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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

Quality and availability targets

The control of jitter and wander within digital networks which are based on the 2048 kbit/s hierarchy

Reedition of CCITT Recommendation G.823 published in the Blue Book, Fascicle III.5 (1989)

NOTES

1 CCITT Recommendation G.823 was published in Fascicle III.5 of the *Blue Book*. This file is an extract from the *Blue Book*. While the presentation and layout of the text might be slightly different from the *Blue Book* version, the contents of the file are identical to the *Blue Book* version and copyright conditions remain unchanged (see below).

2 In this Recommendation, the expression “Administration” is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Recommendation G.823

THE CONTROL OF JITTER AND WANDER WITHIN DIGITAL NETWORKS WHICH ARE BASED ON THE 2048 kbit/s HIERARCHY

(Malaga-Torremolinos, 1984; amended at Melbourne, 1988)

The CCITT,

considering

(a) that jitter, which is defined as the short-term variations of the significant instants of a digital signal from their ideal positions in time, can arise in digital networks;

(b) that, if proper control is not exercised, then under certain circumstances, jitter can accumulate to such an extent that the following impairments can arise:

i) an increase in the probability of introducing errors into digital signals at points of signal regeneration as a result of timing signals being displaced from their optimum position in time;

ii) the introduction of uncontrolled slips into digital signals through store spillage and depletion in certain types of terminal equipment incorporating buffer stores and phase comparators, e.g. jitter reducers and certain digital multiplex equipment;

iii) a degradation of digitally encoded analogue information as a result of phase modulation of the reconstructed samples in the digital to analogue conversion device at the end of the connection;

(c) that, unlike some other network impairments, jitter can be reduced in magnitude by the use of jitter reducers. Depending upon the size and complexity of networks, it might be necessary to employ such devices in certain circumstances;

(d) that wander, which is defined as the long-term variations of the significant instants of a digital signal from their ideal position in time, can arise as a result of changes in the propagation delay of transmission media and equipments;

(e) that it is necessary to accommodate wander at the input ports of digital equipments if controlled or uncontrolled slips are to be minimized,

recommends

that the following guidelines and limits should be applied in the planning of networks and in the design of equipment.

1 The control of jitter in digital networks – basic philosophy

The jitter control philosophy is based on the need:

– to recommend a maximum network limit that should not be exceeded at any hierarchical interface;

– to recommend a consistent framework for the specification of individual digital equipments;

– to provide sufficient information and guidelines for organizations to measure and study jitter accumulation in any network configuration.

2 Network limits for the maximum output jitter and wander at any hierarchical interface

2.1 *Network limits for jitter*

The limits given in Table 1/G.823 represent the maximum permissible levels of jitter at hierarchical interfaces within a digital network. The limits should be met for all operating conditions and regardless of the amount of equipment preceding the interface. These network limits are compatible with the minimum tolerance to jitter that all equipment input ports are required to provide.

In operational networks, account needs to be taken of the fact that signals at an interface can contain jitter up to the maximum permissible network limit. This is particularly important in the design of equipments incorporating jitter reducers where this jitter together with any additional jitter generated in the system prior to the jitter reducer, needs to be accommodated. In circumstances where the maximum permissible jitter amplitude occurs at an interface between two countries, it is left to the discretion of national Administrations to take the appropriate remedial action. This situation is unlikely to occur very often.

The arrangements for measuring output jitter at a digital interface are illustrated in Figure 1/G.823. The specific jitter limits and values of filter cut-off frequencies for the different hierarchical levels are given in Table 1/G.823. The frequency response of the filters associated with the measurement apparatus should have a roll-off of 20 dB/decade. Suitable test apparatus is described in Recommendation O.171.

TABLE 1/G.823

Maximum permissible jitter at a hierarchical interface

Parameter value / Digit rate (kbit/s)	Network limit		Measurement filter bandwidth		
			Band-pass filter having a lower cutoff frequency f_1 or f_3 an un upper cutoff frequency f_4		
	B_1 unit interval peak-to-peak	B_2 unit interval peak-to-peak	f_1	f_3	f_4
64 (Note 1)	0.25	0.05	20 Hz	3 kHz	20 kHz
2 048	1.5	0.2	20 Hz	18 kHz (700 Hz)	100 kHz
8 448	1.5	0.2	20 Hz	3 kHz (80 kHz)	400 kHz
34 368	1.5	0.15	100 Hz	10 kHz	800 kHz
139 264	1.5	0.075	200 Hz	10 kHz	3 500 kHz

Note 1 – For the codirectional interface only.

Note 2 – The frequency values shown in parenthesis only apply to certain national interfaces.

Note 3 – UI = Unit Interval:

for 64 kbit/s = 15.6 μs

for 2 048 kbit/s = 488 ns

for 8 448 kbit/s = 118 ns

for 34 368 kbit/s = 29.1 ns

for 139 264 kbit/s = 7.18 ns

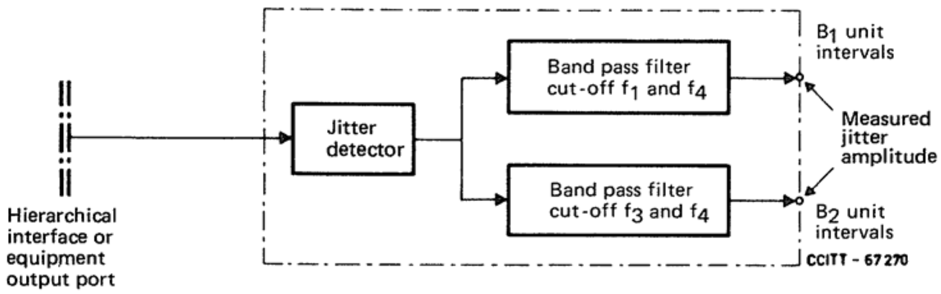

FIGURE 1/G.823

Measurement arrangements for output jitter from a hierarchical interface or an equipment output port

For systems in which the output signal is controlled by an autonomous clock (e.g. quartz oscillator) more stringent output jitter values may be defined in the relevant equipment specifications (e.g. for the muldex in Recommendation G.735, the maximum peak-to-peak output jitter is 0.05 UI).

2.2 *Network units for wander*

A maximum network limit for wander at all hierarchical interfaces has not been defined. Actual magnitudes of wander, being largely dependent on the fundamental propagation characteristics of transmission media and the ageing of clock circuitry (see Recommendation G.811, § 3), can be predicted. Studies have shown that, provided input ports can tolerate wander in accordance with the input tolerance requirements of § 3.1.1, then slips introduced as a result of exceeding the input tolerance, will be rare. For interfaces to network nodes the following limits apply:

The MTIE (see Recommendation G.811) over a period of S seconds shall not exceed the following:

1) $S < 10^4$; this region requires further study;

2) $(10^{-2} S + 10\,000)$ ns: applicable to values of S greater than 10^4.

Note – The resultant overall specification is illustrated in Figure 2/G.823.

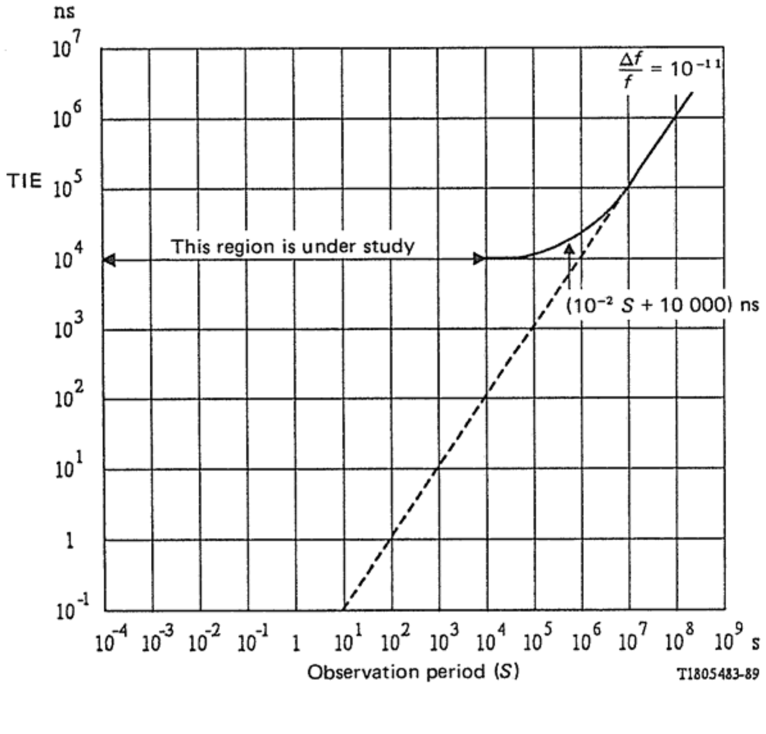

FIGURE 2/G.823

Permissible maximum time interval error (MTIE) versus observation period S for the output of a network node

2.3 *Jitter and wander considerations concerning synchronized networks*

It is assumed that, within a synchronized network, digital equipment provided at nodes will accommodate permitted phase deviations on the incoming signal, together with jitter and wander from the transmission plant thus under normal synchronized conditions, slips will not occur. However, it should be recognized that, as a result of some performance degradations, failure conditions, maintenance actions and other events, the relative time interval error (TIE) between the incoming signal and the internal timing signal of the terminating equipment may exceed the wander and jitter tolerance of the equipment which will result in a controlled slip.

At nodes terminating links interconnecting independently synchronized networks (or where plesiochronous operation is used in national networks), the relative TIE between the incoming signal and the internal timing signal of the terminating equipment may eventually exceed the wander and jitter tolerance of the equipment in which case slip will occur. The maximum permissible long-term mean controlled slip rate resulting from this mechanism is given by Recommendation G.811, i.e. one slip in 70 days.

3 Jitter limits appropriate to digital equipments

3.1 *Basic specification philosophy*

For individual digital equipments it is necessary to specify their jitter performance in three ways:

3.1.1 *Jitter and wander tolerance of digital input ports*

In order to ensure that any equipment can be connected to any recommended hierarchical interface within a network, it is necessary to arrange that the input ports of all equipments are capable of accommodating levels of jitter up to the maximum network limit defined in Table 1/G.823.

For convenience of testing, the required tolerance is defined in terms of the amplitude and frequency of sinusoidal jitter which, when modulating a test pattern, should not cause any significant degradation in the operation of the equipment. It is important to recognize that the test condition is not, in itself, intended to be representative of the type of jitter to be found in practice in a network. However, the test does ensure that the "*Q*" factor associated with the timing signal recovery of the equipments input circuitry is not excessive and, where necessary, that an adequate amount of buffer storage has been provided.

Thus, all digital input ports of equipments should be able to tolerate a digital signal having electrical characteristics in accordance with the requirements of Recommendation G.703 but modulated by sinusoidal wander and jitter having an amplitude-frequency relationship defined in Figure 3/G.823. Table 2/G.823 indicates the appropriate limits for the different hierarchical levels.

In principle, these requirements should be met regardless of the information content of the digital signal. For test purposes, the equivalent binary content of the signal with jitter modulation should be a pseudo-random bit sequence as defined in Table 2/G.823.

In deriving these limits, the wander effects are considered to be predominant at frequencies below f_1, and many transmission equipments, such as digital line systems and asynchronous muldexes using justification techniques, are effectively transparent to these very low frequency changes in phase. Notwithstanding this, it does not need to be accommodated at the input of certain equipments (e.g. digital switches and synchronous muldexes). The requirement below f_1 is not amenable to simple practical evaluation but account should be taken of the requirement at the design stage of the equipment.

Unlike that part of the mask between frequencies f_1 and f_4, which reflect the maximum permissible jitter magnitude in a digital network, that part of the mask below the frequency f_1 does not aim to represent the maximum permissible wander that might occur in practice. Below the frequency f_1, the mask is derived such that where necessary, the provision of this level of buffer storage at the input of an equipment facilitates the accommodation of wander generated in a large proportion of real connections.

A short-term reversal of the relative TIE between the incoming signal, and the internal timing signal of the terminating equipment shortly after the occurrence of a controlled slip should not cause another slip. In order to prevent such a slip, the equipment should be designed with a suitable hysteresis for this phenomenon. This hysteresis should be at least 18 microseconds.

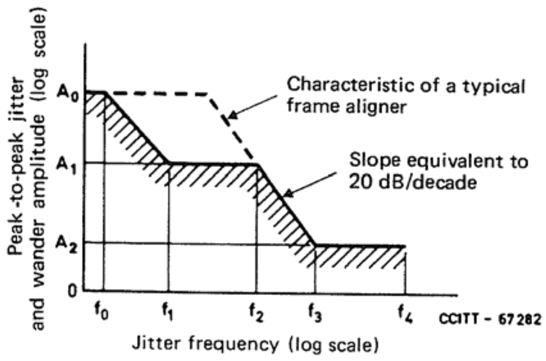

FIGURE 3/G.823

Lower limit of maximum tolerable input jitter and wander

TABLE 2/G.823

Parameter values for input jitter and wander tolerance

Parameter value / Digit rate kbit/s	Peak-to-peak amplitude unit interval			Frequency					Pseudo-random test signal
	A_0	A_1	A_2	f_0	f_1	f_2	f_3	f_1	
64 (Note 1)	1.15 (18 µs)	0.25	0.05	1.2×10^{-5} Hz	20 Hz	600 Hz	3 kHz	20 kHz	$2^{11} - 1$ (Rec. O.152)
2048	36.9 (18 µs)	1.5	0.2		20 Hz	2.4 kHz (93 Hz)	18 kHz (700 Hz)	100 kHz	$2^{15} - 1$ (Rec. O.151)
8448	152 (18 µs)	1.5	0.2	1.2×10^{-5} Hz	20 Hz	400 Hz (10.7 kHz)	3 kHz (80 kHz)	400 kHz	$2^{15} - 1$ (Rec. O.151)
34 368	*	1.5	0.15	*	100 Hz	1 kHz	10 kHz	800 kHz	$2^{23} - 1$ (Rec. O.151)
139 264	*	1.5	0.075	*	200 Hz	500 Hz	10 kHz	3500 kHz	$2^{23} - 1$ (Rec. O.151)

* Values under study.

Note 1 – For the codirectional interface only.

Note 2 – For interfaces within national networks the frequency values (f_2 and f_3) shown in parenthesis may be used.

Note 3 – UI = Unit Interval:

For 64 kbit/s	1 IU = 15.6 µs
For 2048 kbit/s	1 IU = 488 ns
For 8448 kbit/s	1 IU = 118 ns
For 34 368 kbit/s	1 IU = 29.1 ns
For 139 264 kbit/s	1 IU = 7.18 ns

Note 4 – The value for A_0 (18 µs) represents a relative phase deviation between the incoming signal and the internal timing local signal derived from the reference clock. This value for A_0 corresponds to an absolute value of 21 µs at the input to a node (i.e. equipment input port) and assumes a maximum wander of the transmission link between two nodes of 11 µs. The difference of 3 µs corresponds to the 3 µs allowed for long-term phase deviation in the national reference clock [Recommendation G.811, § 3c].

3.1.2 *Maximum output jitter in the absence of input jitter*

It is necessary to restrict the amount of jitter generated within individual equipments. Recommendations dealing with specific systems define the maximum levels of jitter that may be generated in the absence of input jitter. The actual limits applied depend upon the type of equipment. They should be met regardless of the information content of the digital signal. In all cases the limits never exceed the maximum permitted network limit. The arrangement for measuring output jitter is illustrated in Figure 1/G.823.

3.1.3 *Jitter and wander transfer characteristics*

Jitter transfer characteristics define the ratio of output jitter to input jitter amplitude versus jitter frequency for a given bit rate. When jitter is present at the digital input port of digital equipment, in many cases some portion of the jitter is transmitted to the corresponding digital output port. Many types of digital equipment inherent attenuate the higher frequency jitter components present at the input. To control jitter in cascaded homogeneous digital equipment, it is important to restrict the value of jitter gain. The jitter transfer for a particular digital equipment can be measured using a digital signal modulated by sinusoidal jitter.

Figure 4/G.823 indicates the general shape of a typical jitter transfer characteristics. The appropriate values for the levels x and $-y$ dB and the frequencies f, f_5, f_6 and f_7 can be obtained from the relevant Recommendation.

Because the bandwidth of phase smoothing circuits in asynchronous digital equipment is generally above 10 Hz, wander on the input signal may appear virtually unattenuated on the output. However, in certain particular digital equipments (e.g. nodal clocks) it is necessary that wander be sufficiently attenuated from input to output. CCITT Recommendations dealing with synchronous equipment will ultimately define limiting values for particular wander transfer characteristics.

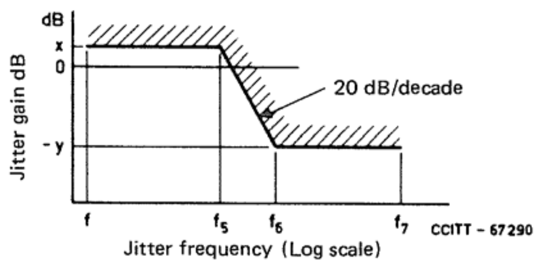

FIGURE 4/G.823

Typical jitter transfer characteristics

3.2 *Digital sections*

To ensure that the maximum network limit (§ 2) is not exceeded within a digital network, it is necessary to control the jitter contributed by transmission systems.

The jitter limits for digital sections are found in Recommendation G.921.

3.3 *Digital muldexes*

The jitter limits for digital multiplexers and demultiplexers are found in the appropriate equipment Recommendations.

4 Guidelines concerning the measurement of jitter

There are two clearly identifiable categories under which jitter measurement may be classified:

– measurements using an undefined traffic signal which may generally be considered as quasi-random (generally applicable under operational circumstances);

– measurements using specific test sequencies (generally applicable during laboratory, factory and commissioning circumstances).

4.1 *Measurements using an undefined traffic signal*

Because of the quasi-random nature of jitter and its possible dependency on traffic loading, accurate peak-to-peak measurements in operational networks need to be made over long periods of time. In practice it is expected that, with experience of particular systems, it will be possible to identify abnormalities measured over a shorter measurement period which would indicate that the maximum permissible limit might be exceeded over a longer measurement interval.

The network limits recommended in § 2 are so derived that the probability of exceeding such levels is very small. The practical observation of such a magnitude with a high degree of confidence requires an unacceptable measurement interval. To take account of such an effect it may be necessary to introduce a smaller, but related, limit which has a greater probability of occurrence, facilitating its measurement over a reasonably short measurement interval. These aspects are the subject of further study.

4.2 *Measurements using a specific test sequence*

Given that it is advantageous to assess the jitter performance of digital line equipment using a specific pseudo-random binary sequence (PRBS), it is necessary to derive limits appropriate to this unique test condition. Although the use of such deterministic test signals is extremely useful for factory acceptance tests and commissioning tests, the results need to relate to an operational situation in which the information content of the signal is likely to be more random (e.g. a telephony type signal). Based on practical experience, it is usually possible to relate a traffic-based measurement to a PRBS-based measurement by the application of an appropriate correction factor (Annex A).

The use of a PRBS in the measurement of jitter may have shortcomings in that for the measurement to be valid the PRBS must have adequate spectral content within the jitter bandwidth of the system being measured. In circumstances where the spectral content is insufficient, a suitable correction must be applied if a measured value is to be meaningfully compared with specified limits. This aspect is the subject of further study (Annex A).

4.3 *Test signal interaction with signal processing devices integral to transmission systems*

The inclusion of additional signal processing devices integral to a transmission system often influences the observed jitter performance. Studies have shown that the transmitted signal, particularly if it is pseudo-random or highly structured, interacts with digital scramblers and line code converters to produce interesting effects which are observed as changes in the performance of such equipments. All interaction effects result in a modification to the statistics of the transmitted signal causing a consequential change in the pattern-sensitive jitter generated within each repeater. A typical manifestation is that successive measurements on a transmission system incorporating these devices, using an identical test signal on each occasion, yield a widely varying range of peak-to-peak and r.m.s. jitter amplitudes.

Studies have shown that the following factors influence the observed jitter performance:

– the feedback connections on both the PRBS test signal generator and the transmission system's scrambler;

– the number of stages on the PRBS test signal generator and the transmission system's scrambler;

– the presence of a code converter in the transmission system.

Consequently, considerations concerning the choice of test signal for equipment validation purposes should take account of the following points:

a) It is inadvisable to use a PRBS test signal generator with a cycle length that has common factors with the scrambler incorporated in the transmission system.

b) The equal configuration of the PRBS test signal generator and the transmission system's scrambler should be avoided if a random signal is required.

5 Jitter accumulation in digital networks

The variability of network configurations prevents the consideration of every possible case. To analyse a particular network configuration, it is necessary to use the information about the jitter characteristics of individual equipments in conjunction with appropriate jitter accumulation models. Annex B aims to provide sufficient information to enable organizations to carry out such evaluations.

ANNEX A

(to Recommendation G.823)

The use of a pseudo-random binary sequence (PRBS) for jitter measurements on digital line, radio and optical fibre systems

A.1 *The relationship between a random traffic-based measurement and a PRBS-based measurement*

It is often convenient to emulate a random type traffic signal using a pseudo-random binary sequence (PRBS). However, jitter measurements using such a test signal tend to give optimistic values when compared with an identical measurement using a traffic signal in which the information content is more random. This disparity arises because the traffic signal, which is generally non-deterministic in nature, is able to cause the generation of an almost unrestricted range of jitter amplitudes, whereas the quasi-random nature of a PRBS means that it is only able to cause the generation of a finite range of jitter amplitudes. Based on operational experience to date, a correction factor relating the two types of measurement has been determined, but it is extremely difficult to establish an accurate value for every conceivable practical situation. Its actual value is dependent on many interrelated aspects such as the measurement period, system length, the value of the timing recovery circuit *Q*, the sequence length, and the presence of scramblers. To relate a random traffic-based measurement (made over a relatively short interval) to a specific PRBS, it is necessary to use the following correction factors which are believed to represent a good practical choice for most circumstances:

– 1.5 at 2 048 kbit/s and 8 448 kbit/s (based on the use of a $2^{15} - 1$ PRBS generated in accordance with Recommendation O.151);

– 1.3 at 34 368 kbit/s and 139 264 kbit/s (based on the use of a $2^{23} - 1$ PRBS generated in accordance with Recommendation O.151).

Therefore:

$$\begin{bmatrix} \text{Estimated jitter amplitude} \\ \text{when transmitting} \\ \text{random signal (traffic)} \end{bmatrix} = \text{correction factor} \times \begin{bmatrix} \text{Measured jitter} \\ \text{amplitude using} \\ \text{a specific PRBS.} \end{bmatrix}$$

A.2 *Spectral content of the PRBS*

By its very nature, the PRBS is cyclical and is therefore characterized by a power spectrum with spectral lines occurring at regularly spaced intervals. For the achievement of a meaningful result, in which the measurement error is acceptable, it is necessary to ensure that the PRBS used when measuring output jitter, has adequate spectral content within the jitter bandwidth of the system being measured. The bandwidth of the jitter spectrum at the output of a chain of digital regenerators is shown to be a function of the *Q* factor of the timing recovery circuit and the number of generators in tandem [1].

Now:

$$\text{Jitter bandwidth} = \frac{f_1}{Q \times n} \text{ [Hz] for large } n$$

where

f_1 = frequency of the timing signal that is extracted from the incoming signal by the timing recovery circuit

Q = Q factor of one repeater

n = number of cascaded repeaters

and

$$\text{PRBS repetition rate} = \frac{f}{L} \text{ [Hz]}$$

where

f = bit rate

L = sequence length

For adequate spectral content, the pattern repetition frequency should be less than $\frac{1}{y}$ of the jitter bandwidth of the system under test. (The value for *y* requires further study).

Thus

$$\frac{f}{L} \leq \frac{f_1}{y + Q \times n}$$

and

$$L \geq y \times n \times Q \times \frac{f}{f_1}$$

Exemples:

For line code B6ZS $f = f_1$ y $L \geq y \times n \times Q$

For a Non-Redundant Quaternary line code $\frac{f}{f_1} = \frac{2}{1}$ and $L \geq y \times n \times Q \times 2$

If the system uses a scrambler or a code translation technique (e.g. 4B3T), this may be taken into account in order to reduce the length of the test sequence.

ANNEX B

(to Recommendation G.823)

B.1 *Jitter accumulation in digital networks*

B.1.1 *Jitter accumulation relationships for cascaded homogeneous digital equipments*

B.1.1.1 *Digital line, radio and optical fibre systems*

With this type of equipment, the relationship applicable is critically dependent on the content of the transmitted signal, the physical implementation of timing recovery, the inclusion of a scrambler/descrambler combination, etc. A number of relationships are identified.

a) *Cascaded homogeneous regenerators*

Most digital repeaters currently in use are fully regenerative and self-timed; that is, the output signal is retimed under the control of a timing signal derived from the incoming signal. The most significant form of jitter arises from imperfections in the circuitry, which cause jitter that is dependent on the sequence of pulses in the digital signal being transmitted, termed pattern-dependent jitter. The mechanisms that generate jitter within a regenerator, that have been extensively studied, are principally related to imperfections in the timing-recovery circuit. [2], [3], and [4].

Since pattern-dependent jitter from regenerated sections is the dominant type of jitter in a network, the manner in which it accumulates must be considered. For jitter purposes, a regenerative repeater acts as a low-pass filter to the jitter present on the input signal, but it also generates jitter, which can be represented by an additional jitter source at the input. If this added jitter were truly random, as distinct from pattern dependent, then the total r.m.s. jitter, J_N, present on the digital signal after N regenerators would be given by the approximate relationship:

$$J_N \simeq J \times \sqrt[4]{N} \qquad (1)$$

where J is the r.m.s. jitter from a single regenerator due to uncorrelated jitter sources. This equation assumes that the jitter added at each regenerator is uncorrelated.

However, most of the jitter added is pattern dependent and, since the pattern is the same at each regenerator, it can be assumed that the same jitter is added at each regenerator in a chain of similar regenerators. In this case, it can be shown that the low-frequency components of the jitter add linearly, whereas the higher-frequency components are increasingly attenuated by the low-pass filtering effect of successive regenerators. If a random signal is being transmitted, the r.m.s. jitter J_N, present on the signal after N regenerators would be given by the approximate relationship.

$$J_N \simeq J_1 \times \sqrt{2N} \quad \text{for large values of } N \qquad (2)$$

where J_1 is the r.m.s. jitter from a single regenerator due to pattern-dependent mechanisms [1].

Note 1 – Based on operational experience to date, values for J_1 in the range 0.4 to 1.5% of a unit interval are achievable using cost-effective designs.

Note 2 – The implementation of timing recovery using a phase-locked loop causes the rate of accumulation to be marginally greater, as given by the approximate relationship:

$$J_N = J_1 \times \sqrt{2NA} \qquad (3)$$

where A is a factor dependent upon both the number of regenerators and the phase-locked loops damping factor. The latter parameter is generally chosen, in this application, such that A has an amplitude marginally greater than unity.

Note 3 – The implementation of timing recovery using a transversal surface acoustic filter produces a rate of accumulation approaching that obtained for uncorrelated jitter sources. This favourable jitter accumulation arises because of the large inherent delay which reduces the correlation between the recovered timing signal and the data stream. Systematic pattern-dependent jitter is therefore effectively randomized and tends to accumulate in a manner similar to that obtained from uncorrelated jitter sources. The only noticeable side-effect is a marginal degradation in the alignment jitter. This favourable jitter accumulation is not exhibited by surface acoustic wave resonators due to their different mode of operation [9].

Note 4 – Repeaters incorporating circuitry involving pattern transformations effectively represent uncorrelated jitter sources causing a non-systematic jitter accumulation. For example, a pattern transformation based on the modulo 2 addition of a signal and its delayed version (Huffman sequence) causes the r.m.s. jitter to accumulate approximately with the fourth root of the number of repeaters [8].

Equations (1) and (2) demonstrate two important results:

a) pattern-dependent jitter accumulates more rapidly than non-pattern-dependent jitter, as the number of regenerators is increased, and

b) the amplitude of jitter produced by a chain of regenerators increases without limit, as the number of regenerators is increased.

The jitter produced by a random pattern is itself random in nature, the amplitude probability distribution function of which is considered to be close to gaussian. Hence, for a given r.m.s. amplitude (standard deviation), the probability of exceeding any chosen peak-to-peak amplitude can be calculated. A peak-to-peak to r.m.s. ratio of between 12 and 15 is often assumed for specification purposes, which has a very low probability of being exceeded.

In contrast, when the signal being transmitted is composed of two repetitive patterns, alternating at low frequency, the jitter appears as a low-frequency repetitive wave, having an amplitude proportional to the number of regenerators. This could lead to very large amplitudes of jitter. In such instances, the maximum peak-to-peak jitter amplitude (J_{NP}) is described by the following relationship:

$$J_{NP} = d \times N \qquad (4)$$

where d is the Pattern Sensitive Jitter (PSJ) produced by a single regenerator when subjected to alternating repetitive patterns. This relationship assumes that the repetition rate is sufficiently low so that steady states are attained. The actual value is dependent on the pattern used.

This situation is very unlikely in normal operation because the signal transmitted is generally made up of traffic from a number of different sources, although not necessarily so at the primary line rate, together with a frame alignment signal and justification control digits, etc. Furthermore, the probability of fixed patterns occurring can be reduced still further by the use of digital scramblers, which tend to randomize the signal.

b) *Cascaded homogeneous digital line, radio and optical fibre systems incorporating scramblers and jitter reducers*

The inclusion of a scrambler/descrambler combination in a digital line, radio or optical fibre system needs to be considered when such homogeneous systems are connected in cascade. In such situations, the jitter contributed to each system is uncorrelated and is therefore found to accumulate in accordance with the fourth root of the number of cascaded systems. Therefore, the r.m.s. jitter, J_M, present on the digital signal after M digital line, radio or optical fibres systems is given by the approximate relationship:

$$J_M \cong J_S \times \sqrt[4]{KM} \qquad (5)$$

where J_S is the r.m.s. jitter from a single system and K is a constant with a value between 1 and 2. For large values of M, $K = 2$.

Where jitter reducers are provided in addition to scramblers, the same accumulation relationship may apply, except that the value for J_s is then significantly reduced. In such circumstances, the r.m.s. jitter, J_s, is given by the following approximate relationship:

$$J_S \cong 2\,N\,J\sqrt{\frac{f_c}{B}} \text{ for large } N \qquad (6)$$

where J is the r.m.s. jitter from a single repeater, N is the number of cascaded repeaters, f_c is the cut-off frequency of the jitter reducer and B is the half bandwidth of a single repeater $\left(B = \frac{W_0}{2Q}\right)$.

Note – The validity of the relationships given in this section requires further study. Particularly in the case where jitter reducers are incorporated, as the degree of randomization, produced by the length of scrambler commonly considered acceptable, may not be sufficient to ensure that the jitter contributions, within the bandwidth of the jitter transfer functions expected, are uncorrelated to the extent that fourth root accumulation is dominant.

B.1.1.2 *Muldex equipments*

With this type of equipment, the only type of jitter that is likely to accumulate to any significant extent is the variable low frequency waiting time jitter which may have components at frequencies within the passband of the demultiplexers phase-locked loop. The expectations are that the accumulation of waiting time jitter will be at a rate between $\sqrt[4]{N}$ and $\sqrt[2]{N}$, where N is the number of cascaded multiplexer/demultiplexer pairs [5], [6], and [7].

Further study is required to determine a more exact relationship.

B.2 *Guidelines concerning the practical application of jitter accumulation relationships in a digital network*

(These aspects require further study.)

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