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GROUP DELAY REQUIREMENTS FOR TELETEXT TRANSMISSION

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ABSTRACT

The effect of group delay distortion on the eye pattern of a 5.72 Mbits/sec NABTS teletext signal transmitted over cable TV systems is studied. A mathematical relationship is derived between the group delay response of a data transmission system and the distortion in the form of intersymbol interference created by the group delay variation. From this relationship, a "theoretical worst case" group delay curve, which maximizes the intersymbol interference, is defined for a teletext signal. This theoretical curve is used to establish limits on peak-to-peak group delay variations in order to ensure a given value of eye height. These limits are relaxed taking into account a) the characteristics of practical group delay curves met on cable TV systems and b) the sensitivity of different portions of the teletext data spectrum to delay variations. Various tolerance masks for monitoring the group delay response of a cable TV channel used for teletext transmission are proposed and discussed. The approach and concepts described in this paper, although developed for teletext transmission over cable TV networks, can be extended to any data transmission system.

1. INTRODUCTION

In this paper, we will analyse and discuss the effect of group delay inequalities on the quality of teletext data reception. Although the approach and concepts developed in this study have been applied to the particular context of teletext transmission in a cable TV environment, they can be generalized and applied to other data transmission systems.

An essential objective of a data transmission system is the preservation of the binary signal shape at the receiver. In a cable TV network, many factors can alter to some extent the teletext signal shape: echoes (from the broadcast antenna feed or impedance mismatch on the cable distribution system), noise (random or impulse) and inequalities in the amplitude and group delay responses of various pieces of equipment (headend processors, AML transmitters, subscriber's equipment, etc...) throughout the network.

Group delay or envelope delay is the measure of the relative phase shift experienced by neighboring components of the frequency spectrum of the data signal and is equal to the slope of the tangent to the phase response curve at any given frequency. If the phase shift is linear, the corresponding group delay is constant across the data channel bandwidth. However, if the phase shift is non-linear, then the group delay varies with frequency and the shape of the data signal is altered. This variation of group delay with frequency will be called "delay inequalities".

When the delay inequalities of a transmission system exceeds a certain level in the energy band of a data signal, the performance of the system becomes unsatisfactory. For smaller values of inequalities, satisfactory performance may be possible but the signal is received with a reduced safety margin against errors due to noise.

The group delay requirements for the transmission of an NTSC TV signal over broadcast or cable TV networks are well defined. In Canada, standards specifications for television broadcasting transmitters are contained in ref. 1 and 2 and require that the group delay be within the limits shown in figures 1.a and 1.b. A variation of ±80 nsec is tolerated between 0 and 2 MHz above picture carrier for high power transmitters (figure 1.a) and ±100 nsec for low power transmitters (figure 1.b). From 3 to 4.18 MHz above picture carrier, the video signal undergoes a group delay pre-emphasis which is compensated in demodulators or TV receivers.

For cable TV systems, the only requirement related to group delay is summarized by the chrominance-to-luminance delay inequality or chroma delay (ref. 3 and 4) which is the difference in group delay between the luminance (0 - .6 MHz) and the chrominance (3 - 4.2 MHZ) portions of the picture signal. Broadcast Procedure BP-23 (ref. 5) stipulates that any chroma delay introduced by the broadband system (portion of the cable TV system in which many signals are treated as a group) and measured at any subscriber terminal shall be within ±150 nsec.

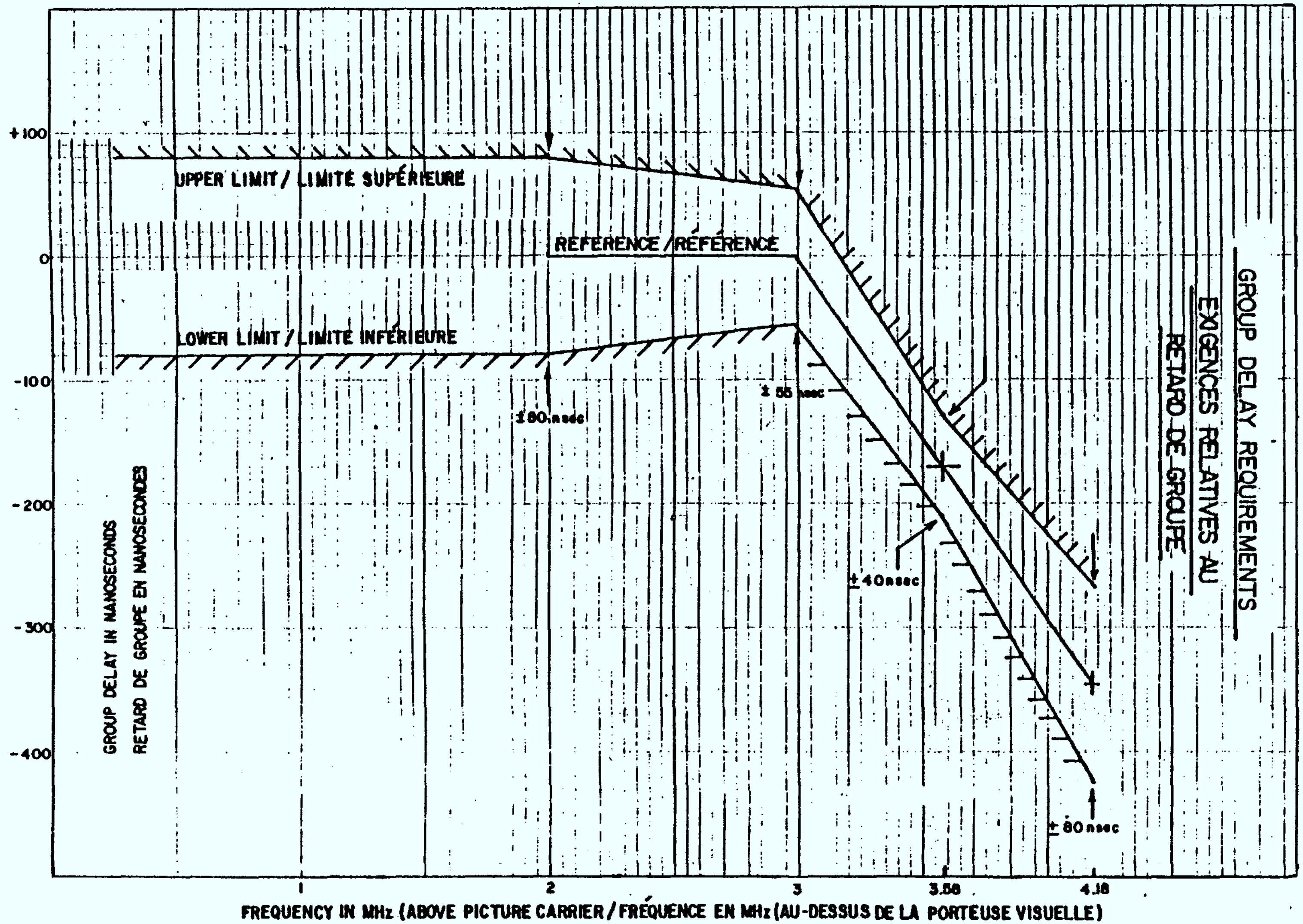


Figure 1.a Group delay requirements for high power television broadcasting transmitters (ref. 1)

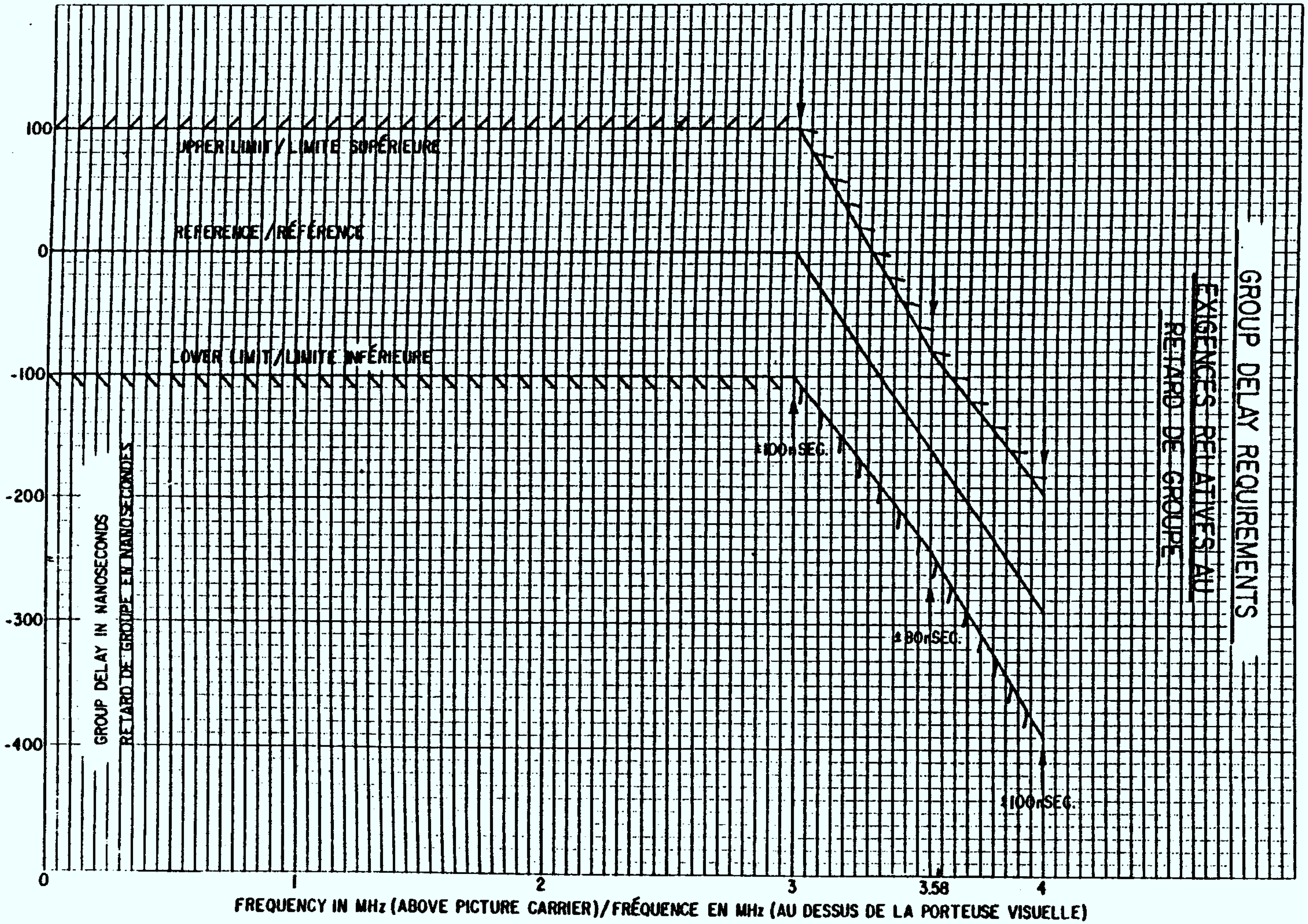


Figure 1.b Group delay requirements for low power television broadcasting transmitters (ref. 2)

For broadcast and cable TV networks, the problem of group delay inequality has not been a major concern up until recently. These networks have been originally planned and designed to convey analog picture signals which are, as shall be seen later, quite less sensitive to delay inequalities than digital signals. However, the need has now arisen to make use of these networks for transmission of digital data at high speeds. Nyquist's I, II and III criteria tell us that it is theoretically possible to transmit at a signaling rate of 8.4 Mbits/sec in a 4.2 MHz video channel. Data transmission on existing TV networks at speeds of 2 Mbits/sec or less will not generally cause major problems. However, as the signaling rates approach or exceed the video channel bandwidth, the resulting "high speed" data signal will require more stringent limits on group delay specifications.

The effect of delay inequalities on the eye pattern of a 5.72 Mbits/sec teletext signal has been studied in ref. 6, 7 and 8. The authors have addressed the problem for a broadcast teletext signal using a group delay curve model as shown in figure 2 which was obtained by measuring the group delay characteristics of typical consumer TV receivers. In ref. 6 and 7, the authors concluded that delay inequalities at high frequencies (>3 MHz) do not have a significant impact on the eye pattern and that the eye height is more sensitive to delay variations at low frequencies (0-2 MHz). In ref. 6, the author found that the low frequency delay inequalities should be limited to ±50 nsec (DL = 100 nsec in figure 2) in order to ensure good teletext reception (50% eye height). In ref. 8, the authors have used a curve shape similar to figure 2 to propose that group delay deviations should be constrained within ±50 nsec throughout the video bandwidth. Those studies have not investigated the possible effect of the transmitters whose tolerance on delay inequalities (figure 1) exceeds the above suggested limitations.

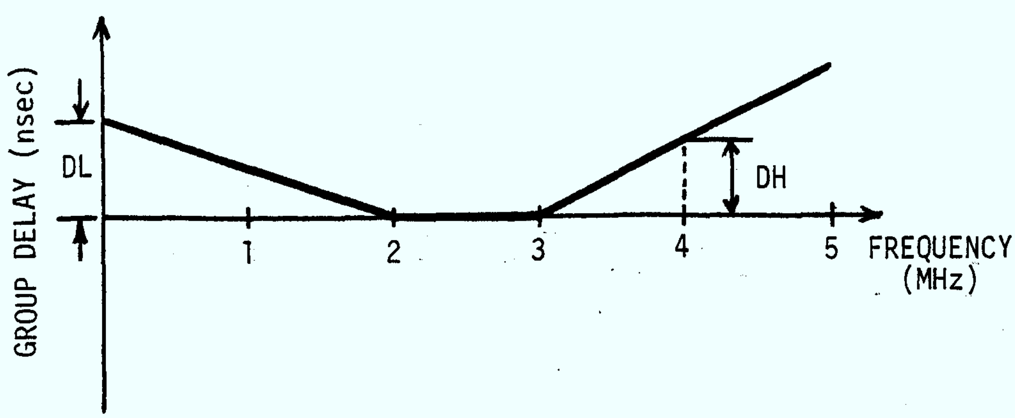


Figure 2 Group delay model for broadcast teletext (ref. 6, 7 and 8)

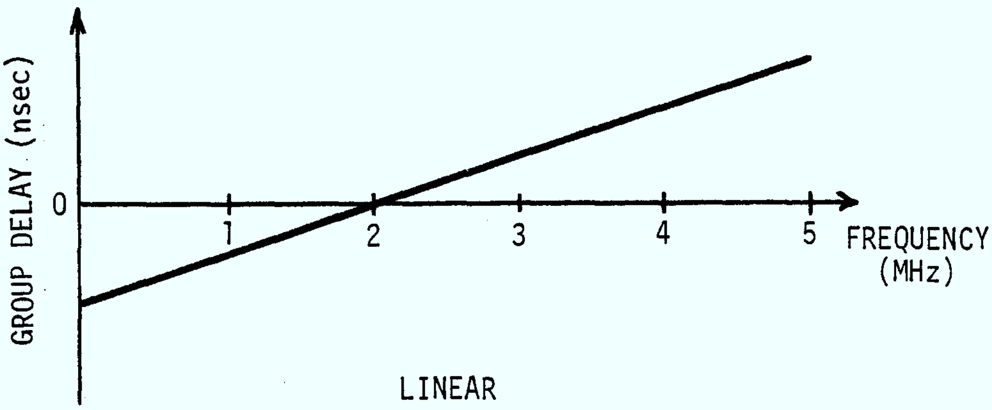
Vincent, in ref. 9, has analysed the influence of two particular shapes of delay inequalities: linear group delay and ramp group delay (figure 3). His results indicated that a teletext signal is most sensitive to transitions of the group delay curve occurring in the 1-2 MHz frequency range. No limitations on delay inequalities were proposed.

In practice however, many different group delay characteristics are encountered on cable TV networks due to the great variety of configurations and pieces of equipment used. It is therefore impossible to derive a group delay response model that would approximate most of the curves met on actual systems. A different approach must be used to answer the following questions:

- **Providing a specific level of performance is required (i.e. 50% eye height), what tolerances must be set on group delay variation such that this minimum performance level will be guaranteed?**

- **What shapes of group delay are particularly bad for a teletext signal?**

In the remainder of this paper, an approximate but systematic method to answer these questions is described. A "worst case" group delay curve is mathematically defined and used to establish limits on peak-to-peak group delay fluctuations in order to guarantee a given value of eye height. Section 2 is devoted to a description of the Canadian BS-14 Teletext Standard and of the North American Broadcast Teletext Standard. A mathematical model of a typical teletext data transmission channel is presented in section 3. The parameters used to assess the quality of a data waveform are described in section 4. A "theoretical worst case" group delay curve is derived in section 5. Limits on group delay are calculated in section 6 using the theoretical worst case curve and are further relaxed taking respectively into account a) the characteristics of practical group delay curves met on cable TV systems and b) the sensitivity of different portions of the teletext data spectrum to group delay transitions. Various tolerance masks are also proposed to monitor the calculated limits. Conclusions are drawn in section 7.



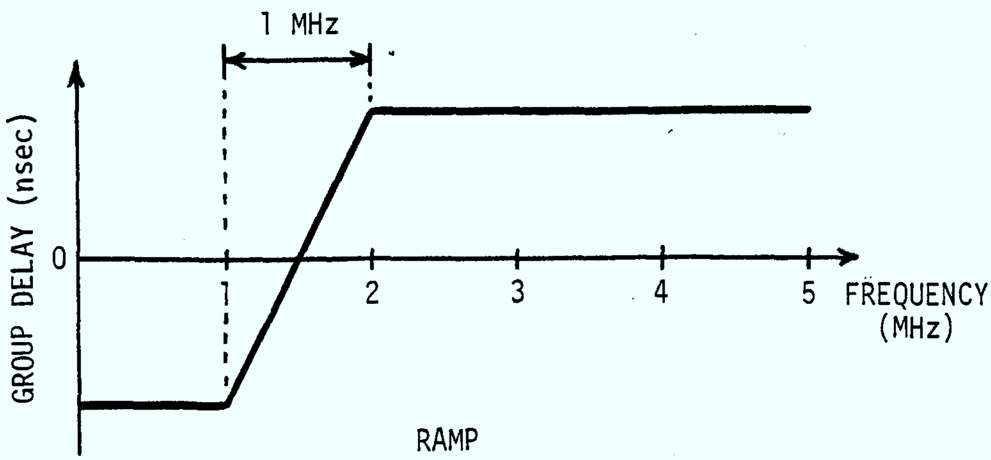


Figure 3 Linear and ramp group delay characteristics (ref. 9)

2. BS-14 AND NABTS TELETEXT

In Canada, the technical requirements for the transmission of digitally encoded data containing alphanumeric and pictorial information are set forth in Broadcast Specification BS-14 (ref. 10) issued in 1981 by the Department of Communications. These requirements are very similar to those stated in the North American Basic Teletext Specification (NABTS) (ref. 11), a joint EIA and CVCC recommended practice for teletext, adopted in 1984.

The teletext signal is usually inserted in one or more lines of the VBI of a 525 line-60 fields-per-second NTSC television signal. Although VBI insertion is most frequently used, full-field data transmission, using all the 525 lines available, is also possible.

Each data line consists of a string of 288 bits (figure 4). The first 24 bits (3 bytes) constitute the Synchronization Sequence which is used to recover the data clock and to slice the information byte-per-byte. The next 5 bytes form the Prefix which contains overhead information related to the address, continuity and structure of the Data Packet. The last 28 bytes are dedicated to the Data Block which contains the useful information and an optional Suffix which is used for error correction/detection.

The transmission rate is 5.727272 Mbits/sec which, in a color television system, is 8/5 of the color sub-carrier frequency (3.579545 MHz) or the 364 multiple of the horizontal TV line rate (15,734.26 Hz). The data is amplitude modulated using Non-Return-to-Zero (NRZ) binary code. Prior to being transmitted, the data pulses are shaped so that their spectrum approximates a raised cosine with a recommended roll-off of 100%. After shaping, the spectrum of the NRZ data must further be bandlimited by a phase-corrected low-pass filter in order to fit in the 4.2 MHz video bandwidth. The spectrum of the NRZ data after shaping and low-pass filtering is typically like the one described in figure 5.

The nominal data levels should be 70±2 IRE units for a logical "1" and 0±2 IRE units (blanking level) for a logical "0". These nominal levels are shown in figure 6. Although nominal data levels are specified, the actual data waveform may contain overshoots that exceed the nominal levels by an amount that depends on the shaping and low-pass filters. Finally, the data on the TV line should start at 10.48±0.34 usec from the leading edge of the horizontal sync pulse as shown in figure 6.

DATA LINE STRUCTURE

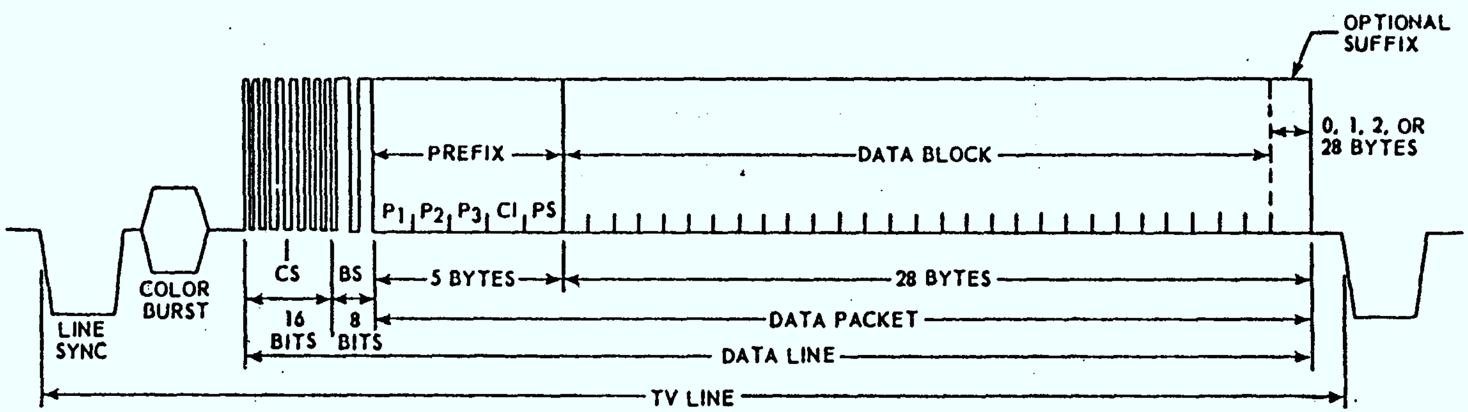


Figure 4 Teletext data line structure (ref. 11)

LOW PASS FILTERED/
100% RAISED COSINE SPECTRUM

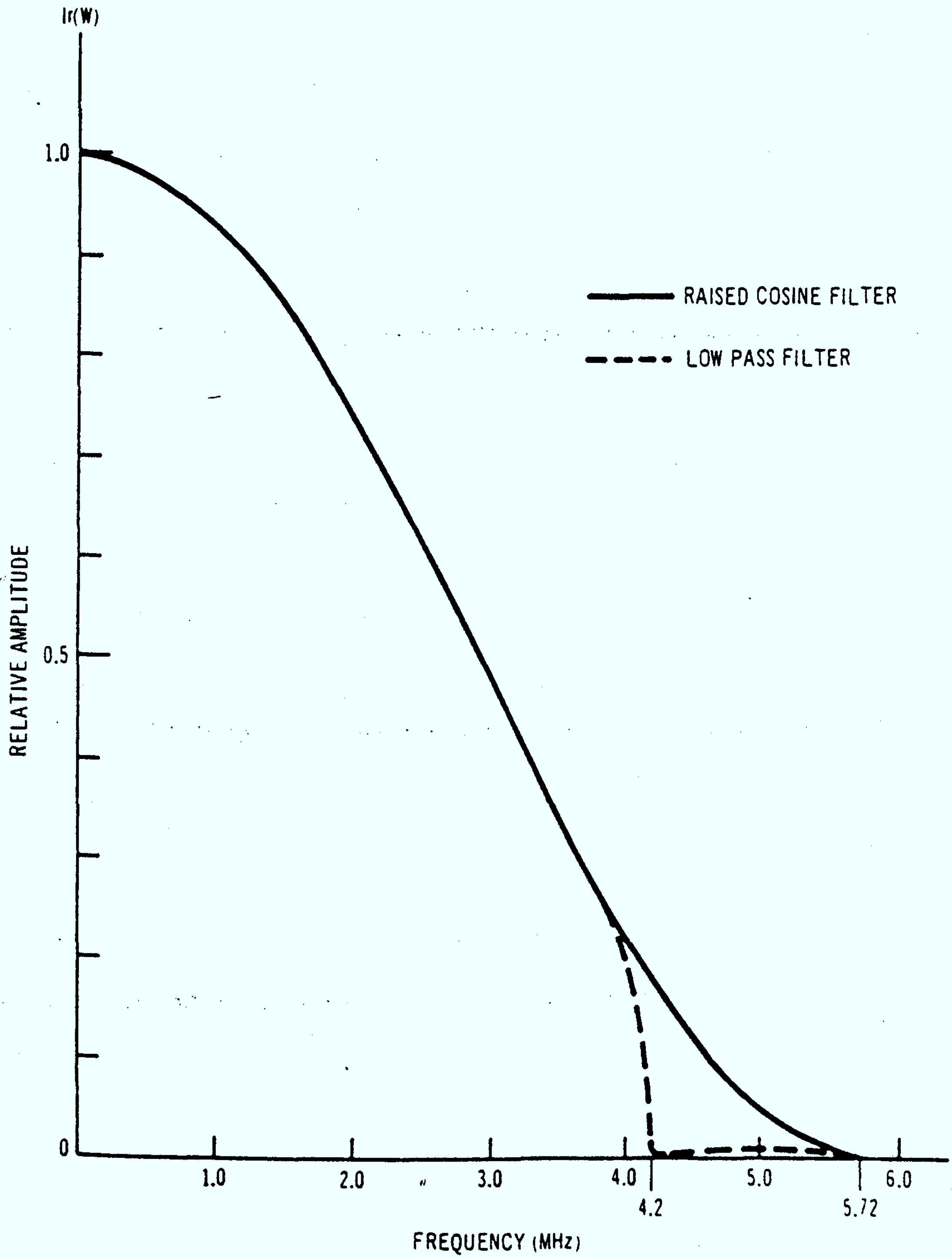


Figure 5 Low-pass filtered/Raised cosine spectrum with 100% roll-off (ref. 11)

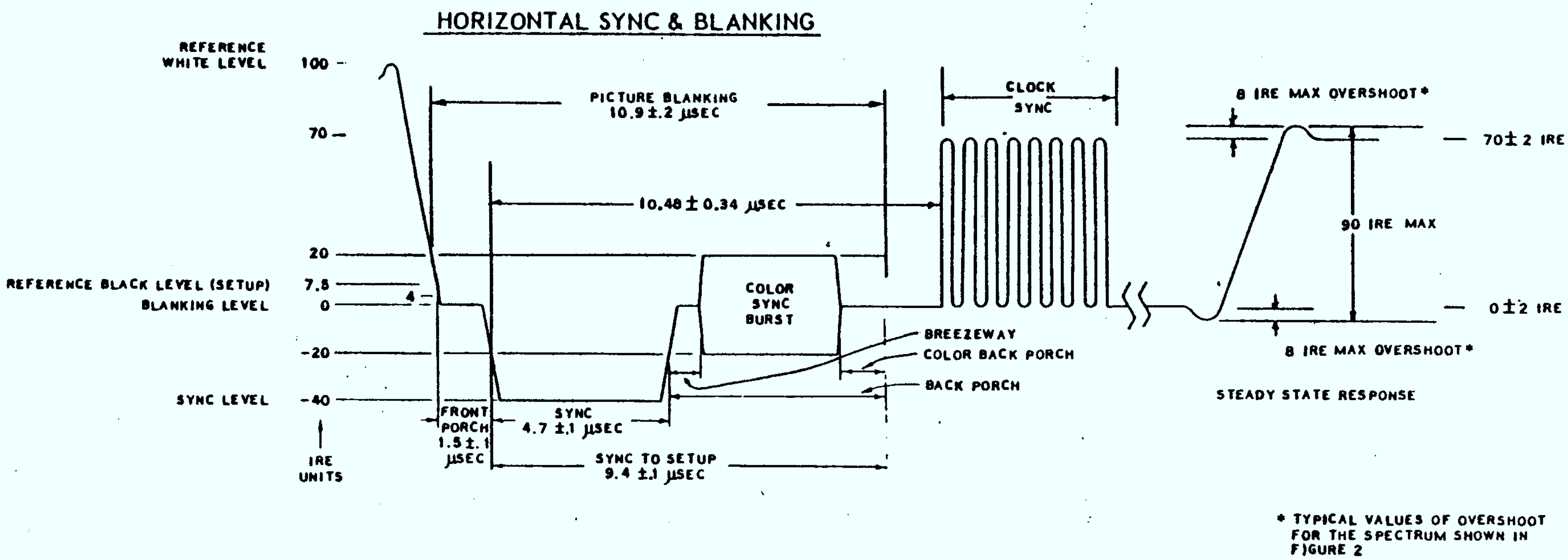


Figure 6 Teletext data levels and timing (ref. 11)

3. TRANSMISSION CHANNEL MODEL

The block diagram of a typical broadcast/cable TV network is described in figure 7. The baseband teletext data is typically inserted in the VBI of a TV program and then transmitted off-air. This broadcast signal is picked up by an antenna at the cable TV headend where it is frequency translated before being delivered to the subscribers via the broadband distribution system. Specialized equipment at the subscriber's location is responsible to recover the multiplexed data signal and submit it to the decoder for interpretation.

We are not concerned in this paper, about the contribution of the individual components of this network to delay inequalities but rather to the overall behavior of the network from the output of the generator (A) to the input of the decoder (B) (baseband-to-baseband). For this purpose, the TV network of figure 7 can be simplified to the equivalent baseband model described in figure 8.

The mathematical model of this baseband system is illustrated in figure 9. In order to simplify the analysis, we will assume that the Data Source generates the binary information at a rate 1/T in the form of a train of unit impulses $\delta(t)$. Those impulses are modulated by the individual bit value $a_n = \pm 1$ such that

$$x(t) = \sum_{n=-\infty}^{\infty} a_n \delta(t-nT) \qquad (1)$$

The transmitted baseband signal s(t) is obtained by shaping the train of impulses x(t) through $G_1(w)$ and low-pass filtering the result through $G_2(w)$. $G_1(w)$ and $G_2(w)$ are zero-phase filters and $G_1(w)$ is such that the signal s'(t) at its output has a raised cosine spectrum.

The transfer function of the channel is $G_3(w)e^{-jB(w)}$ so that the overall transfer function is $H(w)e^{-jB(w)}$ where

$$\begin{aligned} B(w) &= \text{phase response of the channel} \\ \text{and} \quad H(w) &= G_1(w)\, G_2(w)\, G_3(w) \end{aligned} \qquad (2)$$

Consequently, the overall system impulse response is

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H(w) e^{-jB(w)} e^{jwt} dw \qquad (3)$$

which can be reduced to

$$h(t) = \frac{1}{\pi} \int_{0}^{\infty} H(w) \cos(wt - B(w)) dw \qquad (4)$$

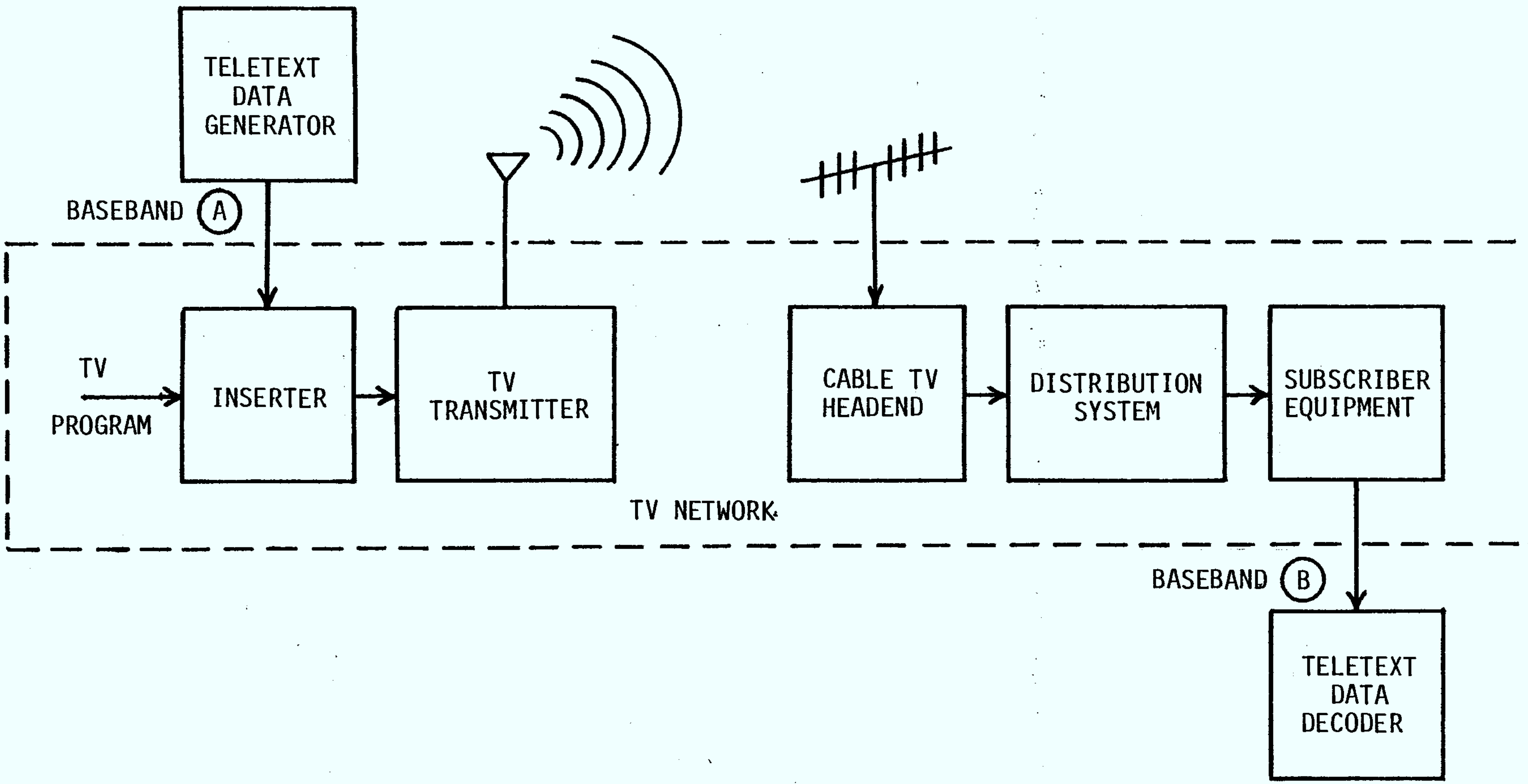


Figure 7 Block diagram of a typical broadcast/cable TV network

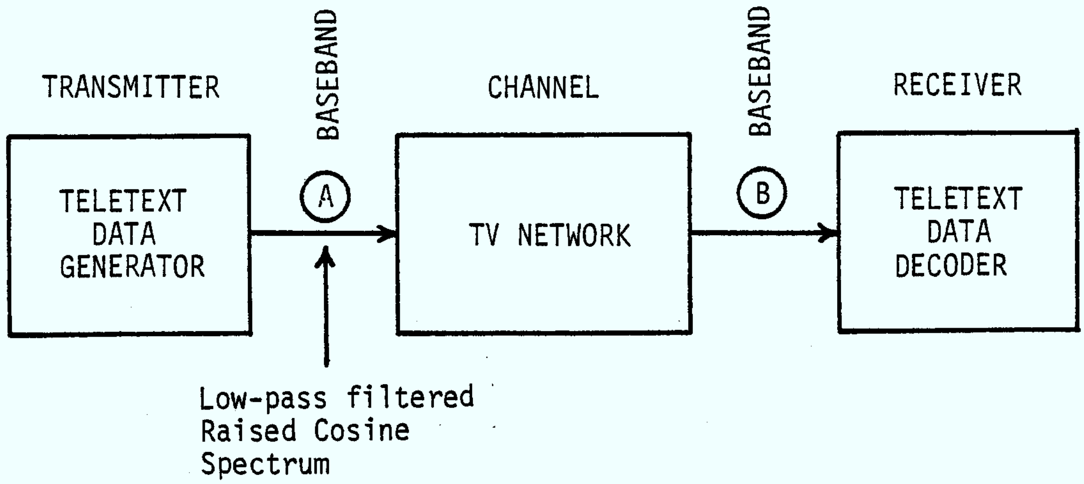


Figure 8 Baseband equivalent model of a teletext data transmission system

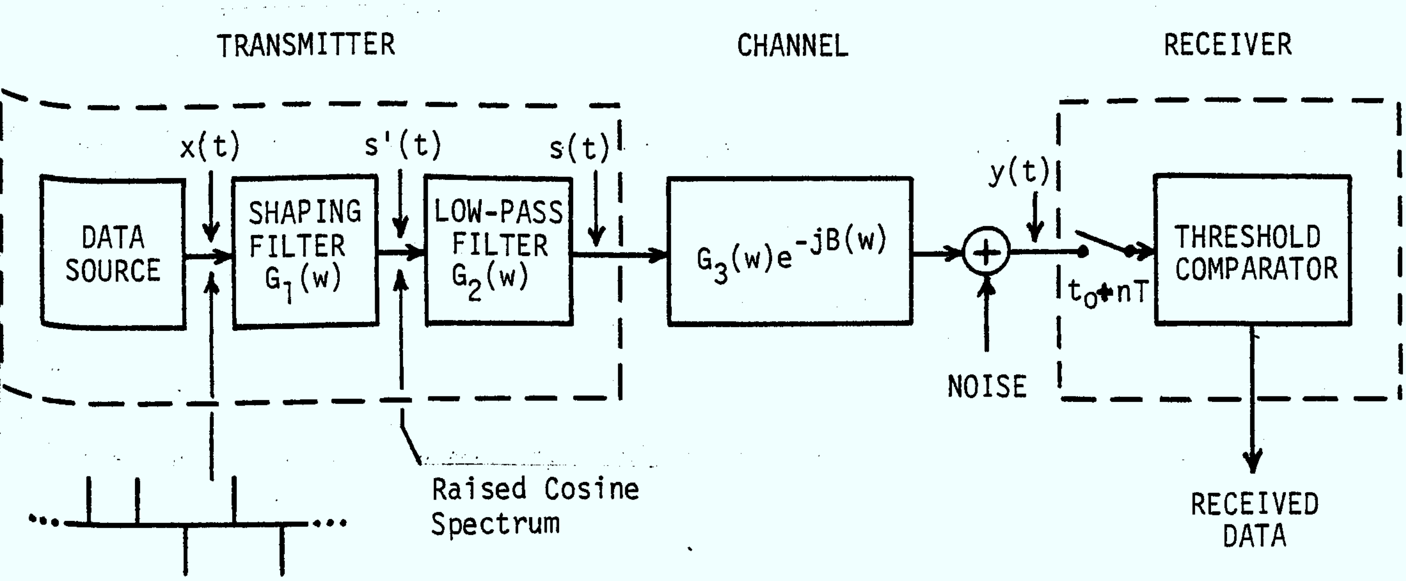


Figure 9 Mathematical model of the baseband system

We will assume a noiseless channel for which the received signal y(t) is

$$y(t) = \int_0^{\infty} h(\tau) \sum_{n=-\infty}^{\infty} a_n \delta(t-nT-\tau)d\tau \qquad (5)$$

which can be rewritten as

$$y(t) = \sum_{n=-\infty}^{\infty} a_n h(t-nT) \qquad (6)$$

This received signal is usually sampled at regular intervals T seconds apart, starting at t_o. At time t_o, the amplitude a_o is expected but the receiver actually gets

$$y(t_o) = \sum_{n=-\infty}^{\infty} a_n h(t_o-nT) = \sum_{n=-\infty}^{\infty} a_{-n} h(t_o+nT) \qquad (7)$$

The error is due to intersymbol interference (ISI) and is equal to

$$E = a_o - y(t_o) = a_o[1 - h(t_o)] - \sum_n{}' a_{-n} h(t_o+nT) \qquad (8)$$

where

$$\sum_n{}' = \sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty} \qquad (9)$$

Since we have assumed that $a_n = \pm 1$ the maximum error is written as

$$E_{max} = a_o(1-h(t_o)) - \sum_n{}' |h(t_o+nT)| \qquad (10)$$

The second term of this expression represents the worst possible effect of ISI distortion and will subsequently be referred to as

$$D = \sum_n{}' |h(t_o+nT)| \qquad (11)$$

4. DATA SIGNAL QUALITY ASSESSMENT

The assessment of a data waveform at any given point of a transmission system is often performed using an eye pattern. It is obtained by superimposing data bits on the screen of an oscilloscope with a time base of a multiple of the data rate (1/T). An example of an eye pattern is shown in figure 10 along with its three main parameters: eye height, eye width and overshoot level.

The overshoot level measures the portion of the signal exceeding the all-ones and the all-zeros levels. Due to the particular nature of the teletext signal format, which is imbedded in a NTSC video signal, the overshoot level must be kept to a minimum in order to prevent certain problems, audio buzz and horizontal sync misinterpretation in particular.

The eye width is a less common measurement. It represents the maximum horizontal dimension of the pupil of the eye. This measurement is more difficult to relate to expected performance.

The eye height is by far the most common parameter used for measuring the analog quality of a data signal: it is the one we shall be concerned with in this study. The eye height allows an evaluation of the level of ISI of the data signal as well as its noise margin. The eye height is defined as the ratio of the pupil aperture to the basic data amplitude (difference between the all-ones and the all-zeros levels).

The aperture of the pupil should be measured at the sampling instant of the data decoder (eye height at sampling: H_s). In practice however, it is measured at the highest pupil opening (maximum eye height: H_m) thus making the assumption that the sampling time is ideal. When a transmission channel introduces significant delay inequalities, this assumption does not hold as the two definitions of eye height yields significantly different values. Figure 10 depicts such a case.

An eye pattern allows a fairly accurate evaluation of H_m but not of H_s because the sampling time chosen by the decoder is usually difficult to assess on an eye pattern. Both the H_s and H_m definitions are difficult to handle mathematically. In order to alleviate this problem while still giving maximum information about the analog quality of the data signal, a third definition of eye height will be proposed and used throughout the remainder of this study. It is the measure of the eye height at a time t_o corresponding to the peak value of the impulse response of the transmission channel and is given by

$$H(t_o) = \frac{h(t_o) - \sum_{\substack{n=-N \\ n\neq 0}}^{N} \left| h(t_o+nT) \right|}{\sum_{n=-N}^{N} h(t_o+nt)} \qquad (12)$$

In practical systems, h(t) is the response of the channel to a single isolated "logical-one" NRZ pulse. The denominator of eq. 12 represents the basic amplitude of the data signal while the sum in the numerator constitutes an estimate (because only 2N terms are used) of the maximum possible ISI distortion. Figure 11 illustrates a typical impulse response onto which the ISI components are identified.

An estimate of the eye height defined by eq. 12, using few ISI components on either side of $h(t_o)$, can easily be measured in the field. A waveform monitor (commonly used in video testing) with a special graticule and a special test signal inserted on one line of the VBI are the only requirements (ref. 12).

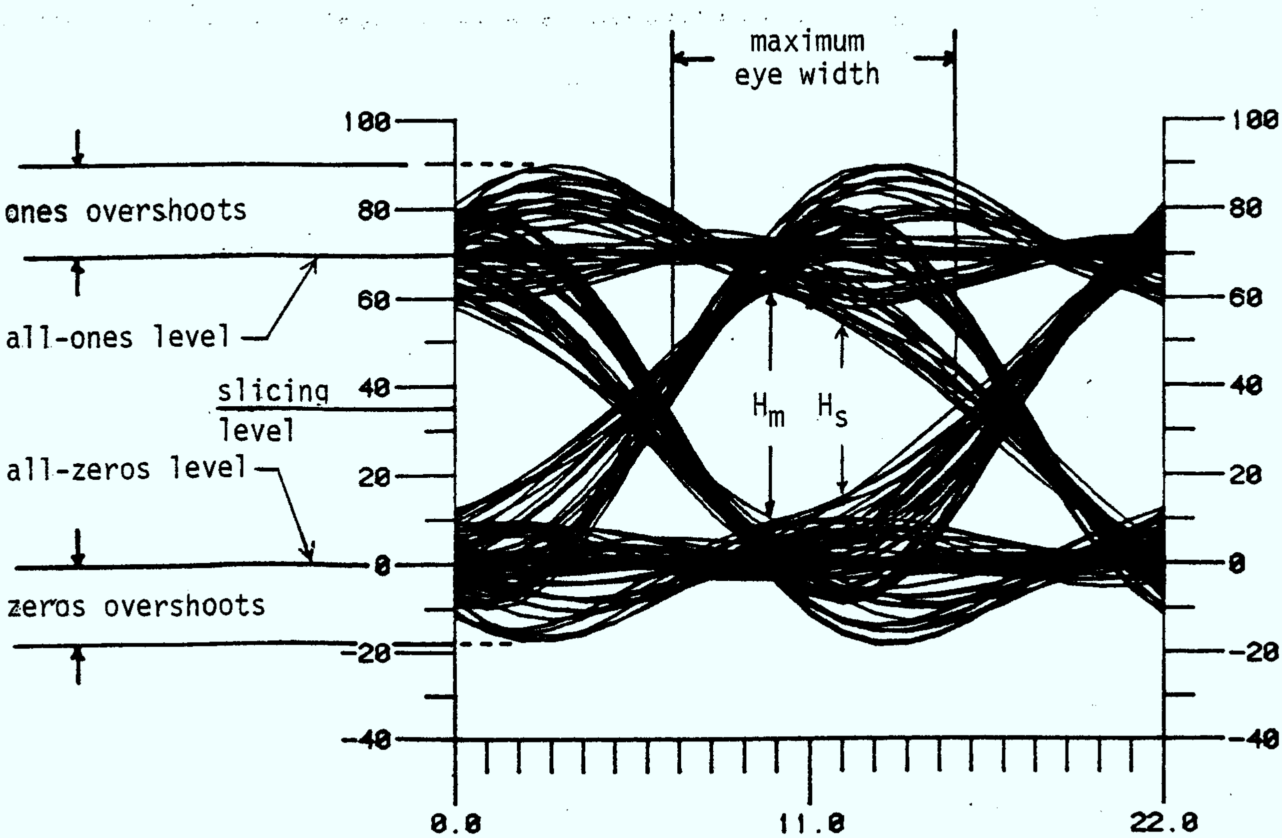


Figure 10 Eye pattern

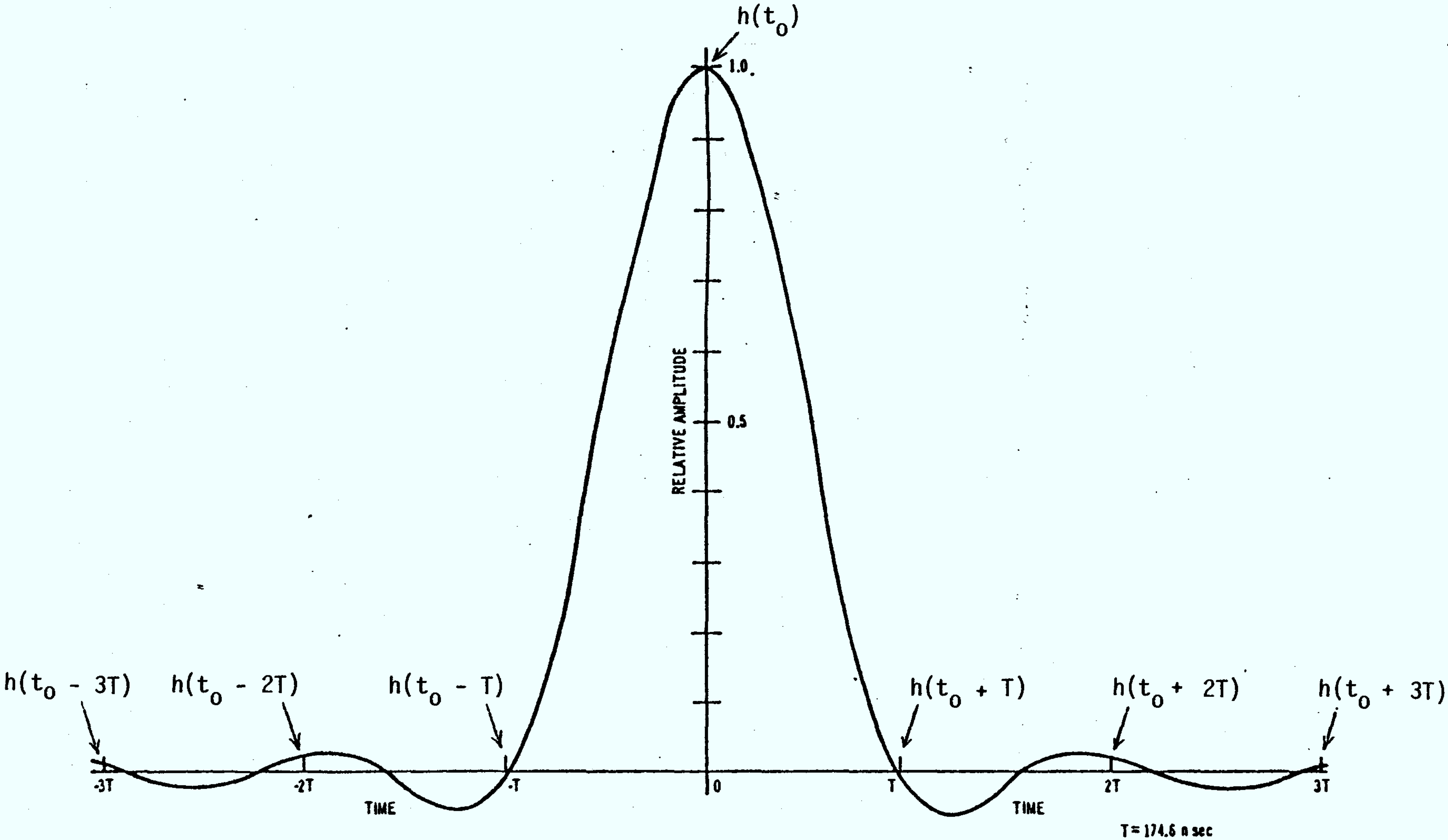


Figure 11 Typical impulse response (single isolated "one-bit" response in practical systems) with ISI components

5. WORST CASE GROUP DELAY SHAPE

5.1 RAISED COSINE SPECTRUM

In this section, a "worst case" group delay shape which minimizes the eye height of a <u>non-bandlimited</u> ($G_2(w) = G_3(w) = 1$ in Figure 9) raised cosine data signal will be defined mathematically. First, a functional dependence of the ISI distortion D (eq. 11) upon the group delay response B'(w) of a transmission channel will be established. Such a functional relationship has been derived by Lucky in ref. 13. His fundamental results relate the distortion D to the group delay through a sequence of scalar products:

$$D = \frac{2}{\pi} \sum_{n=1}^{\infty} |(B',f_n)| \tag{13}$$

where each scalar product (B',f_n) is defined by

$$(B',f_n) = \int_0^W B'(w)f_n(w)dw \tag{14}$$

and W is the maximum frequency component of the system. An approximation of small delay was made to obtain those results which are valid as long as the peak-to-peak group delay variations do not exceed 1.1 bit interval (i.e. 1.1T or 191 nsec for a 5.72 Mbits/sec teletext signal). <u>We shall constraint our study within this limit.</u>

Each scalar product (B',f_n) yields the ISI contribution from a particular set of bit symbols. For example, the ISI produced by the two adjacent bit symbols is:

$$|h(t_o-T)| + |h(t_o+T)| = \frac{2}{\pi}|(B',f_1)| \tag{15}$$

where t_o is the time at the peak value of the impulse response h(t). For many real group delay curves, only the first few terms of eq. 13 are usually significant.

The scalar products (B',f_n) are defined by a sequence of functions f_n, independent of the group delay, obtained from the <u>overall amplitude shaping of the system</u>, H(w), by the following equations:

$$f_n(w) = \int_w^W (a_n x - \sin(nxt))H(x)dx \tag{16}$$

$$a_n = \frac{\int_0^W w\, H(w) \sin(nwt)\, dw}{\int_0^W w^2\, H(w)\, dw} \qquad (17)$$

In order that eq. 16 and 17 be valid, the overall amplitude shaping H(w) of the system must not produce any ISI (i.e. $h(nT) = 0,\ n \neq 0$). In other words, transmission must be perfect in the absence of delay inequalities. This can be stated mathematically by

$$\int_0^W H(w) \cos(nwt)\, dw = 0 \qquad \text{for } n \neq 0 \qquad (18)$$

We will examine the functions $f_n(w)$ for a raised cosine spectrum. We will therefore assume, in this section, that the only amplitude shaping in the system is performed by the shaping filter $G_1(w)$ in figure 9, that is:

$$G_2(w) = G_3(w) = 1 \qquad (19)$$

therefore

$$H(w) = G_1(w) \qquad (20)$$

For a raised cosine shaping with a roll-off factor α, we have:

$$G_1(w) = \begin{cases} 1 & \text{for } w \leqslant (1-\alpha)\frac{w_b}{2} \\ \frac{1}{2}\left[1 - \sin\frac{\pi}{\alpha w_b}\left(w - \frac{w_b}{2}\right)\right] & \text{for } \left|w - \frac{w_b}{2}\right| \leqslant \alpha\frac{w_b}{2} \\ 0 & \text{for } w > (1+\alpha)\frac{w_b}{2} \end{cases} \qquad (21)$$

where $w_b = 2\pi/T$ is the data rate $(1/T)$ expressed in radians/sec.

The first three functions $f_1(w)$, $f_2(w)$ and $f_3(w)$ were computed by substituting eq. 20 and 21 in eq. 16 and 17. The results are shown in figure 12 for the case 100% roll-off ($\alpha = 1.0$). The effect of delay inequalities on the raised cosine system can be visualized by examination of these functions. The curves have the shape of a cosine exponentially attenuated: as the order n increases, the number of cycles of cosine increases and the exponential attenuation lessens. The functions $f_1(w)$, representing adjacent symbol interference, has the greatest energy with higher order function containing less and less energy. A group delay curve $B'(w)$ looking like $f_1(w)$ is among the worst possible shape and the adjacent symbols are the main contributors to ISI in this case. When the group delay consists of a large number of ripples (as in a SAW filter), say n cycles,

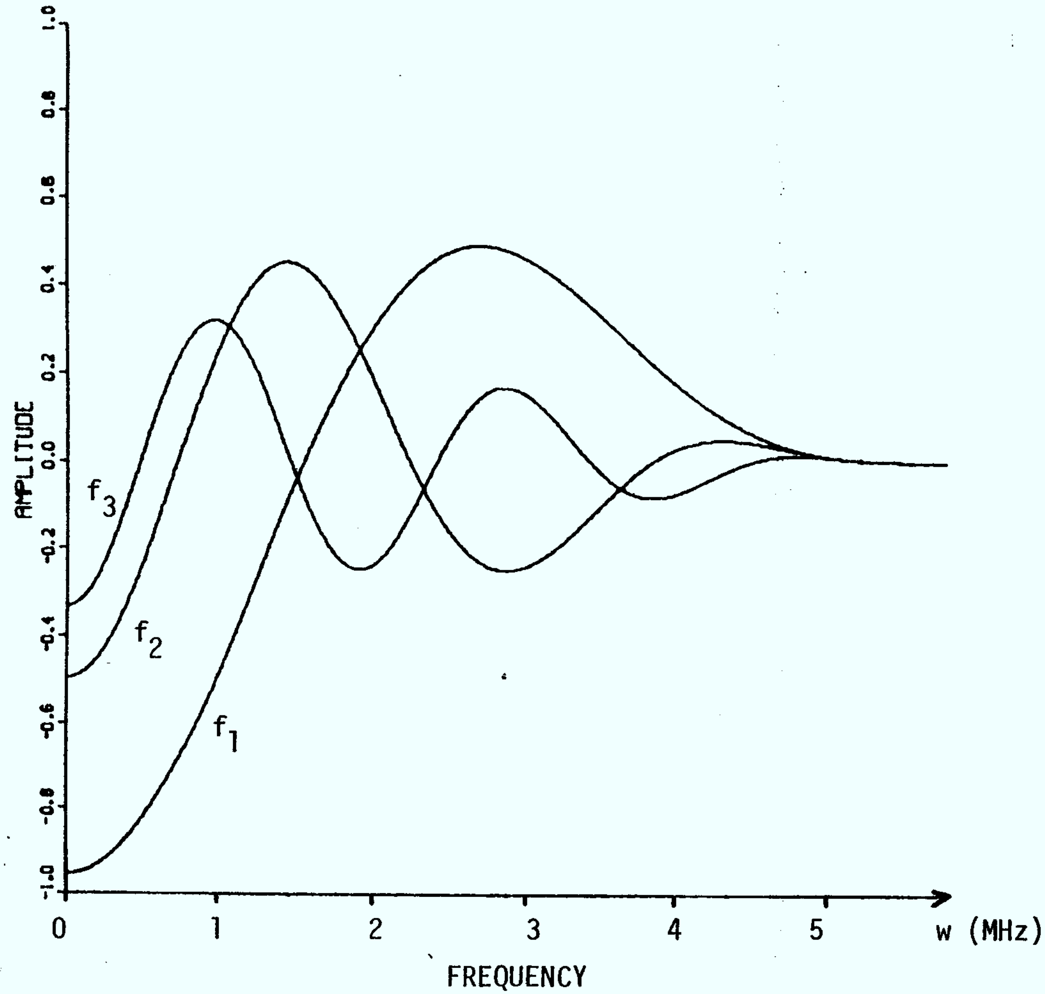


Figure 12 The functions $f_n(w)$ for a raised cosine system with 100% roll-off (α = 1.0)

then the ISI is less severe and comes largely from bit symbols $\pm nT$ away. When the group delay is a slowly varying function of w, the higher order linear functionals (B',f_n) become negligible and only adjacent intersymbol interference is of importance.

We shall now find the shape of group delay which maximizes the distortion D (eq. 11) given the constraint that the group delay peak-to-peak variation be limited to $\pm B'_{max}$ throughout the 4.2 MHz video bandwidth. A development made by Lucky in ref. 13 will be used.

Equation 13 can be rewritten as:

$$D = \frac{2}{\pi} \sum_{n=1}^{\infty} e_n (B',f_n) \quad \text{where} \quad e_n = \begin{cases} +1 & \text{if } (B',f_n) \geq 0 \\ -1 & \text{if } (B',f_n) < 0 \end{cases} \tag{22}$$

$$D = \frac{2}{\pi} (B', \sum_{n=1}^{\infty} e_n f_n) \tag{23}$$

The distortion D is thus a scalar product of group delay and some combination of functions f_n. The sequence of sign coefficients $\{e_n\}$ is chosen so as to maximize this scalar product, that is:

$$D = \frac{2}{\pi} \max_{\{e_n\}} (B', \sum_{n=1}^{\infty} e_n f_n) \tag{24}$$

The scalar product in eq. 24 represents the area under the curve of the product of $B'(w)$ and the combination $\sum e_n f_n(w)$. If $B'(w)$ is peak-limited, then this area will be maximized if $B'(w)$ is set to $+B'_{max}$ when $\sum e_n f_n$ is positive and $-B'_{max}$ when $\sum e_n f_n$ is negative. From a mathematical point of view, these operations are equivalent to setting $B'(w)$ equal to the constant $+B'_{max}$ and multiply it to the absolute value of $\sum e_n f_n$ so that eq. 24 can be rewritten as:

$$D_{max} = \frac{2}{\pi} \max_{\{e_n\}} (B', \left| \sum_{n=1}^{\infty} e_n f_n \right|) \tag{25}$$

$$D_{max} = \frac{2B'_{max}}{\pi} \max_{\{e_n\}} \int_0^W \left| \sum_{n=1}^{\infty} e_n f_n(w) \right| dw \tag{26}$$

The problem now reduces to finding the combination of sign $\{e_n\}$ that will maximize the area under the curve of the absolute value of $\sum e_n f_n(w)$. Lucky in ref. 13 has called $f_{mai}(w)$ (maximum absolute integral) the curve obtained from this maximizing combination. The first n = 30 values of the maximizing sequence were determined by trial and error on a digital computer for a raised cosine system with a roll-off factor of 100%. The results are:

$$e_n = +1 \quad \text{except} \quad e_1 = e_4 = -1$$
$$f_{mai}(w) = \sum_{n=1}^{30} f_n(w) - 2\left[f_1(w) + f_4(w)\right] \qquad (27)$$

This $f_{mai}(w)$ curve is shown in figure 13 along with the corresponding "theoretical worst case" group delay. The worst peak-to-peak delay is positive when $f_{mai}(w)$ is positive and negative when $f_{mai}(w)$ is negative except for the segment extending from 0 to 0.13 MHz. Insignificant error is made by omitting this portion of $f_{mai}(w)$. As a result, the worst case group delay response that can fit between the peak limits $\pm B'_{max}$ for a 100% roll-off raised cosine data signal has the shape of a STEP function with amplitude $2B'_{max}$. The discontinuity of the step occurs at 1.8 MHz when the data rate is 5.72 Mbits/sec.

5.2 BANDLIMITED RAISED COSINE SPECTRUM (TELETEXT)

In the previous section, a step function was shown to be the most deteriorating group delay shape that can affect the eye height of a data signal with a 100% roll-off raised cosine spectrum. The amplitude response of the transmission channel of figure 9 was considered ideal and the low-pass filter $G_2(w)$ was ignored. Those two requirements were a prerequisite to the mathematical demonstration that led to the results of Section 5.1.

However, in real teletext systems, the raised cosine data signal must be bandlimited prior to transmission in the video channel. The low-pass filter $G_2(w)$ used for this purpose introduces some amplitude distortion on the data signal.

An obvious method to determine the "worst case" group delay shape for this bandlimited raised cosine spectrum would be to recapitulate the mathematical analysis of section 5.1 with $H(w) = G_1(w)\,G_2(w)$. This is impossible because the restriction expressed by eq. 18, on which the analysis relies, is longer satisfied when $G_2(w)$ is not ideal.

However, the ISI produced by $G_2(w)$ on the teletext signal is usually not severe. Figure 14 represents the amplitude and group delay characteristics of a typical low-pass filter that satisfies the requirements of BS-14 (ref. 10) and NABTS (ref. 11). Its -3 dB cutoff frequency is 4.0 MHz and its attenuation is 400 dB/decade in the stopband. Its group delay response is ideal. Such a filter removes 0.8% of the total energy of a raised cosine data signal with a 100% roll-off fed at its input.

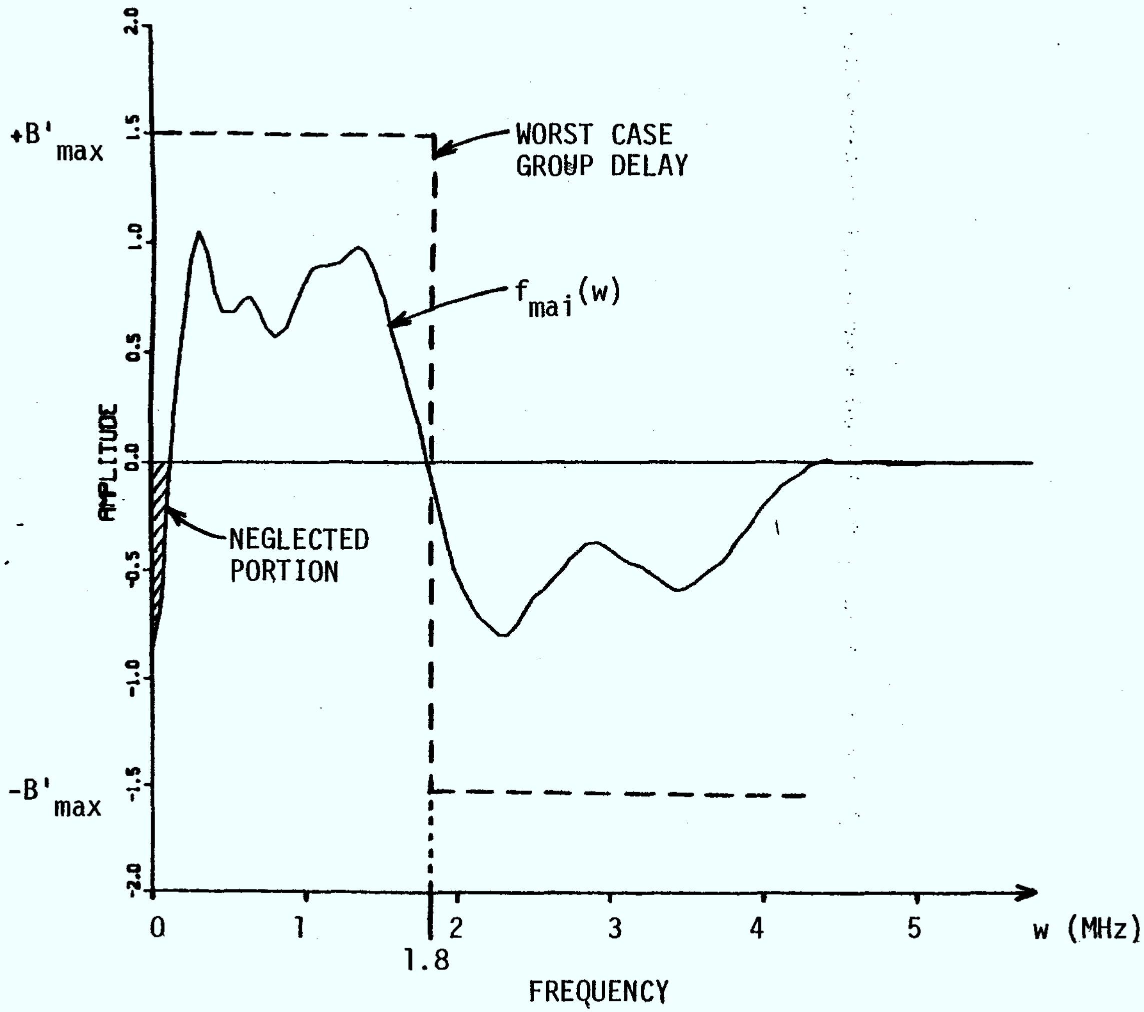


Figure 13 $f_{mai}(w)$ curve and "worst case" group delay curve for a raised cosine spectrum with 100% roll-off

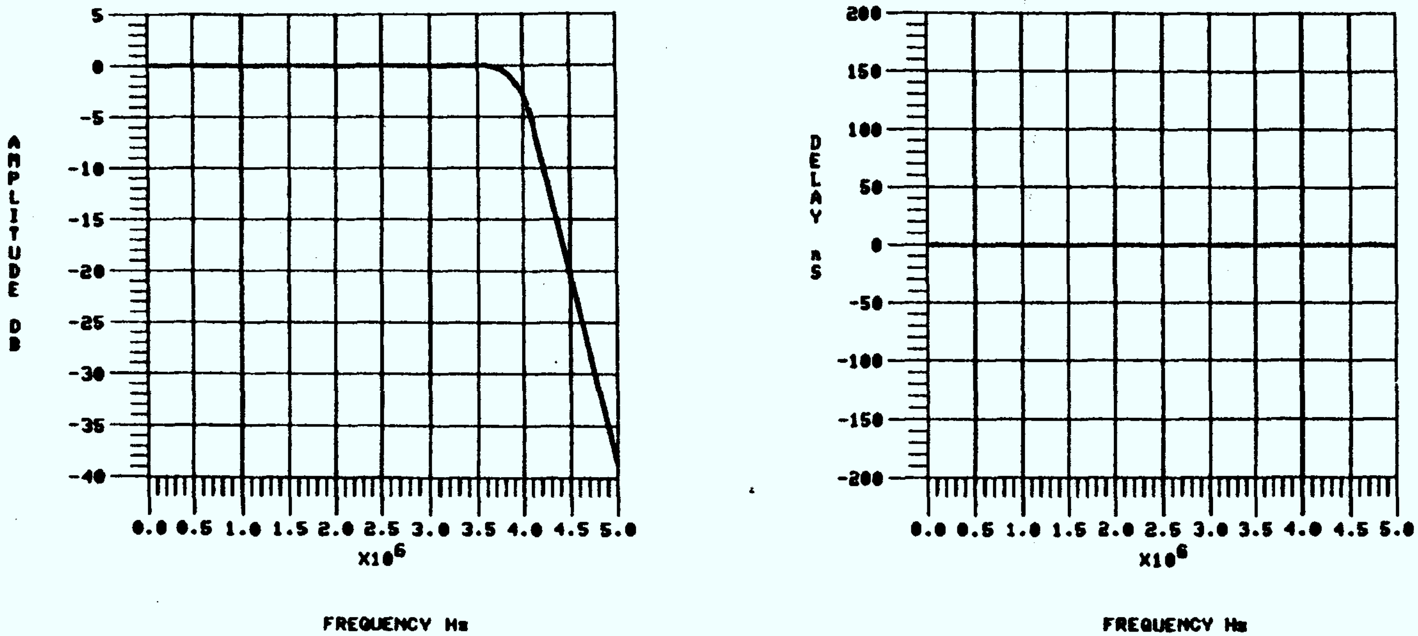


Figure 14 Typical 4.2 MHz low-pass filter

The low percentage of energy removed by this low-pass filter does not alter seriously the shape of the data spectrum as shown in figure 5. Although we cannot demonstrate mathematically that a step function is the worst theoretical group delay shape for a bandlimited raised cosine signal, we can nevertheless say, in a heuristic way, that the step function is certainly among the most harmful delay shapes for this case.

6. LIMITS ON GROUP DELAY FOR A TELETEXT SIGNAL

6.1 CONSTANT LIMITS WITH STEP GROUP DELAY

The step group delay characteristic defined in the previous section and shown in figure 15 will be used here to calculate limits on peak-to-peak group delay variations for teletext transmission.

First, the frequency of discontinuity F_d (figure 15) which yields the lowest eye height value must be determined. Using computer simulation, the teletext signal was successively passed through a series of baseband filters representing different data channels. Each filter had an ideal amplitude response ($G_3(w) = 1$) and a step group delay response ($B'(w)$). The amplitude $2B'_{max}$ of the steps was kept constant but the frequency of discontinuity F_d was changed from filter to filter.

The values of eye height were calculated for each filter and are plotted against F_d in figure 16 (solid lines). Three curves corresponding to step amplitudes $2B'_{max}$ of 50, 100 and 150 nsec were computed. This figure shows a minimum at 1.4 MHz for all three curves. This means that a step function with a peak-to-peak value of $2B'_{max}$ and a discontinuity occurring at 1.4 MHz is one of the worst possible group delay shape that can fit in between the limits $\pm B'_{max}$. In other words, any other delay shape with similar peak-to-peak value will yield a greater value of eye height. This step function can therefore be used to set limits on peak-to-peak group delay variations throughout the 4.2 MHz video bandwidth.

To this end, the teletext signal was then passed through a series of step group delay curves having a constant frequency of discontinuity (F_d = 1.4 MHz) but varying peak-to-peak value ($2B'_{max}$) and the eye height was calculated in each case. The eye height values thus obtained are plotted against $2B'_{max}$ on the solid line of figure 17. This solid curve constitutes a lower bound. If, for example, the tolerated peak-to-peak variations of group delay is limited to $2B'_{max}$ = 140 nsec from 0 to 4.2 MHz, then any delay shape will yield an eye height greater or equal to 30%, as given by figure 17.

These observations allow us to propose some limits to group delay fluctuations and a mask to monitor them. This mask, labeled "type A", is shown in figure 18. Its aperture $2B'_{max}$ depends on the minimal eye height value we want to guarantee and can be determined from figure 17. For instance, if we want to ensure 50% eye height, then the aperture of the mask should be 98 nsec. Any group delay curve that fit in this mask will guarantee, in the absence of serious amplitude distortion, an eye height of at least 50%. However, some less critical group delay shapes may overflow the mask and still yield an eye height greater than 50%.

The threshold of 50% is often used as a minimal requirement for the eye height of a teletext signal at a subscriber terminal. In order to ensure this value, the peak-to-peak variation of the overall group delay characteristic (baseband-to-baseband in figure 7) should therefore be limited to ± 49 nsec throughout the video bandwidth. This requirement is stringent and we shall try to relax it in the next section by considering the characteristics of actual group delay curves met on cable TV systems.

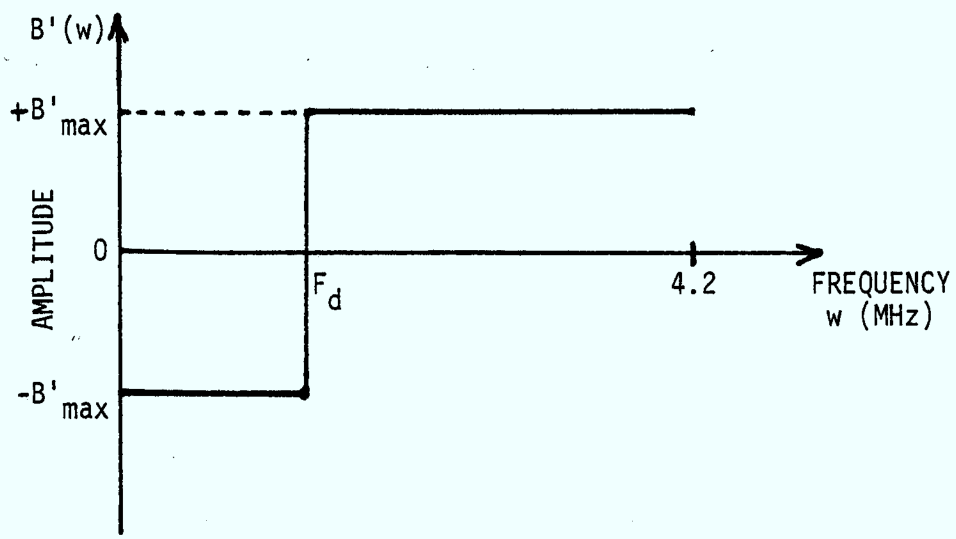


Figure 15 Step group delay shape

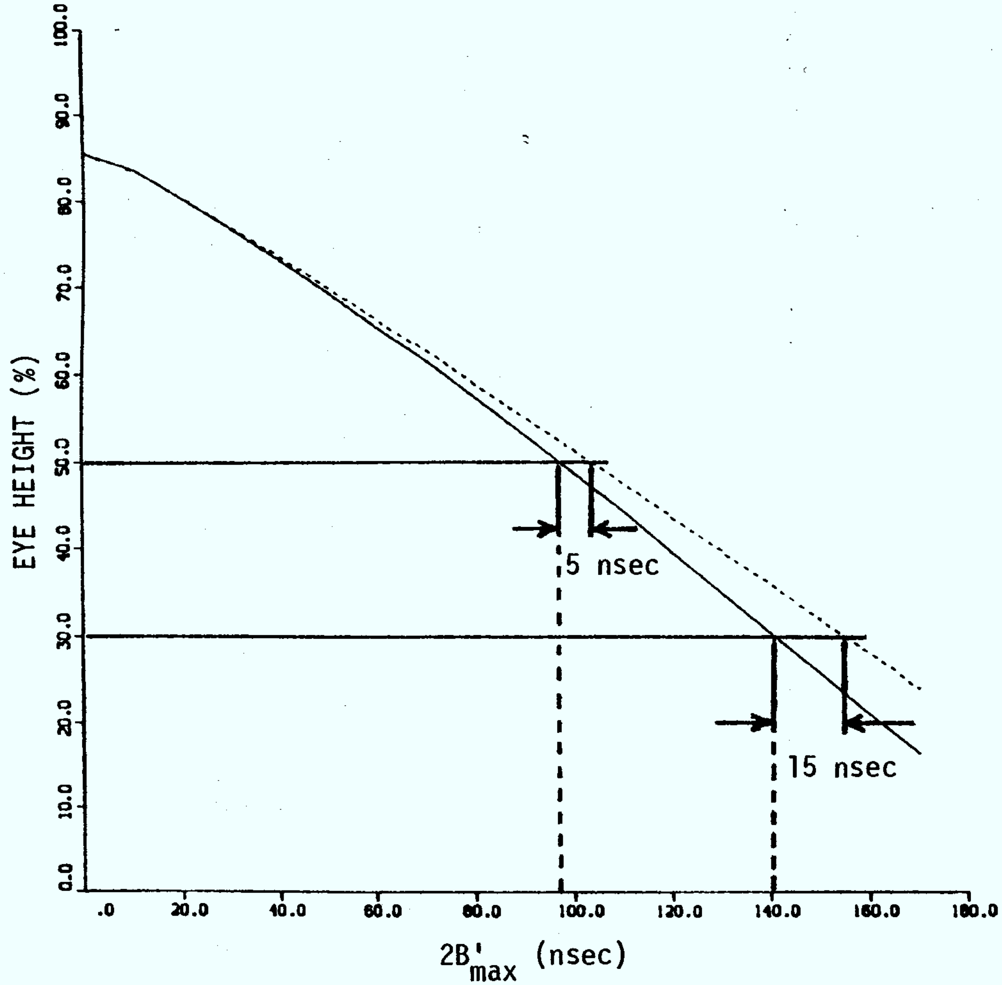


Figure 17 Eye height as a function of the peak-to-peak amplitude $2B'_{max}$ of a

- step group delay shape with $F_d \approx 1.4$ MHz (solid line)
- ramp group delay shape with $F_d = 1.5$ MHz (dash line)

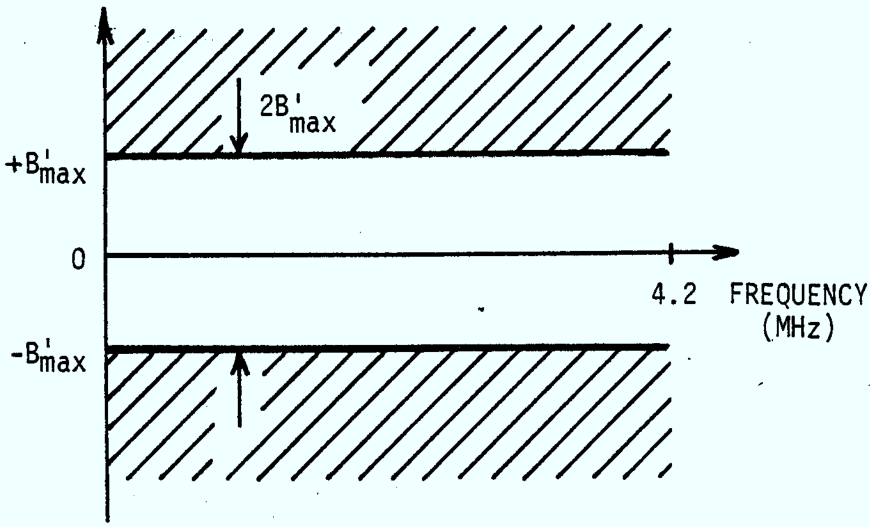


Figure 18 Type A group delay tolerance mask

6.2 CONSTANT LIMITS WITH RAMP GROUP DELAY

In the previous section, limits on peak-to-peak group delay variations were established for a teletext signal using a step group delay curve. Such a characteristic is theoretical and is never met in practice on real networks. The abrupt transition of the step function will be replaced, in this section, by a ramp as shown in figure 19. This ramp shape can be thought of as the "practical worst case" delay shape and will be used to relax the limits set forth in section 6.1.

A slope value must be selected for this ramp. To this end, a repertoire of group delay curves measured on real TV networks was examined. It was found that slopes of 150 nsec/MHz or less are common in the passband of the video channel while slopes exceeding 200 nsec/MHz are possible but rare. Slopes well in excess of 200 nsec/MHz can occur but at the end of the video bandwidth where their effect is negligible on the teletext signal. For these reasons, a slope of 200 nsec/MHz was selected for the tests that follow.

Computer simulations similar to those performed in the previous section with a step function were repeated here with the ramp group delay shape. The dash lines of figure 16 shows the variation of the eye height as the median frequency F_d of the ramp is varied from 0.25 to 4 MHz. The amplitude $2B'_{max}$ was kept constant at 50, 100 and 150 nsec respectively. The eye height reached a minimum at F_d = 1.5 MHz for all three curves.

This particular value of F_d was used in figure 17 where the variation of the eye height as a function of the amplitude $2B'_{max}$ of the ramp is shown by the dash line. This graph shows, among other things, that in order to ensure a 50% eye height, the peak-to-peak variation of any group delay shape should be constrained to 103 nsec throughout the video bandwidth. This represents only a 5 nsec relaxation to the limit of 98 nsec obtained with the step function in the previous section. Better relaxation is to be expected for smaller eye height. In order to guarantee a 30% eye height for instance, group delay fluctuations should be limited to 155 nsec, a 15 nsec relaxation over the limit obtained with a step function (figure 17).

The use of a more "realistic" worst case group delay shape (i.e. a ramp) has led to minimal relaxation in group delay requirements. In order to ensure a 50% eye height, group delay fluctuations still have to be maintained within roughly ± 50 nsec throughout the video bandwidth. Again, it is important to remind that some less critical delay shapes may exceed this limit and still yield an eye height greater than 50%.

It is relatively easy to equalize a group delay curve within a limited frequency interval but more difficult to do it over the entire video bandwidth. For this reason, we will seek, in the next section, means to alter the shape of the tolerance mask proposed in figure 18 taking into account the sensitivity of different portions of the teletext data spectrum to delay variations.

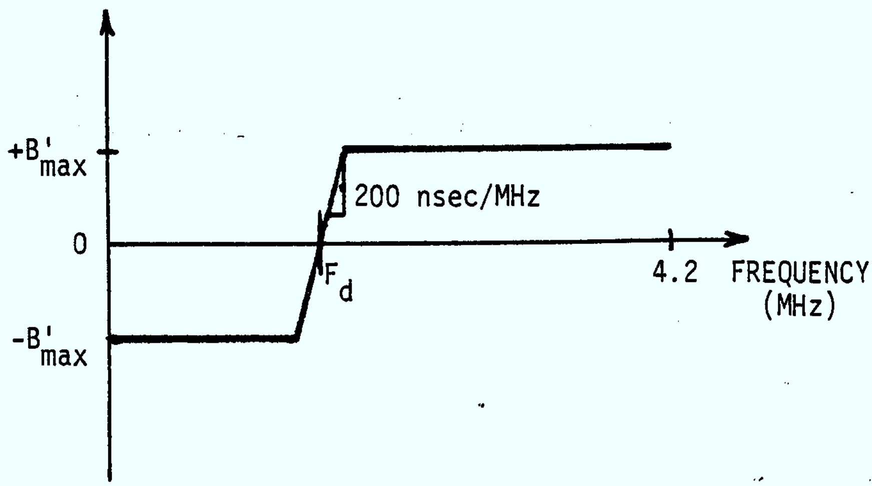


Figure 19 Ramp group delay shape

6.3 FREQUENCY WEIGHTED LIMITS

The curves of figure 16 were obtained by passing the teletext signal through a series of group delay shapes which consisted in a single transition (step or ramp) affecting successively different portions of the frequency spectrum of the data signal. The parameter F_d of figure 16 is the center frequency of the transition.

Some observations can be drawn from these curves for a low-pass filtered 100% roll-off raised cosine signal:

- group delay transitions or inequalities occurring in the 1 to 2 MHz frequency interval have the most deteriorating effect on eye height. Their peak-to-peak amplitude should therefore be limited as much as possible;

- group delay transitions or inequalities occurring above 3 MHz do not affect seriously the eye height. Greater inequalities can be tolerated in this region of the spectrum;

- the intervals spanning from 0 to 1 MHz and from 2 to 3 MHz represents intermediate zones where the eye height reduction varies with F_d. Group delay inequalities should be selectively and progressively limited within these intervals.

The particular frequency values mentioned in the observations above are approximative.

These observations have led to a new tolerance mask labeled "type B" which is illustrated in figure 20: the tolerable limits on peak-to-peak variations have been weighted according to the relative sensitivity of various parts of the data spectrum to delay distortion. The shape of this mask bears, of course, some resemblance with the curves of figure 16 from which it was deducted. A "type B" mask is characterized by five parameters, as shown in figure 20:

F_1 = Frequency of transition no. 1
F_2 = Frequency of transition no. 2
D_1 = Mask aperture at 0 MHz
D_2 = Mask aperture between F_1 and F_2
D_3 = Mask aperture at 4.2 MHz

A simplified version of this mask is illustrated in figure 21. Labeled "type C", this mask can be seen as a particular case of type B mask for which $F_1 = 0$ and $D_1 = D_2$.

The various parameters (F_1, F_2, D_1, D_2, D_3) appearing on figures 20 and 21 will be quantatively defined for a given wanted performance level (i.e. minimal eye height). To do so, the worst case group delay curve that can fit in each of type B and type C tolerance masks must be determined. Stated otherwise, we would like to know the shape of group delay which maximizes the distortion D (eq. 11) given the constraint that the group delay peak-to-peak variations be bounded by either type B (figure 20) or type C (figure 21) mask.

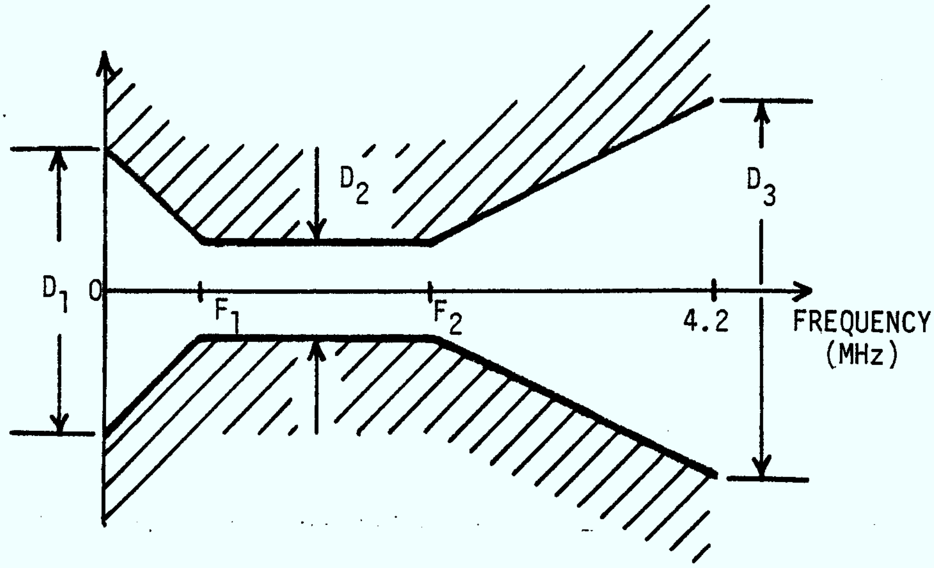


Figure 20 Type B group delay tolerance mask

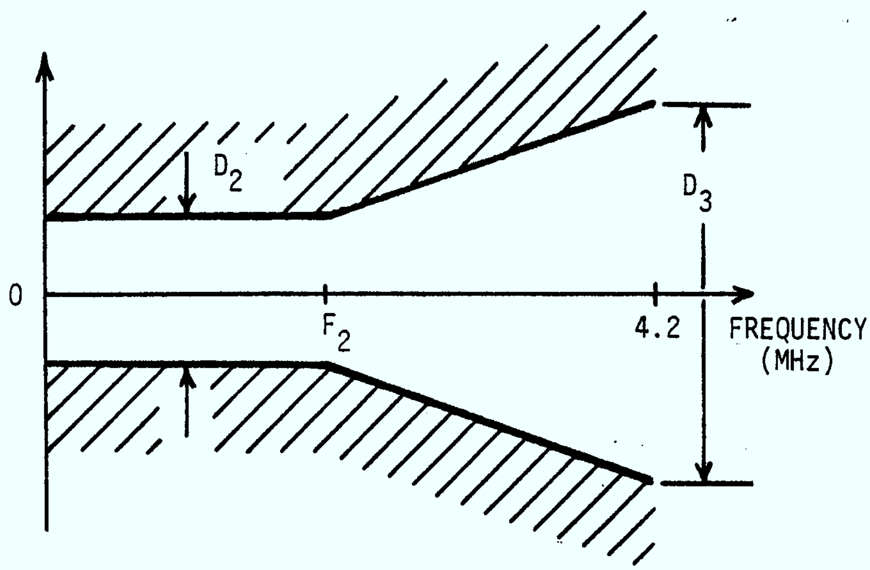


Figure 21 Type C group delay tolerance mask

A mathematical analysis similar to the one performed in section 5.1 will be repeated here for a non-bandlimited raised cosine signal: results will be extended to the bandlimited (i.e. teletext) case. The constant bounds $\pm B'_{max}$ from 0 to 4.2 MHz assumed in section 5.1 for peak-to-peak delay variations will be replaced here by a limit which varies with frequency. In the lines that follow, the analysis will be performed using the limits of type B mask (figure 20).

The distortion D is a scalar product of group delay $B'(w)$ and some combination of function $f_n(w)$ as given by

$$D = \frac{2}{\pi}\left(B'(w), \sum_{n=1}^{\infty} e_n f_n(w)\right) \qquad (28)$$

where $e_n = +1$ or -1.

Our goal is to find the shape of $B'(w)$ that will maximize D knowing that $B'(w)$ has to be bounded by the limits $+B'_{max}(w)$ and $-B'_{max}(w)$ shown in figure 22.

The procedure to achieve that goal is as follows:

1) For each sequence of sign coefficients $\{ e_n \}$, calculate the function $\sum e_n f_n(w)$
2) Set $B'(w) = +B'_{max}(w)$ when the function $\sum e_n f_n(w)$ is positive and $B'(w) = -B'_{max}(w)$ when $\sum e_n f_n(w)$ is negative
3) Calculate the distortion D with equation 28 for that sequence $\{ e_n \}$

The worst case delay shape $B'(w)$ we are looking for is the one obtained with the particular sequence $\{ e_n \}$ leading to the greatest value D.

The first n = 15 values of the maximizing sequence were determined using a digital computer for the following parameters of the tolerance mask shown on figure 22:

F_1 = 1 MHz
F_2 = 2 MHz
D_1 = 150 nsec
D_2 = 50 nsec
D_3 = 200 nsec

These values are arbitrary and are used only for illustrative purposes. The results are $e_n = -1$, n = 1 to 15 except for $e_3 = e_5 = e_7 = e_9 = e_{11} = e_{13} = +1$. The corresponding function $\sum e_n f_n(w)$ is shown on figure 23.a. The worst case group delay is derived from this function by setting $B'(w) = +B'_{max}(w)$ when $\sum e_n f_n(w)$ is positive and $B'(w) = -B'_{max}(w)$

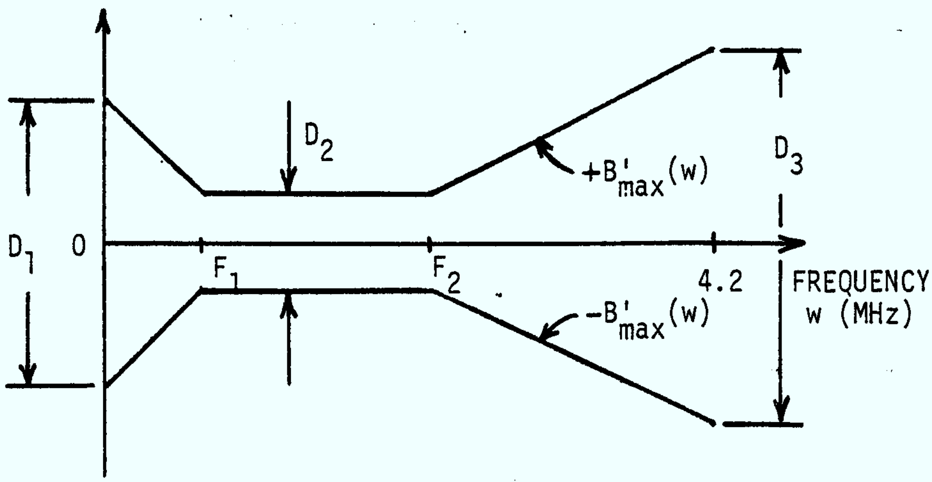


Figure 22 Limits $+B'_{max}(w)$ and $-B'_{max}(w)$ for a type B tolerance mask

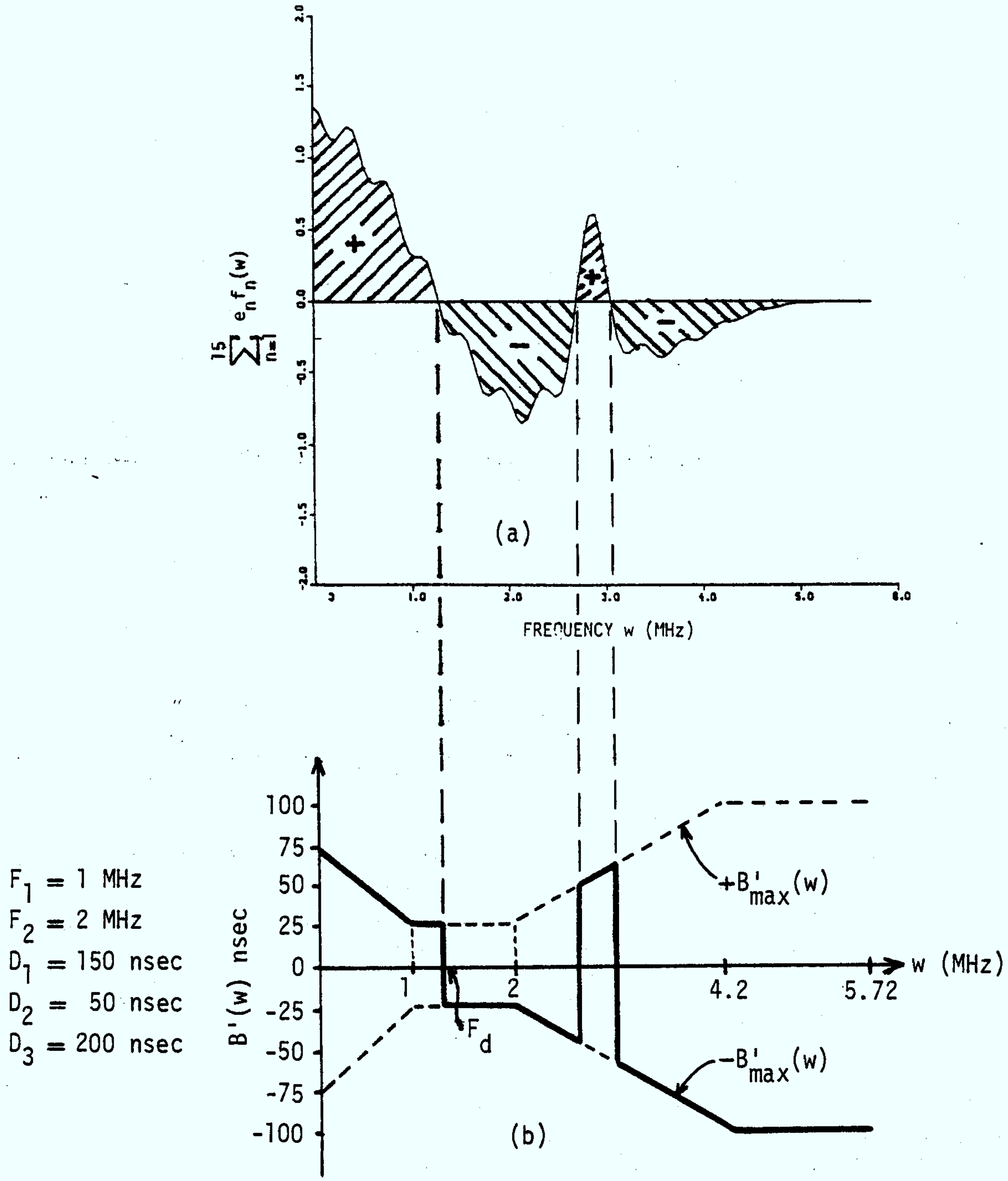


Figure 23 Non-bandlimited raised cosine signal (100% roll-off)

a) Function $\sum e_n f_n(w)$ and

b) Corresponding theoretical worst case delay shape that can fit in the type B tolerance mask shown when $\sum e_n f_n(w)$ is negative and is shown in figure 23.b. The resulting delay shape is theoretical as no cable TV channels will exhibit group delay characteristics with such abrupt transitions.

A good practical approximation to this theoretical curve is depicted in figure 24. For the particular values of F_1, F_2, D_1, D_2, D_3 defined earlier, a value of F_d = 1.5 MHz was found, by trial and error on a digital computer, to lead to the smallest eye height value. The worst case practical curve of figure 24 yielded an eye height only 1% higher than that obtained with the theoretical worst case curve of figure 23.b.

The results obtained above for a non-bandlimited raised cosine signal (100% roll-off) will be simply extended and used for the bandlimited case (i.e. teletext). This generalization of the results is based on the very same argument put forward in section 5.2: the percentage of energy removed by the low-pass filter $G_2(w)$ in figure 9 is typically very low so that its effect can be neglected for all practical purposes. Consequently, the curve shown in figure 24 will be considered hereafter as the worst practical group delay curve that can fit in type B tolerance mask for a teletext signal. The value of frequency F_d is related to the values of the mask parameters (F_1, F_2, D_1, D_2, D_3) and usually falls between F_1 and F_2.

A similar demonstration can be used to show that the worst case practical group delay curve that can fit in a type C tolerance mask for a teletext signal is as depicted in figure 25. Again, the value of frequency F_d depends on the values of the various mask parameters (F_2, D_2, D_3).

The various parameters of mask B (F_1, F_2, D_1, D_2, D_3) will now be quantatively defined so that any group delay curve that fit inside this mask will yield an eye height of 50% or greater. Numerous solutions (i.e. combinations of values for F_1, F_2, D_1, D_2, D_3) are possible. It is beyond the scope of this study to select an "optimum solution". Our intention is to identify and propose the use of a frequency weighted tolerance mask and to demonstrate its feasibility through a typical example.

To this end and to reduce the number of possible solutions, the values of parameters D_1 and D_3 were arbitrarily set to 200 nsec each. Then, using the worst practical group delay curve defined in figure 24, all the possible combinations of F_1, F_2 and D_2 that will ensure a 50% eye height were determined using a digital computer. Values of F_1 were constrained between 0 and 1 MHz and F_2 between 2 and 3 MHz.

The results are shown graphically in figure 26 and in tabulated form in Appendix B. Figure 26 contains, for each combination of F_1 (x axis) and F_2 (y axis), the value of D_2 (z axis) needed to guarantee a 50% eye height, D_1 and D_3 remaining fixed at 200 nsec each. Some 121 combinations of F_1, F_2 and D_2 are shown. We will focus our attention to four limit cases, each one corresponding to a corner of the tri-dimensional curve of figure 26.

The line joining point A and point B contains all the solutions for which F_1 = 0. The resulting mask is of type C. Between A and B, the frequency F_2 is gradually increased from 2 to 3 MHz. As the portion 0 to F_2 of the mask (where delay variations are restricted) is stretched, the allowed peak-to-peak fluctuations increase. This is shown by D_2 increasing from 82 to 97 nsec from point A to B.

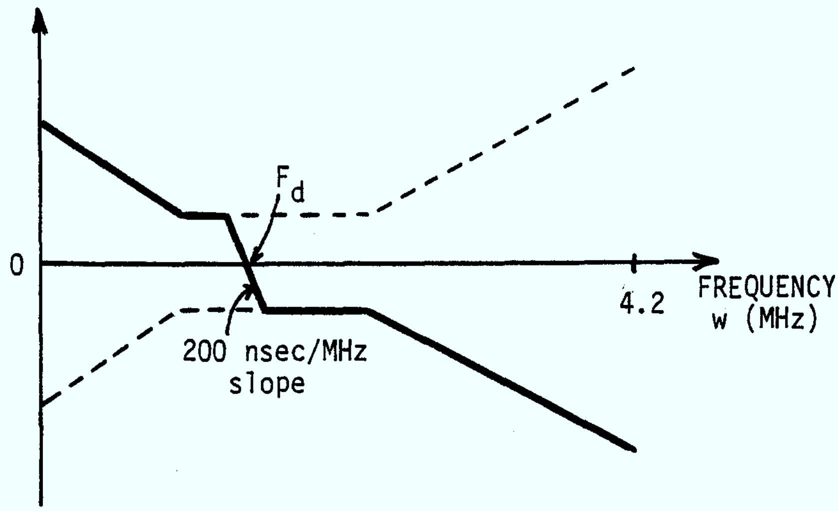


Figure 24 Worst case practical group dealy shape that can fit in type B tolerance mask

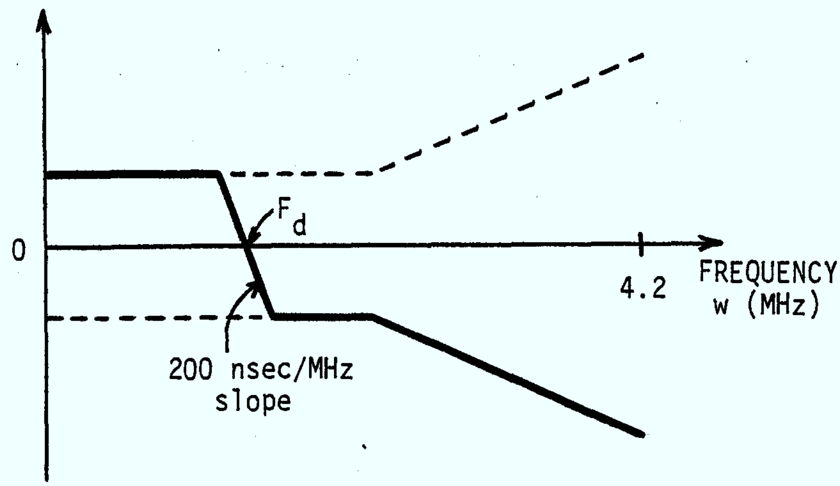


Figure 25 Worst case practical group delay shape that can fit in type C tolerance mask

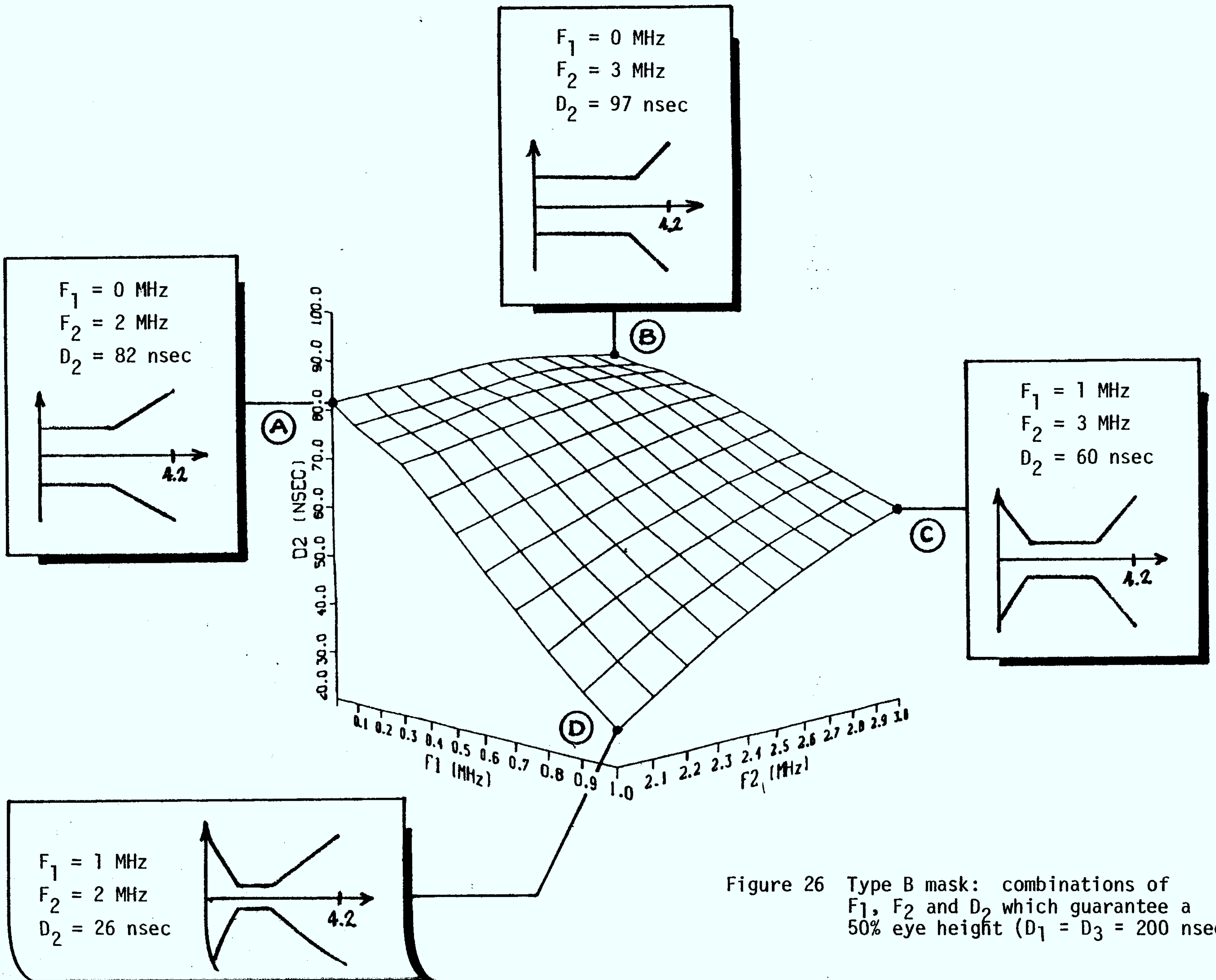


Figure 26 Type B mask: combinations of F_1, F_2 and D_2 which guarantee a 50% eye height ($D_1 = D_3 = 200$ nsec)

It is interesting to note that the price to be paid at low frequencies (< F_2) for allowing greater delay inequalities at higher frequencies (> F_2), is little. At point A for instance, peak-to-peak group delay inequalities must be limited to 82 nsec from to 0 to 2 MHz. This limit is <u>only</u> 18 nsec smaller than the limit of 100 nsec required with type A tolerance mask <u>and</u> has to be respected over a 2 MHz span only, not over the entire 4.2 MHz bandwidth as for type A mask.

From point B to point C, the parameter F_2 is constant at 3 MHz while F_1, is increased from 0 to 1 MHz. In order to compensate for the greater group delay inequalities tolerated between 0 and F_1, the inequalities occurring between F_1 and F_2 must be gradually restricted. This is shown by D_2 decreasing from 97 to 60 nsec between B and C. Similar comments can be made between joint A and D where parameter F_2 is held fixed at 2 MHz while F_1 is increased from 0 to 1 MHz.

From point C to point D, F_1 is held constant at 1 MHz while F_2 is decreased from 3 to 2 MHz. By doing so, greater delay fluctuations are being tolerated at higher frequencies (> F_2). Consequently, the fluctuations occurring between F_1 and F_2 must be progressively restricted in order to maintain a constant eye height (50%): D_2 decreases from 60 to 26 nsec from C to D. At point D, group delay variations has to be peak limited to only 26 nsec between 1 and 2 MHz; however, this very tight equalization has to be made over a 1 MHz frequency interval only.

At point A and point C, group delay equalization is required over a 2 MHz frequency interval. However, the peak-to-peak fluctuations must be equalized to ±41 nsec at point A and to ±30 nsec at point C. The higher fluctuations tolerated by the type C mask defined at point A is a good argument in favor of its selection over the type B mask defined at point C.

Further tests were done on type C tolerance mask. The results are shown graphically in figure 27 and in tabulated form in Appendix C. Figure 27 shows the combinations of F_2 and D_2 required to guarantee a 50% eye height for different values of D_3 (150, 200, 250 and 300 nsec). Parameter F_2 was varied from 1 to 4.2 MHz.

As F_2 is increased, the frequency interval (0 to F_2) over which the group delay has to be more tightly equalized increases as well. However, the allowed peak-to-peak delay fluctuations (D_2) in the 0-F_2 zone increases also. The four curves of figure 27 asymptotically converge towards D_2 = 103 nsec as F_2 approaches 4.2 MHz. When F_2 = 4.2 MHz, the resulting mask is the type A defined in section 6.2. As D_3 is increased from 150 to 300 nsec, more and more delay inequalities are tolerated at higher frequencies (> F_2) and, consequently, the inequalities at lower frequencies (<F_2) must be limited. Stated otherwise, as D_3 is increased, the aperture D_2 of the mask must be reduced for any given value of F_2.

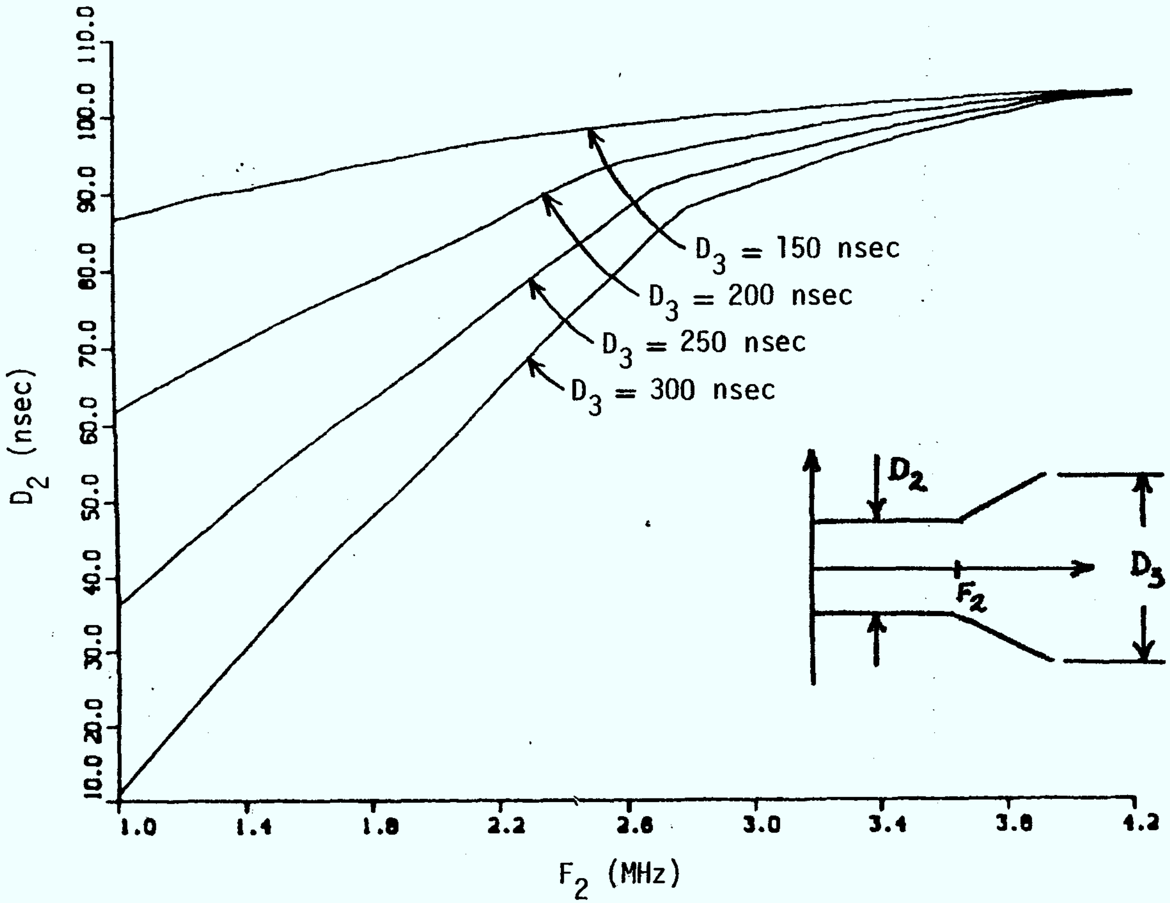


Figure 27 Type C mask: combinations of F_2 and D_2 which guarantee a 50% eye height for D_3 = 150, 200, 250 and 300 nsec

7. CONCLUSIONS

In this report, the effect of group delay inequalities on the eye height of a 5.72 Mbits/sec NABTS teletext signal transmitted over a cable TV channel was studied. The particular definition of eye height used in this study was the one obtained at a time t_0 corresponding to the peak value of the impulse response of the transmission channel. The amplitude response of the data channel was assumed ideal throughout this work. The results summarized below should nevertheless hold true for channels with weak amplitude response inequalities.

A mathematical relationship was derived between the group delay characteristic of a transmission channel and the distortion of the data signal in the form of intersymbol interference created by the group delay variations. Using this mathematical relationship, it was demonstrated that a STEP group delay response, with the discontinuity occurring at 1.4 MHz, was the worst "theoretical" shape that could affect a teletext signal. No other delay shape with similar peak-to-peak fluctuations will produce a lower eye height value.

A RAMP group delay characteristic, obtained by replacing the abrupt transition of the STEP by a slope of 200 nsec/MHz centered at 1.5 MHz, was defined as the worst "practical" shape that can be expected on any cable TV system. Using this RAMP characteristic, it was found that, in order to guarantee a 50% eye height at any subscriber terminal, the overall peak-to-peak group delay fluctuations between the output of the teletext generator and any subscriber terminal (baseband-to-baseband) should be limited roughly to ± 50 nsec throughout the video bandwidth (0 to 4.2 MHz).

This result corroborates the limits proposed in ref. 6 and 8. From these limits, a first tolerance mask, labeled type A, was proposed for monitoring purposes on cable TV systems. It must be reminded that some less critical group delay shapes may overflow these limits and still yield an eye height of 50% or more.

It was further demonstrated that group delay inequalities occurring between 1 and 2 MHz approximately have a strong deteriorating effect on the eye height of a teletext signal. Their peak-to-peak amplitude should therefore be limited as much as possible. Group delay inequalities occurring below 1 MHz or above 2 MHz have a less severe impact on the eye height. Greater inequalities can therefore be tolerated in these portions of the teletext spectrum. The effect of inequalities above 3 MHz can be neglected for all practical purposes.

These observations have led to the proposal of two other tolerance masks which take into account the relative sensitivity of different parts of the teletext data spectrum to delay variations. Labeled type B and type C, they offer the advantage over type A mask of requiring tight group delay equalization over only a small portion of the 4.2 MHz video bandwidth.

It becomes obvious from the above that existing regulations regarding group delay for television broadcasting transmitters and cable TV systems will not guarantee satisfactory delivery of teletext signals over broadcast or cable TV networks. The maximum chroma delay of ±150 in BP-23 (ref. 5) for a cable system is insufficient to ensure good quality teletext reception. The limits of ±80 nsec for high power transmitters and ±100 nsec for low power transmitters tolerated between 0 and 2 MHz are too high and should be reduced towards ±50 nsec if a 50% eye height objective is to be achieved. An alternative would be to adopt variable limits according to frequency as suggested by both type B and type C tolerance masks proposed in this study. Further work would be required in this latter case to optimize the parameters of the proposed masks.

This study has provided ground work for a better understanding of the effect of group delay on the quality of teletext reception. Additional research work could be done to develop and recommend group delay standards for teletext transmission over cable TV networks. In the present context, it is felt that such activities could be more appropriately undertaken, in due time, by a joint committee of the various bodies directly affected by the adoption of teletext transmission standards (broadcasters, cable TV operators, equipment manufacturers and regulation agencies).

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APPENDIX A

LIST OF SYMBOLS AND ABBREVIATIONS

AML	Amplitude Modulation Link
BP-23	Broadcast Procedure 23
BS-14	Broadcast Specification 14
CVCC	Canadian Videotex Consultative Committee
dB	decibels, 10 log (dimensionless ratio of powers)
EIA	Electronic Industry Association
eq.	equation
$H(t_o)$	eye height at time t_o corresponding to peak value of impulse response
H_m	maximum eye height
H_s	eye height at sampling time
Hz	Hertz, frequency unit in cycles per second
IRE	Institute of Radio Engineers
ISI	Intersymbol Interference
Mbits/sec	Megabits-per-second (10^6 bits-per-second)
MHz	MegaHertz (10^6 Hz)
NABTS	North American Basic Teletext Standard
NRZ	Non-Return to Zero
nsec	nanosecond (10^{-9} second)
NTSC	National Television Standard Committee
SAW	Surface Acoustic Wave
T	Bit duration ($1/(5.727272 \times 10^6)$ sec.)
TV	Television
usec	microsecond (10^{-6} second)
VBI	Vertical Blanking Interval

APPENDIX B

TYPE B TOLERANCE MASK PARAMETERS

TABULATED FORM

$D_1 = D_3 = 200$ nsec

F_1 (MHz)	F_2 (MHz)	D_2 (nsec)
.000	2.000	81.600
.000	2.100	83.600
.000	2.200	85.600
.000	2.300	87.800
.000	2.400	90.000
.000	2.500	92.000
.000	2.600	93.600
.000	2.700	94.600
.000	2.800	95.400
.000	2.900	96.000
.000	3.000	96.800
.100	2.000	76.600
.100	2.100	78.800
.100	2.200	81.000
.100	2.300	83.400
.100	2.400	85.600
.100	2.500	88.000
.100	2.600	90.000
.100	2.700	91.400
.100	2.800	92.200
.100	2.900	93.000
.100	3.000	93.800
.200	2.000	72.800
.200	2.100	75.200
.200	2.200	77.800
.200	2.300	80.400
.200	2.400	83.000
.200	2.500	85.200
.200	2.600	87.000
.200	2.700	88.400
.200	2.800	89.600
.200	2.900	90.600
.200	3.000	91.600
.300	2.000	68.800
.300	2.100	71.200
.300	2.200	73.800
.300	2.300	76.200
.300	2.400	78.600
.300	2.500	80.800
.300	2.600	83.000

$D_1 = D_3 = 200$ nsec

F_1 (MHz)	F_2 (MHz)	D_2 (nsec)
.300	2.700	85.000
.300	2.800	86.400
.300	2.900	87.400
.300	3.000	88.400
.400	2.000	62.400
.400	2.100	65.200
.400	2.200	68.000
.400	2.300	70.600
.400	2.400	73.000
.400	2.500	75.400
.400	2.600	77.800
.400	2.700	79.800
.400	2.800	82.000
.400	2.900	83.800
.400	3.000	85.200
.500	2.000	56.000
.500	2.100	59.000
.500	2.200	62.000
.500	2.300	64.800
.500	2.400	67.600
.500	2.500	70.200
.500	2.600	72.600
.500	2.700	75.000
.500	2.800	77.200
.500	2.900	79.200
.500	3.000	81.000
.600	2.000	49.400
.600	2.100	52.800
.600	2.200	56.000
.600	2.300	59.000
.600	2.400	62.000
.600	2.500	64.800
.600	2.600	67.400
.600	2.700	69.800
.600	2.800	72.200
.600	2.900	74.400
.600	3.000	76.600
.700	2.000	43.400
.700	2.100	46.800
.700	2.200	50.200

$D_1 = D_3 = 200$ nsec

F_1 (MHz)	F_2 (MHz)	D_2 (nsec)
.700	2.300	53.600
.700	2.400	56.600
.700	2.500	59.600
.700	2.600	62.400
.700	2.700	65.000
.700	2.800	67.400
.700	2.900	69.600
.700	3.000	71.600
.800	2.000	37.200
.800	2.100	41.200
.800	2.200	45.000
.800	2.300	48.400
.800	2.400	51.800
.800	2.500	54.800
.800	2.600	57.600
.800	2.700	60.400
.800	2.800	63.000
.800	2.900	65.200
.800	3.000	67.400
.900	2.000	31.400
.900	2.100	35.600
.900	2.200	39.600
.900	2.300	43.400
.900	2.400	46.800
.900	2.500	50.200
.900	2.600	53.200
.900	2.700	56.000
.900	2.800	58.600
.900	2.900	61.200
.900	3.000	63.400
1.000	2.000	26.200
1.000	2.100	30.600
1.000	2.200	34.800
1.000	2.300	38.800
1.000	2.400	42.400
1.000	2.500	45.800
1.000	2.600	49.000
1.000	2.700	52.000
1.000	2.800	54.800
1.000	2.900	57.400
1.000	3.000	59.800

APPENDIX C

TYPE C TOLERANCE MASK PARAMETERS

TABULATED FORM

D_3 = 150 nsec	
F_2 (MHz)	D_2 (nsec)
1.000	86.600
1.100	87.600
1.200	88.800
1.300	89.800
1.400	90.400
1.500	91.200
1.600	92.000
1.700	93.000
1.800	93.800
1.900	94.600
2.000	95.400
2.100	96.200
2.200	96.800
2.300	97.400
2.400	97.800
2.500	98.400
2.600	98.800
2.700	99.200
2.800	99.600
2.900	100.000
3.000	100.200
3.100	100.600
3.200	101.000
3.300	101.200
3.400	101.600
3.500	101.800
3.600	102.000
3.700	102.400
3.800	102.600
3.900	102.800
4.000	103.000
4.100	103.000
4.200	103.200

D_3 = 200 nsec	
F_2 (MHz)	D_2 (nsec)
1.000	61.600
1.100	64.000
1.200	66.200
1.300	68.400
1.400	70.600
1.500	72.800
1.600	74.800
1.700	76.600
1.800	78.400
1.900	80.400
2.000	82.200
2.100	84.200
2.200	86.200
2.300	88.600
2.400	90.600
2.500	92.600
2.600	94.000
2.700	94.800
2.800	95.600
2.900	96.400
3.000	97.200
3.100	97.800
3.200	98.600
3.300	99.200
3.400	99.800
3.500	100.400
3.600	100.800
3.700	101.400
3.800	101.800
3.900	102.200
4.000	102.600
4.100	102.800
4.200	103.000

D_3 = 250 nsec	
F_2 (MHz)	D_2 (nsec)
1.000	36.200
1.100	39.800
1.200	43.600
1.300	47.000
1.400	50.600
1.500	53.800
1.600	57.000
1.700	60.000
1.800	62.800
1.900	65.800
2.000	68.800
2.100	72.000
2.200	75.200
2.300	78.400
2.400	81.400
2.500	84.400
2.600	87.600
2.700	90.400
2.800	91.800
2.900	92.800
3.000	94.000
3.100	95.000
3.200	96.000
3.300	97.000
3.400	98.000
3.500	98.800
3.600	99.600
3.700	100.400
3.800	101.000
3.900	101.800
4.000	102.200
4.100	102.600
4.200	102.800

D_3 = 300 nsec	
F_2 (MHz)	D_2 (nsec)
1.000	10.800
1.100	15.800
1.200	20.800
1.300	25.800
1.400	30.400
1.500	35.200
1.600	39.600
1.700	43.800
1.800	47.600
1.900	51.400
2.000	55.600
2.100	59.800
2.200	64.200
2.300	68.400
2.400	72.600
2.500	76.600
2.600	80.400
2.700	84.400
2.800	87.800
2.900	89.400
3.000	90.800
3.100	92.200
3.200	93.600
3.300	95.000
3.400	96.200
3.500	97.400
3.600	98.400
3.700	99.400
3.800	100.200
3.900	101.200
4.000	102.000
4.100	102.400
4.200	102.600

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DATE DUE

JAN 20 1993			