End-to-End Jitter and Wander Requirements for ResE Applications

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Outline

- Introduction
- Jitter and Wander Definitions
- Jitter and Wander Performance requirements
- Inter-Stream Synchronization Requirements
- Next Steps
- Summary of Requirements
- Backup
  - Jitter and wander
  - Detailed derivation of MTIE masks
  - References

Introduction

- This is the third of three related VG presentations
  1) Description of ResE Video Applications and Requirements
  2) Description of ResE Audio Applications and Requirements
  3) Jitter and Wander Requirements for ResE Applications
- This presentation considers jitter and wander requirements
  - Also have requirement for absolute delay for interactive A/V applications
    - While this is not a jitter or wander requirement, it is a timing requirement
    - This requirement is not addressed in this presentation
- More detailed material is contained in the backup slides
  - General description of jitter and wander
  - Jitter and wander performance parameters
  - Detailed derivation of MTIE (Maximum Time Interval Error) masks
  - References
- For convenience, each presentation contains the complete (i.e., combined) reference list for all three presentations

Jitter and Wander Definitions

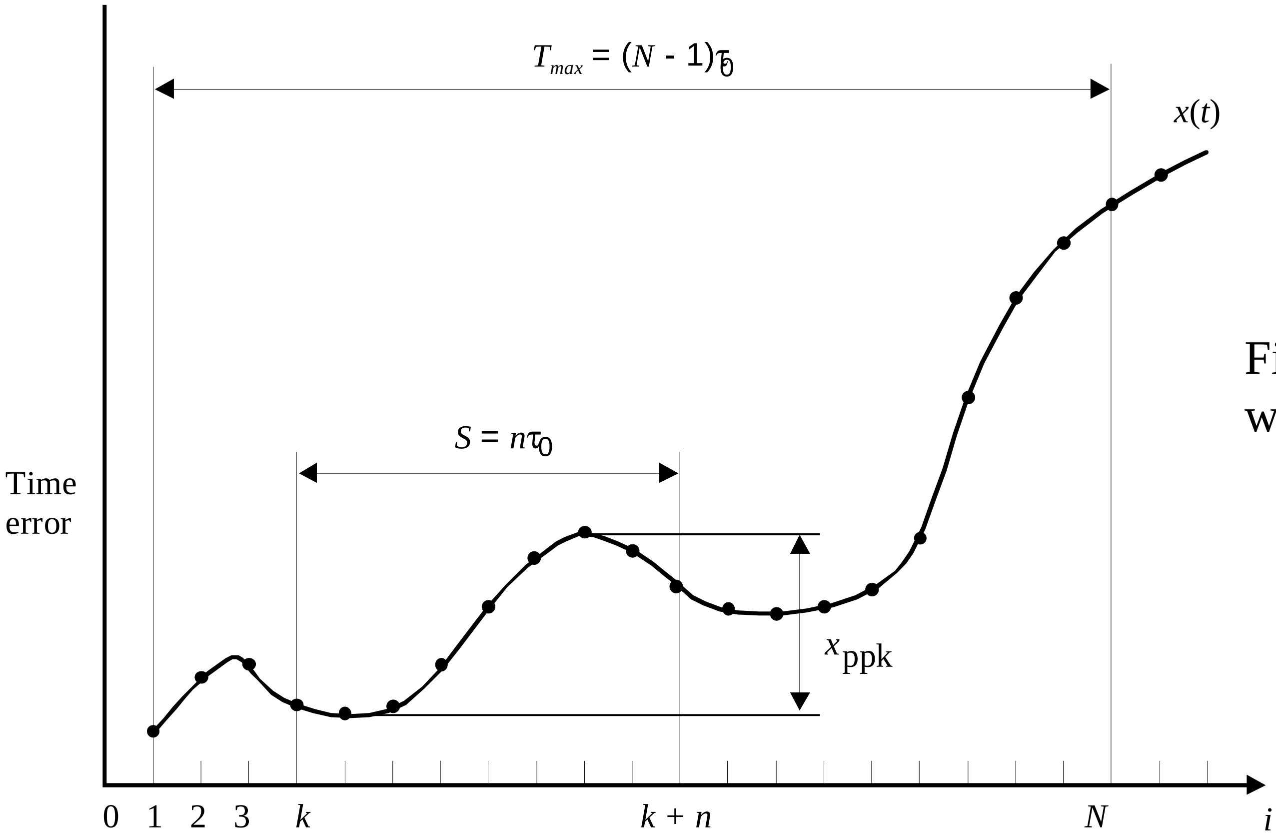
- Phase offset (also called *phase variation* or *time delay*)
  - The phase or time difference between the actual time of an event and its ideal (or nominal) time
  - May be expressed in units of time (e.g., s), UI, rad, degrees, etc.
  - Strictly speaking, it is a discrete-time process $x[n]$ (phase offset of n^{th} event
- Jitter – short-term variation in phase offset
  - Generally, short-term means variation with frequency content $\geq$ 10 Hz
  - In most application, a high-pass jitter measurement filter is specified
  - Jitter is a function of time (i.e., a waveform; often consider peak-to-peak or rms value)
- Wander – long-term variation in phase offset
  - Long-term means variation with frequency content < 10 Hz

Jitter and Wander Definitions (Cont.)

❑Maximum Time Interval Error (MTIE)

- MTIE is peak-to-peak phase variation for a specified observation interval, expressed as a function of the observation interval
- For a phase history measurement of length T_{max} and observation interval S, MTIE(S) is maximum of the peak-to-peak phase variations over all intervals of length S contained in T_{max}
- See figure on next slide (taken from [35])
- Rigorous mathematical definition, as well as expression for confidence interval for MTIE estimate, given in backup slides

Illustration of MTIE Definition



τ_0 = sampling interval
S = observation interval
T_{max} = measurement interval
x_i = the i^{th} phase error sample
x_{ppk} = peak-to-peak x_i within k^{th} observation
MTIE(S) = the maximum x_{pp} for all observations of length τ within T_{max}

Figure taken from [35], with minor modifications

Jitter and Wander Definitions (Cont.)

- Fractional frequency offset *y* – the fractional deviation of the actual frequency ν from the nominal frequency ν_0

$$y = \frac{\nu - \nu_0}{\nu_0}$$

- MTIE for a process that has constant fractional frequency offset *y* is
  - MTIE(*S*) = *yS*
- Frequency drift rate *D* – the rate of change of actual frequency with time
- MTIE for a process that has frequency drift rate *D* is

$$\mathrm{MTIE}(S) = \frac{1}{2} D S^2$$

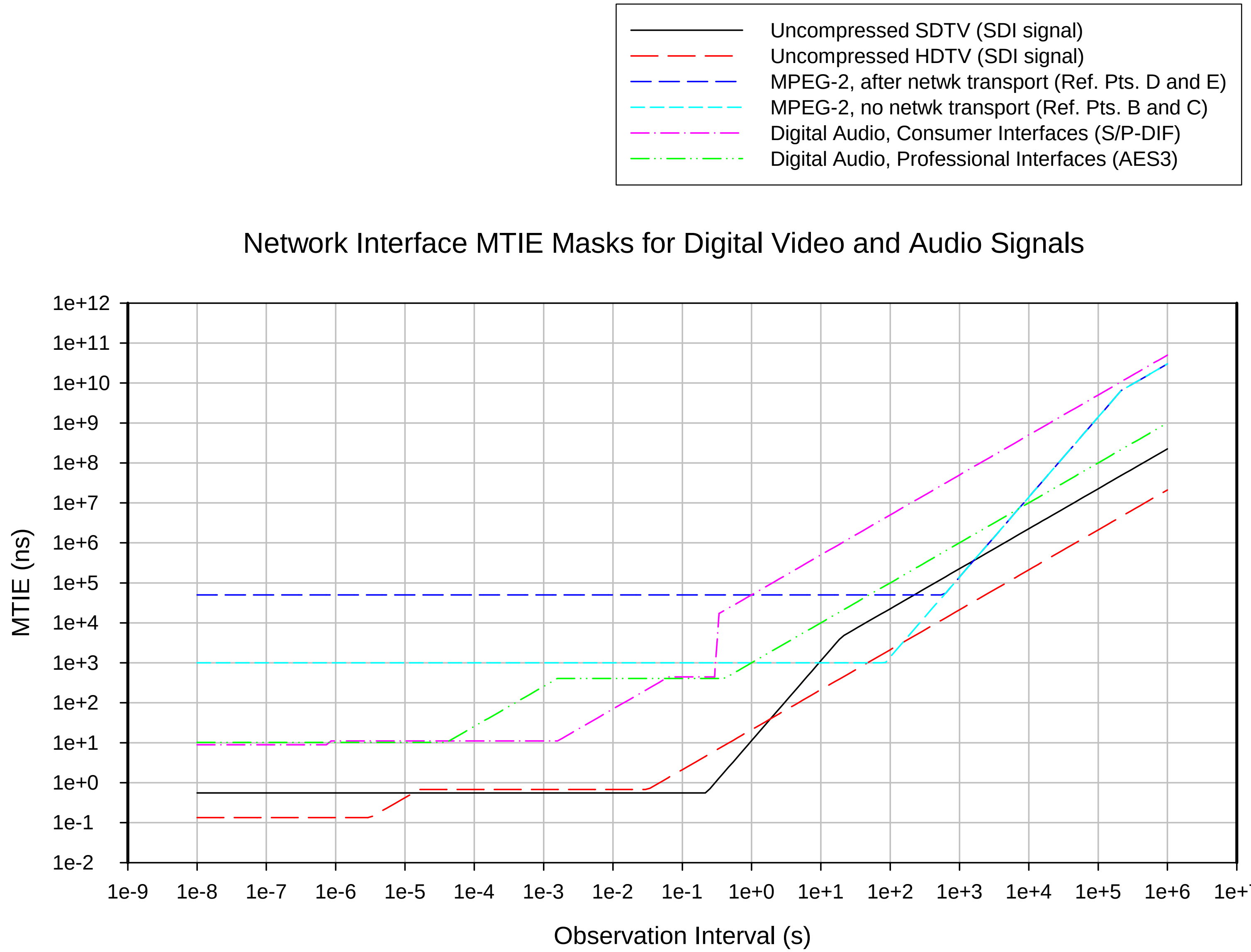
Jitter and Wander Definitions (Cont.)

- Jitter tolerance – often expressed using sinusoidally varying phase offset
  - This is conservative because sinusoidal jitter is closer to its positive and negative peak values for a greater fraction of time compared with more realistic jitter distributions (e.g., Gaussian)
  - A sinusoidal jitter tolerance mask is constructed by giving, for each phase offset frequency, the peak-to-peak amplitude signal that must be tolerate by any equipment at the network interface where the jitter occurs
  - Typical sinusoidal jitter tolerance masks have regions with –20 dB/decade slope (of peak-to-peak sinusoidal amplitude versus frequency) followed by flat-level
    - The corner point where the slope and flat level meet is the bandwidth of a corresponding high-pass jitter measurement filter
    - The flat level is a corresponding network limit
    - See backup slides for detailed derivation
- An MTIE mask MTIE(*S*) can be turned into an equivalent sinusoidal jitter tolerance mask using the transformation
  - $S \rightarrow 1/(\pi f)$
  - See backup slides for detailed derivation

Jitter and Wander Performance Requirements

- MTIE masks were derived for the following signals from the respective requirements on jitter, frequency offset, and frequency drift
  - Uncompressed SDTV (SDI signal)
  - Uncompressed HDTV (SDI signal)
  - MPEG-2, Reference Interface D, E (after transport across a network)
  - MPEG-2, Reference Interface B, C (no transport across a network)
  - Digital Audio, Consumer Interfaces (S/P-DIF)
  - Digital Audio, Professional Interfaces (AES3)
  - MTIE masks are shown on following slide
- Requirements are most stringent for uncompressed video signals (digitized NTSC, PAL, SDTV component video, HDTV component video)
- Requirements are least stringent for MPEG-2 video
- Requirements for digital audio are in between those for uncompressed and MPEG-2 video
- **Note that these requirements are network limits; ResE gets only a budget allocation of these limits**
- **Note also that these requirements do not include inter-stream synchronization limits (described shortly)**

Jitter and Wander Performance Requirements (Cont.)



Inter-Stream Synchronization Requirements

- The jitter, wander, and synchronization requirements described in the previous slides (given in the form of MTIE masks) are for single audio or video streams
- In general, a multi-media stream may contain multiple audio and/or video streams, possibly transported to different locations, e.g.
  - Multiple audio tracks from the same program transported to speakers in different locations
  - The same audio track transported to multiple speakers simultaneously
  - Voice and corresponding video streams from the same program being played simultaneously (lip-synch)
  - Video animation with accompanying audio
  - Other examples are given in [42]
- When multiple audio/video streams are present, the presentation times must be synchronized to within respective thresholds for acceptable Quality of Service (QoS)
  - The skew defined as the offset of one stream relative to another related stream, relative to the ideal timing relationship of the two streams
- Reference [42] describes the results of experiments that investigated the maximum skews that could be tolerated for various types of related streams before degradation in QoS would be perceived

Inter-Stream Synchronization Requirements

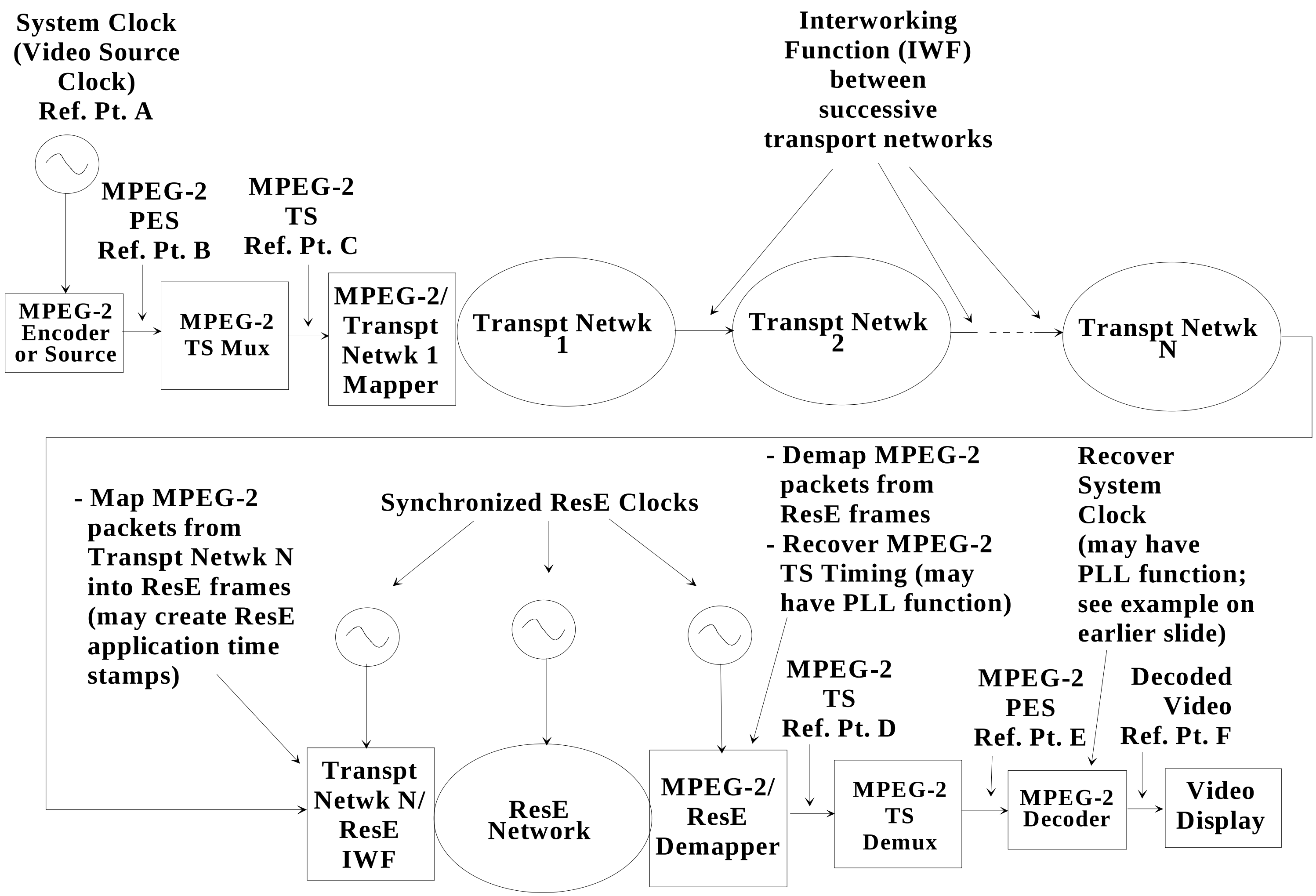
- Results from [42] – required synchronization of different audio/video streams for acceptable QoS
  - Tightly coupled audio (e.g., audio streams delivered to multiple speakers)
    - ±10 μs
  - Lip-synch
    - ±80 ms
  - Video animation with accompanying audio
    - ±80 ms
  - Other examples, and detailed description of experiments, given in [42]

Next Steps

- Develop more detailed Reference Models for video and audio applications, and allocate jitter/wander/synchronization requirements to the ResE network
  - For MPEG-2 video, input will be needed on allocation of jitter and wander requirements to possible service/content provider networks, in order to know what budget component is available for ResE
    - Reference model from VG presentation 1 showing transport across service provider networks and ResE is reproduced on following slide
    - Indicated in presentation 1that MPEG-2 is developed by ISO JTC1/SC29 and by ITU-T SG 16, Q 6
      - Question: Have these groups (or any other group) budgeted jitter and wander to various networks for the case where MPEG-2 is transported across multiple service/content provider networks?
      - If they have not, then how is is ensured that accumulated jitter and wander across a number of transport networks is within limits?
  - For audio, detailed reference models of the sort considered in [43] must be developed
    - Have jitter and wander accumulation in the audio processing devices (e.g., digital mixers, etc.), which depends on jitter generation and transfer (both transfer bandwidth and gain peaking) in these devices
    - Also have jitter and wander generation and accumulation each time a ResE is traversed
  - Likely result will be MTIE masks for ResE that are below the network limit masks developed here

MPEG-2 Transport Across a Network

- Transport across one or more video service provider networks to residence, followed by transport across ResE



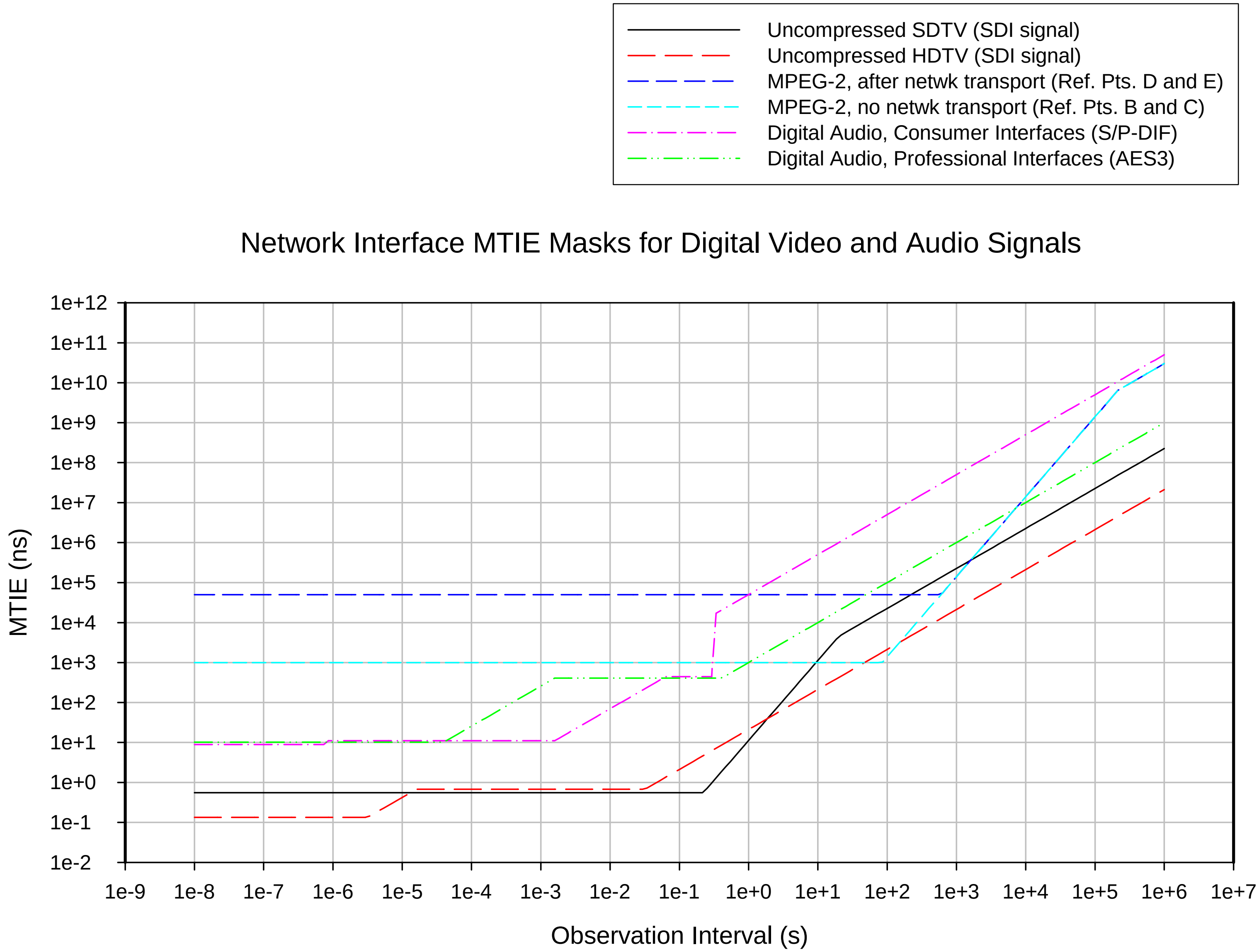
Next Steps (Cont.)

- Develop requirements for any additional applications of interest
  - E.g., MPEG-4
  - Any additional applications and/or network services
- Examine and analyze different approaches for transporting both synchronization and traffic, and compare with existing Ethernet
  - Once detailed requirements (MTIE masks) for ResE are developed, can then perform simulations and analytical calculations of jitter and wander accumulation across ResE, for existing Ethernet and for various ResE network architectures and assumptions

Summary of Jitter/Wander/Synchronization Requirements

Requirement	Uncompressed SDTV	Uncompressed HDTV	MPEG-2, with network transport	MPEG-2, no network transport	Digital audio, consumer interface	Digital audio, professional interface
Wide-band jitter (UIpp)	0.2	1.0	50 µs peak-to-peak phase variation requirement (no measurement filter specified)	1000 ns peak-to-peak phase variation requirement (no measurement filter specified)	0.25	0.25
Wide-band jitter meas filt (Hz)	10	10			200	8000
High-band jitter (UIpp)	0.2	0.2			0.2	No requirement
High-band jitter meas filt (kHz)	1	100			400 (approx)	No requirement
Frequency offset (ppm)	±2.79365 (NTSC) ±0.225549 (PAL)	±10	±30	±30	±50 (Level 1) ±1000 (Level 2)	±1 (Grade 1) ±10 (Grade 2)
Frequency drift rate (ppm/s)	0.027937 (NTSC) 0.0225549 (PAL)	No requirement	0.000278	0.000278	No requirement	No requirement

Summary - Network Interface MTIE Masks



Summary -- Inter-Stream Synchronization Requirements

- Tightly coupled audio (e.g., audio streams delivered to multiple speakers)
  - ±10 μs
- Lip-synch
  - ±80 ms
- Video animation with accompanying audio
  - ±80 ms
- Additional examples and requirements given in [42]

Thank You

Backup

Jitter and Wander

General description, and definitions of performance parameters

Jitter and Wander Performance Parameters

- ❑ Only those definitions and parameters that are needed here are covered
  - See [35] and [36] for more detail and a more exhaustive treatment of jitter and wander performance measures
- ❑ Consider a discrete event process whose events occur at a nominally constant, average rate, but where the actual event times may deviate from the nominal times
  - t_n = actual time of n^{th} event
  - T_0 = nominal time between events (nominal period)
  - ν_0 = nominal frequency = $1/T_0$
  - nT_0 = nominal time of the n^{th} event
- ❑ Define the phase offset $x[n]$ or phase variation for the n^{th} event
  - $x[n] = t_n - nT_0$
- ❑ Strictly speaking, $x[n]$ is a discrete process
  - If the sampling rate is low compared to the underlying event rate, sometimes consider phase offset to be a function of continuous time t
  - If this is done, must ensure that (1) have applied the appropriate anti-aliasing filter prior to sampling, and (2) the precision with which t is expressed is not smaller than T_0

Jitter and Wander Performance Parameters (Cont.)

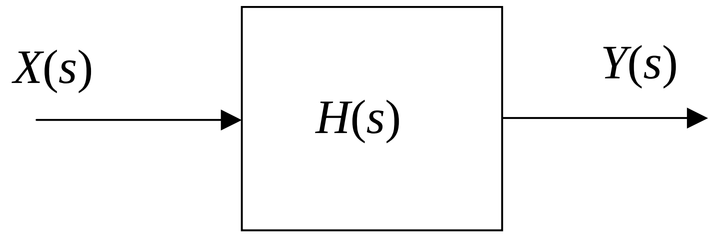
❑Jitter (also referred to as *timing jitter*)

- The short-term variations in $x[n]$
- Generally, *short-term variation* is taken to mean variation with frequency content of 10 Hz or greater
- However, in most applications a high-pass jitter measurement filter is specified; its bandwidth depends on the application and is usually different from 10 Hz
  - For clock recovery circuits, the jitter defined in this manner represents the offset between the ideal sampling time and the recovered sampling time, and is referred to as the *alignment jitter*
  - In general, the jitter is the error signal between the input and output of a low-pass filter that has $x[n]$ applied at the input
    - Can show this (see next slide) by noting that, if $H(s)$ is the transfer function between input and output for a low-pass filter, the transfer function between the error signal (input minus output) and input is $1 - H(s)$, which is a high-pass filter
- Note that if one works with the discrete process $x[n]$, the resulting digital jitter measurement filter depends on sampling time T

❑Wander

- The long-term variations in $x[n]$
- Generally, *long-term variation* is taken to mean variation with frequency content less than 10 Hz

Jitter and Wander Performance Parameters (Cont.)



- $H(s)$ is a low-pass filter
- $Y(s) = H(s)X(s)$
- Define error signal
  - $E(s) = X(s) – Y(s)$
- Then
  - $E(s) = X(s) – H(s)X(s) = [1 – H(s)] X(s)$
- Note that $1 – H(s)$ is a high-pass filter, e.g.
  - If $H(s) = a/(s + a)$, then $1 – H(s) = s/(s + a)$
  - If

$$H(s) = \frac{2\xi\omega_n s + \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2},$$

then

$$1 - H(s) = \frac{s^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

Jitter and Wander Performance Parameters (Cont.)

❑Peak-to-peak jitter over a time interval

- The difference between the maximum jitter value over the time interval and the minimum jitter value over the time interval
  - In defining the maximum and minimum values here, the sign of the jitter must be accounted for; the minimum is the algebraically smallest value
- The high-pass jitter measurement filter must be specified
- The time interval should be specified, but often isn't
  - In practice, this is not a problem because the high-pass filter causes the jitter process to quickly reach a steady-state; actual time interval must be long compared to time constant of the high-pass filter
    - Often a 60 s measurement interval is used
    - Since jitter measurement filter bandwidths are 10 Hz or greater and, consequently, the respective time constants are less than 0.1 s, a 60 s measurement interval is sufficient
- Strictly speaking, the maximum and minimum values should be specified quantiles of a distribution since, often, jitter has a random component
  - In practice, peak-to-peak jitter is evaluated for one or a few measurement time-history samples
  - If we are doing simulations, it is possible to make a sufficient number of statistically independent replications of the same simulation case

Jitter and Wander Performance Parameters (Cont.)

- Maximum Time Interval Error (MTIE)
  - MTIE is peak-to-peak phase variation for a specified observation interval, expressed as a function of the observation interval
  - The discussion below on MTIE is taken from [37]
- Let $x(t)$ be the phase variation at time t (where we approximate the discrete index n by the continuous index t as indicated above
- Assume that data has been collected over total time interval $0 \le t \le T_{max}$
- Let S be a time interval, referred to as the *Observation Interval*, with $0 \le S \le T_{max}$
- Define the random variable $X(S)$ as

$$X(S) = \max_{0 \le t_0 \le T_{\max} - S} \left(\max_{t_0 \le t \le t_0 + S} [x(t)] - \min_{t_0 \le t \le t_0 + S} [x(t)] \right)$$

- Then MTIE(S) is defined as a specified percentile, β, of $X(S)$

Jitter and Wander Performance Parameters (Cont.)

- Reverting to the case where *x*(*n*) is sampled (but using parentheses rather than brackets to indicate that the sampling rate may be less than the event (e.g., bit, packet, etc.) rate, and assuming only one measurement time history, an estimate of MTIE is given by

$$\mathrm{MTIE}(n\tau_0) \cong \max_{1 \le k \le N-n} \left(\max_{k \le i \le k+n} x(i) - \min_{k \le i \le k+n} x(i) \right), \quad n = 1, 2, \ldots, N-1$$

- See the figure on the next slide for an illustration of MTIE calculation (taken from [35])

Jitter and Wander Performance Parameters (Cont.)

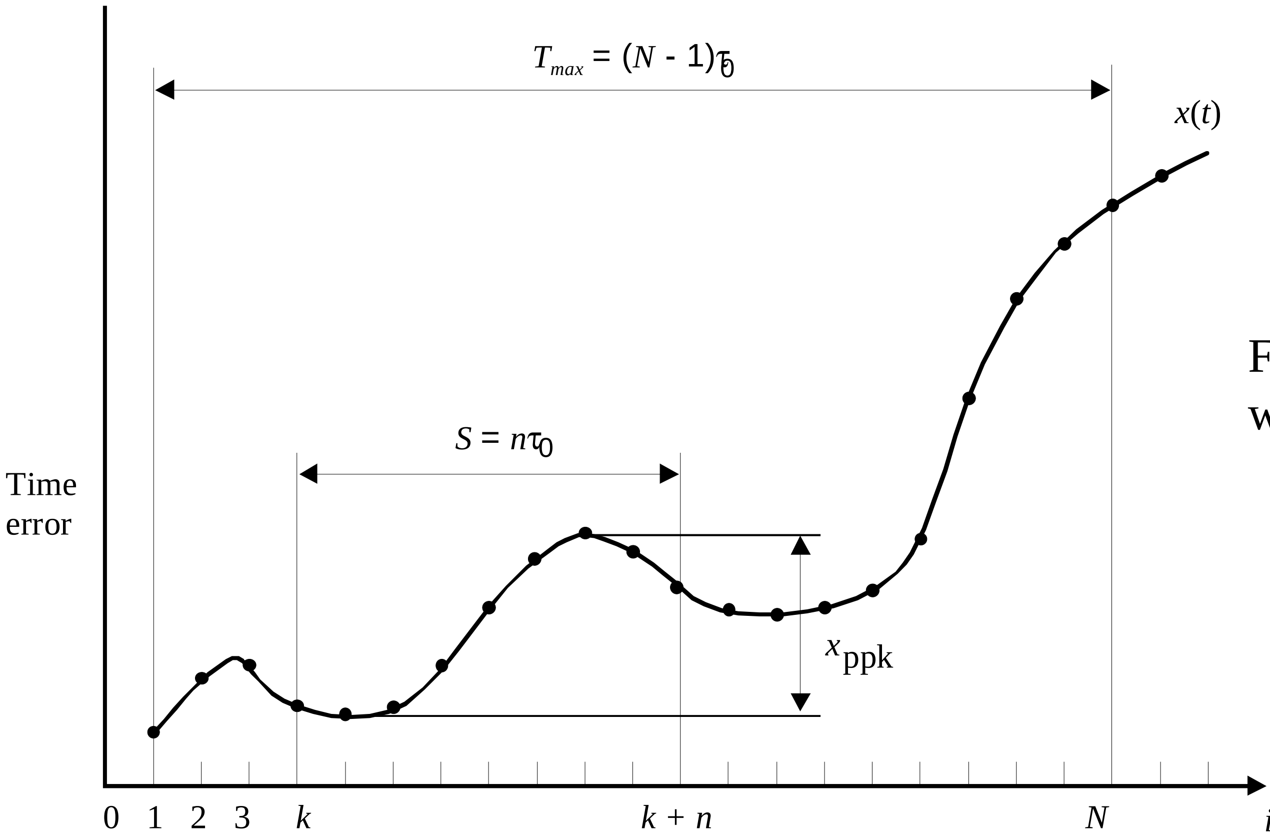


Figure taken from [35], with minor modifications

τ_0 = sampling interval
S = observation interval
T_{max} = measurement interval
x_i = the i[th] phase error sample
x_{ppk} = peak-to-peak x_i within k^{th} observation
MTIE(S) = the maximum x_{pp} for all observations of length τ within T_{max}

Jitter and Wander Performance Parameters (Cont.)

- A confidence interval for a specified quantile of *X*(*S*) may be estimated from multiple time history measurements [35]
  - Let $X_1, X_2,...X_M$ be a set of independent measurement samples of MTIE, for an interval of length *S*, for *M* measurement periods each of length T_{max}
  - Assume that the samples have been put in ascending order, i.e.

$$X_1 \le X_2 \le ... \le X_M$$

  - Let x_β be the β^{th} quantile of *X*

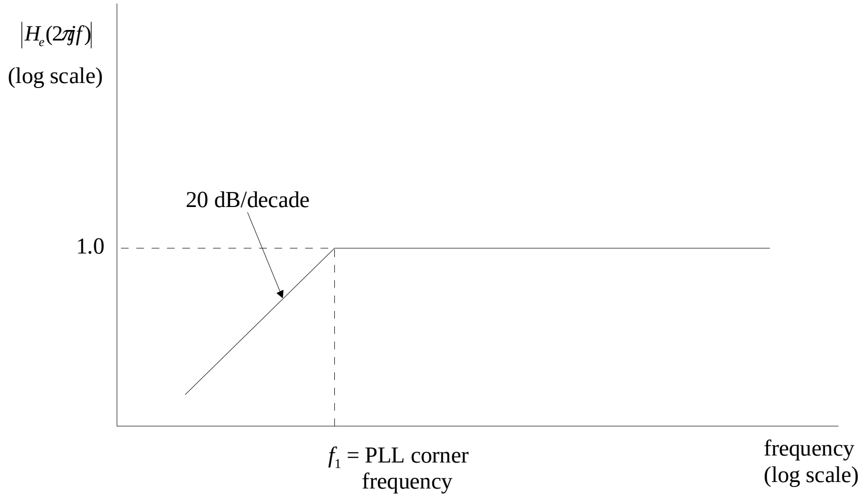
- Then a confidence interval for x_β, expressed as the probability that x_β falls between samples X_r and X_s (with $r < s$), is given by

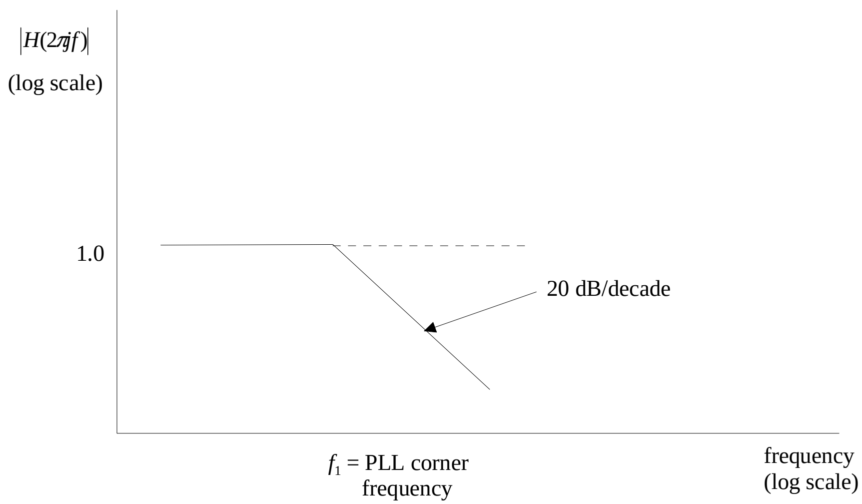
$$P\{X_r \le x_\beta \le X_s\} = \sum_{k=r}^{s-1} \frac{M!}{k!(M-k)!} \beta^k (1-\beta)^{M-k}$$

Jitter and Wander Performance Parameters (Cont.)

- Sinusoidal jitter tolerance and relation to jitter high-pass measurement filter
  - Jitter tolerance is often expressed using sinusoidally-varying phase offset
  - This is conservative because sinusoidal jitter is closer to its positive and negative peak values for a greater fraction of time compared with more realistic jitter distributions (e.g., Gaussian)
  - A sinusoidal jitter tolerance mask is constructed by giving, for each phase offset frequency, the peak-to-peak amplitude signal that must be tolerate by any equipment at the network interface where the jitter occurs
- We stated earlier that the jitter, defined as the output of a specified high-pass measurement filter that has the phase offset applied to the input, represents the difference between the input and output of a low-pass filter of the same bandwidth
- Suppose a piece of equipment at the interface is consistent with the jitter measurement filter, i.e., the equipment has low-pass bandwidth equal to the jitter measurement filter bandwidth
- Then if the transfer function of the equipment is $H(s)$, the transfer function of the jitter measurement filter is $H_e(s) = 1 - H(s)$
- The frequency response of $H(s)$ and $H_e(s)$ are shown on the next slide for the case where both are first-order filters

Jitter and Wander Performance Parameters (Cont.)





$$H(s) = \frac{a}{s+a}$$

$$a = 2\pi f_1 \quad (f_1 = \text{corner frequency})$$

$$\left|H(2\pi jf)\right| = \frac{f_1}{\sqrt{f^2 + f_1^2}}$$

$$H_e(s) = 1 - H(s) = \frac{s}{s+a}$$

$$\left|H_e(2\pi jf)\right| = \frac{f}{\sqrt{f^2 + f_1^2}}$$

Jitter and Wander Performance Parameters (Cont.)

- Let the input signal be sinusoidal with peak-to-peak amplitude $A_0(f)$ (i.e., the input may depend on the frequency of the sinusoid)
- Then the amplitude of the resulting phase error signal is

$$A_e(f) = \left|H_e(2\pi jf)\right| A_0(f) = \frac{fA_0(f)}{\sqrt{f^2 + f_1^2}}$$

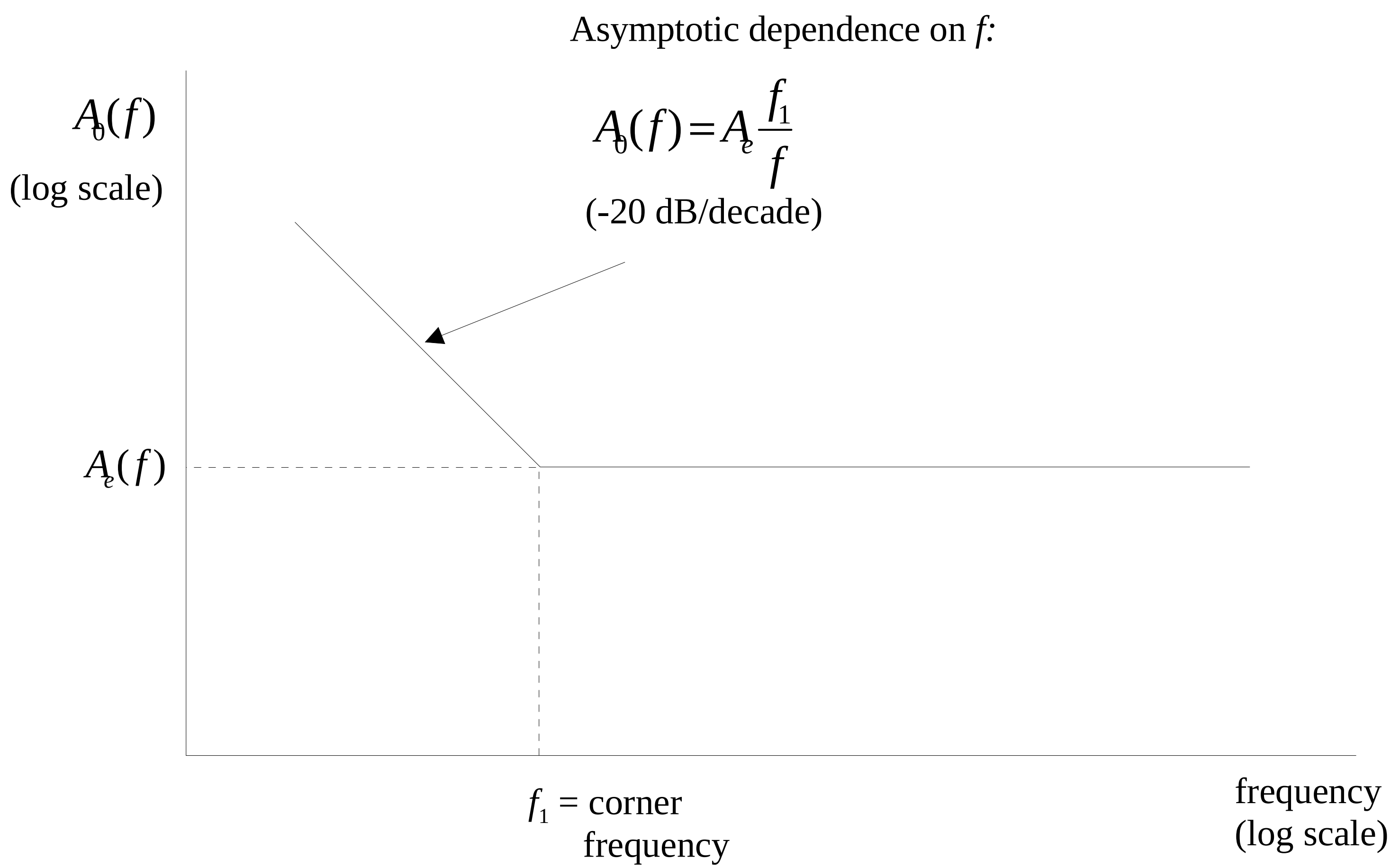
- Therefore

$$A_0(f) = \frac{\sqrt{f^2 + f_1^2}}{f} A_e(f)$$

- Now set $A_e(f)$ equal to the largest amount of phase error the receiving equipment at the interface can tolerate
  - $A_e(f)$ does not depend on frequency, and therefore $A_0(f)$ does depend on frequency
  - $A_0(f)$is shown schematically on the following slide

Jitter and Wander Performance Parameters (Cont.)

❑Form of jitter/wander tolerance mask



Jitter and Wander Performance Parameters (Cont.)

❑Relation between sinusoidal jitter tolerance and MTIE

- Form of sinusoidal input with peak-to-peak amplitude A_0 and frequency f
- $x(t) = (A_0/2)\sin(2\pi ft)$
- MTIE of this phase variation is

$$
\begin{aligned}
&\text{For } S < 1/(2f) \\
&\text{MTIE}(S; A_0, f) = x(S/2) - x(-S/2) \\
&\qquad = \frac{A_0}{2}\sin(\pi fS) - \frac{A_0}{2}\sin(-\pi fS) \\
&\qquad = A_0 \sin(\pi fS) \\
&\text{For } S \geq 1/(2f) \\
&\text{MTIE}(S) = A_0
\end{aligned}
$$

- Need to find a curve MTIE(S) that is an envelope of the above family of curves, for all f

Jitter and Wander Performance Parameters (Cont.)

Relation between sinusoidal jitter tolerance and MTIE (Cont.)

- For $f < f_1$, $A_0 = A_e f_1 / f$

$$\text{For } S < 1/(2f)$$

$$\text{MTIE}(S; A_e f_1, f) = \frac{A_e f_1}{f} \sin(\pi f S)$$

$$\text{For } S \geq 1/(2f)$$

$$\text{MTIE}(S; A_e f_1, f) = \frac{A_e f_1}{f}$$

- For $f \geq f_1$, $A_0 = A_e$

$$\text{For } S < 1/(2f)$$

$$\text{MTIE}(S; A_e f_1, f) = A_e \sin(\pi f S)$$

$$\text{For } S \geq 1/(2f)$$

$$\text{MTIE}(S; A_e f_1, f) = A_e$$

Jitter and Wander Performance Parameters (Cont.)

❑Relation between sinusoidal jitter tolerance and MTIE (Cont.)

- It turns out this curve has the form

$$\mathrm{MTIE}(S) = \begin{cases} A_e & S < 1/(\pi f_1) \\ A_e \pi f_1 S & S \geq 1/(\pi f_1) \end{cases}$$

- This may be shown by plotting the above MTIE curve along with the family MTIE(S; A_0, f), and showing that the latter lie below the former (the method is outlined in [40] and [41])
  - This is done on the next slide, using Mathcad (following [40] and [41])

❑Therefore, to find an MTIE mask equivalent to a given sinusoidal tolerance mask

- $S \rightarrow 1/(\pi f)$
- Flip the mask about a vertical axis so that S is increasing to the right

Jitter and Wander Performance Parameters (Cont.)

$f1 := 1.0$

$Ae := 1.0$

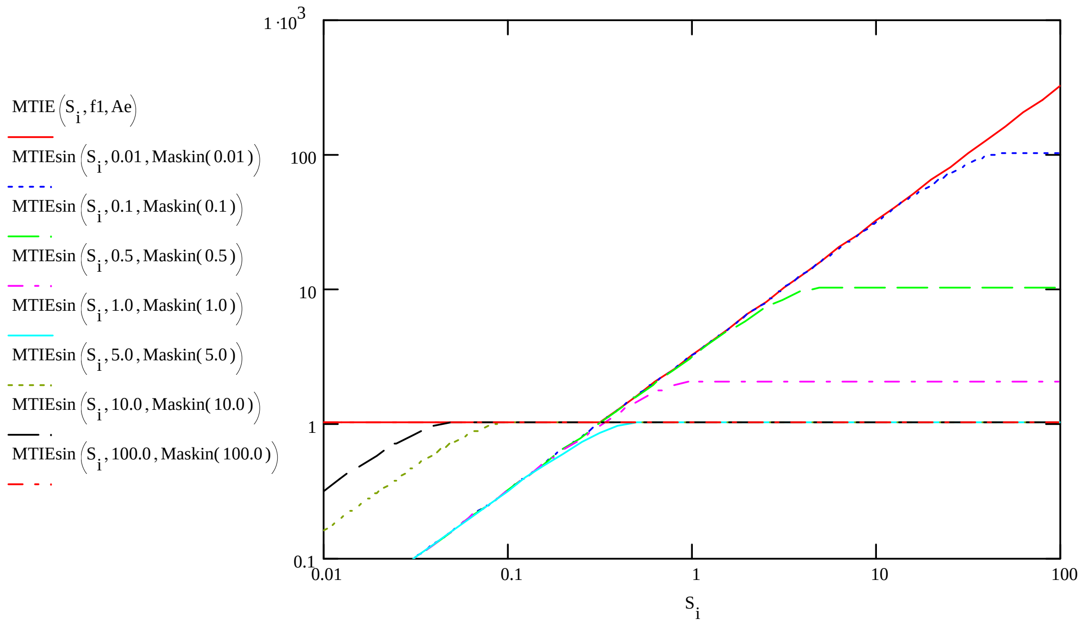
$i := 0, 1 .. 40$

$S_i := 0.01 \cdot 10^{\frac{i}{10}}$

$$MTIE(S, f11, Ae1) := if\left(S < \frac{1}{\pi \cdot f11}, Ae1, Ae1 \cdot \pi \cdot f11 \cdot S\right)$$

$$MTIEsin(S, f, A) := if\left(S < \frac{0.5}{f}, A \cdot \sin(\pi \cdot f \cdot S), A\right)$$

$$Maskin(f) := if\left(f < f1, Ae \cdot \frac{f1}{f}, Ae\right)$$



Jitter and Wander Performance Parameters (Cont.)

❑Frequency offset

- Let the discrete event process described at the outset have frequency ν, which differs from ν_0
- Let the time between successive events be $T = 1/\nu$, which differs from T_0
- The fractional frequency offset, *y*, is defined as

$$y = \frac{\nu - \nu_0}{\nu_0}$$

- The phase offset is given by (the negative sign arises in the last term because $T > T_0$ means that $\nu < \nu_0$

$$x[n] = nT - nT_0 = nT\left(1 - \frac{T_0}{T}\right) = nT\left(1 - \frac{\nu}{\nu_0}\right) = -nTy$$

- Replacing *nT* by the observation interval *S*, MTIE for a frequency offset becomes
  - MTIE(*S*) = *yS*

Jitter and Wander Performance Parameters (Cont.)

❑Frequency offset – alternate derivation of MTIE

- Consider a sinusoidal phase variation with peak-to-peak amplitude *A* and frequency *f*
- $x(t) = (A/2) \sin (2\pi f t)$
- The instantaneous frequency offset, $y(t)$, is the derivative of $x(t)$

$$y(t) = \dot{x}(t) = \pi A f \cos 2\pi f t$$

- Then the maximum magnitude (absolute value) of frequency offset is

$$y_{\max} = \pi A f$$

  - Note that the instantaneous frequency offset varies between $+y_{max}$ and $-y_{max}$
- Then an equivalent sinusoidal phase tolerance mask, $A(f)$, corresponding to maximum frequency offset y_{max}, is

$$A(f) = \frac{y_{\max}}{\pi f}$$

- The equivalent MTIE mask, which agrees with the result on the previous slide, is obtained by letting $f \rightarrow 1/(\pi S)$

$$\mathrm{MTIE}(S) = y_{\max} S$$

Jitter and Wander Performance Parameters (Cont.)

- Frequency drift
  - Consider a process where the frequency of events is changing at a uniform rate *D*
    - The units of *D* may be Hz/s, ppm/s, UI/s^2, rad/s^2, etc.
  - The phase variation is quadratic

$$x(t) = \frac{1}{2} D t^2$$

- Problem with computing MTIE from quadratic phase variation
  - Faster variation at larger times masks slower variation at earlier times
  - If $t \in [0, \infty)$, then MTIE(*S*) diverges for all *S*
- Therefore, use the alternate approach of the previous slide to obtain MTIE, by considering sinusoidal phase variation
  - Consider a sinusoidal phase variation with peak-to-peak amplitude *A* and frequency *f*
  - $x(t) = (A/2) \sin(2\pi f t)$

Jitter and Wander Performance Parameters (Cont.)

❑Frequency drift (Cont.)

- The instantaneous frequency drift is the 2nd derivative of $x(t)$

$$D(t) = -2\pi^2 f^2 A \sin 2\pi f t$$

- The maximum absolute value of frequency drift is

$$D_{\max} = 2\pi^2 f^2 A$$

- Then an equivalent sinusoidal phase tolerance mask, $A(f)$, corresponding to maximum frequency drift D_{max}, is

$$A(f) = \frac{D_{\max}}{2\pi^2 f^2}$$

- The equivalent MTIE mask is obtained by letting $f \rightarrow 1/(\pi S)$

$$\text{MTIE}(S) = \frac{1}{2} D_{\max} S^2$$

Jitter and Wander Performance Parameters (Cont.)

- MTIE equivalent to jitter network limit
  - Consider a requirement on peak-to-peak jitter
  - A_0 = peak-to-peak jitter limit
  - f_1= high-pass jitter measurement filter
- It was shown earlier that the equivalent sinusoidal jitter tolerance mask has breakpoint f_1, is asymptotically flat at level A_0 for $f \geq f_1$, and has a –20 dB/decade slope for $f < f_1$, i.e.,

$$A(f) = \begin{cases} \dfrac{A_0 f_1}{f} & f < f_1 \\ A_0 & f \geq f_1 \end{cases}$$

- The equivalent MTIE is obtained by letting $f \rightarrow 1/(\pi S)$

$$\mathrm{MTIE}(S) = \begin{cases} A_0 & S \leq \dfrac{1}{\pi f_1} \\ A_0 \pi f_1 S & S > \dfrac{1}{\pi f_1} \end{cases}$$

Detailed Derivations of MTIE Masks

Jitter and Wander Performance Requirements

- Requirements were given previously for jitter, maximum frequency offset, and maximum frequency drift, for video signals
  - Uncompressed (SDI) digital video
    - Both SDTV and HDTV signals, at network interface
  - MPEG-2 video
    - Input to MPEG-2 decoder (Reference Points D and E in earlier slide showing reference model)
- Requirements were given previously for digital audio in form of sinusoidal jitter tolerance mask
  - Both consumer and professional interfaces
- We will now construct equivalent MTIE masks for each of the sets of requirements
  - Requirements will be expressed in units of time (rather than UI)

Jitter and Wander Performance Requirements (Cont.)

❑Uncompressed digital video – SDTV

- Jitter requirement – A_0 = 0.2 UIpp
  - Both wide-band (10 Hz) and high-band (1 kHz)
    - Most stringent breakpoint on MTIE mask corresponds to the 10 Hz filter; breakpoint is 1/[π(10 Hz)] = 0.0318 s
  - Most stringent requirement is obtained for highest rate – 360 Mbit/s

    A_0 = 0.2 UI = 0.5556 ns
- Most stringent frequency offset requirement
  - y = 0.225549 ppm = 2.25549 × 10^{-7} = 225.549 ns/s
- Most stringent frequency drift requirement
  - D = 0.0225549 ppm/s = 2.25549 × 10^{-8} s^{-1} = 22.5549 ns/s^2
- Intersection between frequency offset and frequency drift MTIE curves
  - $yS = 0.5DS^2$, which implies
  - $S_{break} = 2y/D$ = 20 s
- Intersection between frequency drift and jitter flat level curves
  - $A_0 = 0.5DS^2$, which implies

$$S_{break} = \sqrt{2A_0 / D} = \sqrt{\frac{2(5.556\times 10^{-10}\ \text{s})}{2.25549\times 10^{-8}\ \text{s}^{-1}}} = 0.22196\,\text{s}$$

Jitter and Wander Performance Requirements (Cont.)

❑Uncompressed digital video – SDTV (Cont.)

- The jitter flat level intersects with the frequency drift curve at a larger observation interval than that corresponding to the jitter measurement filter breakpoint; therefore, this is more stringent
- Then the MTIE mask is

$$\mathrm{MTIE}(S) = \begin{cases} 0.5556\ \mathrm{ns} & S < 0.22196\ \mathrm{s} \\ 11.27745 S^2\ \mathrm{ns} & 0.22196\ \mathrm{s} \le S < 20\ \mathrm{s} \\ 225.549 S\ \mathrm{ns} & S \ge 20\ \mathrm{s} \end{cases}$$

- The MTIE mask is plotted along with others on a subsequent slide

Jitter and Wander Performance Requirements (Cont.)

- Uncompressed digital video – HDTV
  - Wide-band jitter requirement – A_0 = 1.0 UIpp
  - 10 Hz high-pass measurement filter
    - Breakpoint is 1/[π(10 Hz)] = 0.0318 s
    - Most stringent requirement is obtained for highest rate – 1.485 Gbit/s

      A_0 = 1.0 UI = 0.6734 ns
  - High-band jitter requirement – A_1 = 0.2 UIpp
  - 100 kHz high-pass measurement filter
    - Breakpoint is $1/[\pi(10^5 \text{ Hz})] = 3.183 \times 10^{-6}$ s
    - Most stringent requirement is obtained for highest rate – 1.485 Gbit/s

      A_1 = 0.2 UI = 0.1347 ns
  - Frequency offset requirement
    - $y = 10$ ppm $= 10^{-5} = 10^4$ ns/s
  - No frequency drift requirement
  - Intersection between frequency offset and wide-band jitter flat level curves
    - $A_0 = yS$, which implies
    - $S_{break} = A_0/y = 6.734 \times 10^{-5}$ s
    - The wide-band jitter measurement filter breakpoint of 0.0318 s is more stringent; therefore, we use that

Jitter and Wander Performance Requirements (Cont.)

❑Uncompressed digital video – HDTV (Cont.)

- Intersection between high-band jitter 20 dB/decade and wide-band jitter flat level curves

$$\frac{A_1 S}{3.183\times10^{-6}\ \mathrm{s}} = A_0$$

$$S = 5(3.183\times10^{-6}\ \mathrm{s}) = 1.592\times10^{-5}\ \mathrm{s}$$

- Then the resulting MTIE mask is

$$\mathrm{MTIE}(S) = \begin{cases} 0.1347\ \mathrm{ns} & S < 3.183\times10^{-6}\ \mathrm{s} \\ 4.231\times10^{4} S\ \mathrm{ns} & 3.183\times10^{-6}\ \mathrm{s} \le S < 1.592\times10^{-5}\ \mathrm{s} \\ 0.6734\ \mathrm{ns} & 1.592\times10^{-5}\ \mathrm{s} \le S < 0.03183\ \mathrm{s} \\ 21.16 S\ \mathrm{ns} & S \ge 0.03183\ \mathrm{s} \end{cases}$$

Jitter and Wander Performance Requirements (Cont.)

❑MPEG-2 Video

- Peak-to-peak phase variation – A_0 = 50 μs = 5.0 × 10^{-5} s
  - No measurement filter given
- Frequency offset requirement
  - y = 30 ppm = 3 × 10^{-5} = 3 × 10^{4} ns/s
- Frequency drift requirement
  - D = 0.000278 ppm/s = 2.78 × 10^{-10} s^{-1} = 0.278 ns/s^2
- Intersection between frequency offset and frequency drift MTIE curves
  - $yS = 0.5DS^2$, which implies
  - $S_{break} = 2y/D$ = 2.158 × 10^5 s
- Intersection between frequency drift and peak-to-peak phase variation flat level curves
  - $A_0 = 0.5DS^2$, which implies

$$S_{break} = \sqrt{2A_0 / D} = \sqrt{\frac{2(5.0\times 10^{-5}\ \mathrm{s})}{2.78\times 10^{-10}\ \mathrm{s}^{-1}}} = 599.8\,\mathrm{s}$$

Jitter and Wander Performance Requirements (Cont.)

❑MPEG-2 Video (Cont.)

- Then the resulting MTIE mask is

$$\mathrm{MTIE}(S) = \begin{cases} 5.0\times 10^{4}\ \mathrm{ns} & S < 599.8\,\mathrm{s} \\ 0.139S^{2}\ \mathrm{ns} & 599.8\,\mathrm{s} \le S < 2.158\times 10^{5}\ \mathrm{s} \\ 3.0\times 10^{4}\ S\ \mathrm{ns} & S \ge 2.158\times 10^{5}\ \mathrm{s} \end{cases}$$

- The above MTIE mask is much less stringent than the mask for uncompressed SDTV and HDTV
  - Mainly because the peak-to-peak phase variation requirement of 50 μs is much less stringent than the corresponding jitter requirements for SDTV and HDTV
- However, we noted earlier that the 50 μs must be allocated among all the transport networks, and ResE will only get a portion of it
- At present, the precise allocation is not known
  - However, for comparison we can examine the 1000 ns (± 500 ns) peak-to-peak phase variation requirement at Interface Reference Points B and C in the reference model
  - We can obtain an MTIE mask based on this limit
  - Eventual MTIE mask will be based on an allocation of the 50 μs

Jitter and Wander Performance Requirements (Cont.)

❑MPEG-2 Video (Cont.)

- Intersection between frequency drift and 1000 ns peak-to-peak phase variation flat level curves
  - $A_0 = 0.5DS^2$, which implies

$$S_{break} = \sqrt{2A_0 / D} = \sqrt{\frac{2(1.0\times 10^{-6}\text{ s})}{2.78\times 10^{-10}\text{ s}^{-1}}} = 84.8\text{ s}$$

- Then the resulting MTIE mask is

$$\text{MTIE}(S) = \begin{cases} 1.0\times 10^{3}\text{ ns} & S < 84.8\text{ s} \\ 0.139S^{2}\text{ ns} & 84.8\text{ s} \le S < 2.158\times 10^{5}\text{ s} \\ 3.0\times 10^{4}\, S\text{ ns} & S \ge 2.158\times 10^{5}\text{ s} \end{cases}$$

Jitter and Wander Performance Requirements (Cont.)

❑ Digital Audio

- Obtain MTIE masks from the previously given sinusoidal jitter tolerance masks and frequency accuracy requirements
  - Use transformation $f \rightarrow 1/(\pi S)$
- Obtain separate MTIE masks for professional and consumer interfaces
- For now, assume a straight encoding of 1 digital audio UI into 1 ResE bit
  - It is possible to encode the 2-bit digital audio UI as 1 ResE bit, and regenerate the preamble at the ResE egress
    - In this case, one could examine not carrying the preamble, and possibly not carrying other overhead
    - For now, we ignore these possibilities
- Note that the resulting mask represents accumulated jitter/wander after transport over reference model consisting of ResE (possibly multiple traverses) and digital audio equipment
  - Therefore, ResE gets only an allocation of the jitter/wander limit shown in the mask

Jitter and Wander Performance Requirements (Cont.)

Digital Audio – Consumer Interfaces

- Use highest rate – 22.5792 Mbit/s
- Highest frequency range flat level
  - A_0 = 0.2 UIpp = 8.858 ns
  - Breakpoint = $1/[\pi(400 \times 10^3\ \text{Hz})] = 7.958 \times 10^{-7}$ s
  - Minimum observation interval = $1/[\pi(1000 \times 10^3\ \text{Hz})] = 3.183 \times 10^{-7}$ s
- Mid-frequency range flat level
  - A_1 = 0.25 UIpp = 11.072 ns
  - Breakpoint = $1/[\pi(200\ \text{Hz})] = 1.592 \times 10^{-3}$ s
- Lowest frequency range flat level
  - A_2 = 10.0 UIpp = 442.9 ns
  - Intersection between flat level and +20 dB/decade slope to next flat level = $1/[\pi(5\ \text{Hz})]$ = 0.06366 s
  - Maximum observation interval = $1/[\pi(1\ \text{Hz})]$ = 0.3183 s

Jitter and Wander Performance Requirements (Cont.)

❑Digital Audio – Consumer Interfaces (Cont.)

- Frequency offset requirement
  - Level 1 (high accuracy) - ±50 ppm
  - Intersection between frequency offset and lowest frequency range flat level curves
  - $A_2 = yS$, which implies
  - $S_{break} = A_2/y = 8.858 \times 10^{-3}$ s
  - Intersection between frequency offset and mid-frequency range flat level curves
  - $A_1 = yS$, which implies
  - $S_{break} = A_1/y = 2.214 \times 10^{-4}$ s
    - This breakpoint occurs at a shorter observation interval than the jitter breakpoint of 1.592×10^{-3} s (see previous slide); therefore, the jitter requirement (on the previous slide) is more stringent (because the MTIE mask would begin to increase sooner due to the frequency offset requirement than due to the jitter requirement)
    - Therefore, need not consider Level 2 (normal accuracy) or level 3, as these are still less stringent
    - Note that the MTIE mask does jump from the A_2 level to the 50 ppm slope at the maximum observation interval for the A_2 level (i.e., at 0.3183 s)

Jitter and Wander Performance Requirements (Cont.)

❑Digital Audio – Consumer Interfaces (Cont.)

- Then the resulting MTIE mask is

$$\mathrm{MTIE}(S) = \begin{cases} 8.858\,\mathrm{ns} & 3.183\times10^{-7}\ \mathrm{s} \le S < 7.958\times10^{-7}\ \mathrm{s} \\ 11.072\,\mathrm{ns} & 7.958\times10^{-7}\ \mathrm{s} \le S < 1.592\times10^{-3}\ \mathrm{s} \\ 6954.8S\ \mathrm{ns} & 1.592\times10^{-3}\ \mathrm{s} \le S < 0.06366\,\mathrm{s} \\ 442.9\,\mathrm{ns} & 0.06366\,\mathrm{s} \le S < 0.3183\,\mathrm{s} \\ 50000S\ \mathrm{ns} & S \ge 0.3183\,\mathrm{s} \end{cases}$$

Jitter and Wander Performance Requirements (Cont.)

❑Digital Audio – Professional Interfaces

- Use highest rate – 24.576 Mbit/s
- Highest frequency range flat level
  - A_0 = 0.25 UIpp = 10.173 ns
  - Breakpoint = $1/[\pi(8 \times 10^3 \text{ Hz})] = 3.979 \times 10^{-5}$ s
  - Minimum observation interval = $1/[\pi(10 \times 10^6 \text{ Hz})] = 3.183 \times 10^{-8}$ s
- Lowest frequency range flat level
  - A_2 = 10.0 UIpp = 406.9 ns
  - Intersection between flat level and +20 dB/decade slope to next flat level = $1/[\pi(200 \text{ Hz})] = 1.5915 \times 10^{-3}$ s
  - Maximum observation interval = $1/[\pi(10 \text{ Hz})]$ = 0.03183 s

Jitter and Wander Performance Requirements (Cont.)

❑Digital Audio – Professional Interfaces (Cont.)

- Frequency offset requirement
  - Grade 1 - ±1 ppm
  - Intersection between frequency offset and lowest frequency range flat level curves
  - $A_2 = yS$, which implies
  - $S_{break} = A_2/y = 0.4069$ s
  - Grade 2 - ±10 ppm
  - Intersection between frequency offset and lowest frequency range flat level curves
  - $A_2 = yS$, which implies
  - $S_{break} = A_2/y = 0.04069$ s
- The Grade 1 requirement is more stringent (because the MTIE mask would begin to increase at longer observation interval compared to the Grade 2 requirement)
- Therefore, the Grade 1 requirement will be used

Jitter and Wander Performance Requirements (Cont.)

❑Digital Audio – Professional Interfaces

- Then the resulting MTIE mask is

$$\mathrm{MTIE}(S) = \begin{cases} 10.173\,\mathrm{ns} & 3.183\times10^{-8}\,\mathrm{s} \le S < 3.979\times10^{-5}\,\mathrm{s} \\ 255667S\,\mathrm{ns} & 3.979\times10^{-5}\,\mathrm{s} \le S < 1.5915\times10^{-3}\,\mathrm{s} \\ 406.9\,\mathrm{ns} & 1.5915\times10^{-3}\,\mathrm{s} \le S < 0.4069\,\mathrm{s} \\ 1000S\,\mathrm{ns} & S \ge 0.4069\,\mathrm{s} \end{cases}$$

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