RECOMMENDATION ITU-R S.614-3

ALLOWABLE ERROR PERFORMANCE FOR A HYPOTHETICAL REFERENCE DIGITAL PATH IN THE FIXED-SATELLITE SERVICE OPERATING BELOW 15 GHz WHEN FORMING PART OF AN INTERNATIONAL CONNECTION IN AN INTEGRATED SERVICES DIGITAL NETWORK

(Question ITU-R 52/4)

(1986-1990-1992-1994)

The ITU Radiocommunication Assembly,

considering

a) that the concept of an integrated services digital network (ISDN) has been defined by the ITU-T;

b) that satellites operating in the fixed-satellite service (FSS) will have an important role to play in extending the concept of the ISDN to international connections;

c) that satisfactory error performance is an essential feature of any digital transmission system;

d) that the error performance of an international digital connection forming part of an ISDN has been specified by the ITU-T in ITU-T Recommendation G.821 at 64 kbit/s;

e) that the costs of establishing and maintaining digital communication satellite systems are critically dependent on overall error performance;

f) that in defining error performance criteria, it is necessary to take account of all foreseeable error-inducing mechanisms, especially time-varying propagation conditions and interference,

recommends

1. that the bit error ratio (BER) (see Note 2) at the output (i.e. at either end of a two-way connection) of a satellite hypothetical reference digital path (HRDP) operating below 15 GHz and forming part of a 64 kbit/s ISDN connection should not exceed during the available time the values given below:

1.1 1×10^{-7} for more than 10% of any month,

1.2 1×10^{-6} for more than 2% of any month,

1.3 1×10^{-3} for more than 0.03% of any month (see Note 5);

2. that the following Notes should be regarded as part of the Recommendation:

Note 1 – Section 1 was established utilizing the method outlined in Annex 1. It is based on, and sufficient to meet, the required fixed-satellite HRDP error performance objectives given in ITU-T Recommendation G.821 under all envisaged operating conditions. The ITU-T allocations for an FSS HRDP, which are considered to apply to the available time over a period of the order of any one month, can be stated as:

- fewer than 2% of the 1 min intervals to have a bit error ratio worse than 1×10^{-6},
- fewer than 0.03% of 1 s intervals to have a bit error ratio worse than 1×10^{-3},
- fewer than 1.6% of 1 s intervals to have errors.

Note 2 – The BERs in § 1 should be measured over a sufficiently long period of time in order to ensure that they provide a good estimate of the bit error probability (see Annex 1).

Note 3 – The BERs given in this Recommendation have been based on the assumption that contributions to severely errored seconds can be produced by two different error mechanisms: those occurring randomly and those occurring in bursts. For the major portion of the time, the errors are random and are constrained by § 1.1 and 1.2. Severely errored seconds are excluded from the random error measurements made to verify § 1.1 and 1.2, but are included in § 1.3 (see Annex 1).

Note 4 – The BERs in § 1 provide a margin for some burst errors that could arise from sources identified in Annex 1.

Note 5 – The value 0.03% of any month relates to the measured BER during the available time. This objective could be met, for example, by designing the satellite system to an unavailability objective of 0.2% of the worst month (total time). By using a 10% availability factor (ratio of available to total time while the BER is worse than 10^{-3}), this would correspond to 0.02% of the available time of any month. Further, it is necessary to include an allowance to accommodate contributions to those severely errored seconds which occur when the BER is better than 10^{-3}. Taking as an example 0.01% of the worst month for this allowance, the total performance objective would be 0.03% of the available time of the worst month (see Annex 1).

Note 6 – The HRDP referred to in this Recommendation is specified in Recommendation ITU-R S.521.

Note 7 – It may be necessary to make special provision regarding the performance of satellite-to-satellite links. The extent of this provision is a matter requiring further study.

Note 8 – The Recommendation applies only when the system is considered available in accordance with Recommendation ITU-R S.579 and includes periods of high bit error ratio exceeding 10^{-3} which persist for periods of less than 10 consecutive seconds. Short interruptions (less than 10 s) shall be treated as equivalent to the case in which the BER exceeds 10^{-3}.

Note 9 – The error performance objectives given in this Recommendation are designed to meet the specified end-to-end performance of a 64 kbit/s circuit switched, ISDN connection consistent with ITU-T Recommendation G.821. Performance objectives for satellite systems carrying PCM encoded telephony in a non-ISDN connection are given in Recommendation ITU-R S.522. Recommendation ITU-R S.614 may be used in the design of satellite systems carrying other forms of digital information, such as voice band data (e.g. facsimile) or low rate encoded (LRE) speech (under 64 kbit/s), until more specific studies are completed which may lead to improved performance objectives.

Note 10 – The objectives for BERs indicated in § 1 are not unique in meeting the required performance objectives given in ITU-T Recommendation G.821. Other masks for the BERs may be used by the designer where appropriate as long as these masks satisfy ITU-T Recommendation G.821. Examples of alternative masks are shown in Annex 1.

Note 11 – It is desirable that systems be planned on the basis of propagation data covering a period of at least four years. The performance recommended to be met for “any month” should be based on the propagation data corresponding to the median “worst month of the year” taken from the monthly statistics of all the years for which reliable data are available.

Note 12 – The error performance described in § 1 was developed based on the use of the HRDP in the “high grade” section of the hypothetical reference connection (HRX) (see ITU-T Recommendation G.821). Other applications of the HRDP in the HRX are possible and the error performance objectives can be adjusted accordingly.

Note 13 – In order to comply with the values given in § 1, for systems operating above 10 GHz, it may be advantageous to make use of fade countermeasures strategies and techniques for which basic guidance is provided in Recommendation ITU-R S.1061.

Note 14 – A method of measuring BERs against percentage of time is given in Annex 1.

ANNEX 1

Characteristics of a fixed-satellite service hypothetical reference digital path forming part of an integrated services digital network

1. Introduction

This Annex discusses the performance objectives that an FSS HRDP will need to achieve when it forms part of a hypothetical reference connection (HRX) in an ISDN. The ISDN HRX for a 64 kbit/s circuit switched connection is defined in ITU-T Recommendation G.821 (CCITT Blue Book 1988, Fascicle III.3) which uses three circuit classifications for performance quality definition: local, medium and high grade. International satellite circuits are considered part of the high grade performance section.

The apportionment of the overall ISDN HRX performance objectives to the FSS and the impact of this apportionment on the design of FSS systems are presented in the following sections.

2. 64 kbit/s satellite channels forming part of the ISDN HRX

2.1 Performance requirements of the FSS HRDP

2.1.1 Satellite system error performance objectives

The performance of satellite systems is generally given in terms of bit error probability while ITU-T Recommendation G.821 identifies time intervals that must have a specified error ratio for certain time percentages. These percentages are taken over a longer period, i.e. of the order of one month. This section presents the method that has been used for converting from the ITU-T specification to the form of performance objective used for satellite systems, and gives the satellite HRDP performance requirements that result from applying this method to the values quoted in ITU-T Recommendation G.821.

A careful distinction between bit error probability (BEP) and bit error ratio (BER) has been made in this Annex. BEP, which is used extensively in the following sections, is an abstract quantity used to express the theoretical performance of data communications equipment. BER is a quantity that is readily measurable (i.e. bit errors per bits transmitted). By making a sufficient number of measurements each lasting a sufficient time, the BEP can be estimated to within any desired accuracy.

The approach adopted in this Annex is to assume that (at 64 kbit/s) the satellite system link performance is limited by mechanisms that are essentially random in nature and can be analysed by using a Poisson or binomial approach to calculate the probability of experiencing a given number of errors in a given time interval, with a given bit error probability. In practice, system designers must also be aware of bursts of errors which would not be picked up by this approach (some of the mechanisms which could give rise to such bursts are described in § 2.2) and allow sufficient margins to cover these effects.

The bursty errors due to error correction techniques are treated in § 5.

2.1.2 ITU-T Recommendation G.821 requirements

Table 1 summarizes the end-to-end performance objectives given in ITU-T Recommendation G.821 and the satellite HRDP objectives. For each performance classification the overall end-to-end requirement is given, along with the requirement on a satellite HRDP.

2.1.3 BEP models required to meet ITU-T Recommendation G.821

Section 3 outlines the method by which a given BEP versus percentage-of-time distribution can be analysed in terms of the parameters given in Table 1. Using this procedure, it has been possible to derive a number of distributions, or models, based on the general characteristics of satellite systems, which meet or exceed the objectives given in ITU-T Recommendation G.821.

Of the models given in § 3, one is summarized here. This model strikes a compromise between the requirements of propagation limited systems typically operating above 10 GHz, and those of interference limited systems typically operating below 10 GHz and can be met by high-capacity, state-of-the-art satellite systems.

The BEP requirements of this model as indicated by the breaking points of the curve shown in Fig. 3 are as follows:

– BEP = 1×10^{-7} for 90% of the worst month,

– BEP = 1×10^{-6} for 98% of the worst month.

The performance of this model is summarized in Table 2 in terms of degraded minutes, errored seconds and severely errored seconds. The performance is listed in terms of both total time and available time in order to show the relationship between system design calculations and the objectives of Recommendation ITU-T G.821.

TABLE 1

Overall end-to-end and satellite HRDP error performance objectives for international ISDN connections

Performance classification	Overall end-to-end objectives (Note 4)	Satellite HRDP objectives (Note 4)
(a) Degraded minutes (Notes 1, 2)	Fewer than 10% of 1 min intervals to have a bit error ratio worse than 1×10^{-6} (Note 3)	Fewer than 2% of 1 min intervals to have a bit error ratio worse than 1×10^{-6} (Note 4)
(b) Severely errored seconds (Note 1)	Fewer than 0.2% of 1 s intervals to have a bit error ratio worse than 1×10^{-3}	Fewer than 0.03% of 1 s intervals to have a bit error ratio worse than 1×10^{-3}
(c) Errored seconds (Note 1)	Fewer than 8% of 1 s intervals to have any errors (equivalent to 92% error-free seconds)	Fewer than 1.6% of 1 s intervals to have any errors (equivalent to 98.4% error-free seconds)

Note 1 – The terms “degraded minutes”, “severely errored seconds” and “errored seconds” are used as a convenient and concise performance objective “identifier”. Their usage is not intended to imply the acceptability, or otherwise, of this level of performance.

Note 2 – The 1 min intervals mentioned above are derived by removing unavailable time and severely errored seconds from the total time and then consecutively grouping the remaining seconds into blocks of 60.

Note 3 – For practical reasons, at 64 kbit/s, a minute containing four errors (equivalent to an error ratio of 1.04×10^{-6}) is not considered degraded. However, this does not imply relaxation of the error ratio objective of 1×10^{-6}.

Note 4 – Overall end-to-end and satellite HRDP performance objectives are expressed in terms of available time (see § 2.1.5).

The short-term (see Note 1) breakpoint (i.e. BEP 10^{-3}) used in these models was 0.2% of the month (total time) with a propagation availability factor of 10% (§ 2.1.5 and § 3).

Note 1 – The phrase “short-term” refers to the period of time when the satellite portion of the connection is experiencing extremely degraded performance (i.e. error performance $> 1 \times 10^{-3}$). The words “long-term” refer to the period of time when the satellite portion of the connection is not experiencing degraded performance (i.e. error performance $\leq 1.0 \times 10^{-6}$).

TABLE 2

Objectives	Performance	
	Total time (%)	Available time (%)
Degraded minutes	2.05	1.87
Errored seconds	1.74	1.56
Severely errored seconds	0.204	0.024

2.1.4 Satellite transmission considerations

The performance of a satellite digital transmission link is a function of various factors. One highly significant factor is the effect of propagation disturbances on transmission. Using methods developed by Study Group 3 (ex SG 5), the effects of propagation disturbances on digital transmission performance can be predicted.

Section 4 gives the results of calculations comparing the performance of three different international digital satellite systems. These calculations are included to provide insight into the effects of propagation on the short-term BEP, as a function of time for practical systems. Performance limits included in the various models are shown in Fig. 4.

It should be noted that the performance of a satellite digital transmission channel can be designed to meet virtually any performance specification. However, the use of forward error correction, power control and site diversity which can significantly improve system performance has penalties of decreased capacity and/or increased cost. The use of such techniques therefore requires suitable justification.

Radiocommunication Study Group 4 feels that further study is required on the effects of propagation disturbances on satellite digital channel performance and welcomes further information on this topic.

2.1.5 Availability and severely errored seconds performance

In the derivation of the performance models to meet ITU-T Recommendation G.821 described in § 4, it was necessary to consider the proportion of time for which the link is declared available. The generally accepted definition for the unavailable time is:

A period of unavailable time begins when the BER in each second is worse than 1×10^{-3} for a period of 10 consecutive seconds. These 10 s are considered to be unavailable time. The period of unavailable time terminates when the BER in each second is better than 1×10^{-3} for a period of 10 consecutive seconds. These 10 s are considered to be available time and would contribute to the severely errored second performance objective. Excessive BER is only one of the factors contributing towards the total unavailable time. Definitions concerning availability can be found in ITU-T Recommendation G.106.

Availability must be taken into account in the design of satellite transmission links which experience occasional periods of attenuation during precipitation which exceed the margins of the system. This is particularly true at frequencies above 10 GHz and propagation studies illustrate this fact.

A summary of propagation measurements showing propagation attenuation events which do not result in unavailable time is given in Recommendation ITU-R S.579. The conclusion reached indicates that of the total time when attenuation levels likely to cause a BER worse than 10^{-3} are experienced, only 10% of the time is made up of periods that would be defined as “available time” by the ITU-T criteria. The remainder would be unavailable time. This implies a “propagation availability factor” of 10%. As an example, if, for 0.2% of the total time the BEP is 1×10^{-3} or worse, then, due to propagation behaviour, only 10% of this time or 0.02% would be considered available time. This leads to a “short term” performance criterion of a BEP of 1×10^{-3} for 0.2% of the total time.

The unavailability objectives of a satellite HRDP due to equipment and propagation are given in Recommendation ITU-R S.579. A provisional value of 0.2% of a year is assigned to the equipment unavailability objective, whilst a suggested value of 0.2% of the worst month is proposed for the propagation unavailability performance for an HRDP.

Recommendation ITU-R S.579 provides measurement data on propagation availability performance which indicates that for low “availability factors” and various locations and climates, the percentage of unavailable time can exceed 0.2% of the month, for attenuation levels of interest. In any event, the total unavailable time allowance for propagation should not be less than the model short-term objective required to meet ITU-T Recommendation G.821, i.e. 0.2% of the month. Consequently, it was recommended that this value be adopted in Recommendation ITU-R S.579 for frequencies less than 15 GHz.

Further propagation study is required, however, to confirm a representative percentage value for different frequency bands, elevation angles and climatic zones.

Finally, regarding the availability of a transmission system (employing techniques such as TDMA), it should be noted that system availability can differ from propagation availability owing to the possible loss of synchronization when the carrier drops below some synchronization threshold (typically 10^{-2}) for several seconds. Since it usually takes several round trip times for acquisition in the TDMA system, synchronization cannot always follow momentary recoveries of the carrier level. As a consequence, there may be periods when the carrier will rise to a level corresponding to a BER better than 10^{-3}, but due to synchronization delay the circuit may have a measured BER worse than 10^{-3}. These periods may contribute to unavailable time as opposed to available time.

In some operational TDMA systems the terminals make BER measurements on the unique word of each received traffic burst over successive periods of less than 10 s. This period has a duration of 4 s (128 multi-frames) in the case of the EUTELSAT TDMA system. When a BER threshold of 10^{-3} is exceeded during one measurement period a set of high BER maintenance alarms are exchanged between the transmit and receive TDMA terminals. This causes the sending of particular signalling sequences (“a” and “b” bits set to 1 for all circuits concerned or alarm indication signal (AIS)) towards the international switching centre (ISC) from each of the two terminals. These sequences may be interpreted as call release messages and may cause the interruption of the calls concerned. Further study is required to determine the effect on the network availability as a result of high BER alarms.

2.2 Other error-causing mechanisms

Although the major error contributions in digital satellite systems will be due to propagation and interference effects, other error mechanisms do occur. This section provides some information relating to the frequency and duration of such error events specifically with the objective of identifying them to the satellite system designer. In fact, during the design of a digital link a percentage allocation of the overall performance objectives may be assigned to these mechanisms. However, it is assumed that these error events will not cause the satellite link to be considered unavailable, i.e. those of 10 s duration or less. Further information on mechanisms causing unavailability is given in Recommendation ITU-R S.579.

The following corresponding mechanisms have been identified as producing bursts of errors:

- signal path switching in earth-station IF and RF equipment,
- signal path switching in earth-station baseband equipment,
- power supply transients at earth stations,
- signal path switching in the satellite.

Estimates for the frequency and duration of error bursts due to the above mechanisms are shown below and are summarized in Table 3.

TABLE 3

Typical examples of burst error mechanisms

Effect	Frequency	Duration
IF/RF switching	1.0/month	150 ms
Spurious switching	2.0/month	150 ms
Baseband switching	1.2/month	2-128 bits

From Table 3 the following deductions can be made:

- Considering the effect on 64 kbit/s connection over a 1 min integration period, it can be concluded that all the effects in Table 3 cause a 1×10^{-6} per minute objective to be broken, meaning that some of the time for which 10^{-6} is permitted to be exceeded must be allocated to these effects.
- The total number of events in Table 3 is 4.2 per month, hence on average 0.0097% of 1 min periods will be degraded.
- Each of the events in Table 3 lasts less than 1 s and so on average only 4.2 s/month, i.e. 0.0002%, will contain errors as a result of these effects.

The 4.2 occurrences per month present only 0.01% in degraded minutes and 0.00016% in severely errored seconds, whereas Recommendation ITU-R S.614 has a safety margin of 0.13% and 0.006% respectively. Therefore the mask of the present Recommendation does not require modification to cater for the possible existence of burst errors on a particular satellite system. If further study reveals the existence of other burst producing mechanisms, modification of the present BER requirements may be necessary.

2.2.1 Switching at IF and RF

Errors are caused as a result of IF and RF switching to bring stand-by equipment into use because of failures or routine maintenance requirements.

To determine the frequency of switching events, it is necessary to look at the mean time between failures (MTBF) for various components. From this, the number of switch-overs per month can be deduced. An example of some typical MTBFs is given in Table 4 along with the resulting average switch-over frequency.

TABLE 4

Typical earth-station equipment failure rates

Device	MTBF (h)	Average switch-over frequency (per month)
High power amplifier (HPA)	2 000	0.36
Up converter	4 000	0.18
Modem	> 4 000	< 0.18
Low noise amplifier (LNA)	8 000	0.09
Post LNA cabinet	50 000	0.01
Down converter	4 000	0.18
Total		1.0

The “total” figure given in Table 4 relates to a one-way link incorporating one transmit and one receive earth station. It does not, of course, make any allowance for the fact that statistically some months will be worse than this average. The possible need to allow for this requires further study.

The duration of each switch-over will be typically 150 ms including control circuit reaction time.

2.2.2 Switching at baseband

Because of the limited application of digital baseband equipment to date, there is very little experience from which to derive failure rates. The only information available relates to TDMA equipment which is expected to return overall MTBFs of 3 000 h for central terminal equipment and 2 000 h for interface modules. Taken together these will result in 0.6 failures per month, or 1.2 per month total on a complete link. This is a figure which can be closely controlled by use of good design practices.

The switch-over time when failures do occur is very short but the effect on traffic can last rather longer. The result can be anything from 2 or 3 bit errors up to loss of a multi-frame, i.e. 128 bits on any one 64 kbit/s channel.

2.2.3 *Power supply transients*

This effect is very difficult to quantify. The best evidence available is that within the IF/RF equipment, twice as many switch-overs are, on average, the result of these spurious effects as are caused by actual equipment failures. Based on the IF/RF information given above, a figure of two switch-overs per month can therefore be attributed to this effect.

2.2.4 *Signal path switching in the satellite*

Although no data is currently to hand on this effect, it is considered unlikely to be as frequent as earth-station path switching. However, this may change as more complex satellites are put into service, especially if on-board switching or processing is employed, and the subject therefore requires further study.

2.2.5 *Effects of equipment switch-overs on ITU-T Recommendation G.821 parameters*

During tests conducted on TELECOM-1 between Bercenay-en-Othe and Trou-Biran, it was observed that earth-station equipment switch-overs produced the following effects on ITU-T Recommendation G.821 parameters:

	Severely errored seconds	Errored seconds	Degraded minutes
Parametric amplifier	2	2	0
Modem	2	2	0

Further information is needed on this topic, particularly in regard to the effects caused by other IF/RF equipment.

3. Error-performance calculations and models

3.1 *Introduction*

This section describes the method by which the performance of a link, expressed in terms of a BEP versus percentage of time distribution, can be assessed in terms of the parameters given in Table 1. The procedure for determining the performance is outlined in § 3.2 below whilst § 3.3 develops a number of BEP versus percentage of time models which meet ITU-T Recommendation G.821 based on the general characteristics of “real” systems.

3.2 *Method of calculation*

An important first assumption is that satellite system link performance is limited by mechanisms that have essentially random characteristics. This assumption enables a Poisson or binomial approach to be used to calculate the probability of experiencing a given number of errors or error events in a given time interval with a given bit error or error event probability. Within the numerical range of the parameters of interest here, the binomial distribution converges to the Poisson distribution.

Data has shown that the assumption of random occurrences of errors or error events is valid. An example is given in § 5, while further examples which bear out this assumption have been presented during ITU-R meetings. Information is also given in § 5 on the departure of the distribution of the error occurrences from a random distribution due to the use of forward error correction.

In order to assess the performance of a link with regard to satisfying the requirements of ITU-T Recommendation G.821, it is necessary to construct a model of the link performance in terms of BEP versus percentage of time. Once the link model is established, calculations can be made to determine if the particular link model satisfies the errored interval criteria of ITU-T Recommendation G.821. This is done by dividing the percentage of time axis into small intervals, which imply corresponding constant values of BEP for those small intervals, calculating the probability of occurrence of the various errored intervals at the BEP, multiplying by the value of the time interval and summing the probabilities for each errored interval and comparing the resulting total probabilities with the criteria.

To illustrate the method of calculation, the percentage of errored seconds (ES), severely errored seconds (SES), and degraded minutes (DM) are determined as follows:

a) divide the percentage of time axis of the model under consideration into many sections such that the curve may be represented by a ladder approximation. Each stepped interval then possesses a constant BEP;

b) for the BEP value of each stepped section, determine from Fig. 1 or 2 the probability of ES, SES, or DM as appropriate;

c) this probability multiplied by the elemented percentage of time in the interval, gives the ES, SES or DM contributed by this interval;

d) the sum of all contributions gives the total percentage of ES, SES or DM.

Steps a) to d) can be summarized mathematically as follows:

$$\text{Total of all contributions} = \Sigma\,[(1 - P(E, N, BEP)) \cdot \Delta T\,]$$

where:

ΔT: time interval of the stepped section

$P(E, N, BEP)$: probability of the particular objective

E: error threshold

N: number of bits in the time interval of the performance parameter under consideration

BEP: bit error probability;

e) an additional term must be added to the total for SES to include those contributed from the periods that have a BEP in excess of 10^{-3} and which are also available (see § 2.1.5);

f) finally the results may be expressed in terms of the percentage of available time. The results are then in the form of the performance objectives of ITU-T Recommendation G.821 and may be compared with them.

The curves of Figs. 1 and 2 have been calculated using the following Poisson distribution formula:

$$P(E \text{ or fewer errors}) = \sum_{K=0}^{E} \frac{(N \cdot BEP)^K \cdot (\mathrm{e}^{-N \cdot BEP})}{K!}$$

where:

N: number of bits in the desired integrating time interval, e.g. 64 000 × 60 for a 1 min interval

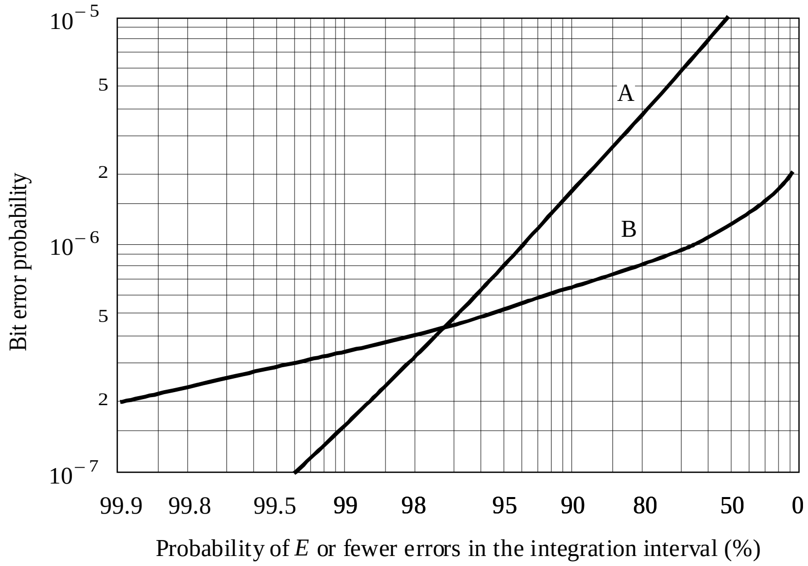
E: error threshold

BEP: bit error probability.

3.3 Performance of models

By application of the conversion process outlined above, it is possible to identify a number of different satellite system performance models that will meet or exceed the objectives of ITU-T Recommendation G.821. Four such models are shown in Fig. 3.

FIGURE 1

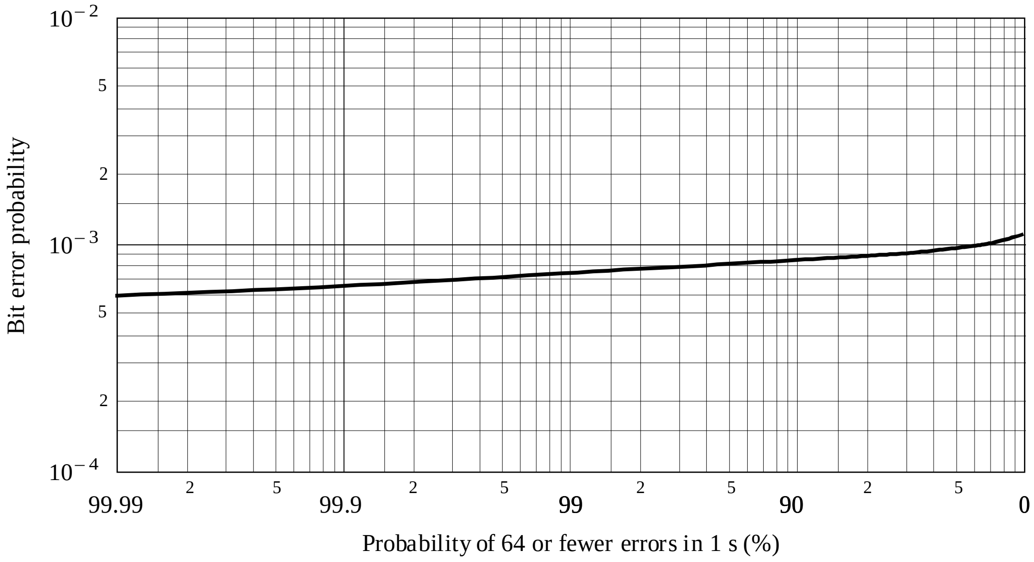


Curves A: probability of error-free seconds, i.e.
(1 – probability of errored seconds)
B: probability of 4 errors or less in a minute, i.e.
(1 – probability of degraded minutes)

D01

FIGURE 2

Probability that the number of errors is less than or equal to 64 in 1 s

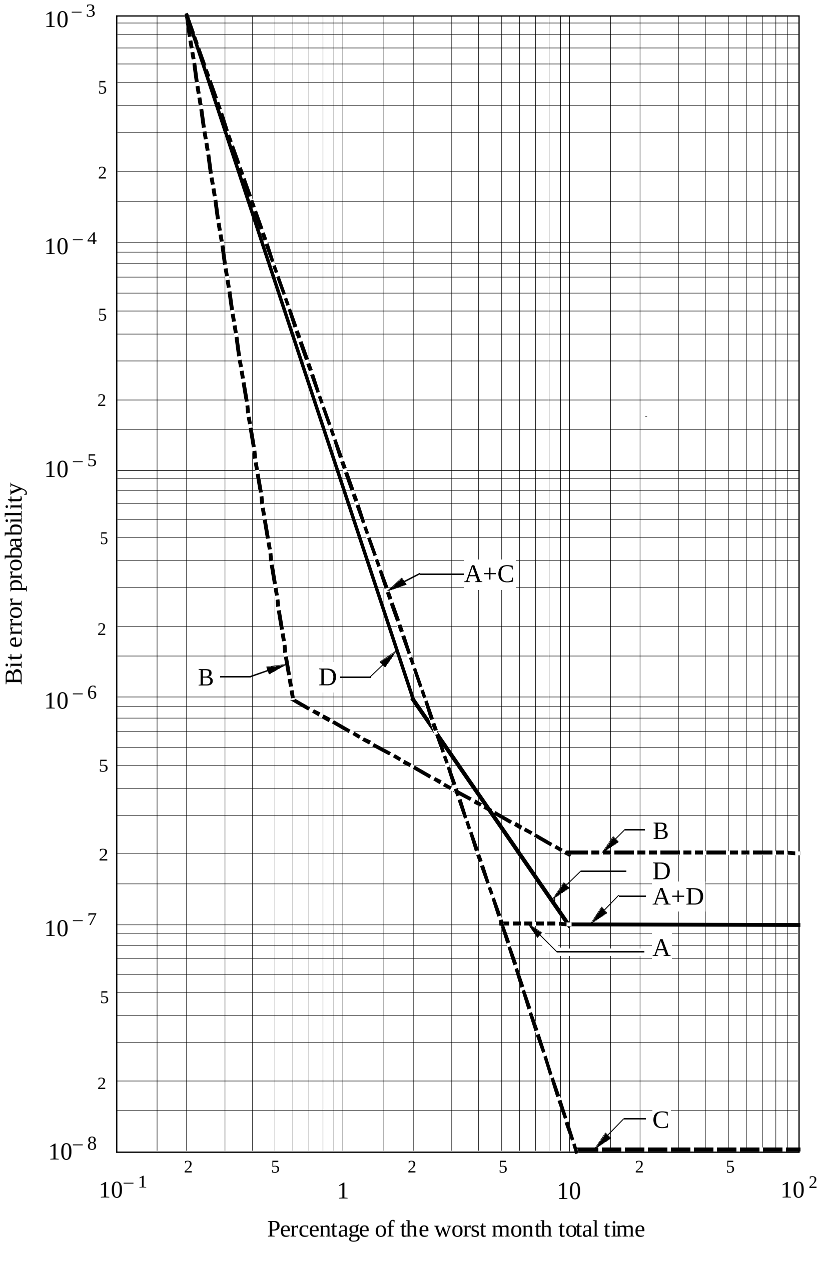


Note 1 – Probability of 64 or fewer errors per second is equivalent to (1 – probability of severely errored seconds).

D02

FIGURE 3

BEP performance models which meet
ITU-T Recommendation G.821



A: model a)
B: model b)
C: model c)
D: model d)

The long-term break points of these models (expressed in terms of the total time of the worst month) are as follows:

- Model a): BEP = 1×10^{-7} for 95% of the worst month
- Model b): BEP = 2×10^{-7} for 90% of the worst month

  BEP = 1×10^{-6} for 99.4% of the worst month
- Model c): BEP = 1×10^{-8} for 89% of the worst month
- Model d): BEP = 1×10^{-7} for 90% of the worst month

  BEP = 1×10^{-6} for 98% of the worst month.

In deriving model c) of Fig. 3 the aim was to produce a model in which performance was held at a low BEP (1×10^{-8}) for as short a time as possible (89% of the worst month). Such a model would be appropriate where performance is limited almost entirely by rain attenuation (i.e. above 10 GHz). The large fade margin required in this situation ensures that a good BEP is achieved for much of the time. In curve A (model a)) the aim was to assess the impact on the long-term BEP break point of adopting a BEP of 1×10^{-7}. In this case a two break point mask was again adopted.

Model b) is intended to allow the highest possible long-term BEP. In this case an additional break point has been included at a BEP of 10^{-6} for 99.5% of the month to more closely model system performance at around these time percentages. This model will probably be appropriate in situations where there is little rain attenuation or where the system is inter- and intra-system interference-limited.

Model d) strikes a compromise between the requirements of propagation limited systems and those of interference limited systems. It is considered possible to meet this model in high capacity, state-of-the-art satellite systems without undue cost or capacity penalties.

A common feature of the four models is the (0.2%, 1×10^{-3}) point and it is important to identify how this point enables the models to comply with the SES objective b) of ITU-T Recommendation G.821. This objective is 10^{-3} for 99.97% of available time in the worst month. In accordance with the definition in ITU-T Recommendation G.821, a period of ten or more consecutive severely errored seconds (those with a BER worse than 1×10^{-3}) is considered as unavailable time. Periods of nine or less consecutive seconds are included in available time. An indication of the proportion of time which is unavailable can be deduced from Recommendation ITU-R S.579.

The performance of these four models, in ITU-T Recommendation G.821 parameters, is given in Table 5. This table gives, for each parameter, percentages of the time interval in the available time in a month. Unavailable time has been subtracted from total time to obtain the results given in the table. Since ITU-T Recommendation G.821 refers to percentages of available time, the form of this table is appropriate for comparing performance with ITU-T Recommendation G.821 requirements.

The values shown in Table 5 have been computed on the basis of a short-term break point (i.e. BER = 1×10^{-3}) of 0.2% total time and a propagation availability factor of 10%.

A significant difference between model b) and the other models can be seen from Table 5 in that models a), c) and d) result in nearly all the parameters equally meeting the objectives of ITU-T Recommendation G.821, whereas with model b) performance is dictated quite clearly by the errored second requirement.

It is clear that any satellite system design objectives could be written in terms of total time (as has been adopted in the past) or of available time. The principal advantage of adopting the latter approach is that it is more immediately apparent that the objectives are consistent with ITU-T Recommendation G.821 since no assumptions about percentage unavailable time have to be made. In the event that a designer does require total time percentages, he can employ a conversion factor appropriate to the frequency band and climatic region being considered. This could well lead, in many cases, to objectives that are not quite so severe as those in a “total time” objective since these have a “percentage unavailable time” assumption incorporated in them.

TABLE 5

Objective	Performance (% of available time)				
	ITU-T Rec. G.821	Model a)	Model b)	Model c)	Model d)
Degraded minutes	2.0	1.97	0.75	1.97	1.87
Errored seconds	1.6	1.59	1.60	1.06	1.56
Severely errored seconds	0.03	0.024(1)	0.022(1)	0.024(1)	0.024(1)

(1) Three decimal places have been given for these values to indicate the contribution to severely errored seconds from the integral of time with BER $\leq 1 \times 10^{-3}$.

Note 1 – The values in the table are given for the purpose of demonstrating, for the particular models studied, compatibility with ITU-T Recommendation G.821. Different values will be achieved using different models.

Note 2 – It should be noted that if a satellite system designer were to base system calculation directly on one of the models of the type shown, the performance of that system would exceed that obtained from the above calculations. This is because the practical system BEP/% time characteristic must inevitably exceed the model in most places.

3.4 Practical measurement procedures

3.4.1 Introduction

Network testing is generally directed towards verifying that the network is meeting performance objectives expressed in terms of the ITU-T Recommendation G.821 parameters (ES, SES, and DM). It is therefore recommended that, wherever possible, these parameters are measured directly, according to ITU-T Recommendation G.821, rather than measuring the BER values of this Recommendation.

However, it may be necessary to also measure the satellite system BER values to compare with the BER values of *recommends* **1.**

This would also allow examination of the relationship between the BER measurements and the ITU-T Recommendation G.821 parameter measurements. If this is the case, it is advisable to follow a consistent procedure to measure BERs versus percentage of time, because the integration period has an impact on the results obtained. Figure 4 demonstrates this principle where integration periods of 2 h, 1 h, 15 min, 1 min, 10 s, 2 s and 1 s are applied to the same set of measured data.

The following algorithms are therefore suggested in order to ensure that the results obtained from different tests can be compared.

3.4.2 Measurement algorithms

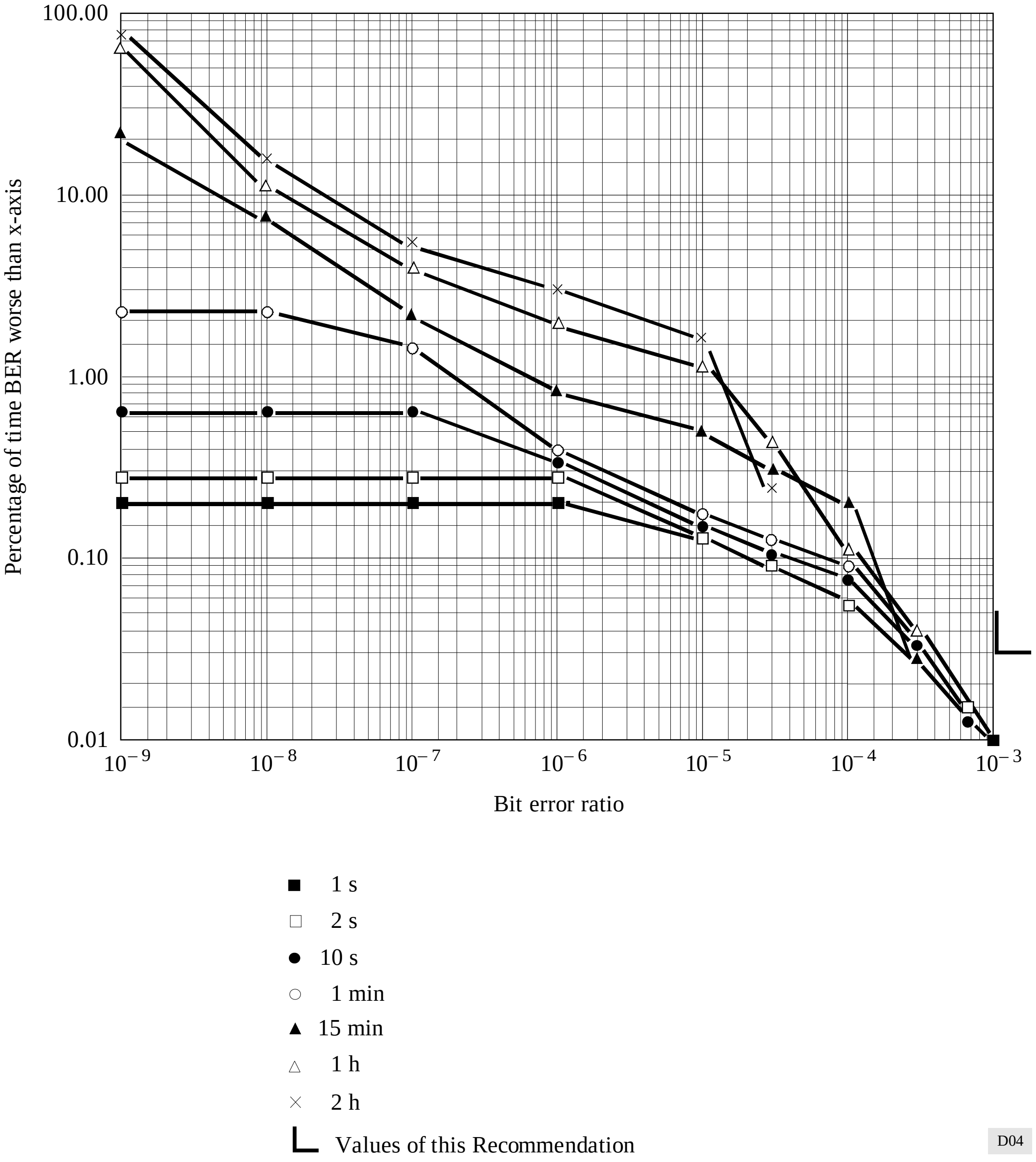
Two algorithms have been developed for this purpose, namely:

a) The data collection algorithm, which is a generic algorithm typical of proprietary test equipment. This algorithm is therefore similar to that used with most existing test equipment.

b) The data analysis algorithm.

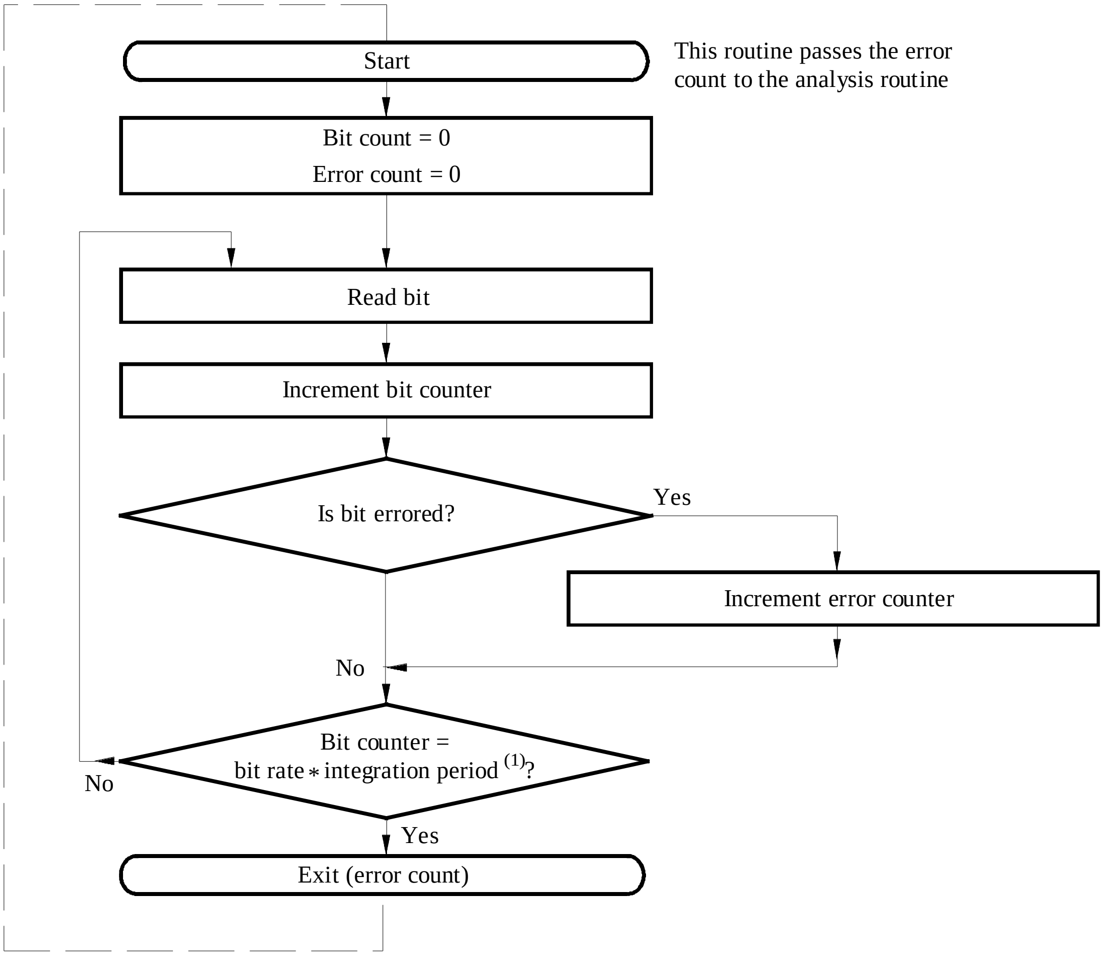
FIGURE 4

Examination of relationship between the BER measurements and ITU-T Recommendation G.821 parameter measurements



It is essential that the same integration period (and bit rate) is used for each algorithm. Flowchart descriptions of each algorithm follow:

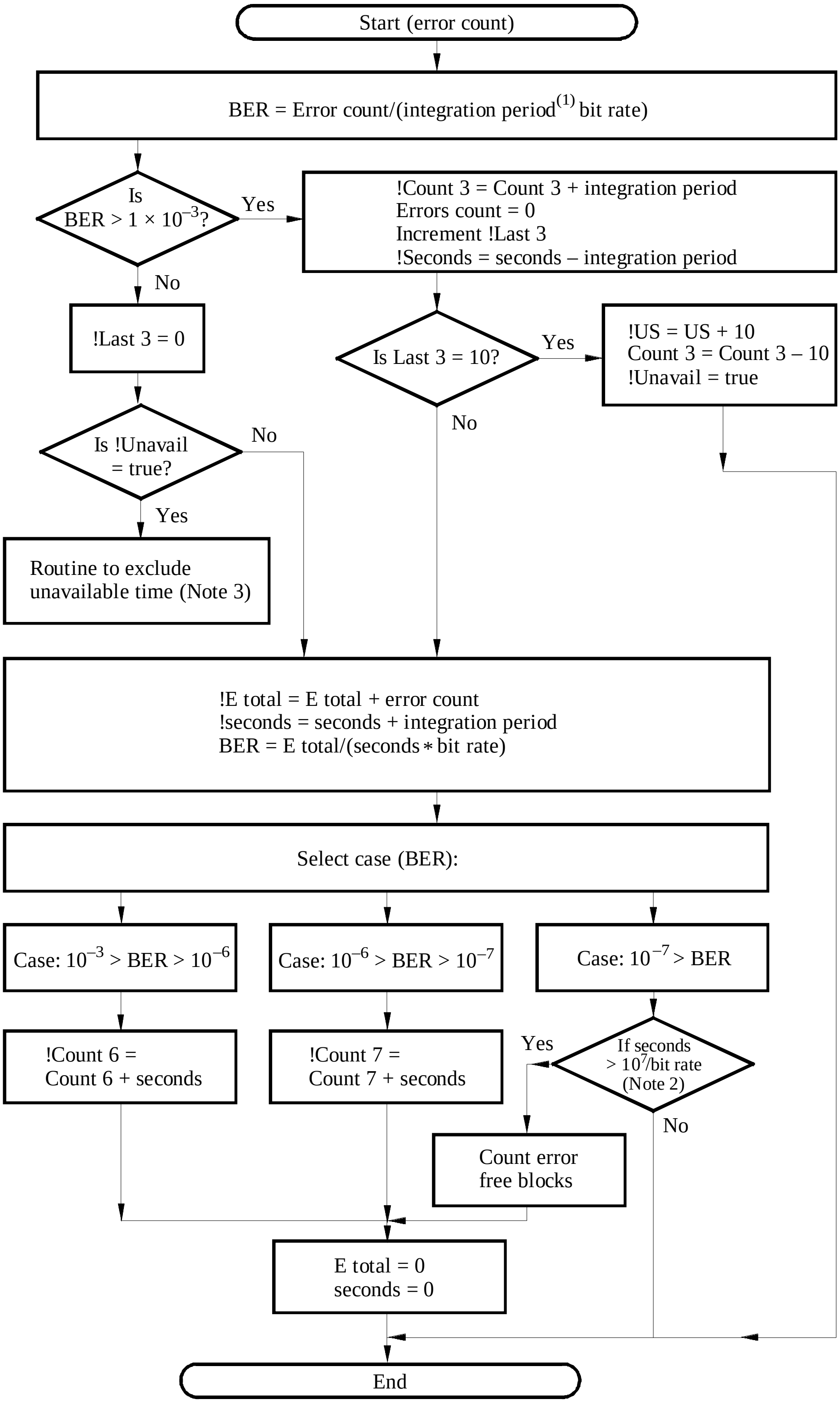
a) The data collection algorithm



(1) This algorithm was written assuming a 1 s integration period would be used to align this Recommendation with the principles of ITU-T Recommendation G.821.

D05

b) The data analysis algorithm



(1) This algorithm was written assuming a 1 s integration period would be used to align this Recommendation with the principles of ITU-T Recommendation G.821.

D06

Note 1 – The use of an “!” prior to a variable name in the algorithm above indicates that the variable should be treated as static, that is, the value should be preserved between each call of this routine during any test. The “!” is normally shown only once for a given variable and all occurrences of that variable name should be treated in the same way.

Note 2 – The value 10^7/bit rate is required to permit the exclusion of error-free periods.

Note 3 – This routine is required to exclude the unavailable periods from the BER analysis until available time is restored. See ITU-T Recommendation G.821 for further information. On re-entering available time as defined in ITU-T Recommendation G.821, the variable !Unavail should be reset to the value “false”.

Note 4 – This routine could be used for any bit rate. The best possible comparison between ITU-T Recommendation G.821 and Recommendation ITU-R S.614 is achieved when a 64 kbit/s circuit is measured.

Note 5 – The three counts (!Count 3, !Count 6 and !Count 7) should be divided by the total measurement duration and then multiplied by 100 to give the percentages of time for each BER (10^{-3}, 10^{-6} and 10^{-7}) for comparison with the objectives indicated in Recommendation ITU-R S.614, e.g.

$$\text{\% time for which BER was} > 1 \times 10^{-3} = \frac{\text{!Count 3}}{\text{Measurement duration}} \times 100$$

4. Examples of typical satellite link performance

This section provides results of calculations of the predicted digital performance for three different satellite digital transmission systems:

- 6/4 GHz INTELSAT-V 120 Mbit/s TDMA,
- 14/11 GHz EUTELSAT 120 Mbit/s TDMA,
- 14/11 GHz INTELSAT-V 120 Mbit/s TDMA (with up-link power control and site diversity).

The choice of these systems was made on the basis that they include existing, or typical satellite systems in both 6/4 GHz and 14/11 GHz bands. These systems could be used as guidelines for the design of satellite portions of future ISDN connections. Different performance characteristics may occur depending upon factors such as elevation angle, rain climate and interference situations. The system designer is cautioned to give full consideration to factors of this type when carrying out the design of a satellite ISDN HRDP.

The results of the link budget calculations are curves of bit error probability as a function of percentage of total time in the worst month. Using these curves, insight can be gained into the implications of the ISDN performance objectives on the design of satellite systems.

Section 4.3 also contains the results of measurements made between Bercenay-en-Othe (France) and Trou Biran (French Guyana) over a 64 kbit/s service channel link. The measurements were conducted over more than one year with a monthly average of 445 hours’ recording.

4.1 Attenuation model

The attenuation model used in this exercise for the INTELSAT-V system calculations is an application of the method provided by ITU-R PN Series. Using this method, percentage of the year statistics of slant path rain attenuation at earth-station locations can be calculated. The statistics are derived using several parameters. These are:

- rain climate – specifically, the point rainfall rate for 0.01% of an average year,
- earth-station height above mean sea level,
- earth-station elevation angle to the satellite,
- earth-station latitude.

With these parameters, the attenuation due to rain that will be exceeded for 0.01% of a year is calculated. Attenuation values for other percentages of a year are determined using the following formula:

$$A_P = b\, A_{0.01}\, P^{-a}$$

where:

A_P: attenuation for the desired percentage of the year

$A_{0.01}$: attenuation for 0.01% of the year

P: desired percentage of the year

a and b: constants.

These yearly attenuation figures can be related to attenuation during a “worst month” by using the following relationship:

$$P_y = 0.29\, P_w^{1.15}$$

where:

P_y: yearly percentage

P_w: worst month percentage.

This method was used to arrive at the INTELSAT-V performance curves shown in Fig. 5. The INTELSAT-V 6/4 GHz performance assumed transmission from the United States of America to Italy where both stations were located in rain climate “K” and the United States earth station had an elevation angle of 25° and the Italian station had an elevation angle of 21°. In the 14/11 GHz INTELSAT case, the transmitting earth station was located in the United Kingdom, with an elevation angle of 29° and the receiving earth station was again located in the United States with the same elevation angle. The United Kingdom earth station is located in rain climate “G” and the United States earth station is again located in rain climate “K”.

The INTELSAT-V 6/4 GHz link budgets took into account interference contributions due to terrestrial, other system, adjacent channel and co-channel interferers. Four-fold frequency re-use with polarization discrimination and spatial isolation was assumed. Transponder output power variations due to operating point changes caused by up-link fading were included by making use of a non-linear transponder transfer characteristic.

For the INTELSAT 14/11 GHz system it was assumed for the purposes of this study that 10 dB of up-link power control is applied in a continuous manner. It was further assumed that site diversity with a site separation of 20 km was used at the receiving stations. Again transponder output power variations due to operating point changes caused by up-link fading were included. Neither of the INTELSAT system curves assume the use of any error correction coding. It should be noted that all INTELSAT TDMA terminals are equipped for the use of an optional forward error correction system using a rate 7/8 BCH (128:112) block code which realizes a coding gain of at least 3 dB for an input bit error ratio of 1×10^{-4}.

The performance for the EUTELSAT system was derived using a similar method. The attenuation statistics used correspond to a typical European mainland climate and are based on measurements made with OTS. These statistics are similar to, but slightly more optimistic than, those labelled climate “H” in ITU-R PN Series.

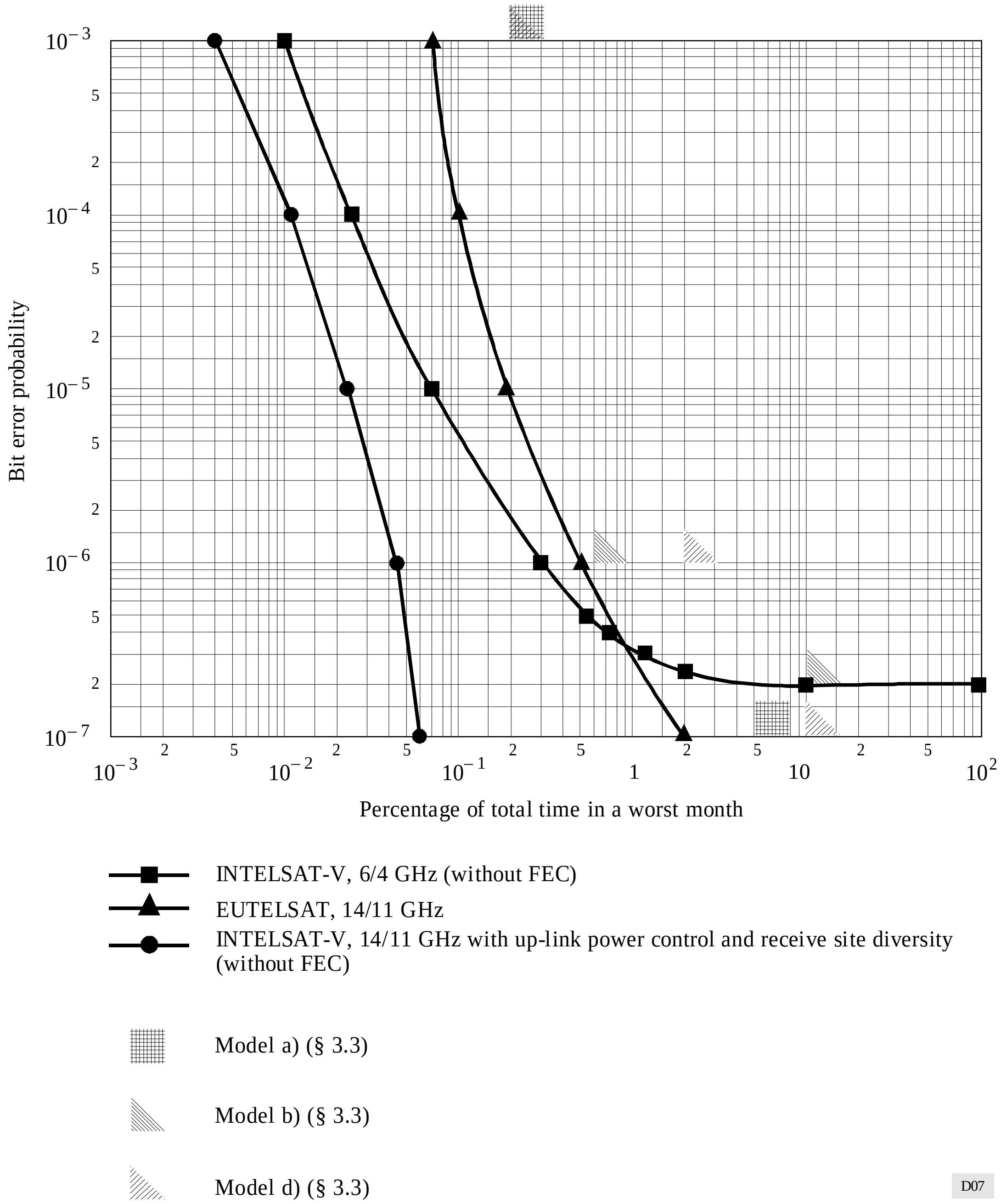
4.2 Propagation considerations relating to short-term objectives

In ITU-R performance Recommendations certain short-term objectives are given in percentages of the year. By contrast, the long-term objectives are quoted in terms of percentages of worst month. The objectives of ITU-T Recommendation G.821 are also quoted as percentages of a period of time of the order of one month. These facts lead to the conclusion that in any future ISDN performance Recommendations for satellites, there may be a need to use monthly attenuation statistics.

The information for performing such a conversion is contained in ITU-R PN Series. From this information it can be seen that the conversion factor varies with climate and time percentage. For 0.01% of the year, a factor of between 4.5 and 6.5 is given, depending on climate.

FIGURE 5

Bit error probability versus percentage of total time in a worst month



With respect to the transmission impact of the attenuation expected at various frequencies, some general observations can be made.

These are:

- for frequencies below 10 GHz, the long-term BEP becomes the controlling factor in the one 6/4 GHz frequency re-use case which was examined;
- for frequencies from 10-15 GHz, the short-term (10^{-3}) BEP is the controlling factor if diversity is not used. Both diversity and non-diversity cases were analysed;
- for frequencies > 15 GHz, particularly at 30/20 GHz, the short-term (10^{-3}) BEP is also likely to be the controlling factor. However, no analysis was carried out.

4.3 *Results of measurements on the TELECOM-1 satellite*

The link characteristics similar to model a) in Fig. 3 were as follows:

- link budget calculated to give an error rate better than 10^{-4} for 99.9% of the time, i.e. a clear-sky error rate of about 10^{-7};
- $E_b/N_0 = 14.00$ dB;
- transmitted bit rate = 8.768 Mbit/s without direct error correction;
- transmission in the 6/4 GHz band.

The test results are shown in Figs. 6 and 7 for DM and ES, respectively. The SES recorded were between 0.01% and 0.02%.

FIGURE 6

Distribution of degraded minutes (DM) on a monthly basis

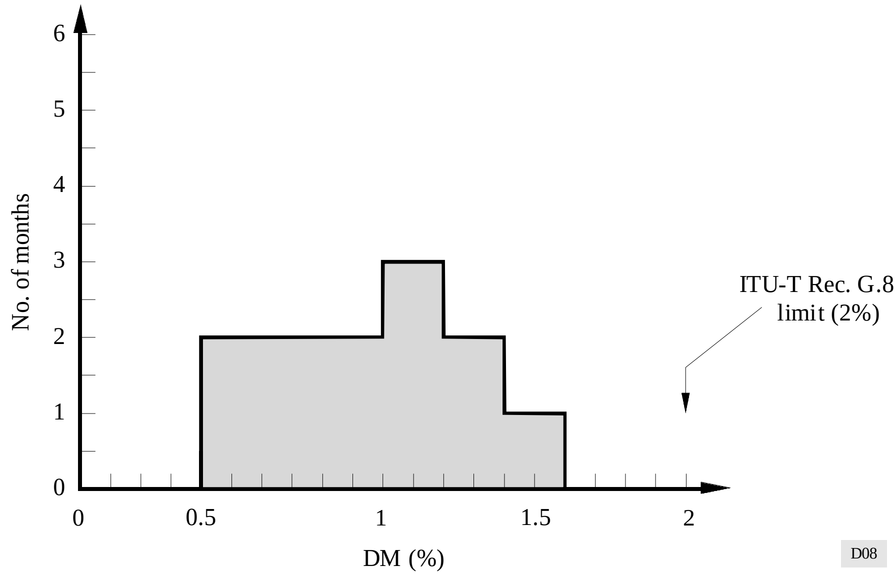
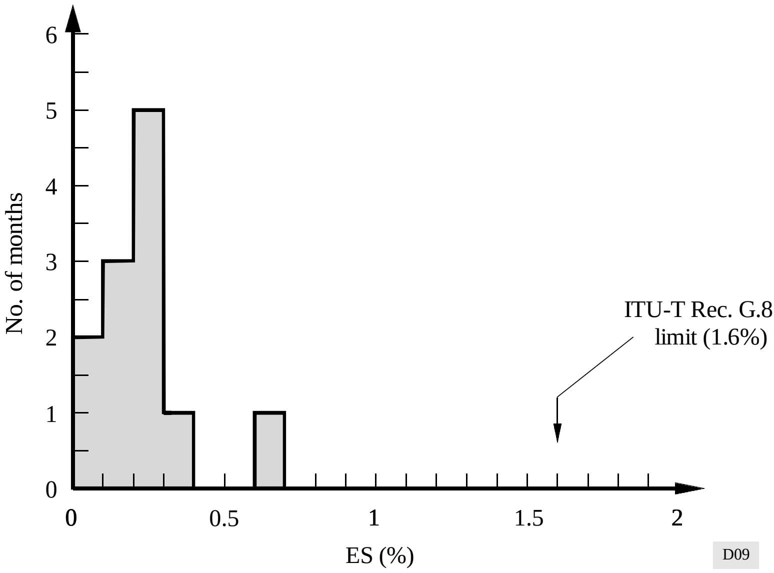


FIGURE 7

Distribution of errored seconds (ES) on a monthly basis



These results do not show the unavailability due to scintillation phenomena encountered in the equatorial zone where the Trou-Biran earth station is located.

During the measurements it was observed that solar interference caused an increase of unavailable time and an increase of the SES. (Recommendation ITU-R S.579 provides for 0.2% unavailability in any month for any phenomenon related to propagation conditions.)

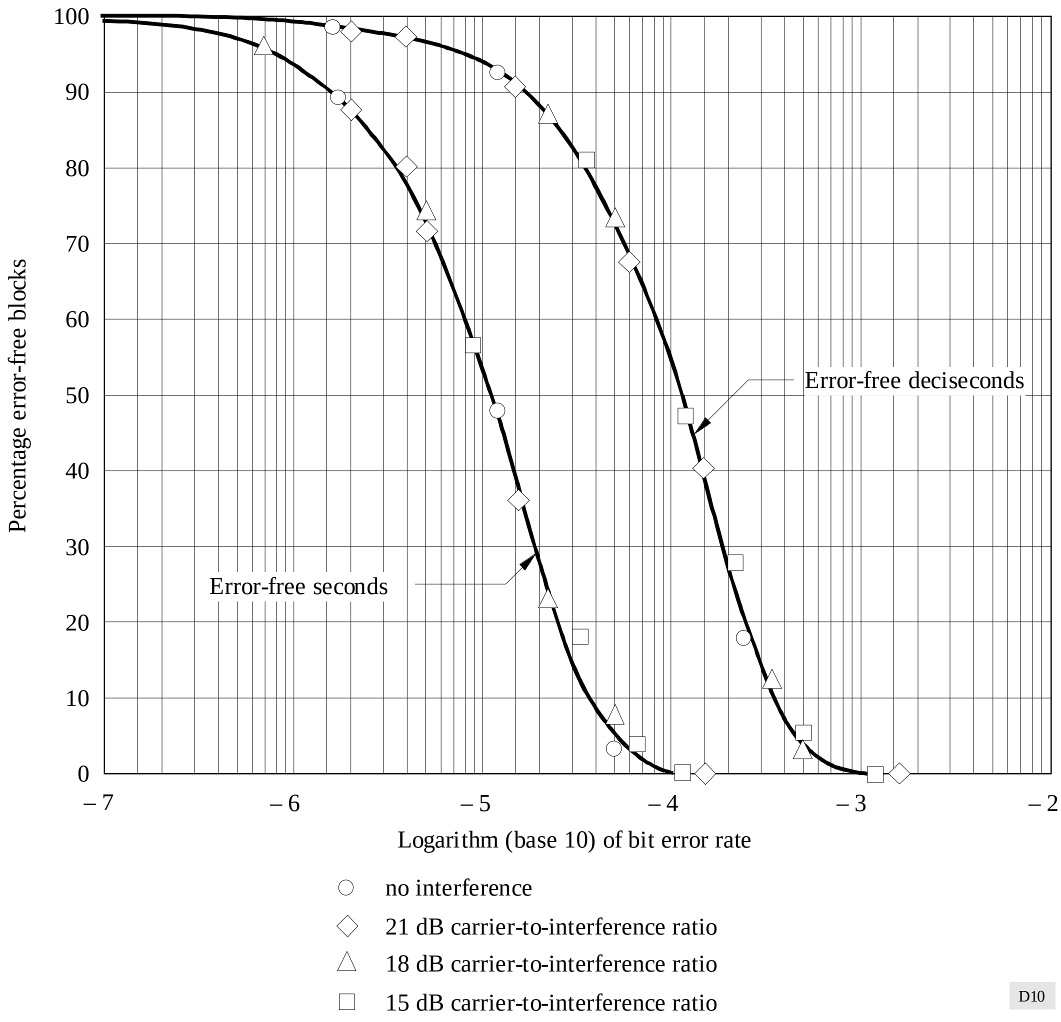
5. Error distributions on a satellite link and the effects of uncoded operation and operation utilizing forward error correction

5.1 Introduction

The method given in this section for determining whether a satellite link performance is sufficient to satisfy the requirements of ITU-T Recommendation G.821 is based upon the assumption that the errors produced by the satellite link occur randomly. For the links that do not employ forward error correction (FEC), this assumption is generally accepted as being true. An example of the validity of this assumption is given in Fig. 8.

FIGURE 8

Distribution of error-free blocks: 64 kbit/s, no FEC coding



For links that utilize FEC, the distribution of individual bit errors is necessarily “bursty” or bunched due to the operation of the FEC decoder. Errors at the decoder output occur in groups where the groups are separated by relatively long error-free intervals. Each group or “error event” can be defined as an interval that begins and ends with a bit error and that has a number of bit errors in between. These “error events” vary in length and the BER within these intervals can be as great as 0.5. Data has been presented to the ITU-R which indicates that the occurrence of these “error events” is random and thus can be modelled using a binomial or Poisson statistics.

An example of the random error assumption is shown in Fig. 8. The results of field measurements are shown which compare the distribution of error-free intervals (EFI), error-free seconds, error-free deciseconds, to a Poisson bit error distribution. The agreement between the measured data and the theoretical distribution is obvious. This data also shows that the agreement holds equally well for systems corrupted by thermal noise and thermal noise plus interference. These measurements were conducted over a 120 Mbit/s looped satellite TDMA link, and were made on a 64 kbit/s sub-channel. The system was operated under various conditions of co-channel interference from a similar continuous 120 Mbit/s carrier.

It has been shown that the major error contributions on digital satellite links are due to propagation and interference effects which can be described by the Poisson distribution. However, when FEC (used in many digital satellite systems to improve performance) is applied to the digital channel, the errors arriving at the output of the decoder tend to occur in groups, and therefore are likely to depart from the Poisson law. This clustering effect is illustrated by the measurement of EFI given in Fig. 9. The degree of departure from the Poisson law will depend on the specific coding and multiplexing schemes used.

This section provides examples of typical coding schemes, gives the results of measurements showing the impact of specific FEC schemes on the digital satellite link and introduces preliminary mathematical models that can be used to describe burstiness.

5.2 Characteristics of typical FEC coding schemes

5.2.1 Rate 7/8 BCH coding

Rate 7/8 Bose, Chaudhuri and Hocquenghem (BCH) FEC coding is currently used on digital satellite systems, e.g. INTELSAT 120 Mbit/s TDMA systems. This block code corrects up to two errors in a block of 127 bits and can detect three errors, but in the latter case the decoder takes no action. Hence, the most probable number of errors contained in a BCH block is three at the decoder output. In this scheme, the bit stream, comprised of 128 bit blocks, is restructured into blocks of 112 information bits to which 15 redundant coding bits and 1 dummy bit are appended, thus retaining the overall 128 bit block length. Consequently, during the coding process, the 128 contiguous bits of a specific 64 kbit/s channel originally appearing in a sub-burst will be split up in one of seven ways:

a) 112:16 b) 96:32 c) 80:48 d) 64:64

e) 48:80 f) 32:96 g) 16:112

As a result, individual channels can exhibit four different degrees of burstiness with a) and g) being the most bursty and d) being the least.

5.2.2 Convolutional encoding-Viterbi decoding

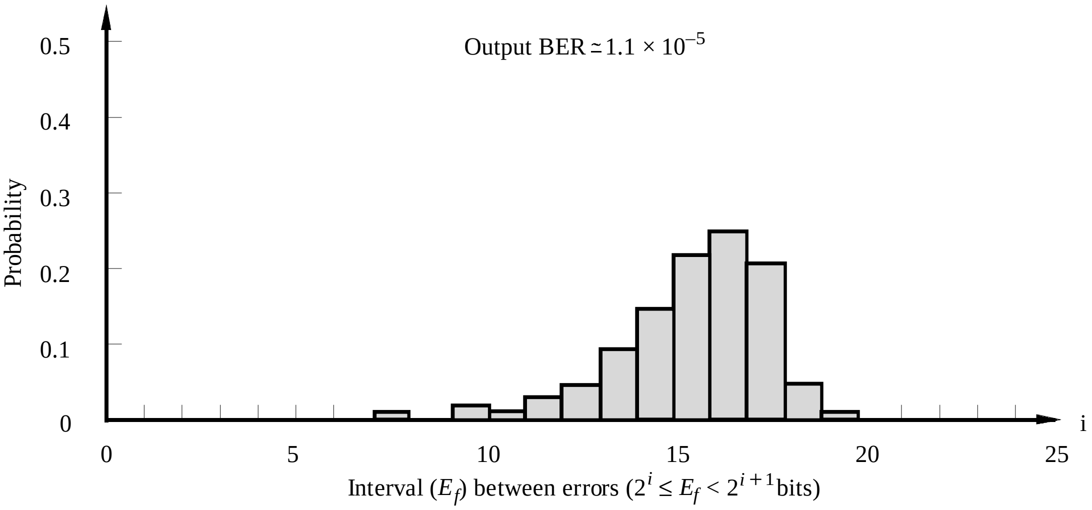
The combination of convolutional coding and Viterbi decoding techniques is also a typical FEC scheme which is being introduced into many satellite systems.

This method involves storing sequences of digits in memory and then comparing those sequences with the received digital stream to determine which one is most likely to be correct. Error events at the output of the decoder are caused by the selection of an incorrect data sequence or path. This incorrect selection gives rise to errors at the output of the decoder, but these errors do not necessarily occur consecutively. The length of the error event is a function of the codec configuration, in particular the length of the path memory. In the case of Viterbi decoding, a rate 1/2, 64 state code with a constraint length of 7 typically has a path memory length of about 37 bits. This path memory length is larger than any error event that occurs with significant probability.

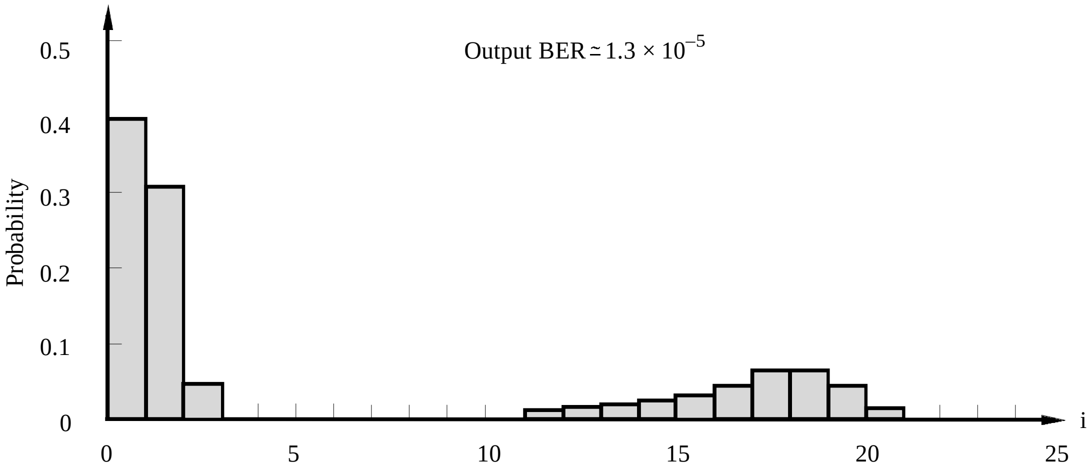
Figure 9 shows typical experimental results on the error distribution without and with FEC decoding in terms of EFI.

FIGURE 9

Distribution of errors with and without FEC



a) Without FEC (random error)



b) With FEC

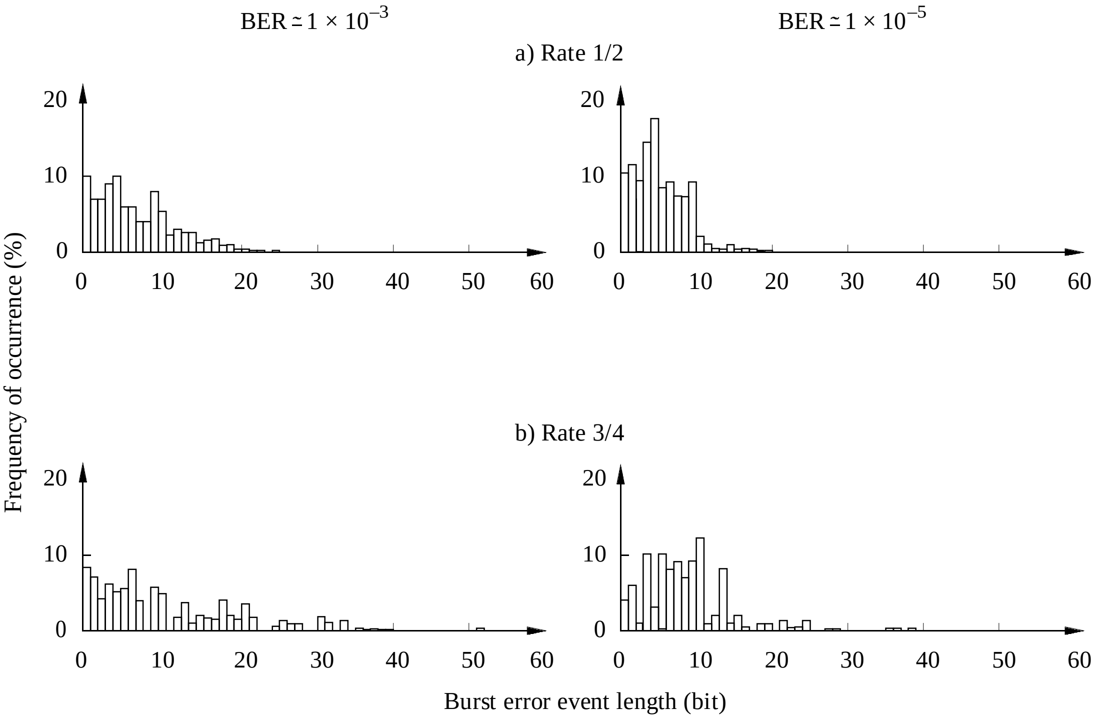
(Rate 1/2 convolutional encoding of (K = 7) and Viterbi decoding)

There are great differences; the former has a peak which is typical of a random distribution, while the latter has two peaks. One peak (right-hand side) shows the distribution of the intervals between burst errors and implies their random occurrences. The other peak (left-hand side) shows the bit error distribution within a burst error.

Figure 10 presents experimental results on the distribution of the burst error length for both rates 1/2 and 3/4 at two values of BER. The length of an error burst event is defined as the number of bits between the first error occurring in the burst and the last error occurring in the burst. Figure 11 shows the relation between the average burst error length and BER after decoding.

FIGURE 10

Distribution of burst error event length



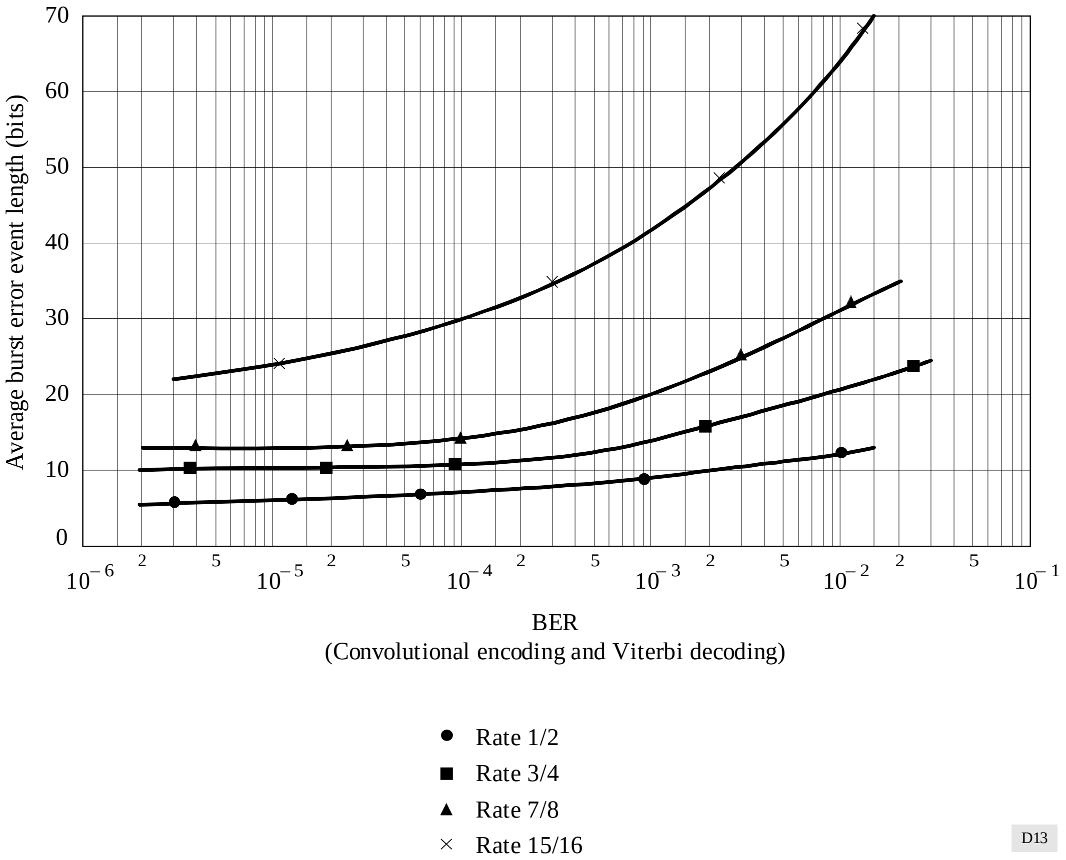
(Convolutional encoding and Viterbi decoding)

D12

It can be observed from these figures that, as the code rate and BER become larger, the duration of the error burst event grows longer. Generally speaking, the average length of error burst events is about five and ten bits for rate 1/2 and rate 3/4 codes, respectively. A few burst error events exceed 20 bits in length. It is important to note that not all of the bits in an error burst event are errors. The error ratio within an error burst event can be regarded as approximately 1/2, that is, the average number of errors included in a burst error event is two or three for rate 1/2 codes and about five for rate 3/4 codes. The above experiments were carried out with an INTELSAT standard E1 earth station in a satellite loop-back mode using a 64 kbit/s IBS carrier.

FIGURE 11

Relation between average burst error event length and BER



As the result of the above discussions, the BER after decoding is given by:

$$P_e \text{ (BER after decoding) } = \frac{L_b/2}{L_b + E_{fb}}$$

where the average interval between burst errors E_{fb} can be derived as:

$$E_{fb} = \left(\frac{1}{2\,P_e} - 1 \right) L_b \simeq L_b \,/\, 2\,P_e$$

and L_b is the average length of burst error.

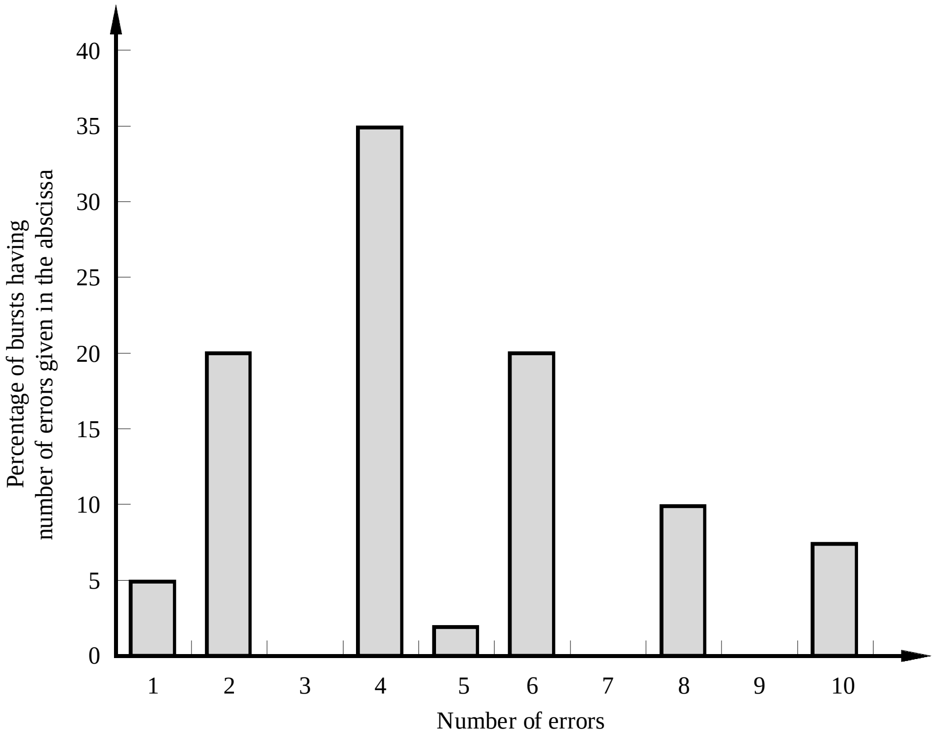
Another effect which requires consideration is the dependence of the burst error structure on the multiplexing of 64 kbit/s channels to primary rates (2 048 kbit/s) or higher; this is shown in Figs. 12a and 12b for a BER of 10^{-6}. In Fig. 12a, a histogram of the number of errors per burst is shown for a composite 1 920 kbit/s (30 time slots) signal in a 2 048 bit stream multiplexed in accordance with ITU-T Recommendation G.704. However, within an individual 64 kbit/s channel, the number of errors per burst tends to be smaller as seen in Fig. 12b.

5.2.3 Convolutional coding-sequential decoding

Sequential decoding uses a probabilistic decoding algorithm in which the computation of the path length is carried out only for a path which has already been examined and the decision on which path to extend is based only on the length of already examined paths.

FIGURE 12a

Histogram of number of errors per burst

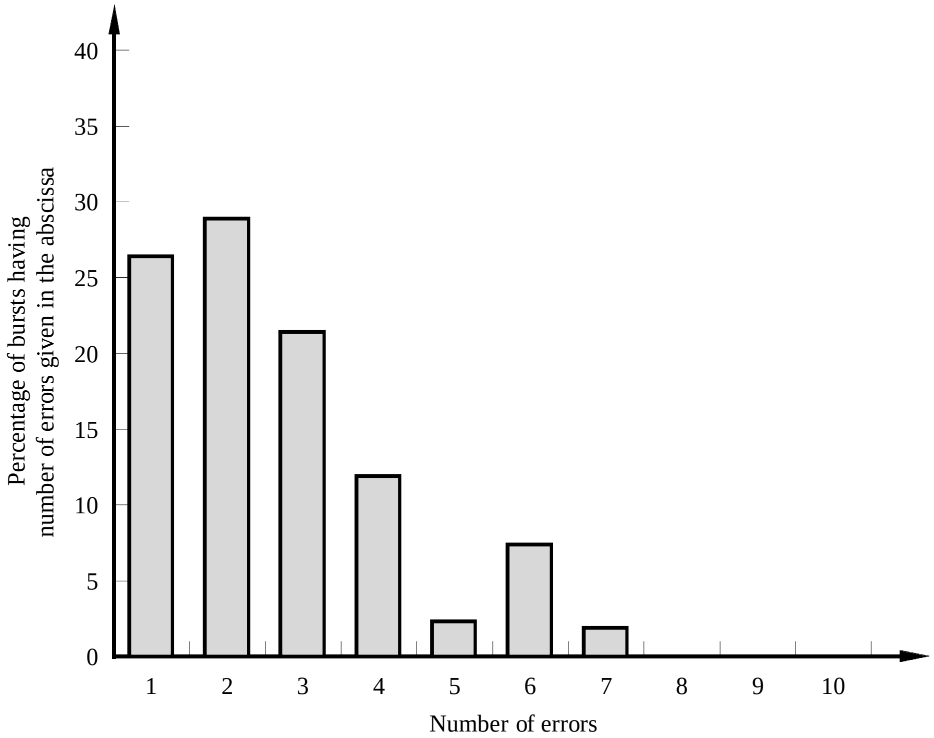


BER = 10^{-6}

FEC (rate 1/2) applied at bit rate of 2 048 kbit/s

FIGURE 12b

Histogram of number of errors per burst in one 64 kbit/s channel within a multiplex at primary rate of 2 048 kbit/s (ITU-T Recommendation G.704)



BER = 10^{-6}

FEC (rate 1/2) applied at primary rate of 2 048 kbit/s

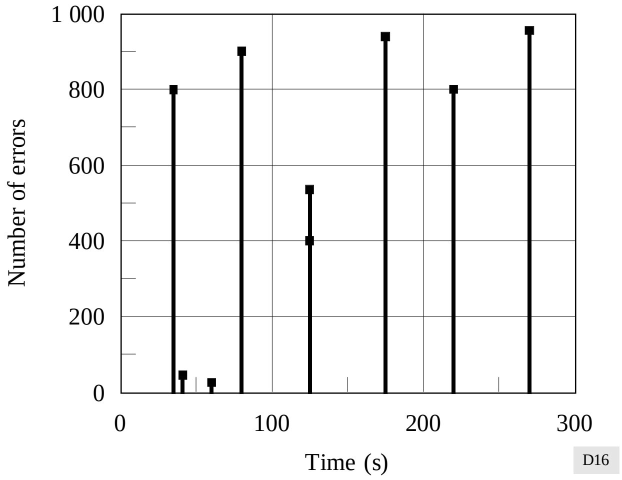
In contrast to Viterbi decoding in which computational complexity grows exponentially with constraint length, sequential decoding allows a much longer constraint length with which BER would be improved substantially. This is because in a convolutional code, BER decreases exponentially with constraint length.

Among various types of sequential decoding algorithms, the Fano algorithm and the stack algorithm are commonly used. This sub-section is concerned with the latter algorithm. The decoder output errors are mainly due to a stack buffer overflow and/or an excess decoding time.

Figure 13 shows an example of error distribution at the decoded BER of around 3 × 10^{-4} for a rate 1/2 sequential decoder with the stack algorithm operating at a 64 kbit/s information rate. It is seen that the decoder output includes a number of long burst errors each far exceeding 65 bits and few random errors between long burst errors.

FIGURE 13

Distribution of errors at the output of the sequential decoder



5.3 *Effects on degraded minutes, severely errored seconds and errored seconds*

5.3.1 *Qualitative discussion*

Effects of burst errors caused by convolutional encoding FEC are as follows:

Degraded minutes (DM)

One DM includes five errors or more. In the case of the rate 3/4 Viterbi decoding which often causes burst errors with five errors or more, the probability of DM may increase compared with random errors even under the same average error ratio. In the case of rate 1/2 Viterbi decoding, this increase might be smaller.

Severely errored seconds (SES)

One SES includes 65 errors or more. Since the number of errors in one burst error event induced by the FEC is far less than 65, one SES will include several tens of burst errors. This may result in no significant difference in the probability of SES between burst and random errors.

Errored seconds (ES)

When error bunching occurs, as is the case for a channel with FEC, the probability of ES will decrease compared with random errors for the same average error ratio.

The influence of burst errors will be less because of the fact that most satellite links multiplex many channels and that burst errors are dispersed over these multiplex channels.

5.3.2 Measurements

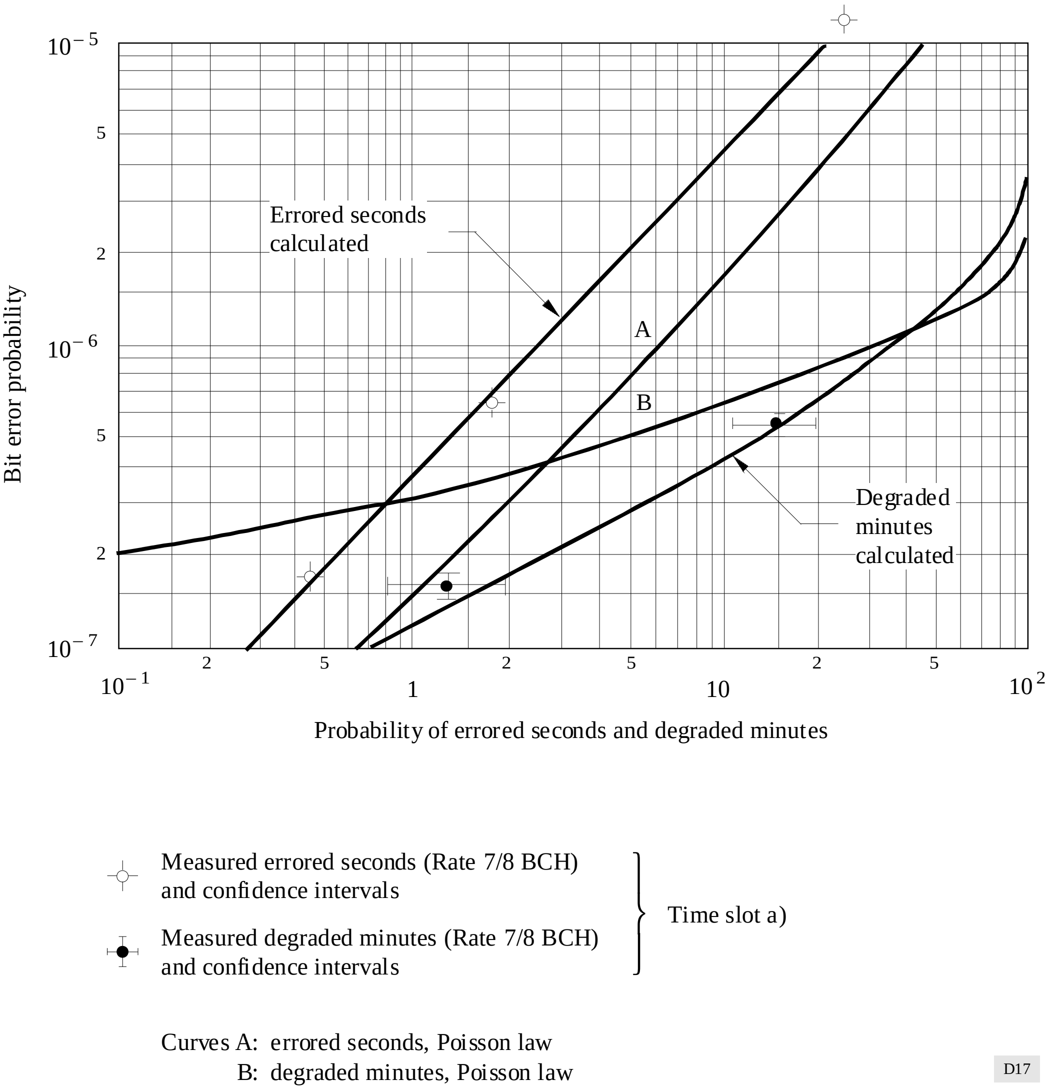
5.3.2.1 BCH coding

Measurements have been conducted on a EUTELSAT 120 Mbit/s TDMA traffic terminal operated in burst mode and looped at IF where noise was added. A 64 kbit/s pseudo-random sequence was generated by a BER analyser and percentage ES, DM and SES were measured in accordance with ITU-T Recommendation G.821.

Measurements were carried out for the two time slots associated with cases a) and d) of § 5.2.1 and it was found that a clear departure from the Poisson law could be observed for ES and DM statistics (Fig. 14).

FIGURE 14

Errored seconds and degraded minutes statistics at 64 kbit/s

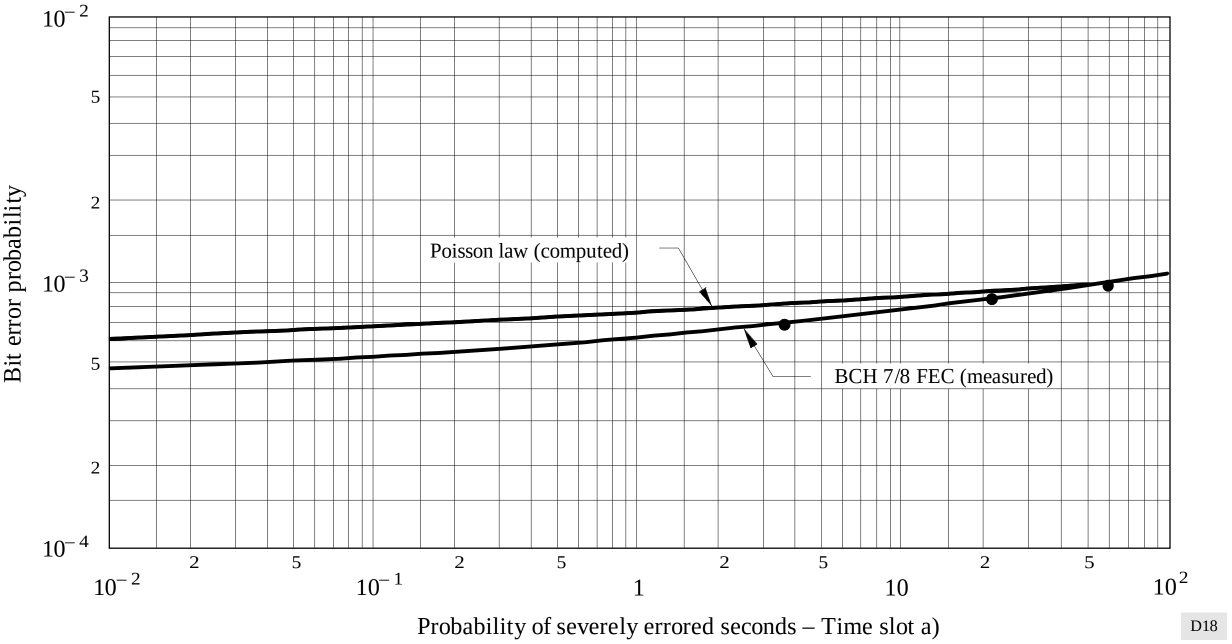


For the SES, a marginal shift could be observed for the small percentages of time on the distribution when FEC is used (Fig. 15). This shift is nevertheless quite small and not very significant when considering the flatness of the distribution, even if the computed confidence intervals prove that an actual shift has occurred.

These measurements were found to agree well with the theoretical prediction explained in § 5.4.2.

FIGURE 15

Probability of severely errored seconds



5.3.2.2 *Convolutional coding-Viterbi decoding*

For convolutional coding-Viterbi decoding, similar measurements have been made and are shown in Figs. 16 to 19. As is seen, results have been obtained for both rates 1/2 and 3/4 at 64 kbit/s and rate 3/4 for one 64 kbit/s channel in a 2 048 kbit/s composite stream.

5.3.2.3 *Convolutional coding-sequential decoding*

The squares in Fig. 18 indicate ES and DM for the sequential decoder in an additive white Gaussian noise (AWGN) channel. It is observed that the ES performance for the sequential decoder is better than that for an uncoded system and it is parallel to the result for an uncoded system. The DM performance, however, is quite different from the one for an uncoded system but akin to the one for Viterbi decoding.

Both ES and DM performances of the sequential decoder are better than those of Viterbi decoding. This is because, as described in § 2.3, for the same average BER, the sequential decoder introduces longer burst errors than Viterbi decoding which may well exceed hundreds of bits and short bursts of random errors between long burst errors.

Therefore, ES of the sequential decoder is better than the one of Viterbi decoding as the latter introduces a number of random errors as well as short burst errors. Furthermore, since the definition of DM excludes the SES events, the DM performance of the sequential decoder is superior to Viterbi decoding.

The squares in Fig. 19 display the SES seconds performance for the sequential decoder. For moderate to low BERs, the SES percentage for the sequential decoder decreases gradually and it is inferior to the one for Viterbi decoding. This is because the sequential decoder, in general, introduces a number of burst errors of longer than 65 bits.

FIGURE 16

Percentage degraded minutes for a 64 kbit/s channel multiplexed (ITU-T Recommendation G.704) in a 2 048 kbit/s bit stream (Rate 3/4 FEC, self-synchronizing scrambler in accordance with INTELSAT IDR specification)

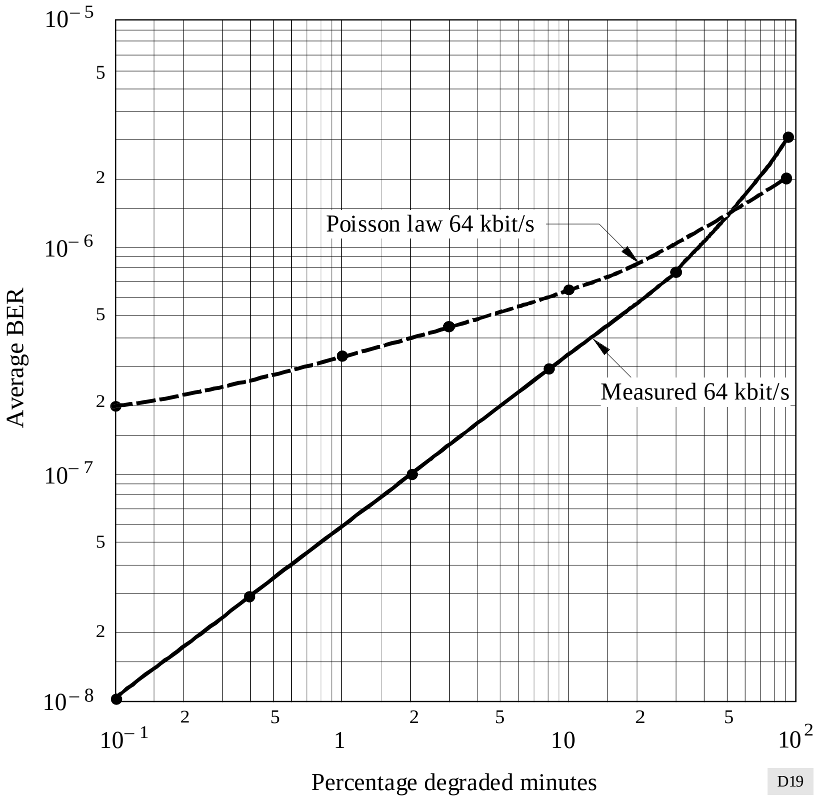


FIGURE 17

Percentage errored and error-free seconds for a 64 kbit/s channel multiplexed (ITU-T Recommendation G.704) in a 2 048 kbit/s stream and for the composite 2 048 kbit/s stream (Rate 3/4 FEC, self-synchronizing scrambler in accordance with INTELSAT IDR specification)

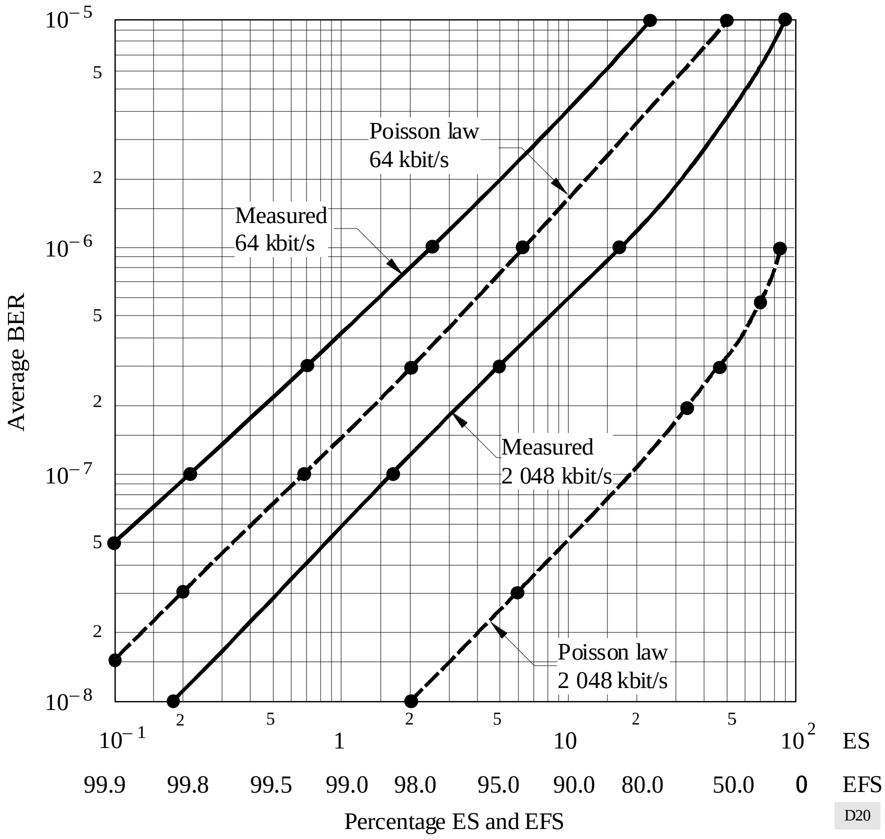


FIGURE 18

Errored seconds and degraded minutes statistics for a 64 kbit/s bit stream (no data scrambling or differential encoding)

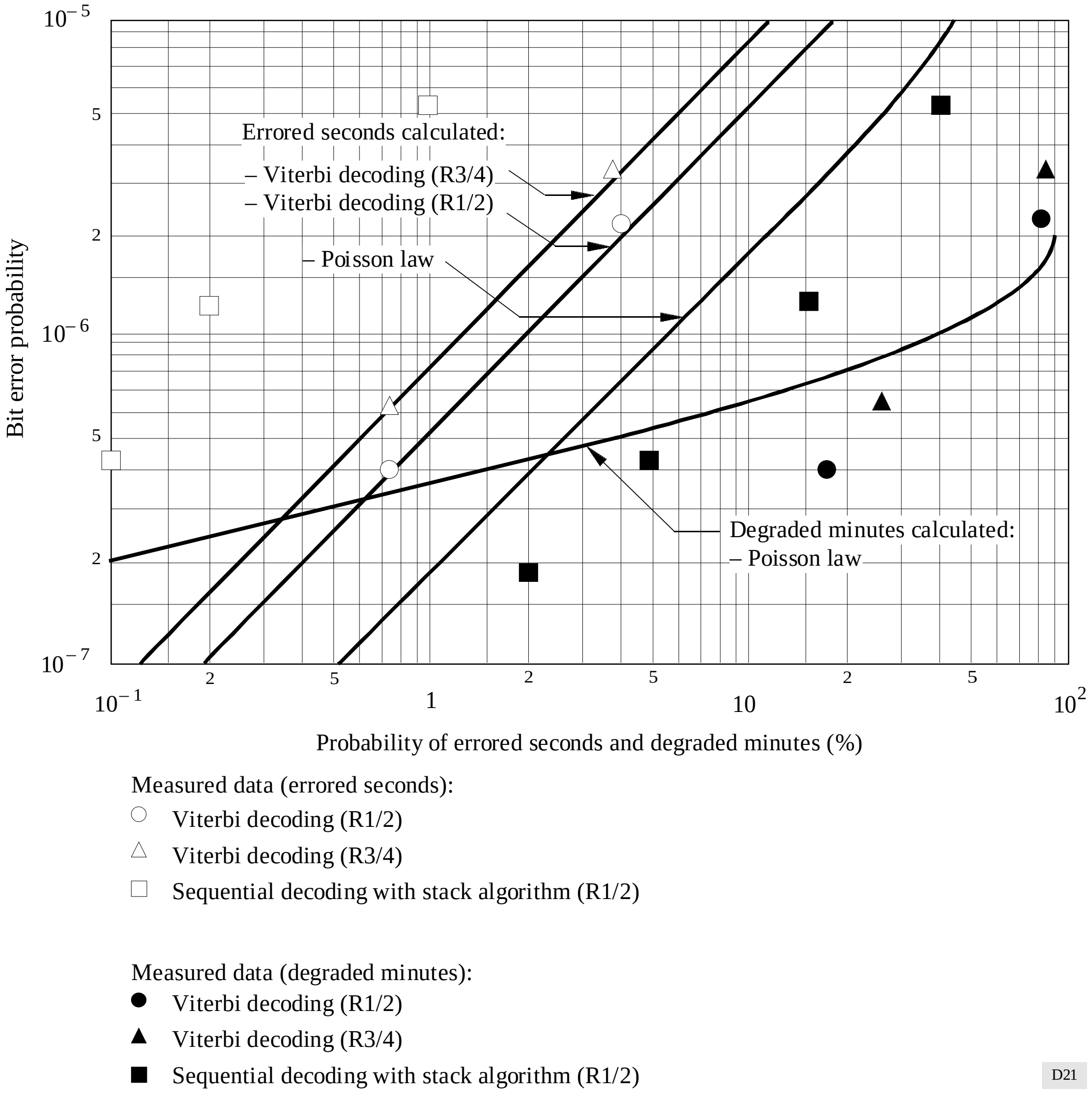
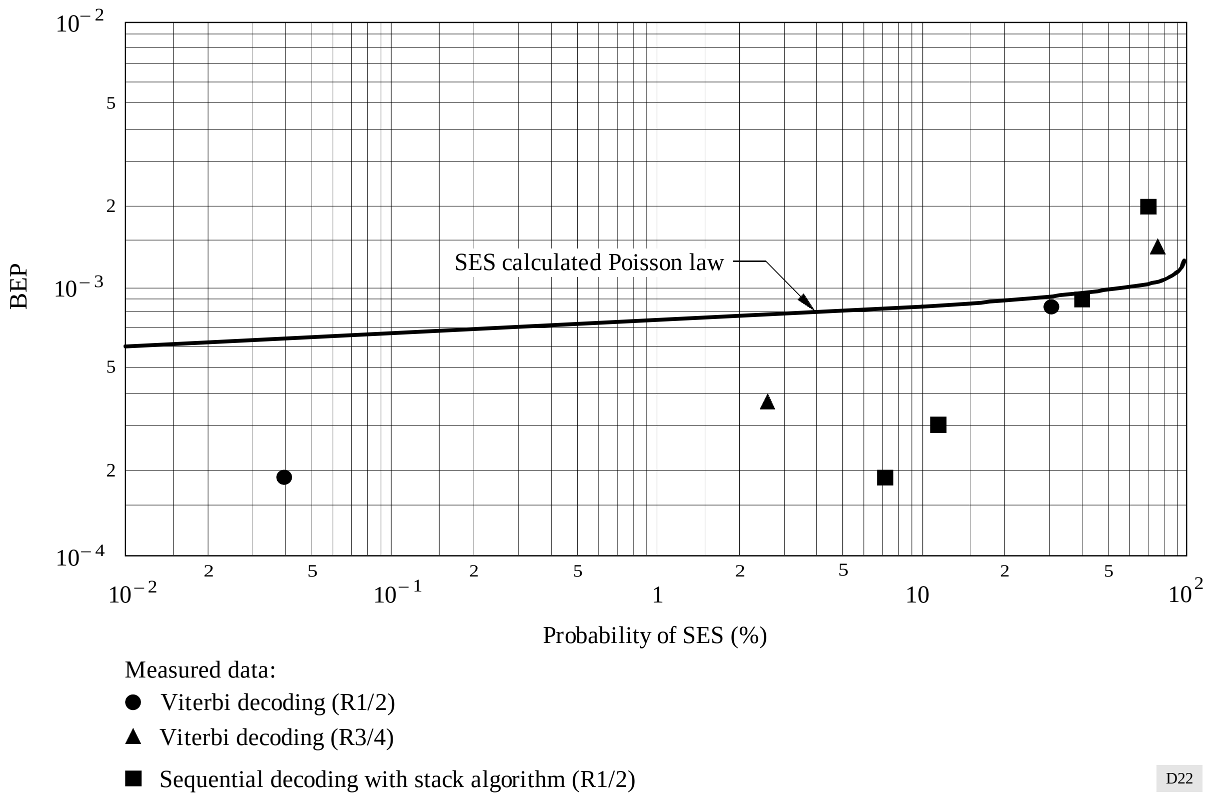


FIGURE 19

Probability of severely errored seconds (SES) for a 64 kbit/s bit stream



5.3.3 *Quantitative analysis*

Figure 20 shows the probability of DM versus the BEP for three different cases of error distribution, named α, β_m and β_w. Case α is the random case considered in this Annex. Cases β_m and β_w assume that the errors are clustered but the bursts themselves occur at random. Case β_m (*m* for moderate) assumes that there are systematically 3 errors per burst. Case β_w (*w* for worst) assumes that there are systematically 5 errors per burst. The formulae used to compute the curves are given in the figure. They are in fact Poisson formulae applied to bursts.

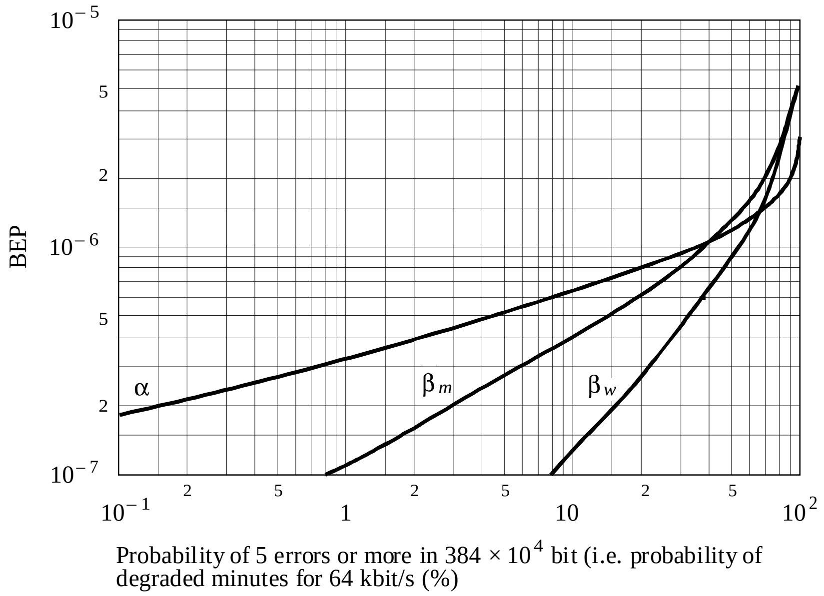
The DM increase with burstiness in the low BEP region. Moreover, if the bursts have systematically more than 5 errors each, then any minute that receives a burst is counted as degraded in the same way as if there were only 5 errors. But if there are more errors per burst then the bursts will be further separated, and more minutes will be burst-free. Thus β_w is the worst-case distribution for this parameter.

If the error distributions of Figs. 10a and 10b (at BER = 10^{-5}) are approximately uniform and the error burst occurrences are considered as independent events, it is possible to calculate the degraded minutes and EFS performance.

Table 6 summarizes the calculation results. The case with double errors, typical for systems with differential coding is also included in the table. The calculations have been performed under the assumption that from the BER point of view, circuit performances comply with model d) of Fig. 3. The values in Table 6 show that error bursts can significantly affect the performances of a digital circuit in terms of requirements given in ITU-T Recommendation G.821. This analysis does not however, consider the effect of multiplex structure. Further study is needed in this area. Pending the results of such studies care should be exercised in the design of systems utilizing FEC in meeting DM objectives.

FIGURE 20

Probability of degraded minutes assuming constant bit error probability



Case α: Random error channel

$$P(DM) = 1 - \left[1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} \right] e^{-x} \qquad x = 384 \cdot 10^4 P$$

Case β_m: Moderately bursty channel (3 errors per burst)

$$P(DM) = 1 - (1 + x)\, e^{-x} \qquad x = 384 \cdot 10^4\, P/3$$

Case β_w: Worst-case bursty channel (5 errors per burst)

$$P(DM) = 1 - e^{-x} \qquad x = 384 \cdot 10^4\, P/5$$

where:

P: bit error probability

$P(DM)$: probability of degraded minutes

D23

TABLE 6

Objective	Performance (percentage of available time)				
	ITU-T Recommendation G.821	Single errors	Double errors	Error bursts (1/2 code)	Error bursts (3/4 code)
Degraded minutes	2.0	1.87	2.67	6.2	6.7
Errored seconds	1.6	1.56	1.4	1.2	1.16

5.4 Mathematical modelling

In order to demonstrate that a particular system meets ITU-T Recommendation G.821 requirements, it is necessary to know:

- BEP statistics with time percentage;
- mathematical model, through which ES, DM and SES are calculated, to describe the error distribution at the 64 kbit/s stage, taking into account the type of FEC applied and method of multiplexing used.

The following two models have been studied.

5.4.1 The Neyman-A contagious distribution

One statistical model which can be used to describe the clustering of probabilistic events is the Neyman-A contagious distribution. In particular, this distribution can describe the burstiness of error arrivals due to propagation and interference effects on digital satellite systems. Applying this model assures that error bursts are independent, i.e. arrive at random and that the duration of the bursts are random (though errors in some FEC schemes typically arrive in bursts of three or four at the decoder output, the actual average number of errors on a given demultiplexed channel needs to be evaluated from the knowledge of the system).

The Neyman-A contagious model is given by:

$$P(n) = \frac{(BEP/A)^n}{n!} \, \mathrm{e}^{-NA} \sum_{k=0}^{\infty} \frac{k^n}{k!} \, (NA)^k \, \mathrm{e}^{-kBEP/A}$$

where:

$P(n)$: probability that n errors occur in N transmitted bits

NA: average number of bursts

BEP/A: mean value of errors per burst.

Then the probability of EFS and DM can be determined, respectively, by:

$$P(\mathrm{o}) = \mathrm{e}^{-NA} \sum_{k=0}^{\infty} \frac{(NA)^k}{k!} \, \mathrm{e}^{-kBEP/A} \qquad \text{with } N = 64 \text{ kbits}$$

$$P(DM) = 1 - \sum_{n=0}^{4} P(n) \qquad \text{with } N = 3.84 \text{ Mbits}$$

5.4.2 Analytical representation for a BCH code

When the transmission system is known (type of FEC used, multiplexing scheme, etc.), analytical formulae can be derived in place of measurements in order to predict the statistics of ES, DM and SES parameters with BEPs.

Analytical expressions can be derived and predictions could be obtained in the case of the BCH 7/8 FEC as used in the INTELSAT and EUTELSAT 120 Mbit/s TDMA systems (see Table 7).

TABLE 7

Summary of formulae to compute the percentage ES, DM and SES

BCH 7/8

ES percentage	$P = 100 \times \{(1 - e^{-L})\} \times u$ $L = \text{BEP} \times 42\,333.3$ $u = 0.667$ For case a) $u = 0.881$ For case d)
DM percentage	$P = 100 \times \{1 - (1 + L + L^2/2! \times (1 - u2) + L^3/3! \times (1 - u3) + L^4/4! \times (1 - u4)) \times e^{-L}\}$ $L = \text{BEP} \times 2.54 \times 10^6$ $u2 = 0.227$ $u3 = 0.506$ $u4 = 0.702$ For case a) $u2 = 0.111$ $u3 = 0.510$ $u4 = 0.713$ For case d)
SES percentage	$P = 100 \times \{1 - (1 + L + L^2/2! + ... + L^{38}/38!) \times e^{-L}\}$ $L = \text{BEP} \times 42\,333.3$

5.5 Impact on system design in the 14/11 GHz band

For 14/11 GHz systems operating in European climatic zones, the constraining criterion of the mask specified in Recommendation ITU-R S.614 in the case of a non-coded satellite link is the “long term” BEP. This is because the difference in C/N required at the input of the earth-station demodulator to achieve BEPs of 10^{-7} and 10^{-3} is larger than the corresponding expected fade levels difference between 10% and 0.2% of the (total) worst month.

As an illustration, Fig. 21 (curves A and B) shows the performance of a system operating at 14/11 GHz band and whose characteristics are such that the long-term criterion at 10^{-7} is exactly met. Curves A and B refer to the performance in terms of percentages of time, when the system is affected by propagation statistics typical of the European coastal climate (curve A) and of the Alpine/Mediterranean climate (curve B).

In the case where FEC is used, the situation requires more careful analysis. On one hand, the difference in $(C/N + I)$s required at the input of the demodulator for the two levels of BER is smaller than in the non-coded case due to the coding gain and this tends to constrain the design on the short-term requirement; on the other hand, a better performance than a BER of 10^{-7} is needed for 10% of the worst month in order to compensate for the bursty nature of the error occurrence, and this sets a high performance requirement under clear-sky conditions.

Figures 21 and 22 illustrate this: Fig. 21 (curve C) shows the performance of a satellite link with the BCH 7/8 block code and Fig. 22 (curves A and B) the performance of a link convolutionally encoded with FEC rates 1/2 and 3/4 respectively, when the system is dimensioned in order to just meet the short-term criterion under propagation statistics of the Alpine/Mediterranean climate, which is the worst case for Europe.

FIGURE 21

Performance of a system operating at 14/11 GHz band, designed to just meet the objectives of the present Recommendation

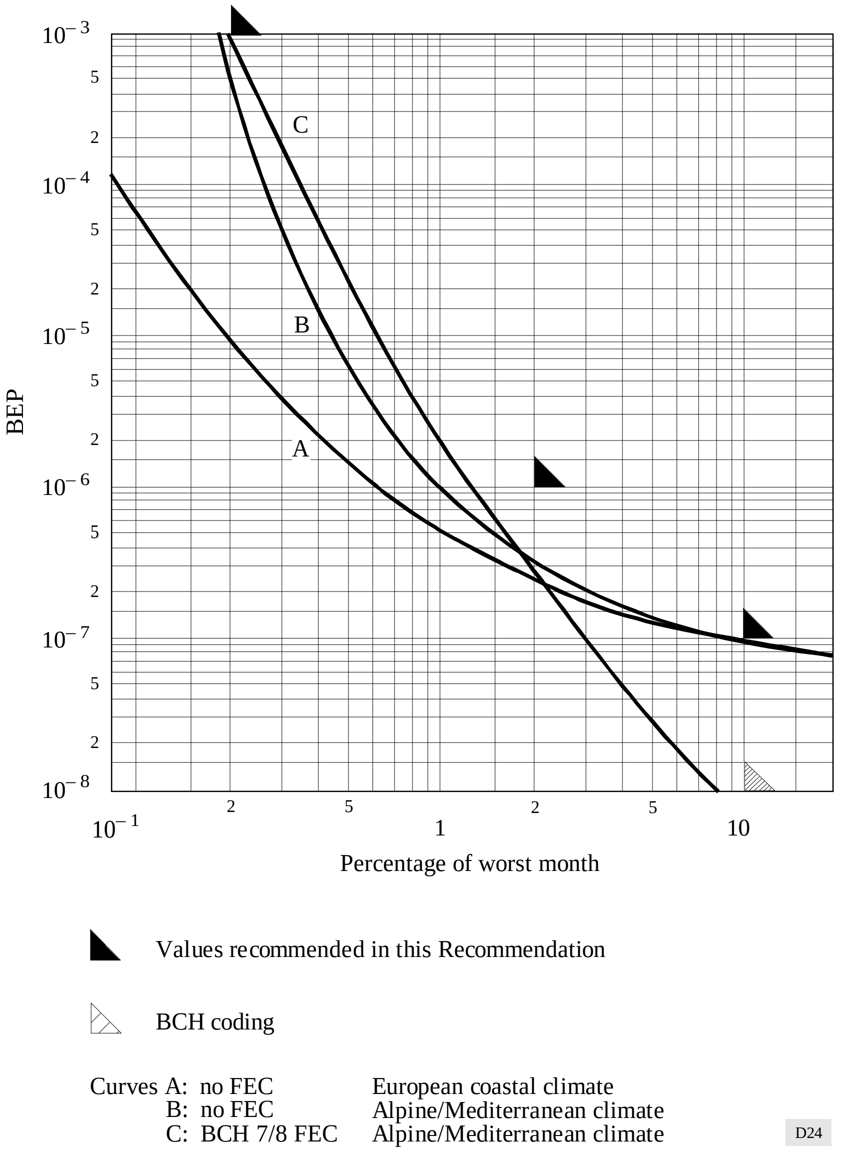
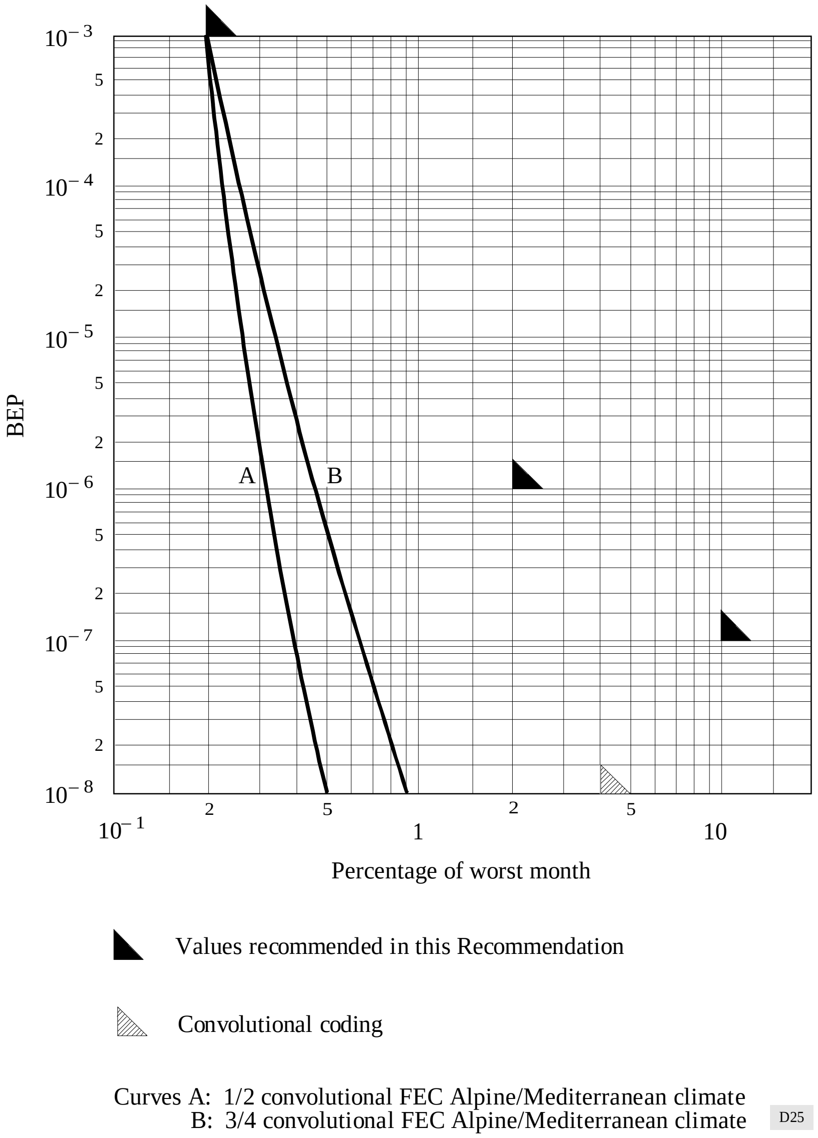


FIGURE 22

Performance of a system operating at 14/11 GHz band, designed to just meet the objectives of the present Recommendation



5.6 Conclusions

This section discusses the error distribution characteristics in satellite communication systems employing several types of FEC as well as their effects on DM, SES and ES which are used to define ITU-T Recommendation G.821 and which have been analysed.

- The FEC, both block coding and convolutional coding, causes errors to exhibit a bursty distribution.
- The probability of DM in the FEC system might be greater than that in the non-FEC system under the condition of the same average BER.
- There will be no substantial difference in the probability of SES for the same BER whether the FEC is used or not.
- The probability of ES will be less in the FEC system than in the non-FEC system for the same BER.
- The influence of burst errors may decrease when the satellite link multiplexes a number of channels.
- Error distribution can be modelled mathematically by expansion of the Poisson distribution. This item needs further study.