



Recommendation ITU-R SM.1046-3
(09/2017)

**Definition of spectrum use and
efficiency of a radio system**

SM Series
Spectrum management



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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R SM.1046-3

Definition of spectrum use and efficiency of a radio system

(1994-1997-2006-2017)

Scope

This Recommendation defines the spectrum use and efficiency of a radio system by theoretical and measurement models.

Keywords

Radiocommunication, spectrum efficiency, spectrum utilization

Abbreviations/Glossary

AM-SSB	Amplitude modulation – single-side band
BER	Bit error ratio
C/N	Carrier to noise
CHR	Conical horn reflector
CSD	Carrier spectrum density
EMC	Electro magnetic compatibility
FEC	Forward error correction
FM	Frequency modulation
MTES	Most theoretically efficient system
OCR	Off channel rejection
P-P	Point to point
PSK	Phase-shift keying
PCM	Pulse-code modulation
QAM	Quadrature amplitude modulation
RSE	Relative spectrum efficiency
SHD	Shrouded dish
SSD	Spectrum setting density
STD	Standard-dish
SUE	Spectrum utilization efficiency
TIA	Telecommunications Industry Association, USA
UHF	Ultra high frequency
VHF	Very high frequency

Related ITU Recommendations, Reports

Recommendation ITU-R F.699 – Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to about 70 GHz

Recommendation ITU-R P.530 – Propagation data and prediction methods required for the design of terrestrial line-of-sight systems

Recommendation ITU-R SM.1047 – National spectrum management

Recommendation ITU-R SM.1880 – Spectrum occupancy measurement and evaluation

Report ITU-R SM.2015 – Methods for determining national long-term strategies for spectrum utilization

Report ITU-R SM.2256 – Spectrum occupancy measurements and evaluation

NOTE – In every case the latest edition of the Recommendation/Report in force should be used.

The ITU Radiocommunication Assembly,

considering

- a) that the spectrum is a limited natural resource of great economic and social value;
- b) that demand for use of the spectrum is increasing rapidly;
- c) that a number of different factors, such as the use of different frequency bands for particular radio services, relevant spectrum management methods for networks in those services, the technical characteristics of transmitters, receivers and antennas used in the services, etc., significantly influence spectrum use and efficiency and through their optimization, particularly in respect of new or improved technologies, significant economies of spectrum can be achieved;
- d) 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;
- e) that comparison of spectrum efficiency between actual radio systems would be very useful, when developing new or improved technologies and assessing performance of existing systems,

recommends

- 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”, as illustrated in Annex 1 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, as illustrated in Annex 1. Some examples of how to use this concept may be found in Annex 2;
- 3 that the basic concept of relative spectrum efficiency as outlined in Annex 1 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 as explained in § 4 of Annex 1;
- 5 that in determining the spectrum efficiency, the interactions of various radio systems and networks within a particular electromagnetic environment should be considered.

Annexes 1 and 2 provide the theoretical model (U), measurement model (U') and examples of spectrum use by different services.

Annex 1

General criteria for the evaluation of spectrum utilization factor and spectrum efficiency

1 Spectrum utilization factor

Efficient use of spectrum is achieved by (among other things) the isolation obtained from antenna directivity, geographical spacing, frequency sharing, or orthogonal frequency use and time-sharing or time division and these considerations reflected in definition of spectrum utilization. Therefore, the measure of spectrum utilization – spectrum utilization factor, U , is defined to be the product of the frequency bandwidth, the geometric (geographic) space, and the time denied to other potential users:

$$U = B \cdot S \cdot T \quad (1)$$

where:

- B : frequency bandwidth
- S : geometric space (usually area)
- T : time.

The geometric space of interest may also be a volume, a line (e.g. the geostationary orbit), or an angular sector around a point. The amount of space denied depends on the spectral power density. For many applications, the dimension of time can be ignored, because the service operates continuously. But in some services, for example, broadcast and single channel mobile, the time factor is important to sharing and all three factors should be considered simultaneously, and optimized.

The measure of spectrum may be computed by multiplication of a bandwidth bounding the emission (e.g. occupied bandwidth) and its interference area, or may take into account the actual shape of the power spectrum density of the emission and the antenna radiation characteristics.

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

Receivers use spectrum-space because they deny it to transmitters. The mere physical operation of the receiver interferes with no one (except as it inadvertently acts as a transmitter or power source). Even then the space used physically is relatively small. However, the authorities deny licenses to transmitters in an attempt to guarantee interference-free reception. The protection may be in space (separation distance, coordination distance), in frequency (guardbands) or even in time (in the United States of America, some MF broadcasting stations are limited to daylight operation). This denial

constitutes “use” of the space by the receiver. The radio astronomy bands are a familiar example of the recognition of receiver use of the spectrum space.

One way to incorporate these facts into a unit of measure of spectrum space is to partition the resource into two spaces – the transmitter space and receiver space – and define dual units to measure the usage of each space. Where simplicity is most important, the two units can be recombined into a single measure for system use.

Further information concerning the general approach to calculate the spectrum utilization factor may be found in Chapter 8 of the National Spectrum Management Handbook (Geneva, 2005).

2 Spectrum utilization efficiency (SUE)

According to the definition of SUE (or spectrum efficiency as a shortened term) of a radiocommunication system, it can be expressed by a complex criterion:

$$SUE = \{M, U\} = \{M, B \cdot S \cdot T\} \quad (2)$$

where:

M : useful effect obtained with the aid of the communication system in question

U : spectrum utilization factor for that system.

If necessary, the complex spectrum efficiency indicator may be reduced to a simple indicator: the ratio of useful effect to spectrum utilization factor:

$$SUE = \frac{M}{U} = \frac{M}{B \cdot S \cdot T} \quad (2a)$$

The method for SUE calculation in equations (2) and (2a) is a theoretical approach. When administrations evaluate SUE independently, the useful effect obtained with the aid of the communication system (numerator M) is not always available. In such case, it can be replaced by the spectrum utilization factor based on the actual measurement (U'):

$$U' = B' \cdot S' \cdot T' \quad (2b)$$

where:

B' : actual measurement result on occupation bandwidth (or regional statistics)

S' : actual measurement result on coverage area (or regional statistics)

T' : actual measurement result on operating time (or regional statistics).

Radio administrations can obtain the above three parameters through measurement and statistics by their own monitoring facilities. In the case of regional statistics, e.g. the arithmetic mean of the results of each sub-region can be used.

Then SUE can be expressed as:

$$SUE = \frac{U'}{U} = \frac{B' \cdot S' \cdot T'}{B \cdot S \cdot T} \quad (2c)$$

3 Relative spectrum efficiency (RSE)

The concept of relative RSE can be used effectively to compare the spectrum efficiencies of two similar types of radio systems providing the same service.

RSE is defined as the ratio of two spectrum efficiencies, one of which may be the efficiency of a system used as a standard of comparison. Hence,

$$RSE = SUE_a / SUE_{std} \quad (3)$$

where:

- RSE : relative spectrum efficiency (ratio of SUEs)
- SUE_{std} : SUE of a “standard” system
- SUE_a : SUE of an actual system.

The likely candidates for a standard system are:

- the most theoretically efficient system,
- a system which can be easily defined and understood,
- a system which is widely used – a *de facto* industry standard.

The RSE will be a positive number with values ranging between zero and infinity. If the standard system is chosen to be the most theoretically efficient system, the RSE will typically range between zero and one.

As an example, the most theoretically efficient system may be characterized according to the principles of information theory. The communication capacity of a communication channel on which a subscriber or a listener receives a wanted communication is determined by the relation:

$$C_0 = F_0 \ln(1 + \rho_0)$$

where:

- F_0 : bandwidth of the wanted communication
- ρ_0 : signal/noise ratio at the receiver output.

If the signal/noise ratio at the receiver input is equal to the protection ratio ρ_s and the bandwidth of the communication channel over which the signals are transmitted is equal to F_m , then the communication capacity is $C_p = F_m \ln(1 + \rho_s)$. It must exceed or at least be equal to the communication capacity of the channel over which the subscriber receives a wanted communication, i.e. $C_p \geq C_0$. Hence the minimum possible value of the protection ratio ρ_s at which the subscriber will receive a communication with a signal/noise ratio equal to ρ_0 is defined as:

$$\rho_s = (1 + \rho_0)^{F_0/F_m} - 1 \quad (4)$$

The major advantage of directly computing the RSE is that it will often be much easier than computing the SUEs. Since the systems provide the same service, they will usually have many factors (sometimes even physical components) in common. This means that many factors will “cancel out” in the calculation before they need to be actually calculated. Often this will greatly reduce the complexity of the calculation.

Some examples of RSE calculations are presented in Annex 2 and in Chapter 8 of the National Spectrum Management Handbook (Geneva, 2005).

4 Comparison of spectrum efficiencies

As described in previous sections, 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 radio communication 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.

Annex 2

Examples of spectrum use by different services

1 Spectrum use by land mobile radio systems

1.1 Spectrum efficiency of an indoor pico-cellular radio system

In the case of an indoor pico-cellular system in the frequency band between 900 MHz and 60 GHz, the spectrum efficiency can also be derived using equation (2). From this equation, the spectrum efficiency of an indoor pico-cellular radio system may be defined as:

$$\text{Erlangs} / (\text{bandwidth} \times \text{area}) \quad (5)$$

where erlangs is the total voice traffic carried by the pico-cellular system, bandwidth is the total amount of spectrum used by the system and area is the total service area covered by the system. Since the pico-cellular system is to be implemented in a high-rise building, the total floor area is used in the calculation of spectrum efficiency. The number of channels required per cell can then be calculated based on the Erlang B Tables for a given number of users on the floor and traffic per user.

1.1.1 Pico-cellular system covering a building

In order to calculate the total bandwidth required for the whole building, the vertical re-use distance in terms of the number of floors is required. This parameter is dependent on the floor losses and is different for different types of buildings.

The total number of half duplex channels required for the building can then be calculated and is equal to:

$$2 \times \text{No. of channels per cell} \times \text{No. of cells per floor} \times \text{No. of floors of separation}$$

The factor 2 is needed here to reflect the number of channels needed for two-way communications.

The spectrum efficiency, $SUE_{building}$, of the system providing coverage in the building can then be calculated using equation (5):

$$SUE_{building} = \frac{\text{Total traffic carried in the entire building}}{\text{Total No. of channels} \times \text{channel bandwidth} \times \text{total floor area}} \quad (6)$$

Example:

In this indoor system operating at 900 MHz

Bandwidth of a (half duplex) channel	25 kHz
No. of channels per cell	10
No. of cells per floor	4
No. of floors of separation	3
Total No. of channels required	120

At a grade of service of 0.5%, the traffic carried on one floor $= T_f = 16$ E or $2 T_f$ due to both base and mobile stations.

$$SUE_{building} = \frac{16 \times \text{No. of floors}}{120 \times 0.025 \times \text{total floor area}} \quad (7)$$

If the floor is 25 m by 55 m, $SUE_{building} = 3880$ E/MHz/km².

1.1.2 Pico-cellular system covering a down-town area

Similarly, the bandwidth required for the whole down-town area may also be calculated if the horizontal re-use distance is known. Again, this parameter is dependent on the building material and the propagation loss of a signal into and out of a building. This re-use distance directly affects the number of buildings that can be placed in a cluster (or interference group).

In this case, the total number of half duplex channels required in the down-town area is equal to:

$$2 \times \text{No. of channels per building} \times \text{No. of buildings per cluster}$$

Again the factor 2 is needed here to reflect the number of channels needed for two-way communications.

The spectrum efficiency, SUE_{area} , of the system providing coverage to the entire down-town area can then be calculated using equation (5):

$$SUE_{area} = \frac{\text{Total traffic carried in the entire area}}{\text{Total No. of channels} \times \text{channel bandwidth} \times \text{total service area}} \quad (8)$$

Here, the total service area is the total floor area of the buildings covered by the pico-cellular system.

Example:

In this indoor system operating at 900 MHz

No. of channels per building	120
No. of buildings per cluster	4
Bandwidth of a (half duplex) channel	25 kHz
Total No. of channels required	480

$$SUE_{area} = \frac{16 \times \text{No. of floors} \times \text{No. of buildings}}{120 \times 4 \times 0.025 \times \text{total floor area}} = 970 \text{ E/MHz/km}^2 \quad (9)$$

NOTE 1 – Additional information may be found in:

CHAN, G. and HACHEM, H. [September, 1991] Spectrum efficiency of a pico-cell system in an indoor environment. Canadian Conference on Electrical and Computer Engineering, Quebec City, Canada.

HATFIELD, D.N. [August, 1977] Measures of spectral efficiency in land mobile radio. IEEE Trans. *Electromag. Compt.*, Vol. EMC-19, 3, 266-268.

1.2 RSE of land mobile radio systems

RSE values of land mobile radio systems using different types of modulation were compared in the relation to the most theoretically efficient system (see Annex 1, § 3 and equation (4)).

For the sake of simplicity and to obtain finite analytical expressions, calculations were made for the simplest models of a network in the form of an ideal rectangular lattice and propagation conditions typical for the UHF frequency band. However, the general laws will be the same for more complex models of real networks with more sophisticated propagation models.

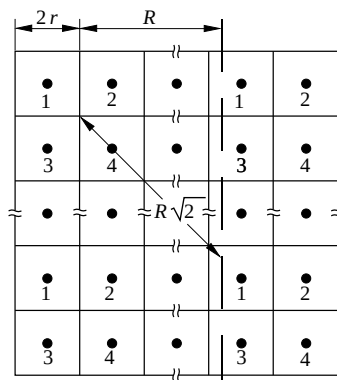
The network model is made up of squares of equal dimensions with the central (base) station being located in the centre of the square (see Fig. 1). The dimension (radius), r , of the service area is considered to be given. In areas bearing the same digit in Fig. 1, the same set of frequency channels can be used if the separation distance, R , between these areas provides sufficient interference attenuation. The antennas of the base stations are not directive ones in the horizontal plane and only use one type of polarization.

In this model, all base station transmitters have the same power and a stable carrier frequency and they do not produce any out-of-band or spurious radiation; base station receivers have ideal selectivity characteristics.

Results of RSE calculations for several specific types of modulation and different signal-to-noise ratios at the receiver output ρ_0 are presented in Fig. 2. Considered types of modulation are:

- Amplitude modulation – single-side band (AM-SSB),
- Frequency modulation (FM),
- 4 (8) phase phase-shift keying (4(8) PSK),
- 16 state quadrature amplitude modulation (16-QAM).

FIGURE 1
Network model



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As it follows from Fig. 2, the FM land mobile systems have the lowest RSE, since when this type of modulation is used, the bandwidth required for a network development is approximately five times greater than in the case of the most theoretically efficient system (MTES). On the other hand, the type of modulation which is closest to the MTES case for all values of the noise protection ratio is 16-QAM. For a relevant network development it requires only 1.5 times the bandwidth needed for the MTES. If the reception quality requirements are not very high, the closest with respect to the MTES is an AM-SSB. However, the RSE of the AM-SSB drops appreciably as the reception quality requirements are increased, particularly if account is taken of the effect of the frequency instability of real transmitters.

NOTE 1 – Additional information may be found in: Annex IV Report 662-3 (Düsseldorf, 1990).

1.3 SUE of land mobile radio systems

For general dispatch land mobile radio systems the SUE may be obtained using equation (2) in the following way.

$$SUE = \frac{M}{B \cdot S \cdot T} = \frac{Occ}{B \cdot S} \quad (10)$$

where

B : total amount of spectrum considered in the land mobile band of frequencies

S : the area under study

Occ : total occupancy in the area

= Occupancy per transmission $\times$ No. of transmissions in the area

= Information transferred/Effective time. Philippe, this turquoise material seems from Japanese contribution.

The total occupancy in the area factor:

$$Occ = \frac{M}{T} \quad (11)$$

where:

M : information transferred

T : effective time.

For general dispatch land mobile radio systems the affected geographical area may be represented as a matrix of cell values (divided into a $i \times j$ matrix, and the size of the matrix is m). Each cell is defined as an area of S_0 . And there are n stations in the geographical area. So the Occ is determined by the equation:

$$Occ = \sum_0^m F_n = \sum_0^{i \times j} F_n(i, j) \quad (12)$$

where:

m : the size of the matrix($i \times j$)

$F_n(i, j)$: the total occupancy of the cell (the unit area of the matrix).

Depending on the transmitting power and propagation characteristics, the transmitted signal will cover a certain area, a number of cells in this case. The cell is considered to be occupied if the proportion of the coverage area in the cell reaches a given threshold. Hence,

$$\eta = \frac{\sum_{n=1}^n S_n}{S_0} \quad (n \geq 1) \quad (13)$$

where:

S_0 : the area of the cell

S_n : the coverage area of current station in the cell.

And when $n=0$, the $\eta = 0$.

For general, if the coverage area occupies more than 10% of the area of the cell, it is considered to be occupied. The total occupancy of the cell is considered as:

$$F_n(i, j) = \frac{M_n}{T_n} \quad (\eta \geq 0.1) \quad (14)$$

where:

M_n : information transferred of the station

T_n : effective time in the cell.

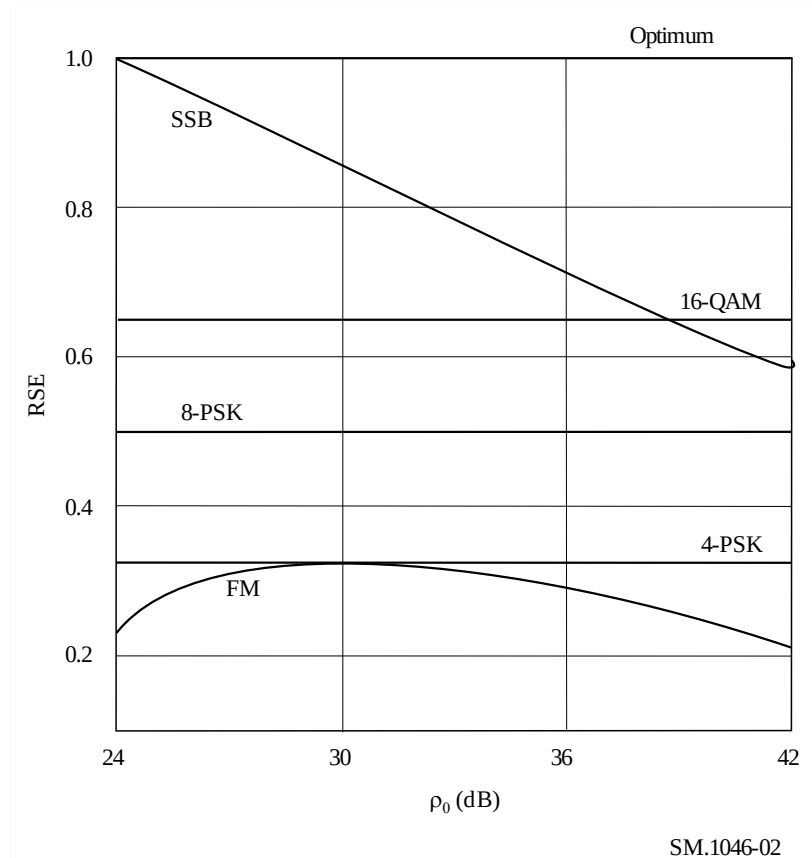
The SUE cell index is defined as the total occupancy in the cell by all n stations in that geographical area divided by the total amount of spectrum considered, B , and the area of the cell, S_0 . The SUE average index of a geographical area can hence be obtained from the total occupancy in the city divided by the total amount of spectrum considered and the total area, S .

$$\text{Cell - index} = \frac{F_n}{B \cdot S_0} \quad (15)$$

$$\text{Average -index} = \frac{Occ}{B \cdot S} \quad (16)$$

The main issue is therefore to calculate the total occupancy in the area. The approach taken is to divide the area under study into a number of cells in which the base stations are located. Depending on the transmitter power and propagation characteristics, the transmitted signal will cover a certain area, in this case, a number of cells. Hence by adding up the cells that are covered by this signal, the occupancy due to this transmission may be calculated. However, if a number of stations share the same frequency, the occupancy will be divided by the number of stations which share the same frequency. All the stations will be accounted for in the total number of transmissions.

FIGURE 2
RSEs in a network with different types of modulation



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For example, a geographical area of 76 km by 76 km is computationally represented as a matrix of cell values. Each cell is defined as an area of 2 km by 2 km. The cell is considered to be occupied if the coverage circle defined by d (to be further explained in the next section) occupies more than 10% of the area of the cell. The total occupancy of the cell is obtained from each active licence, or station, in the frequency band.

1.3.1 Calculation of the occupied and denied spectrum index

In this analysis, the occupied spectrum index and the composite occupied and denied spectrum index are calculated. The former provides a measure of how a given band of spectrum is utilized, while the latter is an indication as to how the spectrum is used and denied to other users.

As described in the last section, in calculating the index, it is necessary first to estimate the value of the coverage distance, d , which is determined by the equation:

$$L(d, f, h_t, h_r) = P_t + G_r - P_{ibm} - OCR(\Delta f) \quad (17)$$

where:

$L(d, f, h_t, h_r)$: propagation model

P_t : e.i.r.p. (dBW)

- G_r : gain of the receiving antenna (dBi)
 P_{ibm} : average received power at the mobile (dBW)
 OCR : off-channel-rejection
 f : transmitting frequency (MHz)
 h_t : base station antenna height (m)
 h_r : mobile antenna height (m).

To obtain an index for the occupied spectrum, $OCR(\Delta f)$ is equal to zero.

To calculate d for various frequency separations, various values of $OCR(\Delta f)$ have to be used.

For example, based on Okumura-Hata propagation model in Recommendation ITU-R P.529, d , less than 20 km, can be calculated as follows:

$$d = \text{anti log} \left[\frac{P_t + G_r - P_{ibm} - OCR(\Delta f) - 26.16 \log f + 13.82 \log h_t + (1.1 \log f - 0.7) h_r - (1.56 \log f - 0.8)}{44.9 - 6.55 \log h_t} \right] \quad (18)$$

The base station antenna is assumed to be omni-directional. Coordinates of the base station which determine the location of the centre of the coverage circle in the matrix of cells are also used.

To obtain an index for the occupied spectrum, P_{ibm} is -128 dBW and $OCR(\Delta f)$ is equal to zero.

For land mobile radio systems, we are interested not only in the occupied spectrum index, but also the denied spectrum index. The denied spectrum results from the fact that adjacent channels of assigned frequencies cannot be used within a certain distance of separation from the particular base station due to interference. This distance is dependent on the frequency separation, among other parameters. To calculate this distance for various frequency separations, P_{ibm} is assumed to be -145 dBW and various values of $OCR(\Delta f)$ have to be used.

Based on the mask of out-of-band emission, the values used for the OCR factor (dB) at the channel offset of Δf (kHz) are:

Δf	0	± 25	± 50	± 75	± 100
OCR	0	57.1	58.6	58.6	58.6

By using these values it is possible to obtain distances comparable to actual propagation conditions, from one set of sample data and according to the calculation of the coverage distances, the occupied distance is 21.9 km. The corresponding denied distances for $\Delta f = 0, \pm 25$ kHz, ± 50 kHz, and beyond are 69.2 km, 1.5 km, and 1.3 km, respectively.

1.3.2 Results

For illustration of this methodology to calculate the SUE, the result for the 5 776 km² area around the core of the 10 Canadian cities in the 138-174 MHz band is given. Table 1 includes the occupied spectrum index and the denied and occupied spectrum index.

The data used to determine the total occupancy is obtained from the Canadian Assignment and Licensing System database.

The land mobile bands considered in this study include both the VHF band of 138-174 MHz and the UHF bands of 406-430 MHz and 450-470 MHz. The channel spacing for VHF is 30 kHz and that for UHF is 25 kHz.

TABLE 1
Occupied and denied spectrum indices (138-174 MHz)

E/kHz/km ² × 10 ⁻³	Occupied and denied index	Occupied index
Toronto	4.19	1.33
Ottawa	4.54	1.30
Windsor	3.68	0.87
Montreal	3.56	0.88
Saint John	3.24	0.65
Halifax	3.32	0.68
Vancouver	3.20	0.62
Winnipeg	3.31	0.74
Calgary	3.05	0.73
Edmonton	2.99	0.60

Also presented are the graphical results for the city of Vancouver, again in the 138-174 MHz band. A 3-D visualization of a matrix of values, in this case the denied and occupied spectrum, is shown in Fig. 3. The matrix is overlaid on a map of the city to present the utilization information with cartographic detail. This presentation greatly enhances our ability to interpret this information. As shown in Fig. 4, the maximum value of a cell of the occupied spectrum in the centre of the city is 1.7×10^{-3} E/kHz/km². The maximum value of a cell of the denied and occupied spectrum for this band is 4.9×10^{-3} E/kHz/km², which is located just to the north and west of the centroid, as seen in Fig. 5. This area is the highly commercialized core of the city of Vancouver.

FIGURE 3
3-D representation of occupied and denied spectrum index of Vancouver

