RECOMMENDATION ITU-R BO.1696

Methodologies for determining the availability performance for digital multiprogramme broadcasting-satellite service systems, and their associated feeder links operating in the planned bands

(Question ITU-R 3/6)

(2005)

Scope

This Recommendation proposes methodologies for determining performance objectives for digital systems in the 11.7-12.7 GHz, and sets availability objectives for digital systems that are higher than those for analogue systems. Annex 1 to this Recommendation provides example implementations of the recommended methodologies, as well as exact and approximate solutions.

The ITU Radiocommunication Assembly,

considering

a) that digital multiprogramme systems are now in use in the broadcasting-satellite service (BSS);

b) that the performance of digital multiprogramme systems is important to administrations implementing such systems;

c) that the system availability performance provides an important reference point for evaluating the relative performance of an administration's BSS assignment, should that assignment be implemented with a digital multiprogramme system;

d) that the reception characteristics of a digital multiprogramme system are significantly different from the reception characteristics of an analogue FM system;

e) that the existing Appendices 30 and 30A of the Radio Regulations performance objective of maintaining a C/N ratio equal to or better than 14 dB for 99% of the worst month is based on analogue FM transmission;

f) that, because of these factors, it is desirable to develop an availability performance objective specifically for digital multiprogramme systems;

g) that a methodology to determine availability performance for digital multiprogramme BSS systems must recognize the wide range of threshold C/N ratios at which these various systems operate;

h) that the development of a digital multiprogramme performance objective is not only useful for the planned BSS band, but also for other BSS bands, for example, the 17/21 GHz band, *further considering*

a) that the performance of digital multiprogramme systems can be characterized by evaluating the system availability corresponding to the quasi-error-free (QEF) point[1], which corresponds to high-picture quality reception,

recognizing

a) that although many operational digital multiprogramme BSS links have QEF link availability better than 99.5% of the worst month (or about 99.86% of an average year for most rain zones), the required availability is determined by specific system performance objectives;

b) that Recommendation ITU-R BO.1516 – Digital multiprogramme television systems for use by satellites operating in the 11/12 GHz frequency range recommends, among other things, that one of the four transmission systems described in Annex 1 of that Recommendation be selected when implementing digital multiprogramme television services via satellite;

c) that Recommendation ITU-R BO.1516 shows that the QEF *C/N* ratio values for these systems is spread over a wide range of values, and that trade-offs among primary digital link parameters can be used to meet performance objectives,

recommends

1 that administrations should use the methodologies provided in Annex 1 to this Recommendation to determine the system availability performance for digital multiprogramme BSS systems, and their associated feeder links, operating in the planned bands;

2 that digital multiprogramme systems should provide, as guidance, QEF performance for at least *X*% of the worst month;

3 that when implementing digital multiprogramme systems, a target *C/N* value of (minimum *C/N* + *Z*) dB should be maintained within the service area or coverage area for at least *X*% of the worst month. As guidance, 99.5% can be taken for the default value of *X*. The values of the minimum *C/N* are defined in Table 1 (also described in Table 2 of Recommendation ITU-R BO.1516). The value *Z* is the additional degradation margin[2].

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[1] QEF generally refers to a BER of approximately one bit error per hour or per day. When a digital multi-programme system is operating at a BER equal to or better than the QEF point, picture quality becomes solely a function of the video compression rates and algorithms in use, and not a function of the channel BER. When a digital multi-programme system is operating at a BER below or worse than QEF, then video quality becomes a function of both the video compression rates and algorithms, and the channel BER.

[2] The value *Z* is the sum of Z_1 and Z_2. In case of System C and System D in Table 1, additional margin Z_1 is needed for hardware implementation and satellite transponder distortions. As guidance, a value of 1.8-2.3 dB, depending on the modulation used can be taken as the default value for Z_1. Z_2 is the margin taking into account interference from intra and interregional BSS satellites, uplink noise, and interference from other sources. The value of Z_2 needs to be determined for each specific case, taking into account the individual system operational and interference environment.

TABLE 1

Minimum *C*/*N* for QEF operation (dB) (quoted from Table 2 of Recommendation ITU-R BO.1516)

Modulation and coding			System A	System B	System C	System D
Modulation modes supported individually and on the same carrier			QPSK	QPSK	QPSK	8-PSK, QPSK, and BPSK
Performance requirement *C*/*N* (dB)			*C*/*N* for QEF[(1)]	*C*/*N* for QEF[(2)]	*C*/*N* for QEF[(3)]	*C*/*N* for QEF[(4)]
Modes	Inner code					
BPSK	Conv.	1/2	Not used	Not used	No	0.2
QPSK	Conv.	5/11	Not used	Not used	2.8/3.0	Not used
		1/2	4.1	3.8	3.3/3.5	3.2
		3/5	No	Not used	4.5/4.7	Not used
		2/3	5.8	5	5.1/5.3	4.9
		3/4	6.8	Not used	6.0/6.2	5.9
		4/5	Not used	Not used	6.6/6.8	Not used
		5/6	7.8	Not used	7.0/7.2	6.8
		6/7	Not used	7.6	Not used	Not used
		7/8	8.4	Not used	7.7/7.9	7.4
8-PSK	Trellis		Not used	Not used	Not used	8.4

(1) At a BER < 10^{-10}. The *C*/*N* values for System A refer to computer simulation results achieved on a hypothetical satellite chain, including input multiplex (IMUX), travelling wave tube amplifier (TWTA) and output multiplex (OMUX), with modulation roll-off of 0.35. They are based on the assumption of soft-decision Viterbi decoding in the receiver. A bandwidth to symbol rate ratio of 1.28 has been adopted. The figures for *C*/*N* include a calculated degradation of 0.2 dB due to bandwidth limitations on IMUX and OMUX filters, 0.8 dB non-linear distortion on TWTA at saturation and 0.8 dB modem degradation. The figures apply to BER = 2×10^{-4} before RS (204,188), which corresponds to QEF at the RS coder output. Degradation due to interference is not taken into account.

(2) At a BER of 1×10^{-12}.

(3) Theoretical QPSK (2-bit per symbol) E_s/N_0, i.e. *C*/*N* as measured in Nyquist bandwidth (baud rate/2) for normal and truncated spectral shaping, respectively. Does not include hardware implementation margin or satellite transponder loss margin. Two values correspond to System C normal and truncated transmit spectral shaping, respectively.

(4) These values were derived from computer simulations and regarded as theoretical values. The values apply to BER = 2×10^{-4} before RS (204,188) and using the Nyquist bandwidth. Does not include hardware implementation margin or satellite transponder loss margin.

Annex 1

Methodologies for determining the availability performance for digital multiprogramme BSS systems, and their associated feeder links operating in the planned bands

1 Introduction

1.1 General remarks

Digital multiprogramme transmission systems are now in widespread use in the BSS. This use has been recognized within ITU-R in several areas. In particular, some of the parameters used in the replanning of the Regions 1 and 3 BSS Plan reflect the introduction of such digital multiprogramme transmission systems. One system parameter that has not adequately been defined for digital multiprogramme transmissions is the system availability performance, taking into account feeder link and downlink propagation fade statistics and the particular characteristics of the digital system (e.g. interference environment). As digital multi-programme transmission systems continue to be studied and implemented, this Annex provides the recommended methodologies for calculating threshold availability performance of contemporary digital systems and propagation models.

1.2 Specific characteristics of digital multiprogramme BSS

The performance of an operating digital BSS system can be characterized by looking at two distinct digital modulation performance thresholds. The first, sometimes called the QEF threshold, is characterized by operation at a BER of approximately one bit error per hour or day (BER of 10^{-9} to 10^{-12}). The second, sometimes referred to as the "freeze frame" point, or the point where video picture continuity is lost, occurs when the BER becomes sufficiently high that a video compression decoder becomes unable to build a picture frame. This freeze frame point is typically very close to the complete unlock of the demodulator carrier and bit timing tracking loops.

Above the QEF point, digital picture quality remains essentially constant for all values of C/N. In fact, the video picture quality level in this region is independent of the link C/N, i.e. it is solely dependent on the quality and compression ratio of the compression video encoder being employed, as well as the information bit rate assigned to the video channel.

Video quality rapidly degrades from the QEF point to the freeze frame point because of the avalanching number of bit errors presented to the video decoder that can no longer be mitigated by the concatenated forward error correction. At error correction lock threshold, video stops abruptly, normally resulting in frozen display of the most recent decoded video frame.

As per Note 2 to *recommends* 1.2 in Recommendation ITU-R BO.1444, the difference in C/N between the freeze frame point and the QEF point is assumed to be 1.5 dB unless an administration specifies otherwise. In this Recommendation, threshold availability is calculated at the QEF point.

2 Description of recommended methodologies

2.1 Introduction of relevant parameters

The performance of the digital BSS link is dependent on the technical design of the link, including the choice of digital coding, multiplexing, and modulation methods, the satellite e.i.r.p. and the figure of merit (G/T) of the BSS receiver. Other parameters that will impact system availability include propagation fading, depolarization due to rain, polarization misalignment, receive antenna mispointing, feeder uplink power control (UPC), on-board satellite automatic gain control (AGC) and interference from neighbouring BSS systems.

Table 2 provides the list of ITU-R Recommendations applied in the following sections. Techniques mentioned in Recommendation ITU-R BO.794 to minimize the effect of rain attenuation on the feeder link are considered and in particular UPC and on-board AGC: UPC allows the feeder link to maintain a given power level at the satellite in presence of propagation fading, while on-board AGC maintains the total satellite receive power to a level such that the power amplifier is driven at a constant level, i.e. the satellite maintains the downlink e.i.r.p. level independently of the uplink channel condition. Given that it is common to assume that the uplink interference signals are not faded at the same time as the desired link, the use of on-board AGC results in increase of the uplink interference signal power, which reduces the uplink C/I. Site diversity, also discussed in Recommendation ITU-R BO.794, is addressed fully in Recommendation ITU-R P.618 where a conversion from single link availability to multiple site diversity availability is provided; if applicable, this conversion can be applied to the results obtained using the methodology presented below.

2.2 System performance

The overall system performance is determined by the overall aggregate carrier-to-noise-plus-interference power ratio, $C/(N + I)$, defined by:

$$C/(N+I) = C/(N+I)_u \oplus C/(N+I)_d \qquad \text{dB} \qquad (1)$$

where:

$$C/(N+I)_u = C/N_u \oplus C/I_u \qquad \text{dB} \qquad (1a)$$

$$C/(N+I)_d = C/N_d \oplus C/I_d \qquad \text{dB} \qquad (1b)$$

and

C/N_u: uplink carrier to thermal noise power ratio (dB)

C/I_u: uplink carrier to interference power ratio (dB)

C/N_d: downlink carrier to thermal noise power ratio (dB)

C/I_d: downlink carrier to interference power ratio (dB)

Operator $\oplus$: $A \oplus B = -10 \log (10^{-A/10} + 10^{-B/10})$.

TABLE 2

Relevant ITU-R Recommendations

Recommendation ITU-R	Title	Application
P.618	Propagation data and prediction methods required for the design of Earth-space telecommunication systems	Propagation attenuation
P.676	Attenuation by atmospheric gases	
P.837	Characteristics of precipitation for propagation modelling	
P.839	Rain height model for prediction methods	
P.840	Attenuation due to clouds and fog	
P.841	Conversion of annual statistics to worst-month statistics	
P.838	Specific attenuation model for rain for use in prediction methods	
P.1511	Topography for Earth-to-space propagation modelling	
P.453	The radio refractive index: its formula and refractivity data	
P.835	Reference standard atmospheres	
P.679	Propagation data required for the design of broadcasting-satellite systems	
BO.790	Characteristics of receiving equipment and calculation of receiver figure-of-merit (*G*/*T*) for the broadcasting-satellite service	Calculation of receiver figure of merit (*G*/*T*)
BO.793	Partitioning of noise between feeder links for the broadcasting-satellite service (BSS) and BSS downlinks	Partitioning of noise
BO.794	Techniques for minimizing the impact on the overall BSS system performance due to rain along the feeder-link path	Rain fade mitigation techniques
BO.1212	Calculation of total interference between geostationary-satellite networks in the broadcasting-satellite service	Calculation of *C*/*I*
BO.1516	Digital multiprogramme television systems for use by satellites operating in the 11/12 GHz frequency range	Modulation and coding parameters

2.2.1 C/N_u calculation

The uplink carrier to thermal noise power ratio C/N_u is given by:

$$C/N_u = EIRP_u - L_{su} - A_{pu}\,(p_u) + UPC(p_u) - BW_{effu} - k + G/T_s \qquad \text{dB} \qquad (2)$$

where:

$EIRP_u$: uplink effective isotropic radiated power (dBW) in clear sky

L_{su}: uplink free space loss (dB) calculated as:

$20 \log (4\pi\, R_u / \lambda_u)$

where:

R_u: range (m) between feeder-link station and satellite

λ_u: uplink wavelength (m)

$A_{pu}(p_u)$: total uplink propagation loss (dB) exceeded p_u% of time; defined by ITU-R P.618, § 2.5 as

$= A_{gu} + A_u\,(p_u)$

where:

A_{gu}: uplink gaseous absorption (dB) (Recommendation ITU-R P.676)

$$A_u(p_u) = \sqrt{(A_{ru}(p_u) + A_{cu}(p_u))^2 + A_{su}^2(p_u)}$$

$A_{ru}(p_u)$: uplink rain attenuation (dB) exceeded p_u% of time (Recommendation ITU-R P.618)

$A_{cu}(p_u)$: uplink cloud and fog attenuation (dB) exceeded p_u% of time

$A_{su}(p_u)$: uplink scintillation fading (dB) exceeded p_u% of time

P_u: uplink exceedance or unavailability (%)

$UPC(p_u)$: uplink power control factor (dB) calculated as:

= 0, under clear-sky condition or when uplink power control is not used

$= \min\,(A_u(p_u), UPC_{max}) - \varepsilon$, under faded condition

where:

UPC_{max}: maximum increase in transmit power (dB) in presence of path propagation attenuation

ε: uplink power control peak positive error (dB)

Bw_{effu}: effective uplink noise bandwidth (dB/Hz) of digital carrier

k: Boltzmann's constant = –228.6 (dB(W/K · Hz))

G/T_s: satellite receiver figure of merit (dB/K).

2.2.2 C/N_d calculation

With the use of on-board AGC and/or UPC, BSS systems are designed such that the satellite transponder is driven at a constant level up to the point where the uplink $C/(N+I)$ falls below a threshold, creating a system outage independent of the downlink channel condition. Accordingly, the satellite e.i.r.p. is maintained constant and thus the downlink availability performance is, for all practical purposes, decoupled from the uplink performance. Under these conditions, the downlink carrier to thermal noise power ratio C/N_d is given by:

$$C/N_d = EIRP_d - L_{sd} - A_{pd}(p_d) - BW_{effd} - k + G/T_g - Z_1 - dT(p_d) \quad \text{dB} \qquad (3)$$

where:

$EIRP_d$: downlink effective isotropic radiated power (dBW)

L_{sd}: downlink free-space loss (dB) calculated as:

$= 20 \log (4\pi R_d/\lambda_d)$

where:

R_d: range (m) between satellite and receiver terminal

λ_d: downlink wavelength (m)

$A_{pd}(p_d)$: total downlink propagation loss (dB) exceeded p_d% of time; defined by Recommendation ITU-R P.618, § 2.5 as

$= A_{gd} + A_d(p_d)$

where:

A_{gd}: downlink gaseous absorption (dB) (Recommendation ITU-R P.676)

$$A_d(p_d) = \sqrt{(A_{rd}(p_d) + A_{cd}(p_d))^2 + A_{sd}^2(p_d)}$$

$A_{rd}(p_d)$: downlink rain attenuation (dB) exceeded p_d% of time (Recommendation ITU-R P.618)

$A_{cd}(p_d)$: downlink cloud and fog attenuation (dB) exceeded p_d% of time

$A_{sd}(p_d)$: downlink scintillation fading (dB) exceeded p_d% of time

P_d: downlink exceedance or unavailability (%)

BW_{effd}: effective downlink noise bandwidth (dB/Hz) of digital carrier; same as BW_{effu} for "bent pipe" repeater satellite

G/T_g: receiver terminal usable figure of merit (dB/K) under clear-sky condition, i.e. including only gaseous absorption effect (Recommendation ITU-R BO.790, Annex 1, § 1 without rain and cloud attenuation)

Z_1: adjustment factor (dB) for satellite transponder distortion

$dT(p_d)$: increase in noise temperature (dB/K) due to path attenuation from rain and clouds exceeded p_d% of time (e.g. difference in G/T when applying Recommendation ITU-R BO.790, Annex 1, § 1 with:

1. path attenuation set to $A_{gd} + A_{rd} + A_{cd}$,

2. path attenuation set to A_{gd} only).

2.2.3 Overall *C/I* calculation

The overall aggregate carrier-to-interference power ratio, C/I, is given by:

$$C/I = C/I_u \oplus C/I_d \qquad \text{dB} \tag{4}$$

where:

C/I_u: uplink carrier to interference power ratio (dB)

C/I_d: downlink carrier to interference power ratio (dB).

Recommendation ITU-R BO.1212 is used to calculate the clear-sky uplink and downlink C/I's including intra- and inter-BSS system interference. Under channel fading, the inter-system interference signals are assumed to be non-faded. Combined with the use of UPC and/or on-board AGC, the faded inter-system C/I's are equivalent to the clear-sky C/I's reduced by the level of channel fading such that:

$$C/I_u = [C/I_{cu} - A_u(p_u) + UPC(p_u)] \oplus C/I^u_{intra}(p_u) \qquad \text{dB} \tag{4a}$$

$$C/I_d = [C/I_{cd} - A_d(p_d)] \oplus C/I^d_{intra}(p_d) \qquad \text{dB} \tag{4b}$$

where:

C/I_{cu}: clear-sky uplink inter-system C/I (dB) according to Recommendation ITU-R BO.1212 when considering only atmospheric gaseous absorption (Recommendation ITU-R P.676) for both the interfered and wanted links and without consideration of UPC

C/I_{cd}: clear-sky downlink inter-system C/I (dB) according to ITU-R BO.1212 when considering only atmospheric gaseous absorption (Recommendation ITU-R P.676) for both the interfered and wanted links

$$C/I_{intra} = C/I^u_{intra}(p_u) \oplus C/I^d_{intra}(p_d) \qquad \text{dB}$$

C/I_{intra}: overall aggregate carrier to intra-system interference ratio (dB)

$C/I^u_{intra}(p_u)$: uplink carrier to intra-system interference ratio (dB) according to Recommendations ITU-R BO.1212 and ITU-R P.618 for the rain depolarization

$C/I^d_{intra}(p_d)$: downlink carrier to intra-system interference ratio (dB) according to Recommendations ITU-R BO.1212 and ITU-R P.618 for the rain depolarization.

2.3 Overall system availability

The overall system availability defines the ability of the system to maintain its overall aggregate $C/(N + I)$ above a given threshold over time. Path propagation fading in the links determines this availability performance over time.

Given that the use of UPC and/or on-board AGC maintains constant the satellite e.i.r.p. independently of the feeder-link fading, the uplink and downlink $C/(N+I)$ are thus decoupled. Defining:

$$\left(\frac{n+i}{c}\right)=10^{-0.1C/(N+I)};\ \left(\frac{n+i}{c}\right)_u=10^{-0.1C/(N+I)_u};\ \left(\frac{n+i}{c}\right)_d=10^{-0.1C/(N+I)_d}$$

such that $\left(\frac{n+i}{c}\right)=\left(\frac{n+i}{c}\right)_u+\left(\frac{n+i}{c}\right)_d$

and given that feeder link and service link path fading can be assumed to be uncorrelated, the overall aggregate $\left(\frac{n+i}{c}\right)$ is a function of the sum of two independent random variables. Thus the probability density function (PDF) of the overall aggregate $\left(\frac{n+i}{c}\right)$ (and thus of $C/(N+I)$) is the convolution of the PDFs of the uplink and downlink $\left(\frac{n+i}{c}\right)$.

Approximations can be used to obtain an upper bound and an approximated lower bound on the overall system availability, thus avoiding the somewhat complex calculations required for the exact solution. These approaches are described in the following sections.

The annual availability probability obtained below can be converted to worst-month availability using the conversion method from Recommendation ITU-R P.841, for mean annual global (for planning purpose) or other climates.

2.3.1 Exceedance percentage as a function of fade level

In carrying out the calculation in the following sections, one needs to derive the exceedance probability as a function of the fade level. Recommendation ITU-R P.618 does not provide a direct methodology to do so. Two methodologies are presented below.

The exceedance percentage for a given fade level can be found directly from a plot of the attenuation curve for the BSS link under study. Taking as an example the BSS link defined in Table 3, the total downlink propagation loss $A_{pd}(p_d)$ is shown in Fig. 1 as a function of annual exceedance probability p_d, calculated in accordance with Recommendation ITU-R P.618. This plot shows for example that a 3 dB total downlink propagation loss corresponds to about 0.025% exceedance, or 99.975% availability. In a computer code implementation, the data points describing the curve can be stored in a table and when the required propagation fade level falls between two data points, an interpolation technique can be used to estimate the associated exceedance probability.

An alternative methodology to using plotted/tabulated attenuation curves is to develop computer code that will:

– calculate the propagation fade level for a given exceedance percentage of time as described in Recommendation ITU-R P.618; and

– iterate for different values of exceedance percentage of time until the desired value of fade is achieved. This latter method is used to generate the results for the example in § 3.

Note that once the relationship between the exceedance percentage of time and attenuation level is obtained, equations (1) to (4) can be used to derive a corresponding relationship between the $C/(N + I)_u$ or $C/(N + I)_d$ and the exceedance percentage of time.

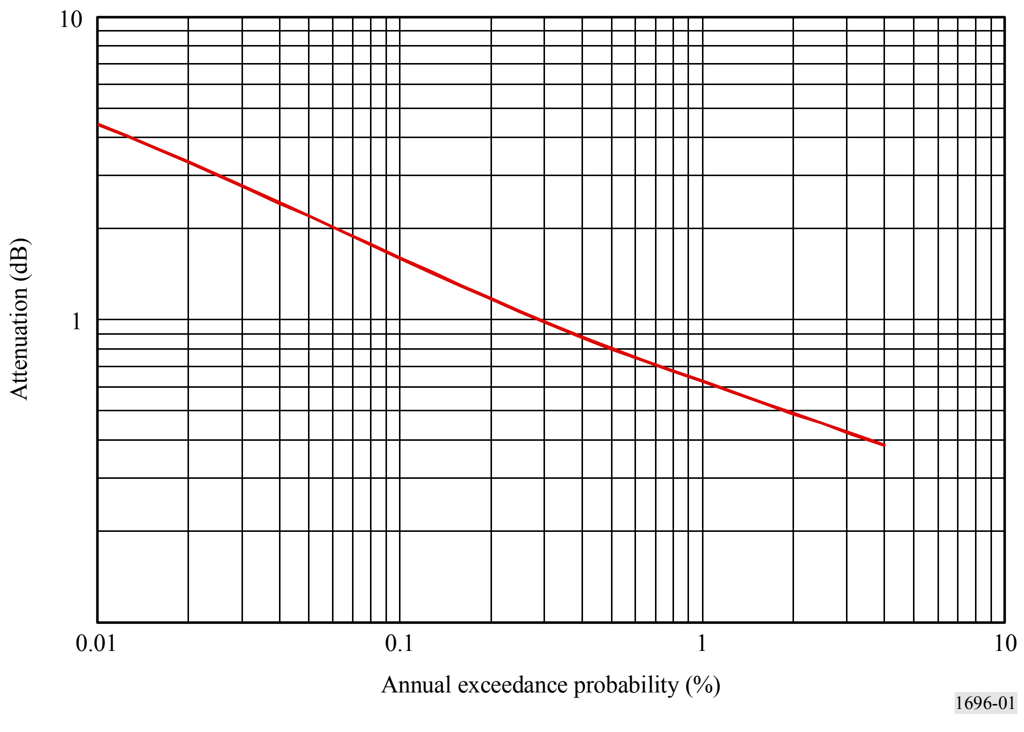
TABLE 3

Example system

Downlink frequency (GHz)	12
Polarization	Circular
Elevation angle (degrees)	30
Terminal latitude (° N)	50
Terminal longitude (° W)	10
Height above mean sea level (km)	0 (Calculated, Recommendation ITU-R P.1511)
Terminal antenna diameter (cm)	60
Terminal antenna efficiency (%)	70
Season	Global mean annual climate

FIGURE 1

Example link propagation loss curve



2.3.2 Exact system availability

To precisely determine the overall system availability P_s, it is necessary to derive the PDFs for each of $\left(\frac{n+i}{c}\right)_u$ and $\left(\frac{n+i}{c}\right)_d$, and to convolve these two PDFs to generate the PDF of the overall aggregate $\left(\frac{n+i}{c}\right)$. Equations (1) to (4) are used to find the relationship between the exceedance percentage of time (or unavailability p_u and p_d) and the associated uplink or downlink $\left(\frac{n+i}{c}\right)$. These relationships are the cumulative distribution functions (CDF) of the uplink and downlink $\left(\frac{n+i}{c}\right)$. Taking the derivatives of these functions provides the required PDFs. After convolving the two PDFs, we obtain the overall PDF that, when integrated, results into the CDF of the overall aggregate $\left(\frac{n+i}{c}\right)$, which then can easily be converted to a system availability corresponding to a given $C/(N+I)$ threshold.

Section 1 of Appendix 1 to this Annex provides an example of implementation in a computer code of these calculations. There are obviously numerous other approaches that can be designed to arrive at the same results.

2.3.3 Approximated system availability

2.3.3.1 Upper bound

An upper bound of the overall system availability P_s can be obtained by assuming that an outage will occur when *either* the uplink or downlink $C/(N+I)$ will fall below their respective QEF thresholds, such thresholds being defined as the point where an outage will occur under the condition that the other link is not rain faded. In this case, the system availability ($P_s = 100 - p_s$) is derived from:

$$p_s = p'_u + p'_d - \frac{p'_u \, p'_d}{100} \tag{5}$$

where:

- p_s: overall system unavailability (%)
- p'_u: uplink exceedance or unavailability: probability (%) that the uplink $C/(N+I)$ is below the uplink QEF threshold
- p'_d: downlink exceedance or unavailability: probability (%) that the downlink $C/(N+I)$ is below the downlink QEF threshold.

Determination of the system availability when only one of the links is rain faded is a complicated process due to the need to consider availability-dependent cloud and scintillation fading in the overall link. For the feeder link, it can be assumed that the uplink rain margin will mitigate the cloud and scintillation fading during non-rain periods of time. In addition, under uplink rain, cloud and scintillation fading will be small contributors to the total path propagation fading. Thus cloud and scintillation fading can be ignored in the feeder link. However BSS downlinks have less margin, such that cloud and scintillation fading should be considered. Accordingly, an iterative approach is required to determine the overall system availability, to address the dependence of certain parameters such as cloud and scintillation fading and receiver noise temperature increase on system availability. Appendices 1 and 2 to this Annex present such an approach.

2.3.3.2 Approximated lower bound

In conventional BSS systems, clear sky $C/(N + I)_u$ is normally designed to be much higher than that of downlink. Even when high propagation attenuation exists in the uplink path, it is possible to maintain the $C/(N + I)_u$ well above the QEF threshold by implementing uplink fade mitigation techniques such as UPC and/or site diversity. Therefore, by assuming a constant minimum $C/(N + I)_u$ well above the QEF threshold and, if the effect of p'_u can be neglected, the overall system unavailability p_s is derived from the downlink exceedance or unavailability ($p_s = p'_d$) directly, taking into account the constant $C/(N + I)_u$.

3 Example

A hypothetical system is considered to compare system availability performance results obtained using the two methodologies presented in § 2.3.

Specifications for this system are presented in Table 4. In this example, a constant overall aggregate intra-system carrier-to-interference ratio, C/I_{intra}, is used. The calculated availability performance results are presented in Table 5 for the exact solution and approximation methodologies implemented according to Appendix 1. Figure 2 presents the downlink and uplink exceedance cumulative distribution function versus $C/(N + I)$, ignoring the C/I_{intra} contribution while Fig. 3 presents the CDF of the overall aggregate $C/(N + I)$.

TABLE 4

System specifications

Polarization	Circular
Satellite longitude (° E)	–130
Satellite downlink e.i.r.p. in clear sky (dBW)	50
Satellite receiver figure of merit G/T (dB/K)	4
Uplink frequency (GHz)	17.3
Downlink frequency (GHz)	12.2
Satellite transponder distortion adjustment factor Z_1 (dB)	0
Effective uplink noise bandwidth of digital carrier (MHz)	24
Effective downlink noise bandwidth of digital carrier (MHz)	24
QEF threshold $C/(N + I)$ (dB)	7.6
Feeder station latitude (° N), longitude (° E)	50, –90
Uplink power control: UPC_{max} (dB) ε (dB)	3 0.25
Feeder station uplink e.i.r.p. in clear sky (dBW)	80
Feeder station antenna size (m)	7
Feeder station antenna efficiency (%)	65
Terminal latitude (° N)/longitude (° E)	60, –110
Terminal figure of merit G/T (dB/K) calculated from Recommendation ITU-R BO.790	12.5
Recommendation ITU-R BO.790 inputs: θ_1, θ_2, θ_3 (degrees)	0.4, 0.01, 0.05
Recommendation ITU-R BO.790 input: antenna noise temperature in clear sky (K)	50
Recommendation ITU-R BO.790 input: total coupling losses α	1
Recommendation ITU-R BO.790 input: receive antenna 3 dB beamwidth (degrees)	3.8
Recommendation ITU-R BO.790 input: receiver noise figure in clear sky (dB)	0.91
Terminal antenna diameter (cm)	45
Terminal antenna efficiency (%)	70
Downlink clear sky inter-system C/I (C/I_{cd}) (dB)	21
Uplink clear sky inter-system C/I (C/I_{cu}) (dB)	25
Overall aggregate intra-system C/I (C/I_{intra}) (dB)	18
Season (e.g. global mean annual climate)	Global mean annual

TABLE 5

Calculated availability performance

Approximated system availability	
Uplink exceedance p'_u (%)	0.001
Downlink exceedance p'_d (%)	0.2
System availability p_s (%) annual statistics	99.79
Exact system availability	
System availability p_s (%) annual statistics	99.774

FIGURE 2

Exceedance (CDF) for uplink and downlink

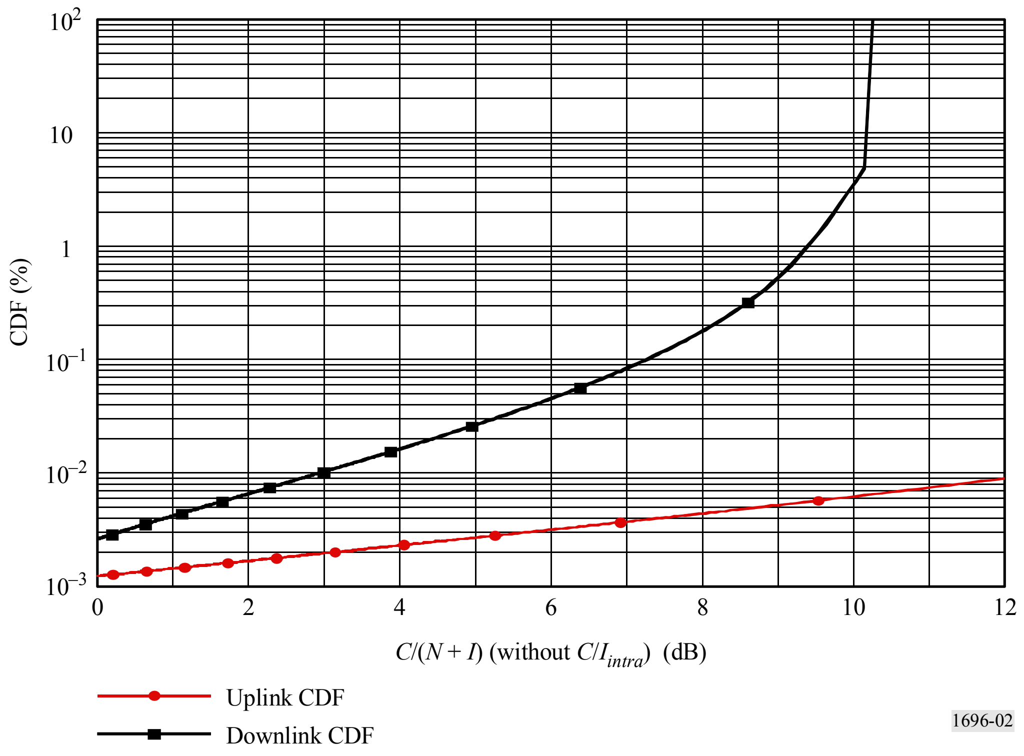
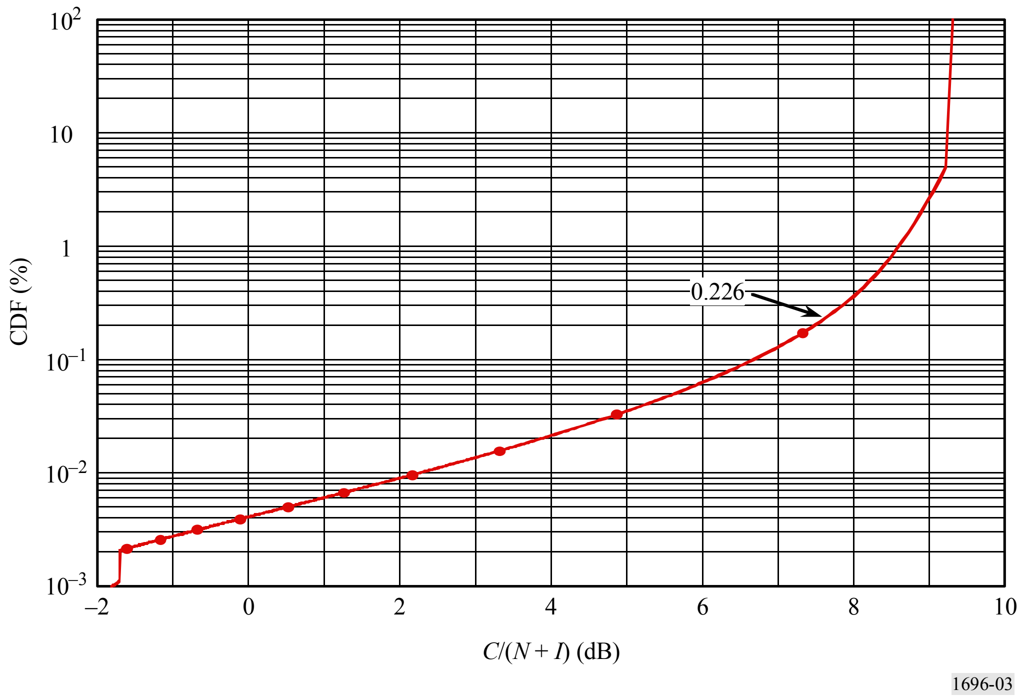


FIGURE 3

Overall aggregate CDF



Appendix 1
to Annex 1

Example implementations of recommended methodologies

The proposed methodologies described in § 2.3.2 and 2.3.3 of Annex 1 can be implemented in various ways. The following sections describe one approach to implementing each of these methodologies.

1 Exact system availability

The following algorithm describes one possible approach to implementing the exact solution methodology described in § 2.3.2 to determine the overall system availability P_s.

Note that the propagation models in Recommendation ITU-R P.618-8 for cloud, rain and scintillation fading are only valid over a combined range of exceedance (p_u or p_d) of 0.01% to 5%, the lower bound being imposed by the scintillation fading model. In the following procedure, this range is extended down to 0.001% by assuming that the scintillation fading at 0.01% is maintained for lower percentages.

Step 1: Set $p_u = p_d = 0.001\%$ and calculate the associated $C/(N + I)_u$ and $C/(N + I)_d$ respectively using equations (1a), (1b), (2), (3), (4a) and (4b). Denote these as $Y_u = C/(N + I)_u$ and $Y_d = C/(N + I)_d$. These represent the minimum $C/(N + I)$ of interest in each link.

Step 2: Set $p_u = p_d = 5\%$ and calculate the associated $C/(N+I)_u$ and $C/(N+I)_d$ respectively using the same equations as in Step 1. Denote these as $X_u = C/(N+I)_u$ and $X_d = C/(N+I)_d$. These represent the maximum $C/(N+I)$ of interest in each link.

Step 3: Set $X = \max(X_u, X_d)$ and $Y = \min(Y_u\ Y_d)$.

Step 4: Define the number of points, M, in the required uplink and downlink PDFs. M should be chosen such that the required resolution on the final PDF is achieved. As a guideline, $M >$ round[$(X$-$Y)/0.1$] should be sufficient where round(x) is the next integer greater than x.

Step 5: Define M equally spaced values in the interval $[10^{-X/10} - dw, 10^{-Y/10}]$ and denote them as $w(n)$ where for $n = M - j + 1$ we get $w(M - j + 1) = 10^{-Y/10} - (j-1)*dw;$ $dw = (10^{-Y/10} - 10^{-/10})/(M-2)$ and $j = 1, \ldots, M$. The array $w(n)$ defines the values of $\left(\frac{n+i}{c}\right)$ over which the uplink and downlink PDFs will be defined.

Step 6: For $j = 1$ *to* M

if $w(j) < 10^{-X_u/10}$

set $P_u(j) = 1$;

else, if $w(j) > 10^{-Y_u/10}$

set $P_u(j) = 0$;

else,

calculate $A_{pu}(p_u)$ required to achieve $C/(N+I)_u = -10 \log w(j)$;

calculate p_u associated with this A_{pu} using Recommendation ITU-R P.618-8;

set $P_u(j) = p_u/100$;

end.

End-for-loop.

At the end of this step, we have the array $P_u(j)$ defining the CDF for the $\left(\frac{n+i}{c}\right)_u$ values of interest (i.e. $w(j)$).

Step 7: Repeat step (5) to find $P_d(j)$ given $C/(N+I)_d$, X_d and Y_d. At the end of this step, we have the array $P_d(j)$ defining the CDF for the $\left(\frac{n+i}{c}\right)_d$ values of interest (i.e. $w(j)$).

Step *8*: Denote the PDF of $\left(\frac{n+i}{c}\right)_u$ as $f_u(\cdot)$ and of $\left(\frac{n+i}{c}\right)_d$ as $f_d(\cdot)$ defined by:

$$f_u(j-1) = \text{Prob}\left\{\left(\frac{n+i}{c}\right)_u = w(j-1)\right\} = P_u(j-1) - P_u(j) \qquad j = 2,3,\ldots,M$$

$$f_d(j-1) = \text{Prob}\left\{\left(\frac{n+i}{c}\right)_d = w(j-1)\right\} = P_d(j-1) - P_d(j) \qquad j = 2,3,\ldots,M$$

Step 9: Define $k = m + j - 1$, then $z(k) = w(m) + w(j)$ for $m, j = 1, \ldots, M - 1$ and thus $k = 1, 2, \ldots, 2{*}M - 3$.

Step 10: Apply the convolution of the individual PDFs as follows:

$$f(z(k)) = \sum_{j=1}^{M-1} f_u(j)\, f_d(k-j) \qquad k = 1, \ldots, 2 * M - 3$$

Note that if n is not in the interval [1, $M - 1$], then $f_u(n) = 0$ and $f_d(n) = 0$.

Step 11: The PDF of the overall aggregate $C/(N + I)$ is then given by:

$$\text{Prob}(C/(N + I) = -10 \log z(k)) = f(z(k))$$

Step 12: The system availability P_s which is the probability of the overall aggregate $C/(N + I)$ being greater than a threshold (Z) is given by:

$$P_s = \sum_{k=1}^{L} f(z(k))$$

where L is such that $-10 \log z(L) \geq Z$ and $-10 \log z(L + 1) < Z$.

2 Approximated system availability

The following algorithm describes one possible approach to implementing the approximation methodology described in § 2.3.3 of Annex 1 to determine an upper bound and an approximated lower bound of the overall system availability P_s.

2.1 Upper bound

The approach consists of first solving p'_d and then p'_u, assuming that when the link of interest is rain faded, the other link is not.

For solving p'_d, the target $C/(N + I)_d$ required to meet the QEF threshold $C/(N + I)$ for clear-sky uplink is determined, from which is derived an upper bound on the downlink propagation loss with which the system can close the downlink. An iterative algorithm then determines the increase in receiver noise temperature as a function of system unavailability and downlink propagation loss, converging to a solution for the overall system unavailability which, when applied to both clear-sky uplink and rain faded downlink, meets the QEF threshold $C/(N + I)$.

For solving p'_u, a first estimate of overall system unavailability p_s is calculated assuming an ideal downlink, i.e. no rain, cloud or scintillation fading. p'_u is then iteratively recalculated assuming the previous p_s to determine the cloud and scintillation fading effect on the $C/(N + I)_d$ which impacts on p'_u. This iteration eventually converges to a final solution for p_s and p'_u.

As mentioned in the previous section, the propagation models in Recommendation ITU-R P.618-8 for cloud, rain and scintillation fading are only valid over a combined range of exceedance (p_u or p_d) of 0.01% to 5%, the lower bound being imposed by the scintillation fading model. In the following procedure, this range is extended down to 0.001% by assuming that the scintillation fading at 0.01% is maintained for lower percentages.

2.1.1 p'_d calculation

The following algorithm implements the calculation of p'_d.

Step 1: Using equations (1) to (4), calculate the target $C/(N+I)_d$ at which the overall $C/(N+I)$ = QEF threshold $C/(N+I)$, assuming clear-sky uplink ($A_{pu} = 0$; $UPC = 0$).

Step 2: Set $p_d = 0.001\%$ and calculate A_{pd} and dT.

Step 3: Calculate the lowest $C/(N+I)_d$ using the above A_{pd} and dT values.

Step 4: If the lowest $C/(N+I)_d$ is above the target $C/(N+I)_d$, then set $p'_d = p_d = 0$ and skip the remaining Steps.

Step 5: Calculate A_{pd} to meet the target $C/(N+I)_d$ assuming $dT = 0$.

Step 6: Using Recommendation ITU-R P.618, determine the downlink unavailability p_d associated with A_{pd}.

Step 7: Calculate dT associated with p_d.

Step 8: Recalculate A_{pd} to meet the target $C/(N+I)_d$ given the above dT.

Step 9: Repeat Steps 6 to 8 until the recalculated A_{pd} converges within an acceptable error (delta) at which point $p'_d = p_d$ has been solved for the scenario of clear-sky uplink and rain faded downlink.

2.1.2 p'_u and p_s calculation

As discussed above, uplink cloud and scintillation fading can be ignored for this calculation. Hence $A_u = A_{ru}$.

Step 1: Using equations (1) to (4), calculate A_{ru} at which the overall $C/(N+I)$ = QEF threshold $C/(N+I)$, assuming: no rain fading on the downlink ($A_{rd} = A_{cd} = A_{sd} = 0$), and maximum uplink power control ($UPC = UPC_{max}$) if applicable. This initial value of A_{ru} represents an upper bound on the uplink rain attenuation with which the system can close the link.

Step 2: Using Recommendation ITU-R P.618, determine the uplink unavailability p_u associated with A_{ru}. This represents a lower bound on unavailability.

Step 3: Calculate the overall unavailability p_s using equation (5) with $p'_u = p_u$ and p'_d calculated in § 2.1 above.

Step 4: Set p_d to a fraction of p_s at the first iteration or augment p_d by this fractional amount thereafter. The fraction is related to the accuracy required. As an example, set the fraction to be ten times smaller than the accuracy sought. Keeping in mind that the procedure is valid for exceedance percentages above 0.001%, then the step size cannot be less than 0.001%.

Step 5: Calculate A_{pd} and $C/(N+I)_d$ for p_d and without downlink rain attenuation $(A_{rd} = 0)$ i.e. including only gas absorption, cloud and scintillation fading.

Step 6: Recalculate A_{ru} at which the overall $C/(N+I)$ = QEF threshold $C/(N+I)$ given $C/(N+I)_d$ from Step 5.

Step 7: Using Recommendation ITU-R P.618, determine the new uplink unavailability p_u given A_{ru}.

Step *8*: Recalculate p_s using $p'_u = p_u$ and p'_d calculated in § 2.1 above.

Step 9: Repeat Steps 4 to 8 until the recalculated p_s converges within an acceptable error (i.e. changes by less than this acceptable error with subsequent iterations).

2.2 Approximated lower bound

The following algorithm implements a methodology described in § 2.3.3.2 of Annex 1 to determine an approximate lower bound of the overall system availability P_s.

Step 1: Using equations (1), (3) and (4), calculate the target $C/(N+I)_d$ at which the overall $C/(N+I)$ = QEF threshold $C/(N+I)$, assuming a constant $C/(N+I)_u$ well above QEF.

Step 2: Set $p_d = 0.001\%$ and calculate A_{pd} and dT.

Step 3: Calculate the lowest $C/(N+I)_d$ using the above A_{pd} and dT values.

Step 4: If the lowest $C/(N+I)_d$ is above the target $C/(N+I)_d$, then set $p_d = 0$ and skip the remaining steps to step 10.

Step 5: Calculate A_{pd} to meet the target $C/(N+I)_d$ assuming $dT = 0$.

Step 6: Using Recommendation ITU-R P.618, determine the downlink unavailability p_d associated with A_{pd}.

Step 7: Calculate dT associated with p_d.

Step 8: Recalculate A_{pd} to meet the target $C/(N+I)_d$ given the above dT.

Step 9: Repeat Steps 6 to 8 until the recalculated A_{pd} converges within an acceptable error (delta).

Step 10: The overall system availability $P_s = 100 - p_d$.

Appendix 2
to Annex 1

Additional information on digital BSS multi-programme availability in the 12 GHz bands

1 Impact of current propagation data on the availability of digital BSS systems

This section addresses current propagation data as well as their impact on the availability of digital BSS links.

An analysis was conducted to determine the effect of the propagation data contained in Recommendations ITU-R P.618 and ITU-R P.837[3] on the availability of digital BSS carriers transmitted to cities in Regions 1, 2 and 3. A major difference with the previous propagation data is the use of continuous curves for rainfall rates based on measured data at actual sites as opposed to rainfall rates based on a discrete number of rain climatic zones.

When conducting the analysis, the following formula was used:

$$(C/N)_p = (C/N)_{cs} - A_p$$

where:

- $(C/N)_p$: carrier-to-noise level exceeded for p% of the time
- $(C/N)_{cs}$: clear-sky carrier-to-noise level
- A_p: attenuation level not exceeded for p% of the time
- P: percentage of time used to specify the target availability.

In the case of Regions 1 and 3, digital BSS links with characteristics given in Table 6 were assumed to be transmitted to over 600 major cities from orbital locations as per the Regions 1 and 3 Plan. The orbital location associated with transmissions to each city was chosen to be that of the corresponding administration's Plan assignment.

It was assumed that, for Region 2, digital BSS carriers with characteristics given in Table 7 were transmitted to 158 cities.

The rainfall rates derived for each of the carriers are plotted in Figs. 4-7. These Figures indicate rainfall rates between 1 mm/h and 159.44 mm/h.

The C/N ratio exceeded for various time percentages varying from 99.9% to 99% were derived, and the statistical distribution of the C/N levels attained for various time percentages is given in Tables 8 and 9. The distribution in Tables 8 and 9 shows that approximately 90% of carriers meet an availability of 99.86% (99.5% of worst month) at lower C/N levels. At an average e.i.r.p. within a service area, it is expected that an even higher percentage should be able to meet an availability of 99.86%.

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[3] These calculations are based on former versions of Recommendations ITU-R P.618 and ITU-R P.837, i.e. they used the rain model of Recommendation ITU-R P.618-6 and the associated Recommendation ITU-R P.837-2.

TABLE 6

Nominal characteristics of Regions 1 and 3 digital BSS Plan assignments

Minimum e.i.r.p. within service area (dBW)	55.9[(1)]
Frequency band (GHz)	12
Rx antenna diameter (cm)	60
Rx antenna gain (dBi)	35.5

(1) Equivalent to nominal maximum e.i.r.p. = 58.9 dBW.

TABLE 7

Characteristics of example digital systems that may be implemented with Region 2 Plan assignments

e.i.r.p. (dBW)	55.5
Frequency band (GHz)	12.5
Rx antenna diameter (cm)	45
Rx antenna gain (dBi)	33.5
Elevation angle (degrees)	40

TABLE 8

Statistical distribution of the *C*/*N* levels attained for various time percentages for digital Regions 1 and 3 BSS links

***C*/*N* level exceeded**	**Percentage of carriers for which the *C*/*N* level is exceeded for 99.9% of the time**	**Percentage of carriers for which the *C*/*N* level is exceeded for 99.7% of the time**	**Percentage of carriers for which the *C*/*N* level is exceeded for 99.5% of the time**
6	95.1	100	100
7	90.5	100	100
8	85.2	99.7	100
9.6	71.6	95.5	100
10	68.1	92.8	99.7

TABLE 9

Statistical distribution of the *C*/*N* levels attained for various time percentages for Regions 2 BSS links

C/*N* level exceeded	Percentage of carriers for which the *C*/*N* level is exceeded for 99.9% of the time	Percentage of carriers for which the *C*/*N* level is exceeded for 99.7% of the time	Percentage of carriers for which the *C*/*N* level is exceeded for 99.5% of the time
5	81.6	100	100
7	67.1	91.8	100
7.6	63.3	88.6	100
8	62.0	84.2	98.7
9	53.8	74.7	89.9
9.6	50.0	69.0	84.2

FIGURE 4

Rainfall rates associated with carriers 1 to 212

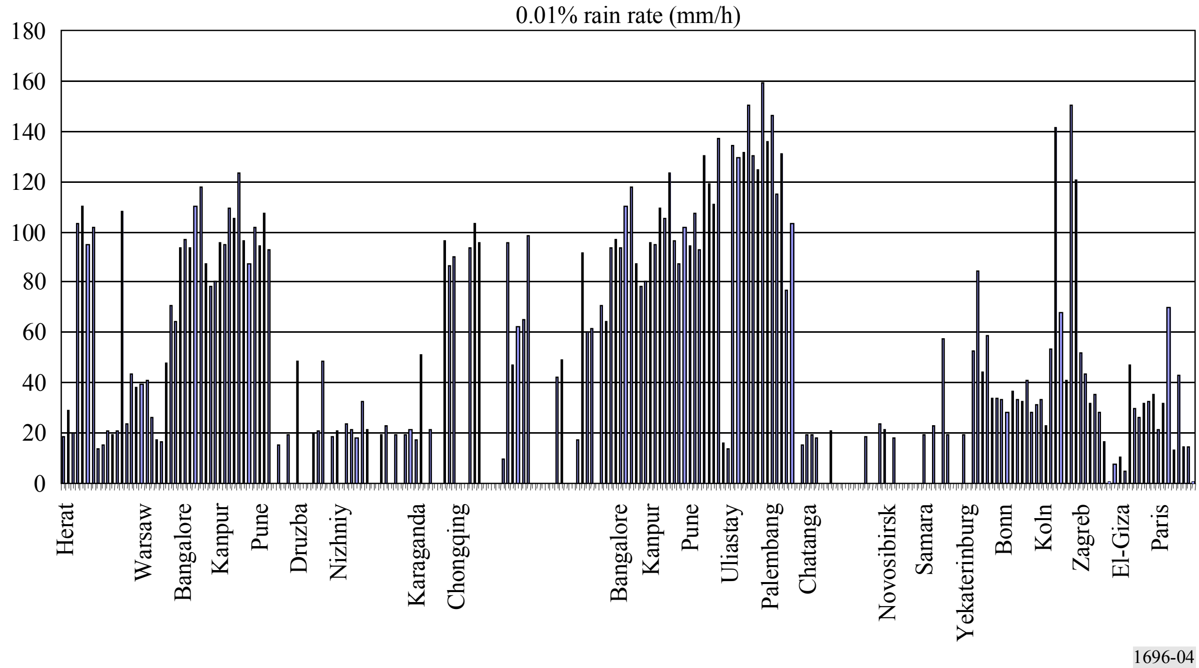

FIGURE 5

Rainfall rates associated with carriers 213 to 435

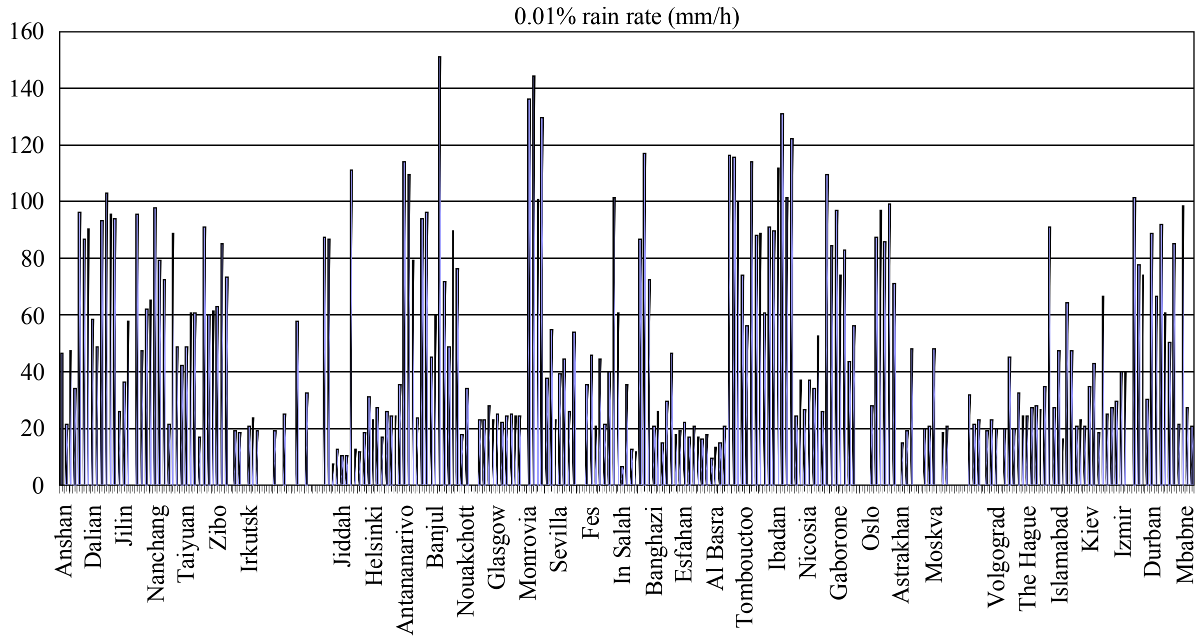

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FIGURE 6

Rainfall rates associated with carriers 436 to 617

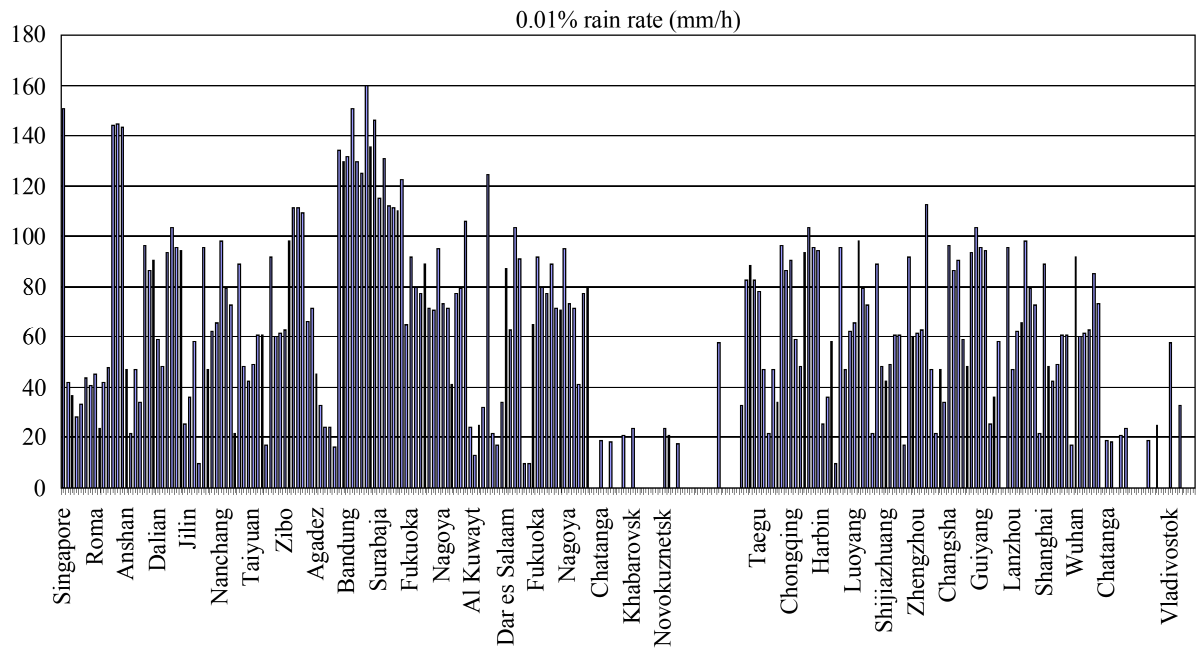

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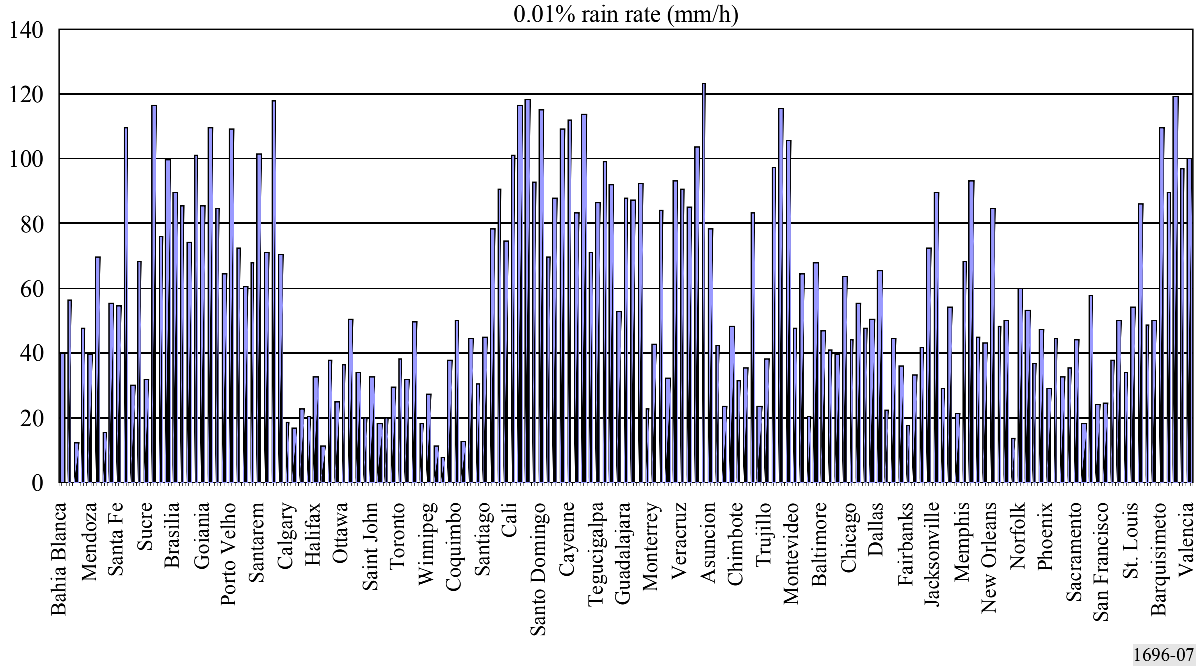
FIGURE 7

Rainfall rates associated with Region 2 carriers



2 Example availability performance for several Region 1 and 3 cities

Table 11 shows the worst-month availability performance of digital links for several Regions 1 and 3 cities using the system parameters shown in Table 10. The modulation schemes considered are QPSK and 8-PSK.

TABLE 10

Example characteristics of a digital BSS Region 1 or 3 system

Area	Edge of coverage	Near boresight
e.i.r.p. (dBW)	55.9	58.4
Frequency band (GHz)	12	
Rx antenna diameter (cm)	60	45
Rx antenna gain (dBi)	35.5	33.0
C/*N* (clear-sky) (27 MHz band width)[(1)] (dB)	18.2	18.2

[(1)] Receiving site: Geneva, Orbital location: 18.8° W, attenuation due to atmospheric gases: 0.2 dB, pointing loss of receiving antenna: 0.3 dB, receiver NF: 1.0.

Note that all QPSK modulated links in Table 11 exceed an availability of 99.5% of the worst month.

Table 11 compares outage duration increase with incremental 0.5 dB increases in the required *C*/*N*. This type of Table is useful for investigating a desired signal total degradation limit in the presence of interference, noise and rain.

TABLE 11

Worst-month availability performance of example digital dBS links for Regions 1 and 3 cities*

		Percentage/minutes of outage during the worst month (increase (%) with respect to a baseline *C*/*I* of 7.6 dB)			
Modulation	**Required *C*/*N* (dB)**	**Moscow**	**London**	**Paris**	**Istanbul**
QPSK	7.6	0.023/10 (–)	0.025/11 (–)	0.022/10 (–)	0.019/8 (–)
	7.6 + 0.5	0.026/11 (13)	0.029/13 (16)	0.025/11 (14)	0.022/10 (16)
	7.6 + 1.0	0.031/13 (35)	0.034/15 (36)	0.029/13 (32)	0.026/11 (37)
	7.6 + 1.5	0.036/16 (57)	0.040/17 (60)	0.034/15 (55)	0.030/13 (58)
	7.6 + 2.0	0.042/18 (83)	0.047/20 (88)	0.040/17 (82)	0.036/16 (89)
		Percentage/minutes of outage during the worst month (increase (%) with respect to a baseline *C*/*N* of 11 dB)			
Modulation	**Required *C*/*N* (dB)**	**Moscow**	**London**	**Paris**	**Istanbul**
8-PSK	11.0	0.068/29 (–)	0.076/33 (–)	0.064/28 (–)	0.057/25 (–)
	11.0 + 0.5	0.082/35 (21)	0.091/39 (20)	0.077/33 (20)	0.068/29 (19)
	11.0 + 1.0	0.099/43 (46)	0.110/48 (45)	0.093/40 (45)	0.082/35 (44)
	11.0 + 1.5	0.120/52 (76)	0.135/58 (78)	0.113/49 (77)	0.100/43 (75)
	11.0 + 2.0	0.148/64 (118)	0.166/72 (118)	0.139/60 (117)	0.122/53 (114)

TABLE 11

Worst-month availability performance of example digital dBS links for Regions 1 and 3 cities*

		Percentage/minutes of outage during the worst month (increase (%) with respect to a baseline *C*/*N* of either 7.6 dB (QPSK) or 11.0 dB (8-PSK))			
Modulation	**Required *C*/*N* (dB)**	**Tokyo**	**Kagoshima**	**Seoul**	**Bangkok**
QPSK	7.6	0.080/35 (–)	0.109/47 (–)	0.032/14 (–)	0.231/100 (–)
	7.6 + 0.5	0.091/39 (14)	0.123/53 (13)	0.037/16 (16)	0.263/114 (14)
	7.6 + 1.0	0.103/44 (29)	0.140/60 (28)	0.043/19 (34)	0.299/129 (29)
	7.6 + 1.5	0.118/51 (48)	0.159/69 (46)	0.050/22 (56)	0.341/147 (48)
	7.6 + 2.0	0.136/59 (70)	0.182/79 (67)	0.058/25 (81)	0.390/168 (66)
8-PSK	11.0	0.205/89 (–)	0.272/118 (–)	0.090/39 (–)	0.574/248 (–)
	11.0 + 0.5	0.240/103 (17)	0.318/137 (17)	0.106/46 (18)	0.662/286 (15)
	11.0 + 1.0	0.283/122 (38)	0.373/161 (37)	0.127/55 (41)	0.765/330 (33)
	11.0 + 1.5	0.336/145 (64)	0.440/190 (62)	0.152/66 (69)	0.885/382 (54)
	11.0 + 2.0	0.403/174 (97)	0.525/227 (93)	0.185/80 (106)	1.026/443 (79)

* The satellite radiating to each city is assumed to be located at the orbital position of its Plan assignment. Pointing loss of the receiving antenna is assumed to be 0.3 dB. Recommendations ITU-R P.676-5, ITU-R P.836 and ITU-R P.1510 were used to calculate attenuation due to atmospheric gases. Recommendations ITU-R P.618-7 and ITU-R P.837-3 were used to calculate the attenuation due to rain.

3 Non-QPSK modulation

Recommendation ITU-R BO.1516 and the response to Circular-letter CR/116 show that not only QPSK but also 8-PSK and BPSK will be used for digital DBS links. Technical improvements will lead to increased usage of high spectrum efficient schemes (e.g. 8-PSK, 16-QAM, 16-APSK, etc.). The methodology for derivation of availability performance for non-QPSK systems is the same as that discussed in Annex 1. As 8-PSK and other non-QPSK modulation/coding schemes become widely adopted, it is expected that Table 2 of Annex 1 will be expanded.

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