy Task Force (SPTF) of the FCC²⁵ issued a public initiative to consider methods to quantify or evaluate spectrum efficiency in such way as to allow a fair and significant comparison between the different radiocommunication services, as well as the definition and quantification of *spectrum efficiency*. In November 2012, the SPFT published the "*Spectrum Efficiency Working Group Report*"²⁶ (the Report). This report shows and compares different definitions for *spectrum efficiency*, displaying their advantages and drawbacks, as well as technical and regulatory recommendations to the FCC to improve *spectrum efficiency*.
- 55 In this report, same as Leslie A. Berry, the SPTF deemed that spectrum efficiency shall be evaluated as the output/input rate of a system that, in terms of spectrum, may be expressed considering the amount of information transmitted and the amount of spectrum used to obtain an output. However, the SPTF argued that (same as the positions shown above) *spectrum efficiency* shall not only involve the technical subject but other features shall also be considered, such as cost to improve such efficiency, the number of persons that benefit from the service and the service's added value. Consequently, the SPTF developed three definitions related to efficiency, which are quoted below:

"SPECTRUM EFFICIENCY occurs when the maximum amount of information (i.e., output) is transmitted within a given amount of spectrum (i.e., input), or equivalently, when the least amount of spectrum is used to transmit a given amount of information. This could be expressed as:

$$\text{Spectrum Efficiency} = \frac{\text{Output}}{\text{Utilized spectrum}}$$

TECHNICAL EFFICIENCY occurs when all inputs are deployed in a way that generates the most output for the least overall cost in resources, including not only the spectrum but also the equipment, other capital, and labor (i.e., all inputs). This could be expressed as:

$$\text{Technical Efficiency} = \frac{\text{Output}}{\text{Cost of all inputs}}$$

²⁵ FCC is the Federal Telecommunications Commission of the United States of America.

²⁶ SPTF, "Report of the Spectrum Efficiency Working Group", *Federal Communications Commission*, United States, November 15, 2012. Recovered on February 15, 2018, available at: https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf

[...]

ECONOMIC EFFICIENCY occurs when all inputs are deployed in a way that generates the most value for consumers. [...] Economic efficiency could be expressed as:

$$\text{Economic Efficiency} = \frac{\text{Value of the outputs}}{\text{Cost of all inputs}}$$

[...] While spectrum efficiency creates the most output with the least amount of spectrum and technical efficiency creates the most output with the least amount of all inputs, economic efficiency creates the most value with the least amount of all inputs"²⁷.

56 To understand the interaction between efficiencies, the following example may be quoted:

"A production line manager is focused on getting the most "widgets" produced during each job shift (i.e., maximizing the output for a given input). However, the plant foreman might be looking at getting the most "widgets" produced at the least cost, varying the number of workers, utilizing overtime, and buying the cheapest parts to make the widget (i.e., maximizing the output while minimizing the overall cost). The company president, on the other hand, might be thinking about whether the factory line might be better used to make "gizmos" instead of "widgets" (i.e., maximizing the value of the output while minimizing the overall cost)"²⁸.

57 In this context, spectrum, technical and economic efficiencies are not only efficiencies that evaluate the higher benefit of a radiocommunication system separately, but the three of them are part of a clockwork in which they complement each other. Economic efficiency evaluation may even be quite relevant, with a significant influence on spectrum and technical efficiencies.

58 Keeping this in mind, and after an analysis of some spectrum efficiency formulae²⁹, the SPTF concluded the following:

*"The Working Group concludes that **it is not possible, nor appropriate, to select a single, objective metric that could be used to compare efficiencies across different radio services**. Any metric would provide, inherent in its assumptions, advantages to certain services and technologies, and disadvantages to others. The Working Group does conclude, however, that rough estimates of spectrum efficiency may be useful in certain situations, as they could allow for some comparisons between technologies. **While not adopting a single metric, the Working Group still believes it to be possible, and prudent, to promote the efficient access to and use of spectrum**"³⁰.*

(Emphasis added).

²⁷ *Ibidem*.

²⁸ *Idem*.

²⁹ *Idem*.

³⁰ *Idem*.

III. DEFINITION OF SPECTRUM EFFICIENCY BY THE RADIO SPECTRUM UNIT

3.1 Proposal of a definition of spectrum efficiency

⁵⁹ Once the relevant aspects of the State of the Art have been analyzed in the preceding section, it is to be noted that many authors, including the ITU itself, use the concepts of *efficiency* and *effectiveness* as synonyms. Therefore, it is convenient to previously define and clearly distinguish such terms. Based on the Royal Academy of the Spanish Language, the definitions established by Oxford Reference³¹ in the different areas of study (economy, engineering, social sciences, etc.), as well as the sources indicated in the preceding chapter, it is possible to delimit the definitions of *efficiency* and *effectiveness* as follows:

Effectiveness: to attain a goal regardless of the resources invested.

Efficiency: the capacity to obtain the highest result using the less possible amount of resources.

⁶⁰ Consequently, the Radio Spectrum Unit (UER) deems that the appropriate term to refer to the maximum use of the spectrum is **efficiency** since “effectiveness” seeks to attain a certain purpose regardless of the invested resources (which may be optimized or wasted), while *efficiency* seeks to **maximize the purpose** optimizing the invested resources: any scarce resource, as is the case of the spectrum, shall be rationed and optimized as a fundamental condition to maximize efficiency.

⁶¹ To explain this without the need of mathematical expressions, the term *efficiency* may be understood as a simple relation between the output and input of a system: from a certain amount of input, a certain amount of output may be obtained. So, a system will be efficient if it is possible to obtain the highest output from the lowest input. Within the context of the radio spectrum, the system is any telecommunications and/or broadcasting network; the input is the amount of the spectrum available to the network for its operation and the output is the transmitted information. The fact that it is not enough to transmit the information, but it shall be delivered and perceived with the necessary quality levels for a proper provision of a certain service will be addressed and detailed later.

⁶² However, the UER also considers that, to be able to quantify the *efficiency* in the use of the spectrum, it is necessary to observe those factors external to technology, such as regulatory framework, social and economic environment in which the services are provided, and the quality of the offer. Among the aspects other than the technological ones, there are those that intervene in the socioeconomic valuation of the spectrum. For example, the different alternatives to attribute and assign frequency to certain radiocommunication services, types of concessions and their modalities of use, as well as the ponderation of public policy's objectives for the provision of telecommunication and broadcasting services.

³¹ OXFORD University Press, “Oxford Reference”, United Kingdom, 2017. Recovered on February 15, 2018, available at: <http://www.oxfordreference.com/>

Furthermore, from economic theory perspective, it could be considered other efficiency dimensions, such as productive efficiency, allocative efficiency, distributive efficiency, and dynamic efficiency, among others. Hence, it is necessary that the spectrum efficiency metrics' regulation established in the near future should be clearly defined not only in technical aspects but also in other ones. In the next points it will be explained why was considered those factors.

3.1.1 The regulatory framework

- 63 Generally speaking, to use, enjoy and exploit the spectrum, a spectrum holder shall own a concession title which grants it the right to use a certain amount of spectrum to provide its services during a determined time (concession term) and within a delimited geographic area (authorized coverage for the enabling title). Such concession title not only enables the concessionaire to use the spectrum but also includes the technical characteristics indicating the way in which it shall operate its services and other administrative and regulatory obligations to which it must abide.
- 64 It shall be mentioned that enabling titles granting the right to use the spectrum have been granted under different legal frameworks through the years, which has resulted in the existence of different enabling titles under legal figures such as permits, authorizations, assignments or concessions, which include diverse operating conditions and obligations. Some of these conditions may be interpreted as *limitations* to maximize the exploitation of the spectrum, preventing the concessionaire to exploit the spectrum even further. For example, it is common to find that a concessionaire was only enabled to provide one service (among many possibilities) over the granted frequency bands (for example, to exploit fixed services but not mobile services), or to have certain regulatory limitations imposed on it to migrate to more efficient technologies or services (for example, the case of MMDS³² services versus broadband services in the 2.5 GHz band).
- 65 In addition, some general administrative provisions (such as the Mexican Official Standards or Technical Provisions) have an influence on the way concessionaires provide their services, since those frequently establish technical operating parameters for the services³³ or equipment and devices. Therefore, a close relationship exists on the degree to which a concessionaire can make an efficient use of the spectrum and the technical specifications included in the general administrative provisions.
- 66 Besides, newly created general administrative provisions exist, published after the issuance of certain concession titles enabling the concessionaire, through technical and operating conditions, to make a more *efficient* use of the spectrum. In other words, different regulatory instruments exist that directly affect the way concessionaires use the spectrum. For example, the General Guidelines for the Authorization of Lease of the Radio Spectrum, the General Guidelines for Access to Multiprogramming or the Policy for the Transition to Digital Terrestrial Television.

³² MMDS - Acronym for Microwave Multipoint Distribution Services; a service widely used to provide pay television services over the 2.5 GHz band. Later, such band was more useful for the provision of broadband services.

³³ For example, see "Technical Standard IFT-013-2016: Minimum specifications and requirements to install and operate television stations, auxiliary equipment and complementary equipment, available in: http://www.dof.gob.mx/nota_detalle.php?codigo=5468230&fecha=30/12/2016

3.1.2 Social and economic aspects

- 67 Prior to the obtention of a concession title and arising from the analysis of market competition, the concession needs to have established a short, mid and long term business plan, which may, intrinsically and unwillingly, impair or enhance the efficient use of the spectrum, depending on the times for the deployment of the infrastructure, the technology to be deployed and those technological changes, improvements or updates that it may develop during the concession's life.
- 68 Also, due to business profitability matters, concessionaires usually deploy their networks only over a portion of the total coverage area assigned in their concession titles, since it is the portion where the highest number of potential subscribers or audience is concentrated, which will allow them to recover their investment in the network and obtain revenue for the provision of their services. From the viewpoint of maximizing profits, concessionaires have little or no incentives to serve the remaining portion of their coverage. This translates into a deployment of infrastructure over economically attractive population centers (usually urban areas), leaving behind other areas, which are mainly located in hard to reach geographic regions and have a highly disperse population. Besides, in view of the capital to invest, the concessionaire may prefer to deploy low cost technologies, which are not necessarily more efficient but do allow a "sufficient" deployment of its services and guarantee some profitability.
- 69 Following this line of thought, it is also possible that some concessionaires do cover hard to reach locations. For these cases, the value of the connectivity provided by the concessionaires to the population gains importance for the regulator since they provide the only connectivity means for the population to access telecommunications and/or broadcasting services. A sign of this issue is present in the coverage conditions of current concession titles, as well as the terms of various tenders.
- 70 In this sense, it is common that rural or hard to reach areas and locations an ample offer of wireless services is inexistent, and in many cases just one single provider is available. So this provider, not facing any competition in these markets, will not have any incentive to apply technological improvements in its network or to deliver higher quality services, which, if implemented, would contribute to a more efficient use of the spectrum.

3.1.3 Quality aspects

- 71 Due to the improvement and evolution of the technical characteristics of the air interface (signal compression methods, techniques to access the means, modulation schemas, etc.), it is increasingly possible to transmit a higher amount of information over each spectrum channel, with the consequent improvement on the efficiency of the use of the spectrum. However, a threshold exists (depending on the radiocommunication system) in which it is possible to delimit to which point such technical parameters shall be implemented. If this threshold is not observed, transmitted signals (along with the transmitted information), may experience reception and/or decoding problems, causing degradation of the radioelectric link and up to a "signal break". In this sense, the receiver perceives a "low" quality signal, information with errors, illegible information, or no signal at all. So, to make an efficient use of the radio spectrum through the indicated techniques is not a synonym of signal quality

degradation but a threshold shall be proposed where the relation between an efficient use of the spectrum and the transmitted signal's quality is balanced.

- 72 In this sense, for example, the “*General Guidelines for Access to Multiprogramming*”³⁴ establish that those broadcasting concessionaires authorized for multiprogramming shall abide by the *technical quality* principle, which implies that the signal compression format be MPEG-2 (10 Mbps for high definition and 3 Mbps for standard definition) or MPEG-4 (6 Mbps for high definition and 2.5 Mbps for standard definition). Also, these guidelines also establish different minimum transmission rates, depending on the number of channels to be multiprogrammed.
- 73 This being said, the UER proposes to define spectrum efficiency as:

Spectrum Efficiency: is the *capacity** of telecommunications or broadcasting systems to transmit *the highest amount of information* using *the lowest amount of radio spectrum* maintaining the quality of communications to at least the established minimum.

* Such capacity depends on the technological and regulatory characteristics, as well as the social and economic environment, related to the corresponding telecommunications or broadcasting service.

3.2 Definition of Spectrum Efficiency Integral Metric (SEIM)

- 74 To use Spectrum Efficiency (SE) as a useful tool to quantify and evaluate the efficient use of the spectrum between diverse types of services, it is necessary that the metrics observe the following principles: *objectivity*, *precision*, *verification* and *temporariness*. So, the metric shall be:
- *Objective*: the formula shall include those factors based on facts and logic, and not subjective and/or arbitrary arguments;
 - *Precise*: to attain the quantification of spectrum efficiency a formula for such purpose shall exist, to be obtained through a clear methodology which does not give place to confusion, discretionarily or ambiguity, for both the Institute and the regulated parties;
 - *Verifiable*: a mechanism by the Institute shall exist to allow the concessionaire to verify that the formula's computation has been done in a transparent manner, and, above all, that the information provided by the concessionaire for the computation of the metric may be corroborated or verified by the Institute.
 - *Temporary*: due to the dynamism of the technology, society and the markets, as well as the continued evolution of radiocommunication services, a metric will never be perpetual, so it shall be reviewed periodically and modified when necessary to avoid obsolescence.

- 75 So, the UER proposes the following definitions:

³⁴ IFT, “General Guidelines for Access to Multiprogramming”, *Federal Official Gazette*, Mexico, 2015. Recovered on February 15, 2018, available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5382262&fecha=17/02/2015

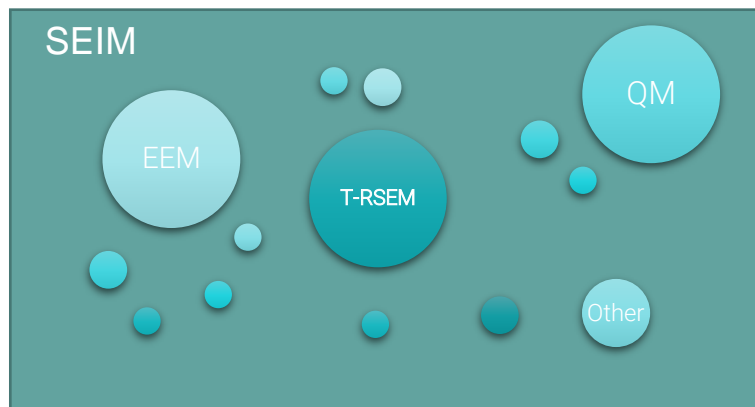
Metrics: set of qualitative and/or quantitative considerations used to measure, compare and/or track an object.

Methodology: the procedure to attain an objective.

76 However, SE, as has been said, is influenced by three factors: the applicable regulatory framework, the social and economic environment, and the quality of communications. Therefore, a metric that measures the indicated factors in a unified manner would be an integral metric. So, the UER proposes the following definition:

Spectrum Efficiency Integral Metric (SEIM): a set of sub-metrics, composed of qualitative and/or quantitative considerations, used to measure, compare and track spectrum efficiency.

77 Additionally, the UER contemplates that the SEIM be composed of at least three sub-metrics, which are: the Technical-Regulatory Spectrum Efficiency Metrics (T-RSEM), the Economic Efficiency Metric (EEM) and the Quality Metric (QM), exemplified in the following figure:



78 The following sub-metric may be defined under the UER’s authority:

Technical-Regulatory Spectrum Efficiency Metric: a set of quantitative parameters based on the technology and the features of the infrastructure used by the concessionaire in its network to provide the services authorized by its enabling title and on the quality of such services. Such parameters shall be in accordance with the applicable regulatory framework for the service.

79 Relating to the QM, since it is affected directly by the technical aspects of the concessionaire’s network, it may be included within the T-RSEM. Besides, the QM may also

incorporate subjective aspects from the perception of the end user, assuming that an established measurement methodology is present. For example, "Recommendation ITU-R BS.1387. Method for objective measurements of perceived audio quality"³⁵ establishes a full evaluation mechanism for different audio compression formats and the premises to be considered for the subjective evaluation made by the end user.

- 80 Besides, the EEM may consider aspects related to sociodemographic matters and economic indicators on the areas serviced by a certain service, including the number of providers of the same type of service in the area, to establish a metric that shows, from an economic viewpoint, the efficiency with which the radio spectrum is being used, possibly favoring other aspects such as the benefit given to regions or areas with a higher marginality index or lacking service offers, seeking to promote the existence of services in those geographic areas where they are currently unavailable. Another example is that the EEM evaluated concessionaires of the same services differently, based on the region³⁶ where they have their infrastructure deployed. This, because the socioeconomic differences existing between the states that integrate their cellular regions.

³⁵ Further information is available at: https://www.itu.int/dms_pubrec/itu-r/rec/bs/R-REC-BS.1387-1-200111-!!!PDF-S.pdf

³⁶ To assign concessions for some telecommunications services, the country was divided in 9 regions, known as cellular regions or PCS regions.

IV. CONSIDERATIONS TO APPLY THE SPECTRUM EFFICIENCY INTEGRAL METRIC

81 This section addresses various aspects to be considered in the definition and evaluation of a spectrum efficiency metric.

4.1 About the concessionaires' spectrum reserve

82 As has been mentioned, prior to the obtention of an enabling title, the concessionaires have a business model designed for the short, mid and long term, to deploy their network. Therefore, the possibility exists that the concessionaire does not use the whole of the assigned bandwidth from the beginning of the term of its concession; this because, depending on the type of service, the coverage objectives and the necessary time to deploy the sites, from the acquisition of lease of property, obtention of permits, supply and installation of equipment, etc. The effective use of the assigned bandwidth over the assigned coverage would be gradual, as the networks deployment progresses.

83 Besides, the possibility exists that the concessionaire's business model contemplates a reserve of available spectrum capacity, for future implementations in its own network, for a business based on spectrum lease or even for a different service (within those enabled in its spectrum concession). So, when evaluating the spectrum efficiency associated to this concessionaire, it is possible to find important differences in relation to other concessionaires who offer the same type of service, because it has an "unused" portion of spectrum. Likewise, spectrum concessions exist for a service such as "provision of capacity" for third parties to contract channels or bandwidth from the concessionaire, so that the concessionaire provider of capacity will have unused spectrum while a third party reaches it to exploit such resource.

4.2 About the protection of the technological neutrality principle upon application of the metrics

84 As is well known, one of the Institute's guiding lines is to care for the technological neutrality principle, this is, that the Institute does not impose any specific technology or standard on the concessionaires to deploy their services. Under this principle, it is possible that, to provide some service, diverse concessionaires use different technologies, or even that one concessionaire uses different technologies within its own network, provided that they guarantee communications interoperability and the established quality levels. This, based on the planning of the business model and the investment costs destined to the deployment of the service that the concessionaires may have determined. So, for example, within a specific band two concessionaires may exist who provide the same services through two different technologies, each one with a different spectrum efficiency.

85 In a more concrete case, for mobile wireless access services in the 850 MHz band, concessionaires may provide services through different cellular technologies: 2G, 3G and 4G; where the three may converge in one same geographic region or be divided according to the location where the concessionaire provides the service. Due to access techniques, as well as the bandwidth occupied, 4G (LTE) technology is especially more efficient than the others (2G and 3G). However, to what degree one technology or another is deployed by each concessionaire depends on their business models, their investment capacity and their short, mid and long-term plans.

4.3 About the consideration of the GoS in the metrics

- 86 Some telecommunications services exist that are designed to operate with a certain Grade of Service (GoS). This GoS defines a level of connectivity to the end user. For example, for public security and disaster relief networks, the GoS shall be at least 95%, which means that whenever a terminal device seeks to access the network, the latter shall be available at least 95% of the time. So, the higher the GoS, the less waiting time for the end user to establish communication. Also, networks shall be designed to support huge traffic demands during emergency situations.
- 87 However, to attain a high GoS and provide robustness to the network against a high traffic demand, it is necessary that it has a higher spectrum amount (as compared with a network design for commercial purposes). This is the case of the 806-814/851-859 MHz segment, used by radiocommunications systems destined to public security and disaster relief applications, pertaining to federal, state and municipal entities³⁷. Some users of this frequency band are enabled to operate locally while others may operate all over the country. In this context, certain bands of the spectrum are reserved nationwide to provide this type of services, however, emergency cases are not present at all times. Besides, not all states have effectively deployed this type of radiocommunication services and the probability of traffic congestion is low.

4.4 About the implementation of the metrics on concession titles

- 88 As has been mentioned, spectrum efficiency metrics may be applied at a certain time after the concessionaire has obtained its concession title. Likewise, it is possible that minimum reference thresholds be established that the concessionaires should observe for the services determined by the Institute.
- 89 In the case of concessions for frequency bands that imply the installation or deployment of new networks or stations, the Institute shall determine which mechanisms will be used to establish the observance of the metrics, where one of the ways might be the inclusion of an *ex profeso* obligation in the concession titles. In this case, the regulator shall clearly specify the minimum spectrum efficiency threshold to be complied by the concessionaires and established as an obligation in the new concession titles, to be complied within a previously determined term, after which the Institute would proceed to verify the concessionaire's spectrum efficiency.

4.5 About the consideration of the end services in the computation of the metrics

- 90 As stated in Chapter II, among the factors that may be included in the metrics, the coverage, the number of users of the service, the amount of used spectrum, etc. are involved. However, in the case of mobile wireless access services, besides providing the end user with voice services, data and short messages are also included. Therefore, this set of provided services through the mobile wireless access service result in a more efficient use since the granted

³⁷ IFT, "RESOLUTION BY WHICH THE GOVERNING BOARD OF THE FEDERAL TELECOMMUNICATIONS INSTITUTE APPROVES THE PLAN FOR THE 806-824/851-869 MHZ BAND AND APPROVES THE PROPOSAL FOR CHANGES OF FREQUENCY BANDS FOR INDIVIDUALS OR LEGAL ENTITIES HOLDING RIGHTS OVER THE USE, ENJOYMENT AND EXPLOITATION OF THE 806-824/851-869 MHZ FREQUENCY BANDS", *Federal Official Gazette*, Mexico, 2016. Recovered on February 15, 2018, available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5452357&fecha=13/09/2016

spectrum is being exploited with more end user services. Besides, the trunking service market niche is based on trading mainly voice services; however, concessionaires currently exist that also offer data services (short messages, image transfers and low-resolution video download and upload), exploiting and diversifying this way the use of the spectrum.

By creating a metric formulated with the number of services of the concessionaire for the end user, negative effects may be caused to the free development of the telecommunications and broadcasting markets since, in some way, the direction of the telecommunications and broadcasting offer may be biased, without considering the parallel risk of biasing the technologies to be acquired by the concessionaires to provide the services established in the metrics.

92 Besides, even if the concessionaires provide the same radiocommunication service in a common frequencies band, their market niches may be totally different. For example, concessionaire “A” may only provide voice services in a rural area and concessionaire “B” provide voice and data services in a metropolitan area. So, in case the Institute establishes that the metric comprises the evaluation of voice and data services, concessionaire “A” would have to deploy new technology to also offer data services in order to comply with the services established in the metric, although it may not be its market niche and, therefore, the return on its investment would be difficult to recover during the life of its concession.

4.6 About the obtention of the necessary information for the computation of the metrics

93 As explained in Chapter II, the factors that may be included in the metrics may be different across the services to be measured. To start the evaluation of the SEM and proceed to their computation, the Institute shall have the necessary information inputs (for example, the number of serviced users, coverage per area unit, amount of granted spectrum, amount of granted but unused spectrum, implemented technologies, etc.).

94 However, much of the necessary information to compute the metrics is unknown to the Institute and, regardless that the Institute has authority to request information from the concessionaires about their network, a data collection mechanism shall be established to ensure certainty, comparability and transparency on the evaluation of the metrics, for both the concessionaires and the Institute itself, and that the obtention, organization, processing and reporting of such information is as uncostly and simple as possible, so that the mechanisms to collect information do not translate into an effort representing high costs on the regulated parties or that the information and data requested is not directly useful to quantify spectrum efficiency.

4.7 About the application of the metrics to MVNOs

95 The “*Guidelines for the Trading of Mobile Services by Mobile Virtual Network Operators*”³⁸ establish the terms and conditions for the Wholesale Mobile Concessionaires (WMC) to

³⁸ IFT, “RESOLUTION by which the Governing Board of the Federal Telecommunications Institute issues the Guidelines for the Trading of Mobile Services by Mobile Virtual Network Operators”, *Federal Official Gazette*, Mexico, 2016. Recovered on February 15, 2018, available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5429202&fecha=09/03/2016

provide wholesale services³⁹ to Mobile Virtual Network Operators (MVNO). Generally, the WMC shall guarantee the following to the MVNO:

1. Provide the necessary technical infrastructure to the MVNO for the provision of the services.
2. Maintain the MVNO informed about the implemented traffic management and network administration measures and actions.
3. Provide information generated by the users relating to traffic, as well as all performance data and indicators and necessary measurements so that the MVNO may comply with the efficient provision of the mobile services.

⁹⁶ Besides, the WMC and the MVNO may agree upon additional or complementary aspects that allow an efficient provision of the mobile services⁴⁰. Also, such guidelines contemplate that the MVNO will be responsible before the end user for the provision of the offered services.

⁹⁷ Besides, such guidelines contemplate that the agreement executed between the WMC and the MVNO shall establish the responsibility schemas that determine the responsible subject in face of one of the actions or mechanisms implied in the obligations before the authority (the Institute). Likewise, the agreement shall include a clause by which the WMC guarantees the quality contracted by the MVNO, at least under the same conditions offered to its own end users, ensuring compliance with the quality parameters established in applicable provisions.

⁹⁸ Based on the description above, it may be inferred that the MVNO contribute in a positive way to an efficient use of the spectrum. While the WMC is in charge of supplying the resources of infrastructure to the MVNO, the latter is responsible for the quality of the service before the end user, which means that the MVNO is co-responsible of the quality of the provided services and, therefore, for the efficient use of the spectrum.

⁹⁹ As indicated in the guidelines, the clause determining the responsible subject before the authority shall be agreed between the WMC and the MVNO. In this line of thought, the SEM will be mandatory, which makes them a part of what the WMC and the MVNO should stipulate in their agreement.

4.8 About the application of spectrum efficiency metrics to concessionaires who implement opportunistic spectrum technologies

¹⁰⁰ Technologies are currently under development to offer broadband services, characterized by the transmission through “available” segments of the spectrum, this is, segments over which no service is being provided at a certain space and/or time. This type of technologies usually operates supported by a dynamic database (with a specific software to process data) which allows the transmitting and receiving devices to discover with what power and over which frequency they may communicate. The transmission/reception time may be very short (at the milliseconds level) or constant (as traditionally done).

³⁹ Mobile Service consisting on the supply of access to individual elements, and to technical, economic, operating and commercial capacities of a network or service, including interconnection, used by Mobile Virtual Network Operators, to promote such services to mobile end users.

⁴⁰ Telecommunications service provided to mobile end users that in accordance with the corresponding concession titles and authorizations is provided through Mobile Terminal Devices, which do not have a determined geographic location.

101 Since this type of technologies may cover a wide range of spectrum, transmit and receive information through free spectrum, and even transmit over granted bands under a no-interference schema, it is necessary to analyze if these type of technologies and schemas of shared use of the spectrum may be involved in the determination of the metric and to what extent. Also, it is convenient to delimit the responsibility of the concessionaires in terms of the possible use of the spectrum by users that are not necessarily a part of their network and, therefore, the concessionaire has no control whatsoever on the quality and continuity of the services provided using opportunistic access to the spectrum techniques.

4.9 About the feasibility of defining the metrics

102 As has been said, the computation of the SE is achieved from the application of a formula and its related methodology, for which the parameters have not been yet defined. In this line of thought, the Institute shall consider, to define the factors to be part of the metrics, that they shall not be highly complex and/or costly to obtain by the concessionaires. Also, concessionaires of the same type of service currently exist that operate under different regulatory conditions and obligations. Therefore, when the application of the metric is desired to evaluate certain services, the value of the metric may not deliver comparable results among some of the concessionaires, besides the possibility that the metric is not designed to evaluate all the concessionaires of such service equally.

4.10 About the application of the metrics for public, social and private concessionaires

103 Public, social and private use concessionaires may face economic resources scarcity scenarios, since they are not allowed to provide services for profit or to share the radio spectrum with third parties⁴¹. In this line of thought, the LFTR does not exclude social, public or private concessionaires from the application of the efficient spectrum use metrics. As has been explained, a way to improve SE by the concessionaires is through technological updates on their network infrastructure, which may translate into a high economic investment and be difficult to reach by public and social use concessionaires. Also, little or no incentives exist for the private use concessionaire to update its network's technology, aside that this type of concessions are not intended for public services, but address the particular and specific needs of this kind of user.

4.11 About the consideration of multiprogramming as a factor in the spectrum efficiency metric for broadcasting services

104 As a result of the transition to Digital Terrestrial Television (DTT), the concessionaires may currently implement multiprogramming which consists of the ability to transmit more than one programming channel (audiovisual contents) over a 6 MHz bandwidth, which is defined in the *"General Guidelines for Access to Multiprogramming"*⁴². It shall be noted that access to multiprogramming for concessionaires is optional for those who desire to implement it, provided that the technical conditions for signals transmission are complied with, such as the compression format and transfer rates (for high definition and standard definition contents).

⁴¹ Except for the provisions of the second paragraph of Article 83 of the LFTR.

⁴² IFT, "General Guidelines for Access to Multiprogramming", *Federal Official Gazette*, Mexico, 2015. Recovered on February 15, 2018, available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5382262&fecha=17/02/2015

105 Likewise, for the case of FM sound broadcasting services, the concessionaires may optionally implement hybrid digital radio using IBOC technology⁴³, which enables one FM radio station with a 400 kHz bandwidth to support multiprogramming of up to 4 high definition digital channels in addition to the analog channel. However, even when multiprogramming for broadcasted television and the use of IBOC technology for sound broadcasting are both optional for concessionaires, it is evident that their implementation in the concessionaires' broadcasting stations results in a more efficient use of the spectrum.

⁴³ IBOC: Acronym for In Band On Channel, a standard adopted in Mexico for digital radio through the "RESOLUTION by which the terrestrial digital radio standard is adopted and the policy for broadcasting concessionaires and licensees in the 535-1705 kHz and 88-108 MHz bands to voluntarily perform the transition to digital technology is issued", *Federal Official Gazette*, Mexico, 2011. Recovered on February 15, 2018, available at: http://dof.gob.mx/nota_detalle.php?codigo=5196204&fecha=16/06/2011

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