RECOMMENDATION ITU-R SM.1046

DEFINITION OF SPECTRUM USE AND EFFICIENCY OF A RADIO SYSTEM

(Question ITU-R 47/1)

(1994)

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, as a basic concept, spectrum utilization efficiency, or spectrum efficiency in short, should be measured in terms of a ratio of the amount of information transferred over a distance (or communications achieved) to 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.

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:

$$U = B \cdot S \cdot T \tag{1}$$

where:

B: frequency bandwidth

S: geometric space (usually area) and

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 licences 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 radioastronomy 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 6 of the National Spectrum Management Handbook.

2. Spectrum utilization efficiency

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

$$SUE = \frac{M}{U} = \frac{M}{B \cdot S \cdot T} \tag{2}$$

where:

M: amount of information transferred over a distance.

3. Relative spectrum efficiency

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

Relative spectrum efficiency 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,

$$RSE = SUE_a / SUE_{std} \tag{3}$$

where:

RSE : relative spectrum efficiency = ratio of SUE-s

SUE_{std} : spectrum utilization efficiency (SUE) of a "standard" system

SUE_a : spectrum utilization efficiency (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:

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

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 may be found in Chapter 6 of the National Spectrum Management Handbook.

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 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.

ANNEX 2

Examples

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:

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

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 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:

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

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):

$$SUE_{\text{building}} = \frac{\text{Total traffic carried in the entire building}}{\text{Total number of channels} \times \text{channel bandwidth} \times \text{total floor area}} \tag{6}$$

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
The total number 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.

$$SUE_{\text{building}} = \frac{16 \times \text{no. of floors}}{120 \times 0.025 \times \text{total floor area}} \tag{7}$$

If the floor is 25 m by 55 m, $SUE_{\text{building}} = 3\,880\ \text{E/MHz/km}^2$.

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):

$$SUE_{\text{area}} = \frac{\text{Total traffic carried in the entire area}}{\text{Total number of channels} \times \text{channel bandwidth} \times \text{total service area}} \tag{8}$$

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
The total number of channels required	480

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

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.

2. Spectrum use efficiency in the terrestrial point-to-point radio-relay system

2.1 Introduction

For radio-relay systems that operate continuously, the dimension of time may be ignored. Referring to equation (2), the spectrum utilization efficiency can be written as:

$$SUE = \frac{C}{B \cdot S_\alpha} \tag{10}$$

where:

C: measure for communications capacity, for example telephone channels or bit/s

S_α: geometric measure, for example, area, or the angle between branching links at a node.

2.2 Spectrum utilization efficiency for a long artery with branching links at the nodes

Normalized communication capacity which gives the SUE efficiency for the terrestrial point-to-point radio-relay system, is defined as:

$$SUE = \frac{N \cdot A}{B_c} \tag{11}$$

where:

N: allowable number of branching links (that is, two-way radio routes) for one repeater station

A: transmitting capacity (e.g. number of telephone channels) per radio channel

B_c: required RF bandwidth per radio channel.

This formula includes the geometric measure, *N* (*N* depends on the allowable angle between branching links).

Spectrum use efficiency in the terrestrial point-to-point radio-relay system was calculated for telephone transmission using the above formula.

The assumptions used are:

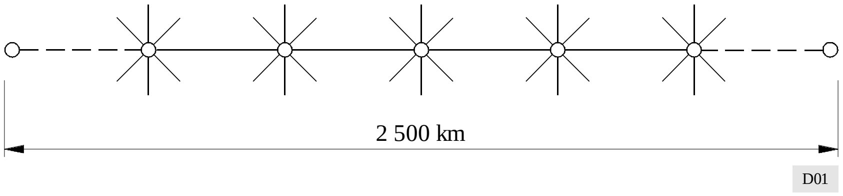
- telephone signal is transmitted;
- probability of fading is the same as that given in Recommendation ITU-R PN.530;
- circuit length is 2 500 km; and circuit model is as shown in Fig. 1;
- required carrier-to-noise radio (*C/N*) is expressed as:

$$C/N = 10 \log [(2^n - 1) / 3] + 11.8 \qquad \text{dB} \tag{12}$$

  where *n* is *n*-state QAM;
- one tenth of the overall radio-relay circuit noise for the 2 500 km circuit is assigned as the interference noise from other routes;
- interference from other routes has the same frequency as the wanted signal;
- a reference antenna diagram for a circular antenna in Recommendation ITU-R F.699 and a dual offset tri-reflector antenna used in Japan for a digital microwave radio, as shown in Fig. 2, are used;
- links with random branching angles.

FIGURE 1

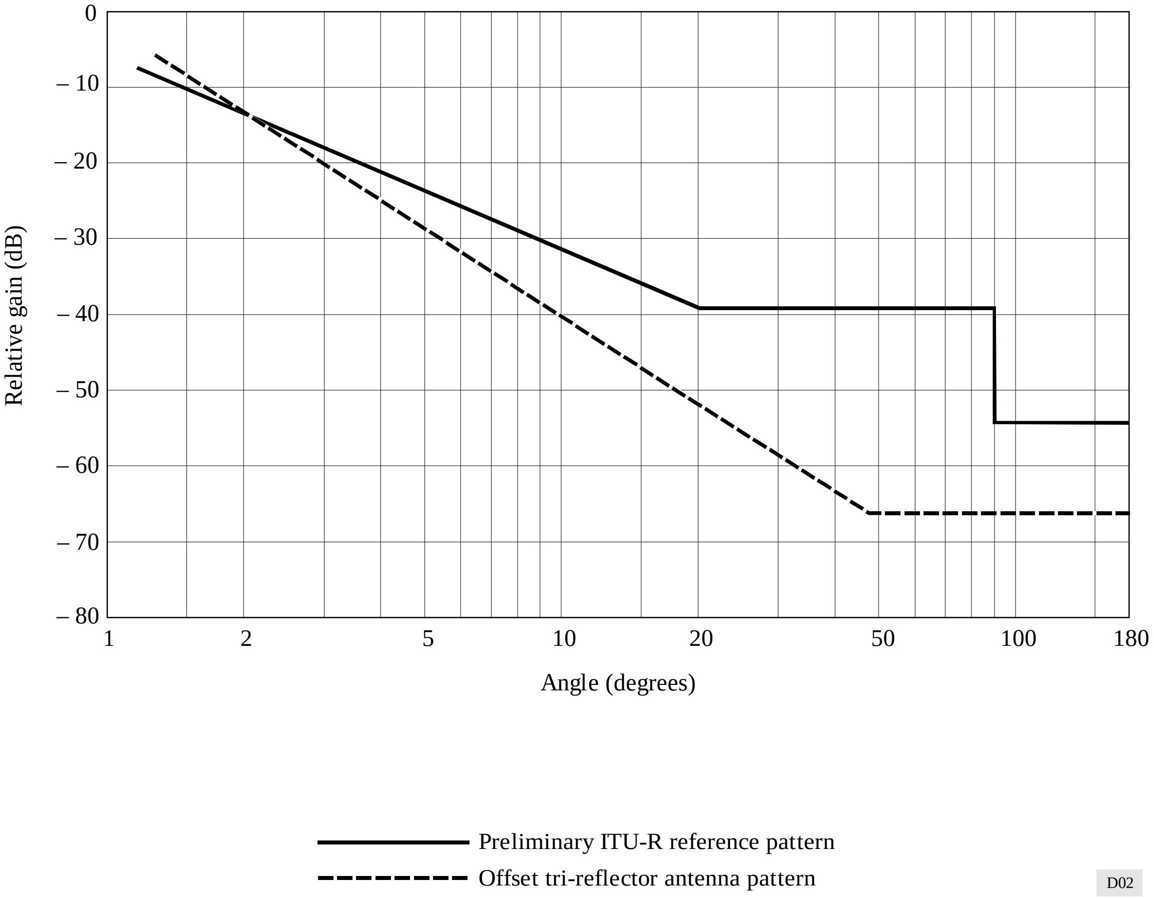
Circuit model



The normalized communication capacities for these two types of antenna were calculated and are shown in Fig. 3. The performance of the circular antenna in Recommendation ITU-R F.699 is insufficient to estimate the spectrum use efficiency of high-level modulation systems. As the results depend on antenna performance, if a high performance antenna can be used, higher level modulation such as 256 QAM is effective.

FIGURE 2

Antenna pattern



3. Spectrum utilization efficiency in randomly arranged radio-relay links

3.1 *Formulation*

Figure 4 shows a radio-relay link X-Y with another radio station Z operating on the same frequency. Station Z is randomly located on a circle around station Y.

Station Y receives a desired signal of frequency f_1 from station X. Station Z transmits a signal of the same frequency f_1 in an arbitrary direction.

The normalized communication capacity which gives the spectrum utilization efficiency, is defined as:

$$SUE = \frac{N \cdot A}{B_c} = \frac{\overline{p}}{p} \frac{A}{B_c} \tag{13}$$

where:

N: number of radio links possible using the same frequency: $N \approx \overline{p} / p$

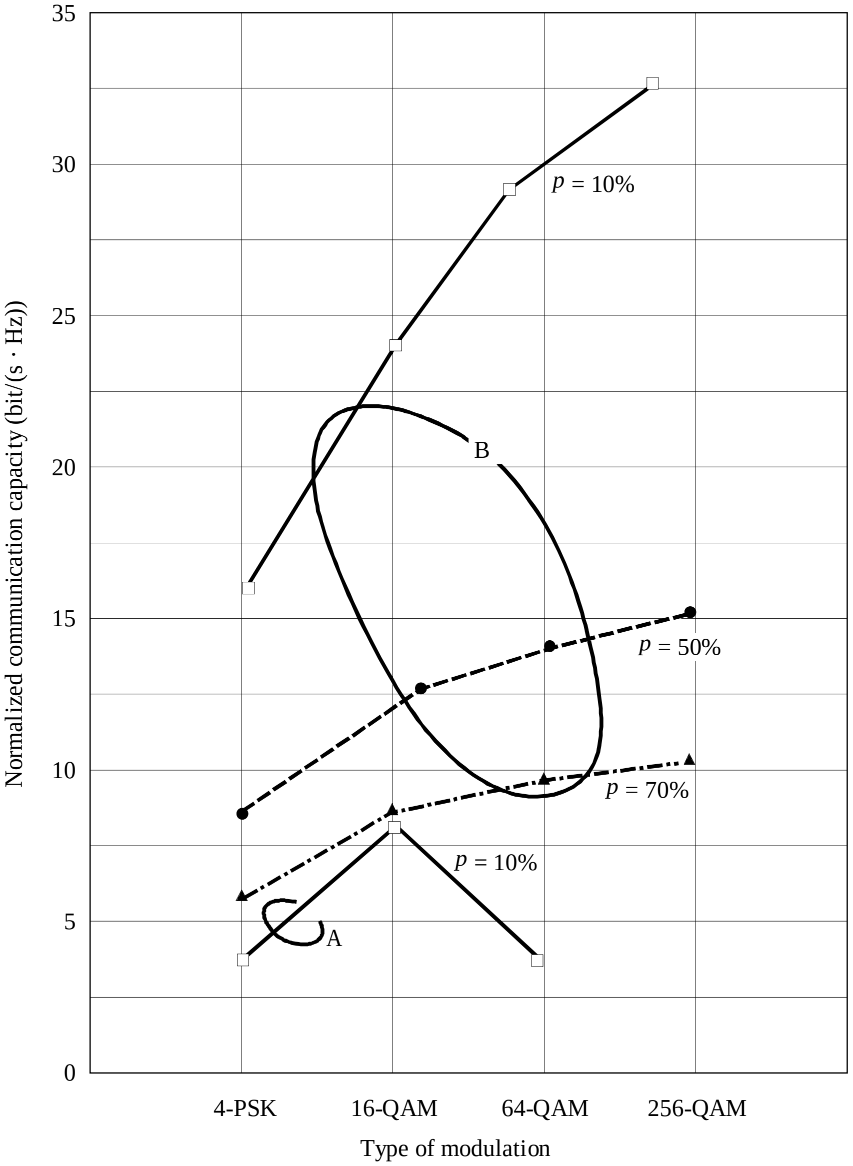
A: transmitting capacity per radio channel.

The probability p that station Y receives interference exceeding the acceptable limit is calculated by considering the combination of the antenna pattern of stations Y and Z and $\overline{p}$ is the maximum permissible probability of interference.

As the accumulation of interference from two or more stations has been neglected, some margin should be provided in any actual application.

FIGURE 3

Normalized communication capacity



Fading margin:	20 dB
Repeater spacing:	50 km
Channel capacity:	64 kbit/s
Allotment to branch noise:	10%

p: probability of interference
A: preliminary ITU-R reference pattern
B: offset tri-reflector antenna pattern

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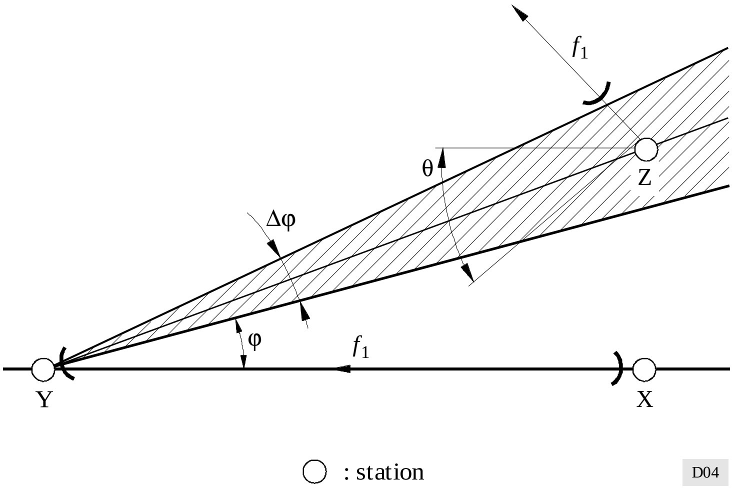
FIGURE 4

Random layout



3.2 *Application: spectrum efficiency in 2 GHz band radio-relay systems*

The spectrum utilization efficiency for a small-capacity terrestrial point-to-point radio-relay system operating in the 2 GHz band was calculated for telephone transmission using the above formula.

The relative spectrum utilization efficiency for 1.8 m diameter antennas was calculated using the permissible interference ratio and corresponding efficiency for each type of modulation in Table 1. The results are shown in Fig. 5.

The digital system is superior to the analogue system for smaller fading margins. In this study, the attenuation due to fading is the same as the degradation of *W/U* (wanted signal level to unwanted signal level ratio) caused by interference. If space-diversity techniques are used, the necessary fading margin is lower. In general, digital systems tend to deliver superior spectrum utilization efficiency.

For digital modulation, a change from 2-phase to multi-phase or multi-state requires less bandwidth, but it may have lower spectrum utilization efficiency when interference is high. The exact value depends on the antenna characteristics, etc., but the 4-phase PSK system may be optimum from the macroscopic viewpoint in cases where other radio links operating around the repeater station are randomly located in an area.

3.3 *Spectrum utilization efficiency in a random mesh network*

In order to perform a fair comparison of modulation techniques, one can assume an interleaved frequency plan with a channel spacing corresponding to a given performance degradation caused by adjacent channel interferences. Table 2 gives tentative values of the normalized channel spacing *X* defined in ex-CCIR Report 608 (Kyoto, 1978) and the corresponding spectrum efficiency in bit/(s · Hz). Even if different results could be derived, based on other assumptions, it should be noted that the calculated results of Table 2 are quite near the values which could be derived from specific channel arrangements, as suggested by ITU-R Recommendations (for example 140 Mbit/s, with 16-QAM modulation and 40 MHz channel spacing between cross-polarized channels). Measured values might be different from these calculated values.

TABLE 1

Parameters of various modulation types in the 2 GHz band

Modulation type		Permissible S/N or error ratio	Interference reduction factor (IRF)		Permissible wanted signal/unwanted signal ratio W/U	Parameters related to B		Spacing to adjacent channels B	Number of channels A	A/B(1) (channels/kHz)
Analogue transmission	MF	58 dB	20 dB		38 dB	Frequency deviation for test tone: 100 kHz r.m.s.		520 kHz	24	0.046
	SSB	58 dB	9.5 dB		48.5 dB	Highest baseband frequency: 108 kHz Filter coefficient: × 2 Frequency tolerance: 20 kHz		236 kHz	24	0.1
Digital transmission			(C/N)	(Degradation)		Clock frequency	Filter coefficient			
	2-phase PSK	10^{-6}	10.7 dB	5.5 dB	16.2 dB	1544 kHz	× 1.3	2 MHz	24	0.012
	4-phase PSK	10^{-6}	13.7 dB	5.5 dB	19.2 dB	772 kHz	× 1.4	1.1 MHz	24	0.022
	8-phase PSK	10^{-6}	19.1 dB	5.5 dB	24.6 dB	515 kHz	× 1.5	0.77 MHz	24	0.031
	QPRS	10^{-6}	16.8 dB	5.5 dB	22.3 dB	722 kHz	× 1.1	0.85 MHz	24	0.028
	16-QAM	10^{-6}	21.4 dB	5.5 dB	26.9 dB	386 kHz	× 1.6	0.62 MHz	24	0.039

(1) The proper efficiency for each type of modulation.

The assumptions used are:

- acceptable interference and spectrum efficiency for each modulation type are as shown in Table 1. 80% of the total circuit noise is allotted to interference;
- distances between a station subject to interference (station Y) and the interfering stations are assumed to be the same; this assumption is considered to cause little error in efficiency calculation since the free-space losses of two links differ by only 6 dB even if they differ in length by a factor of two;
- fading in the wanted signal and in the interfering signals is assumed to have no correlation;
- the antenna radiation pattern is the reference diagram in Recommendation ITU-R F.699;
- all stations have the same transmitting output power;
- the limit on the probability of interference, $\overline{p} = 0.1$.

FIGURE 5

Spectrum utilization efficiency of random layout

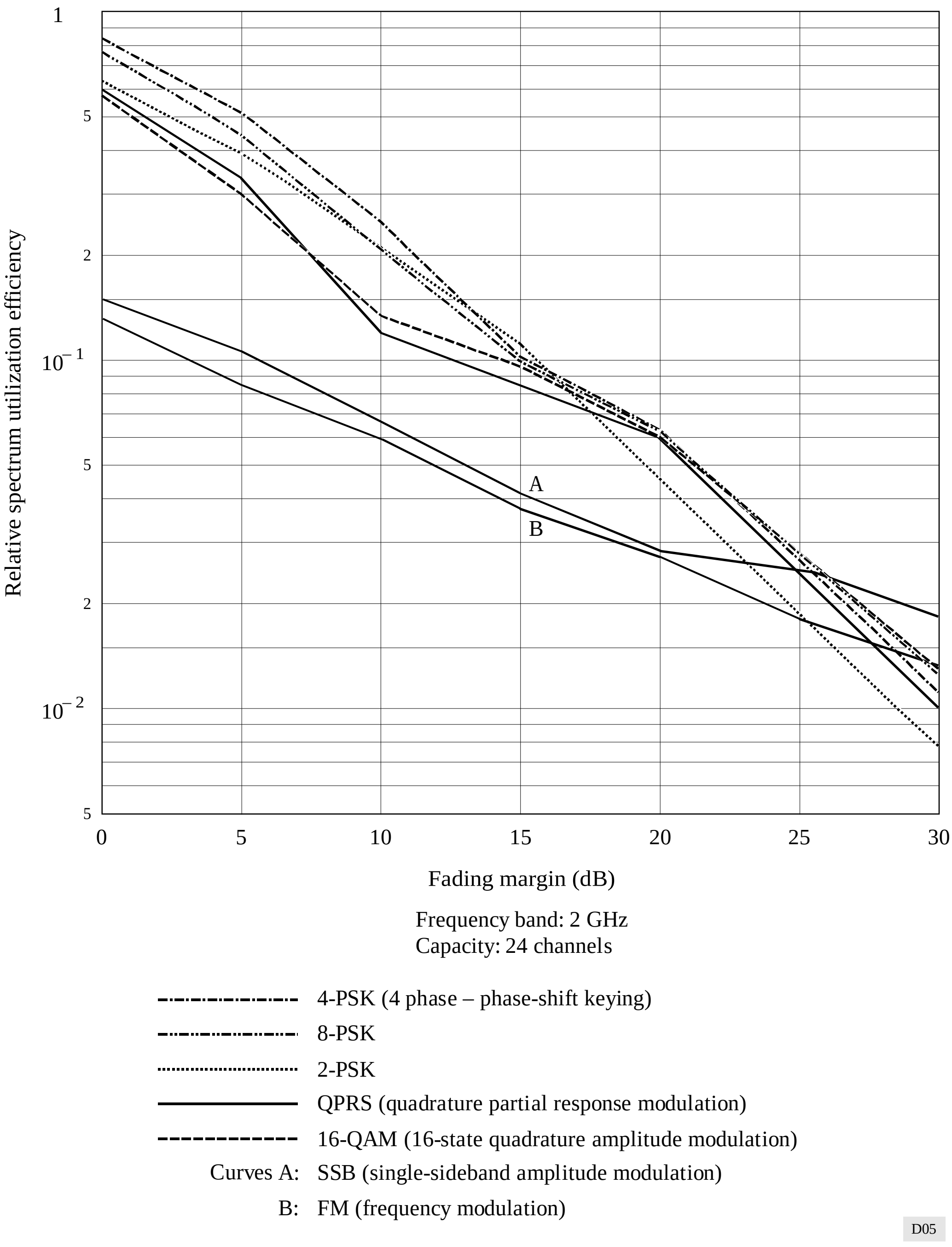


TABLE 2

Modulation method	Normalized channel spacing X	Spectrum efficiency (bit/(s · Hz)
4-PSK	1.88	2.13
8-PSK	2.16	2.77
16-QAM	2.23	3.59

Note 1 – Degradation due to adjacent channel interference: 0.5 dB.

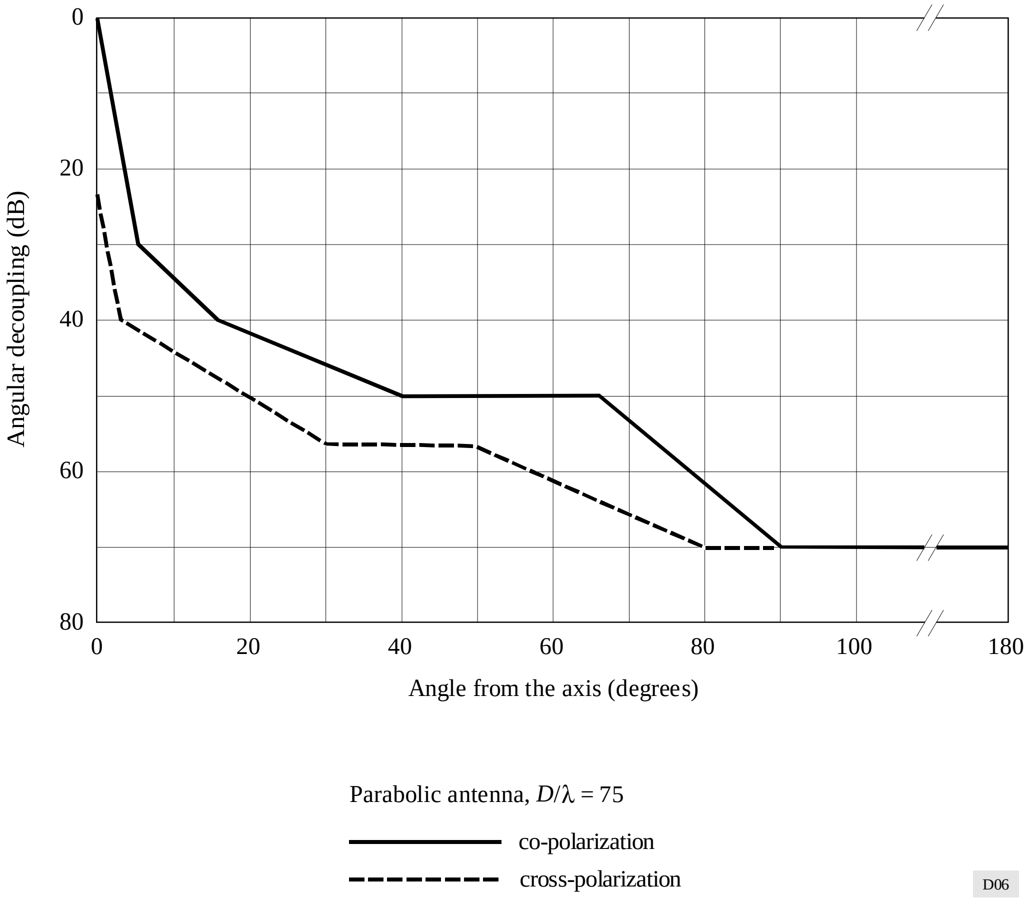
– Channel filters: raised cosine roll-off 0.5.

– Decoupling between cross-polarized channels (residual XPD): 12 dB.

The antenna radiation pattern used in the analysis is shown in Fig. 6; it is for a typical parabolic antenna. It has been assumed that performance degradation (and a bit error ratio of 10^{-3}) due to co-channel interference from other links is not greater than 1 dB. It is assumed that the interfered-with link is at the threshold, with 40 dB fade margin, while the interfering link is receiving its nominal value.

FIGURE 6

Antenna radiation masks



A normalized network density γ has been defined as:

$$\gamma = \frac{2N\rho^2}{\text{overall area covered by the network}} \tag{14}$$

where:

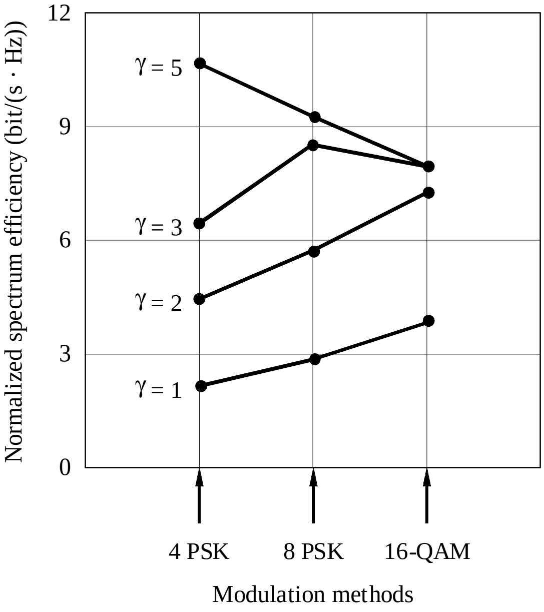
N: number of radio nodes in the network

ρ: mean square hop length.

The results of Fig. 7 show that in high density networks the highest efficiency is achieved with 4-PSK modulation. However, the modulation method moves in favour of 8-PSK or even 16-QAM when the network density is lower. This shows that the spectrum utilization efficiency of modulation methods depends on the interference environment.

FIGURE 7

Spectrum efficiency in a mesh network



Antenna radiation mask of Fig. 6.
Performance degradation due to frequency re-use: 1 dB

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Note 1 – Additional information may be found in:

DODO, J., KUREMATSU, H. and NAKAZAWA, I. [8-12 June, 1980] Spectrum use efficiency and small capacity digital radio-relay system in the 2 GHz band. IEEE International Conference on Communications (ICC ’80), Seattle, WA, United States of America.

TILLOTSON, L.C. *et al*. [1973] Efficient use of the radio spectrum and bandwidth expansion. *Proc. IEEE*, 61, **4**.