Simulation Results for 802.1AS Synchronization Transport with Clock Wander Generation and Updated Residence and Pdelay Turnaround Times

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Outline

- Introduction
- Review of HRM
- Review of simulation model
- Model for local clock wander generation
- Results
- Conclusions
- Future work

Introduction - 1

- References [1] and [2] presented simulation results for synchronization transport performance over a network of 802.1AS time-aware systems, using latest requirements for Sync and Pdelay intervals
  - Sync interval: 0.125 s
  - Pdelay interval: 1.0 s
- The results were presented in the form of Maximum Time Interval Error (MTIE), and were compared with MTIE masks that are equivalent to current requirements for various applications
  - Uncompressed SDTV (Serial Digital Interface (SDI) video)
  - Uncompressed HDTV (Serial Digital Interface (SDI) video)
  - Compressed (MPEG) video
  - Digital audio (consumer interfaces)
  - Digital audio (professional interfaces)
  - Various cellular base station requirements (CDMA, CDMA2000, WCDMA TDD, Femtocell)

Introduction - 2

- The simulation cases endpoint filter bandwidths ranging from 1 mHz to 10 Hz
  - Cases included 1 mHz, 10 mHz, 100 mHz, 1 Hz, 10 Hz
- The results were based on single simulation runs for each case
- The results indicated that
  - MTIE masks for all applications were met with a 1 mHz endpoint filter
  - MTIE masks for all applications except for uncompressed SDTV (SDI video) were met with a 10 mHz filter
  - MTIE masks for compressed video (MPEG) and digital audio were met with a 1 Hz filter
  - MTIE masks for compressed video (MPEG) and professional digital audio were met with a 10 Hz filter
    - Note that the MTIE mask for professional audio is less stringent than for consumer audio because the professional audio equipment is required to tolerate more jitter

Introduction - 3

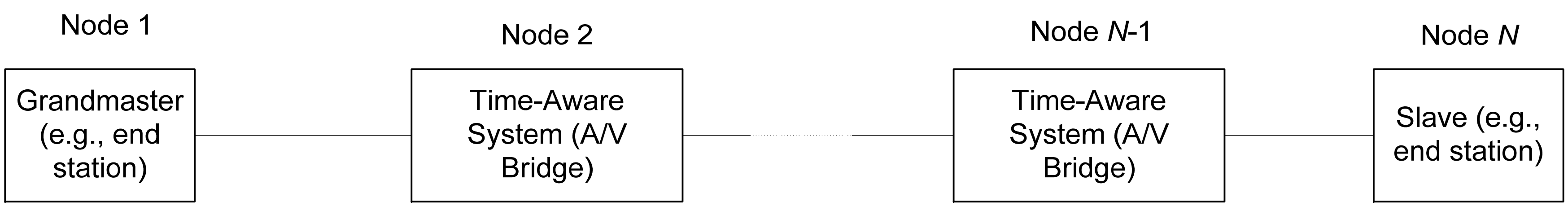
- Since the simulations of [1] and [2] were performed, the following changes were made to the IEEE P802.1AS requirements
  - The residence time was increased from 1 ms to 10 ms
  - The Pdelay turnaround time (i.e., the maximum time interval between the receipt of Pdelay_Req and the sending of Pdelay_Resp) was increased from 1 ms to 10 ms
- In addition, the results in [1] and [2] assumed no local clock wander generation
- Annex B of P802.1AS (subclause B.1.3.2, see [3] for latest draft) contains a local clock wander generation requirement, in the form of a TDEV mask
  - The wander on the output timing signal of the free-running LocalClock entity shall have TDEV that does not exceed the mask of Figure B-1 and Table B-1 (see B.1.3.2 of P802.1AS, D7.0 for full details)

Introduction - 4

- When the residence and Pdelay turnaround time requirements were increased, and when the clock wander generation requirement was added to the P802.1AS draft, it was indicated that simulations would have to be performed to verify that the end-to-end (network) wander performance could be met
- The current presentation provides new simulation results, for cases with
  - Residence and Pdelay turnaround times of 10 ms and 50 ms
  - Clock wander generation at the level of 802.1AS, Figure B-1 and Table B-1
- Results are compared with the results of [1] and [2]
- Note that [2] contains results with and without propagation time averaging; here we focus on cases without propagation time averaging

Review of Hypothetical Reference Model (HRM) (from [1])

- Number of hops = $N - 1 = 7$
  - i.e., N = 8 nodes (time aware systems) numbered from 1 to 8, with the grandmaster as node 1



Review of Simulation Model (adapted from [1]) – 1

- Model is discrete-event; the events are the sending and receiving of Sync, Pdelay_Req, and Pdelay_Resp messages
- Each node contains a free-running clock, for which the following is specified
  - Frequency tolerance y
    - At initialization, the actual frequency offset is chosen randomly from a uniform distribution over $[-y, y]$
  - Frequency drift D
  - Phase measurement granularity
  - Parameters of power-law noise models (details of these models given in later slides):
    - White Phase Modulation (WPM)
    - Flicker Phase Modulation (FPM)
    - White Frequency Modulation (WFM)
    - Flicker Frequency Modulation (FFM)
    - Random Walk Frequency (RWFM)

Review of Simulation Model – 2

- Each link is associated with a delay model
  - For now, the link delay is fixed, but can be asymmetric
- Times associated with messages; fixed for now
  - Sync interval
  - Pdelay interval
  - Pdelay turnaround time (time between receipt of Pdelay_Req and sending of Pdelay_Resp)
  - Residence time (time between receipt of Sync by a node that is not the Grandmaster (GM), i.e., node $j > 1$ in slide 5, and sending of Sync to node $j+1$)

Review of Simulation Model - 3

- The basic operation of the simulator is

```
generateInitialEvents(); /* Sending initial Sync by GM; sending initial
  Pdelay_Req from node j to node j – 1, for j= 2, …, N */

while (timer <= endTime) {
    removeNextEvent();
    computeFreeRunningClockTimesAtTimeOfNextEvent(); /* clock
  wander generation model is invoked here */
    computeUnfilteredSynchronizedTimeEstimateAtTimeOfNextEvent();
    /* based on current estimate of rateRatio relative to GM and most
  recent (freeRunningTime, synchronizedTime) association */
    computeFilteredSynchronizedTimeEstimateAtTimeOfNextEvent();
    eventHandler();
}
```

- The events are maintained in a linked list, in chronological order relative to global timer

Review of Simulation Model - 4

- Filter model is the same as that used in [4] – [7]
- In setting the integration time step for the filter, the time between the current and next event is divided into the smallest number of time steps such that the size of the time step is not larger than a specified maximum, i.e.,
  - If T = time between events
  - Δt_{max} = maximum time step (input parameter)
  - Δt = actual time step
  - Then
  - $N_{steps} = \text{ceil}\,(T/\,\Delta t_{max})$
  - $\Delta t = T/N_{steps}$

Model Summary - 5

- The following is a high-level overview of the processing of each event type
- Sending Pdelay_Req event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Schedule next sending of Pdelay_Req event and add to linked
- Receipt of Pdelay_Req event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Schedule sending of Pdelay_Resp event
- Sending of Pdelay_Resp event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Place Pdelay turnaround time in message structure
  - Schedule receipt of Pdelay_Resp event

Model Summary - 6

❑Receipt of Pdelay_Resp event

- Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
- Compute neighborRateRatio
  - A granularity for the neighborRateRatio computation can be specified (e.g., based on a given number of bits of precision for the computation)
- Compute neighborPropDelay
- Note that there is no new event to generate in this case

❑Sending of Sync event

- Generate time stamp relative to free-running time corresponding to current value of timer)
- Compute residence time, corrected for cumulativeRateRatio, based on time stamp and saved time stamp (relative to free-running timer) of most recently received Sync
- Add residence time and current neighborPropDelay to correctionField
- Schedule receipt of Sync at downstream node

Model Summary - 6

❑Receipt of Sync event

- Generate time stamp relative to free-running time corresponding to current value of timer)
- Compute correctedMasterTime (GM time estimate), which is the sum of the preciseOriginTimestamp, correctionField, and neighborPropDelay)
- Compute cumulativeRateRatio relative to GM using received cumulativeRateRatio and current neighborRateRatio
- Compute unfiltered phase offset, which is the difference between the correctedMasterTime and current local clock time (the time stamp for receipt of the Sync)
  - Note that the (time stamp, correctedMasterTime) becomes the current association of free-running and GM time

Local Clock Wander Generation Model - 1

- See [4] and [5] for initial discussion of clock phase noise models
- Clock phase noise is typically modeled as a sum of random processes with one-sided power spectral density (PSD) of the form $Af^{-\alpha}$
- In the most general case usually considered in practice, 5 terms are considered (see [8] and [9])
  - α = 0, White Phase Modulation (WPM)
  - α = 1, Flicker Phase Modulation (FPM)
  - α = 2, White Frequency Modulation (WFM)
  - α = 3, Flicker Frequency Modulation (FFM)
  - α = 4, Random-Walk Frequency Modulation (RWFM)
- Can write the PSD, $S_x(f)$ as

$$S_x(f) = \frac{A}{f^4} + \frac{B}{f^3} + \frac{C}{f^2} + \frac{D}{f} + E, \text{ where } S_x(f) \text{ has units of } \mathrm{ns}^2/\mathrm{Hz}$$

  - Often express as (ν_0 = nominal clock frequency)

$$S_\phi(f) = (2\pi\nu_0)^2 S_x(f), \text{ where units of } S_\phi(f) \text{ are } \mathrm{rad}^2/\mathrm{Hz}$$

Local Clock Wander Generation Model - 2

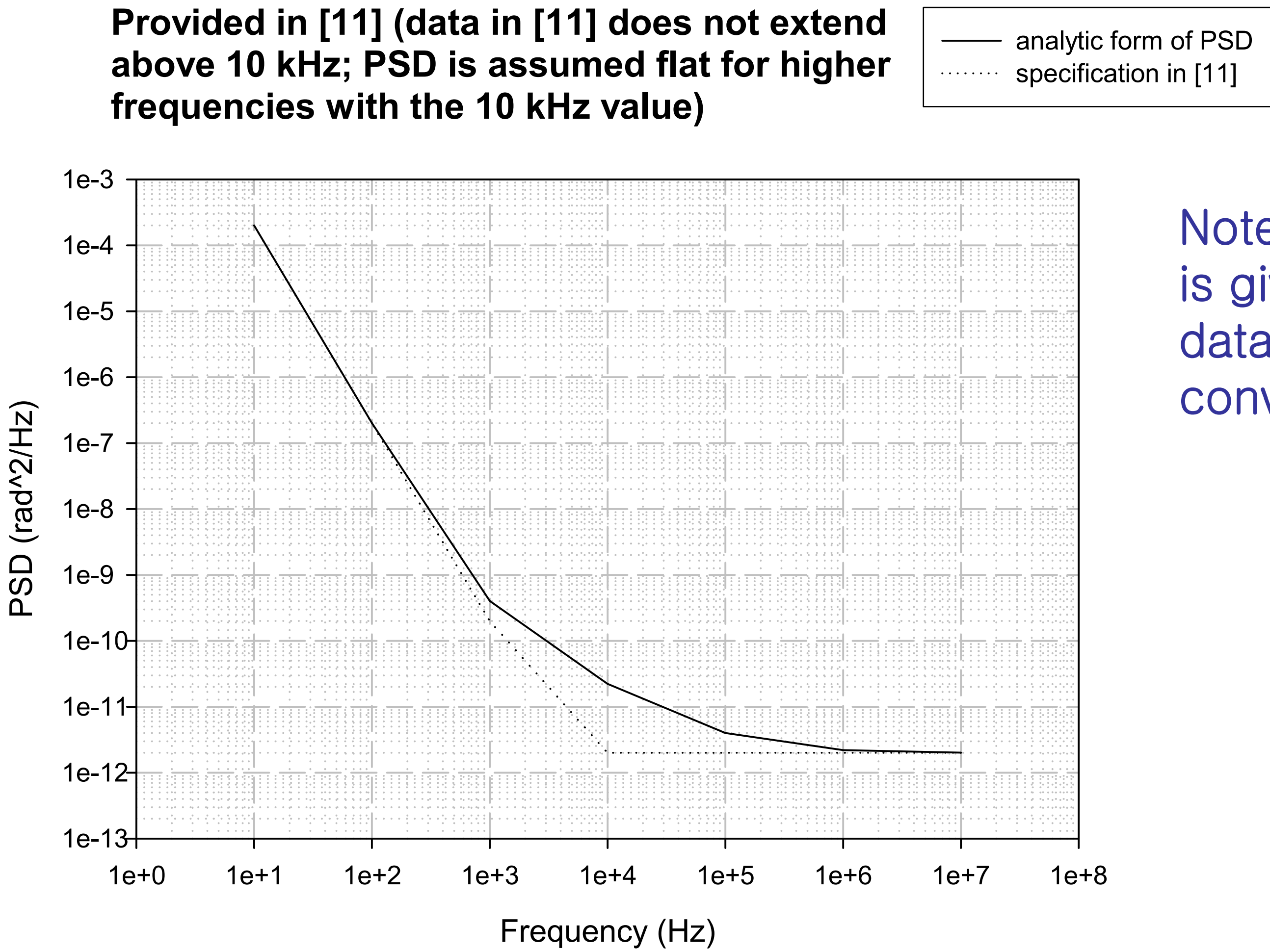
- Often, the one-sided PSD $S_\phi(f)$ is expressed in dBc/Hz, using the conversion

$$S_\phi(f)\ [\text{dBc/Hz}] = 10\log_{10}\{S_\phi(f)\ [\text{rad}^2/\text{Hz}]\}$$

  - Must be careful on whether the PSD is one-sided or two-sided; respective equations will contain additional factors of 2 in converting between them
  - An example PSD specification is given in Figure 12 of [11], and reproduced on the next slide (this was presented in [4] and [5]; note that a similar example is given in Figure 2 of [10])
    - Data in [11] is given in dBc/Hz; data has been converted to rad^2/Hz
    - Data in [11] is given only for frequencies below 10 kHz; here, we assume the PSD is flat above 10 kHz
    - Dotted curve on the next slide is the converted data of [11]; solid line is a conservative fit of the above power law sum
- The above example specification contains WPM, FPM, and FFM terms
  - In the wander region ($f \le 10$ hz), the FFM term (B/f^3) dominates
  - The 802.1AS wander generation specification is base on FFM behavior

Local Clock Wander Generation Model - 3

Example Clock Phase Noise Specification Provided in [11] (data in [11] does not extend above 10 kHz; PSD is assumed flat for higher frequencies with the 10 kHz value)



Note: Data in [11] is given in dBc/Hz; data has been converted to rad^2/Hz

Local Clock Wander Generation Model - 4

- Another measure for clock noise, which is more convenient because it is a time domain parameter, is Time Variance (TVAR) [8], [9]
  - Time Deviation (TDEV) is the square root of TVAR
- TVAR is 1/6 times the expectation of the square of the second difference of the phase error averaged over an interval
  - TVAR is related to Modified Allan Variance (MVAR) (see next slide), which is in turn a generalization of Allan Variance (AVAR)

$$\mathrm{TVAR}(\tau) = \frac{1}{6} E\left[\left(\Delta^2 \bar{x}\right)^2\right]$$

where $E[\cdot]$ denotes expectation,

$\bar{x}$ denotes average over the integration time τ,

and Δ^2 denotes second difference

Local Clock Wander Generation Model - 5

- TVAR may be estimated from measured or simulated data using [9]

$$\mathrm{TVAR}(n\tau_0) = \frac{1}{6n^2(N-3n+1)} \sum_{j=1}^{N-3n+1} \left[\sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2, \quad \mathrm{n} = 1, 2, \ldots, \text{integer part}(N/3)$$

where τ_0 is the sampling interval and $\tau = N\tau_0$

- TVAR is equal to $\tau^2/3$ multiplied by the Modified Allan Variance
- For power-law noises with PSD proportional to $f^{-\alpha}$, TVAR is proportional to τ^{β}, where $\beta = \alpha - 1$

Local Clock Wander Generation Model - 6

- The magnitude of TVAR may be related to the magnitude of PSD for power-law noises; see [8] and [9] for details

  - FFM $S_x(f) = \dfrac{B}{f^3}$ $\mathrm{TVAR}(\tau) = \dfrac{(2\pi)^2 9 \ln 2}{20} B\tau^2$

  - WFM $S_x(f) = \dfrac{C}{f^3}$ $\mathrm{TVAR}(\tau) = \dfrac{(2\pi)^2}{12} C\tau$

  - FPM (result is from [8]; a more exact expression is given in [9])

    $S_x(f) = \dfrac{D}{f}$ $\mathrm{TVAR}(\tau) = \dfrac{3.37}{3} D$

  - WPM $S_x(f) = E$ $\mathrm{TVAR}(\tau) = \dfrac{\tau_0 f_h}{\tau} E$

f_h = noise bandwidth

Local Clock Wander Generation Model - 7

- TVAR and TDEV (or Allan Variance or Modified Allan Variance) are used to characterized phase noise in oscillators rather than classical variance
  - The time-domain estimator for classical variance diverges for some power-law noise processes
  - The time-domain estimators for TVAR, Allan Variance, and Modified Allan Variance converge for all power-law noise processes
- For the 802.1AS Annex B, Figure B-1 TDEV mask

$$\mathrm{TDEV}(\tau) = 5 \times 10^{-9} \tau \qquad 0.05\ \mathrm{s} \le \tau \le 10\ \mathrm{s}$$

$$\frac{(2\pi)^2 9 \ln 2}{20} B = (5 \times 10^{-9})^2$$

$$B = \frac{(5 \times 10^{-9})^2 (20)}{(2\pi)^2 9 \ln 2} \quad \mathrm{s}^2/\mathrm{Hz} = 2.0302 \times 10^{-18} \quad \mathrm{s}^2/\mathrm{Hz}$$

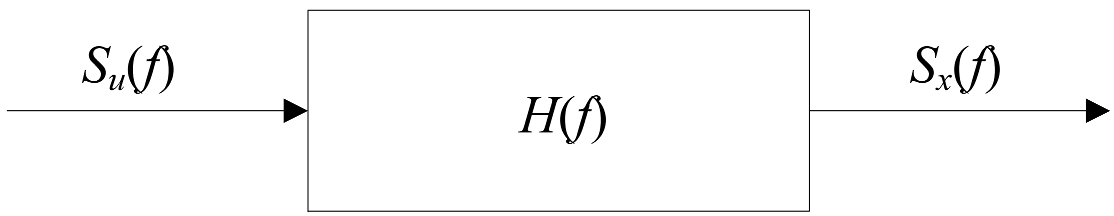
$$B = 2.0302 \quad \mathrm{ns}^2/\mathrm{Hz}$$

Local Clock Wander Generation Model - 8

❑Simulation of FPM

- FPM is simulated by passing a sequence of independent, identically distributed random samples through a Barnes/Jarvis filter [12] – [14]
  - If white noise is input to a filter with frequency response $H(f) = f^{-1/2}$, the output is a random process with PSD proportional to $1/f$
  - The Barnes/Jarvis filter approximates an $f^{-1/2}$ frequency response using a bank of lead/lag filters
    - –The actual frequency response of this filter is a "staircase"
    - –The spacings of the poles and zeros are chosen such that the average slope is –10 dB/decade
- Noise distribution is taken as Gaussian with zero mean
- Variance determines TDEV level
  - Choose variance such that the computed TDEV from a sample history is close to value obtained from above relation between TDEV and PSD

Local Clock Wander Generation Model - 9



$$S_x(f) = |H(f)|^2 S_u(f)$$

If $S_u(f) = K = \text{constant (WPM)}$ and $H(f) = 1/\sqrt{f}$, then

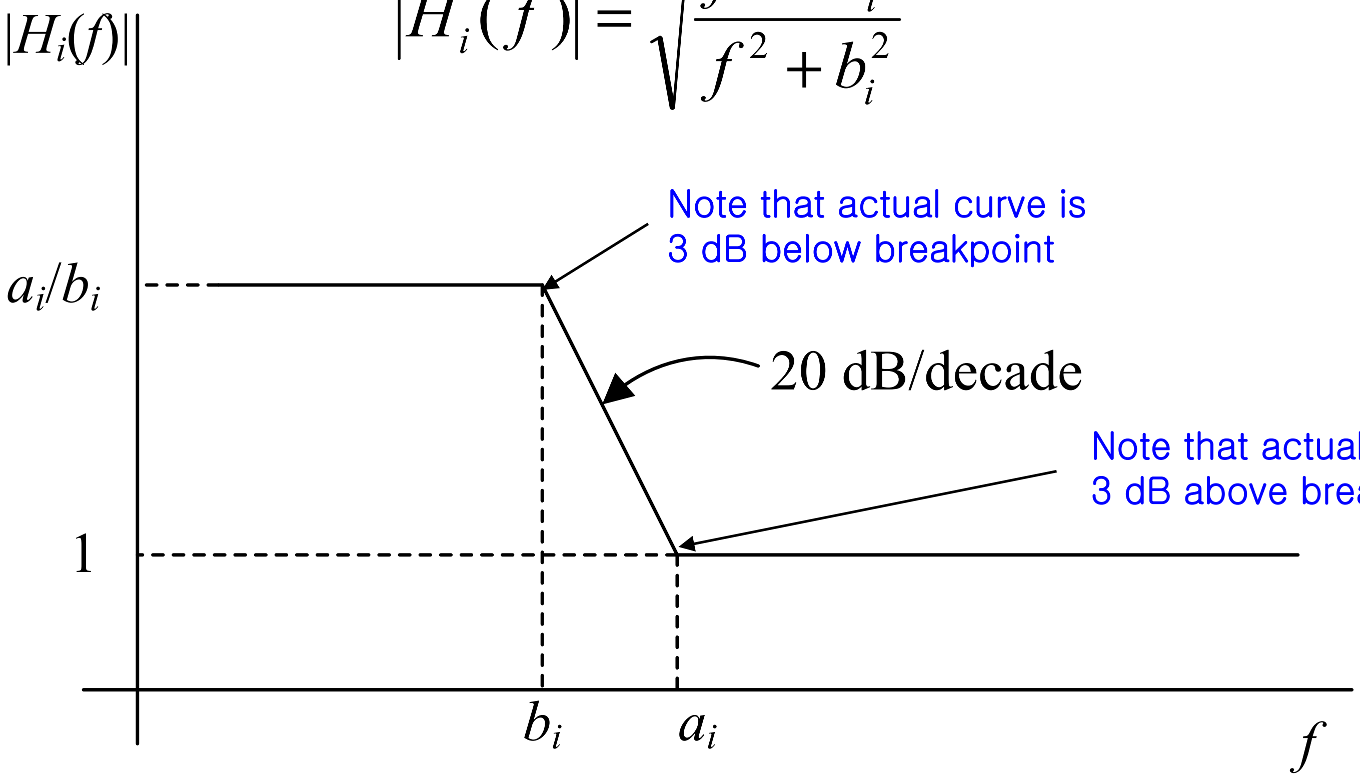
$$S_x(f) = K/f \text{ (FPM)}$$

Local Clock Wander Generation Model - 10

- Consider

$$H_i(f) = \frac{jf + a_i}{jf + b_i}, \qquad a_i > b_i$$

$$\left|H_i(f)\right| = \sqrt{\frac{f^2 + a_i^2}{f^2 + b_i^2}}$$

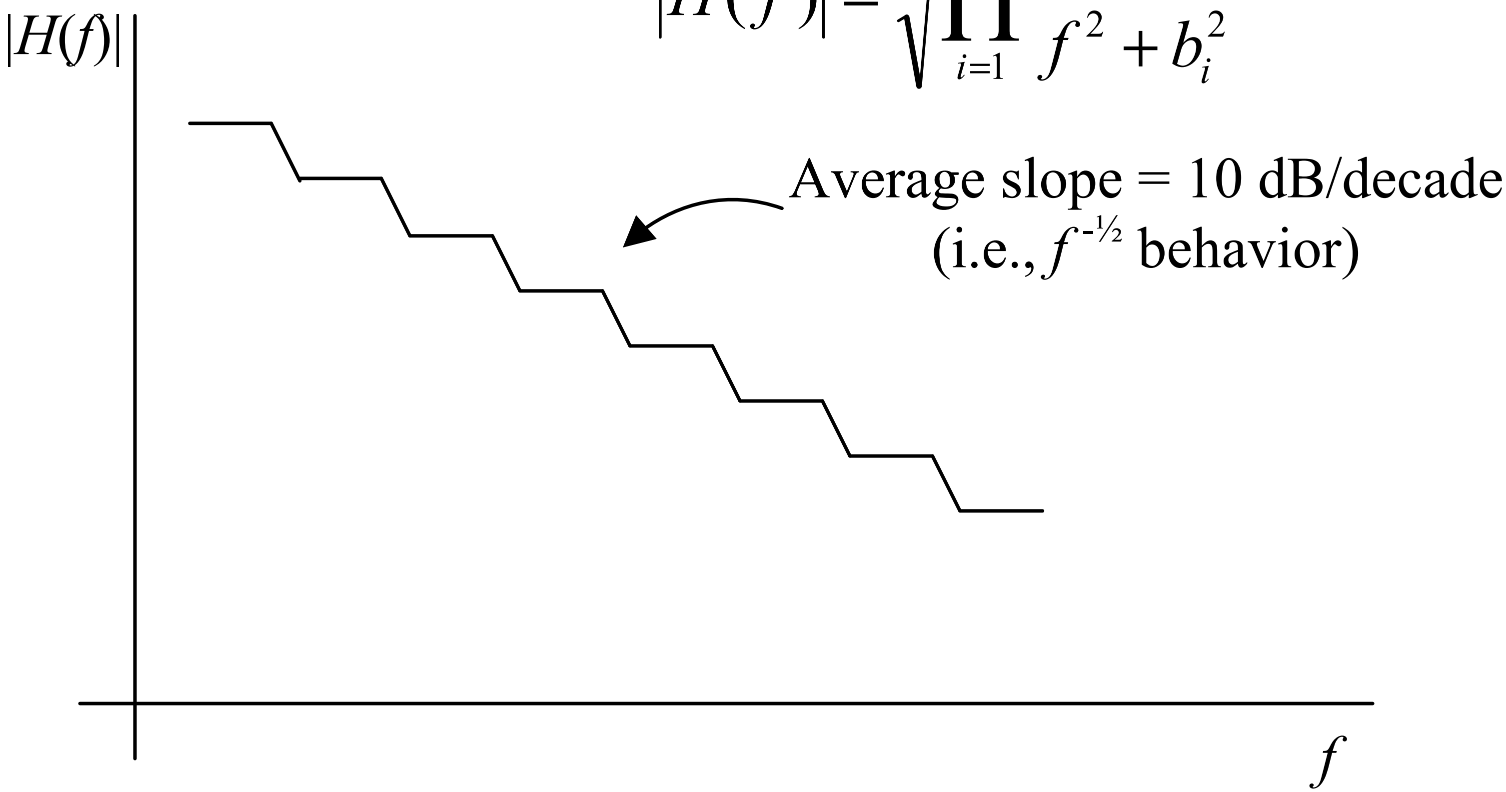


Local Clock Wander Generation Model - 11

- Next, consider

$$H(f) = \prod_{i=1}^{N} \frac{jf + a_i}{jf + b_i}, \qquad a_i > b_i$$

$$|H(f)| = \sqrt{\prod_{i=1}^{N} \frac{f^2 + a_i^2}{f^2 + b_i^2}}$$

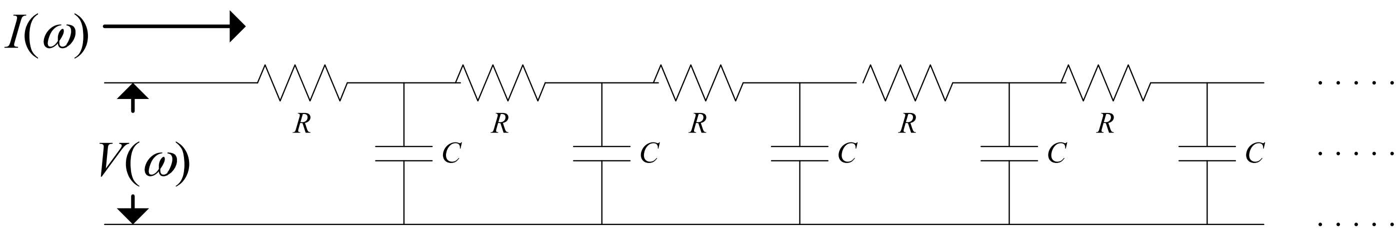


Local Clock Wander Generation Model - 12

- A discrete-time implementation of the filter bank is given by Barnes and Greenhall in [13]
  - In the implementation here, 8 stages are used, to simulate FPM (and integrate to obtain FFM, see below) over approximately 7 decades
- Simulation of FFM
  - Input a sequence of independent, identically distributed random samples through a Barnes/Jarvis filter followed by an integrator (accumulator)
  - Noise distribution is taken as Gaussian with zero mean
  - Variance determines TDEV level
    - Choose variance such that the computed TDEV from a sample history is close to value obtained from above relation between TDEV and PSD

Local Clock Wander Generation Model - 13

- Note: It can be shown (see [15]) that the impedance of an RC network approaches a $1/\omega^{1/2}$ dependence in the limit as the extent of the network (in one direction) becomes infinite, $R \to 0$, $C \to 0$, $R/C \to K$ (K is a constant)



$$Z(\omega) = \frac{V(\omega)}{I(\omega)} = \frac{R}{2} + \left(\frac{R^2}{4} + \frac{R}{j\omega C}\right)^{1/2} \to \sqrt{\frac{R}{C}} \frac{1}{(j\omega)^{1/2}}$$

as $R \to 0, C \to 0, R/C \to K$

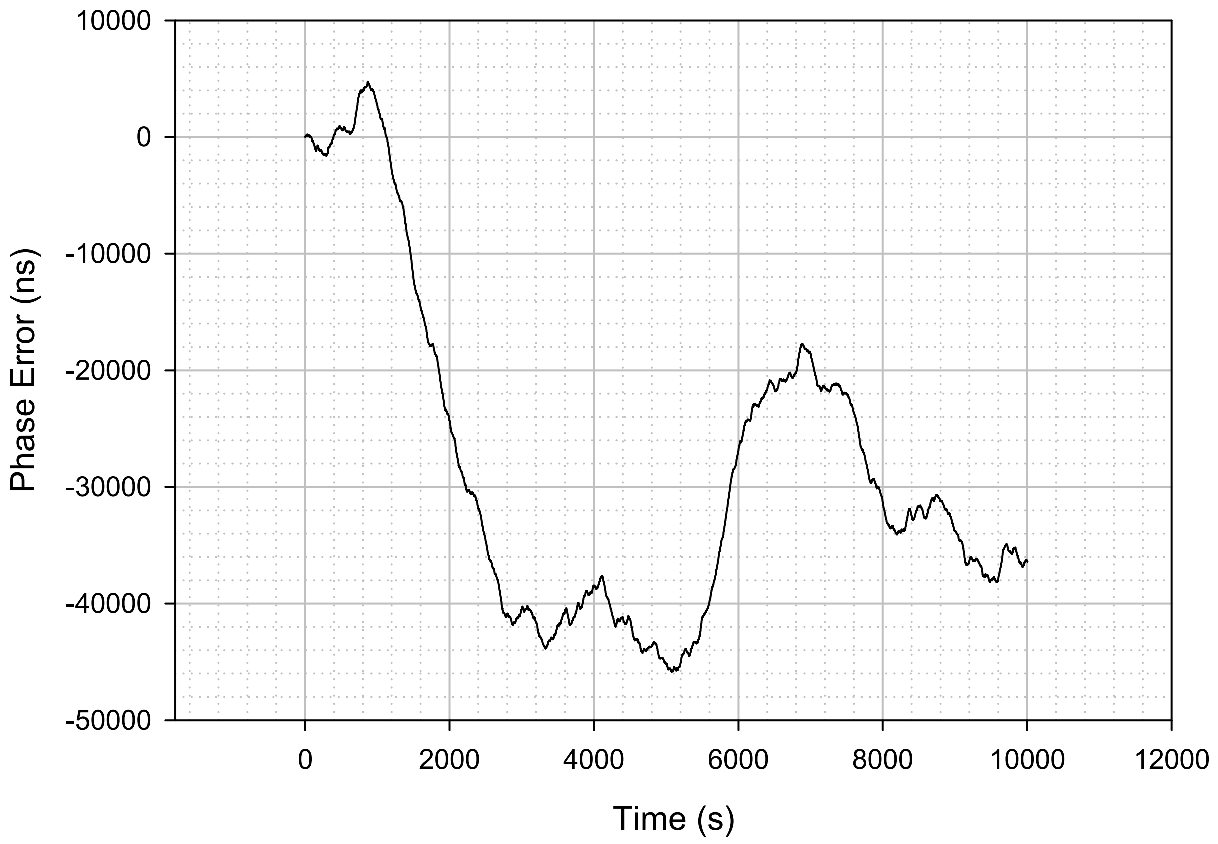
$$|Z(\omega)| \to \sqrt{\frac{R}{C}} \cdot \frac{1}{\omega^{1/2}}$$

$$|Z(\omega)|^2 \to \frac{R}{C} \cdot \frac{1}{\omega} \quad \text{(i.e., has a } 1/\omega \text{ dependence)}$$

Local Clock Wander Generation Model - 14

❑Sample local clock phase noise history

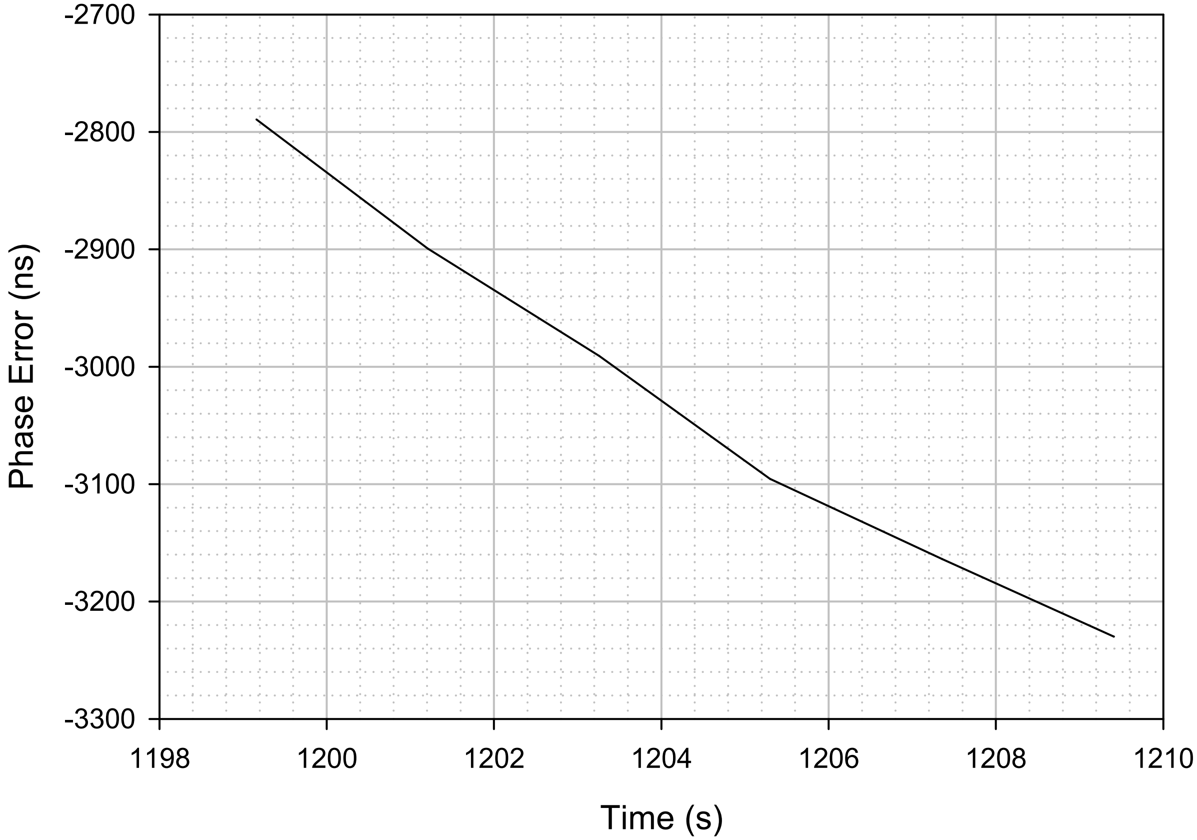
Sample phase error history corresponding to 802.1AS Annex B, Figure B-1 TDEV mask



Local Clock Wander Generation Model - 15

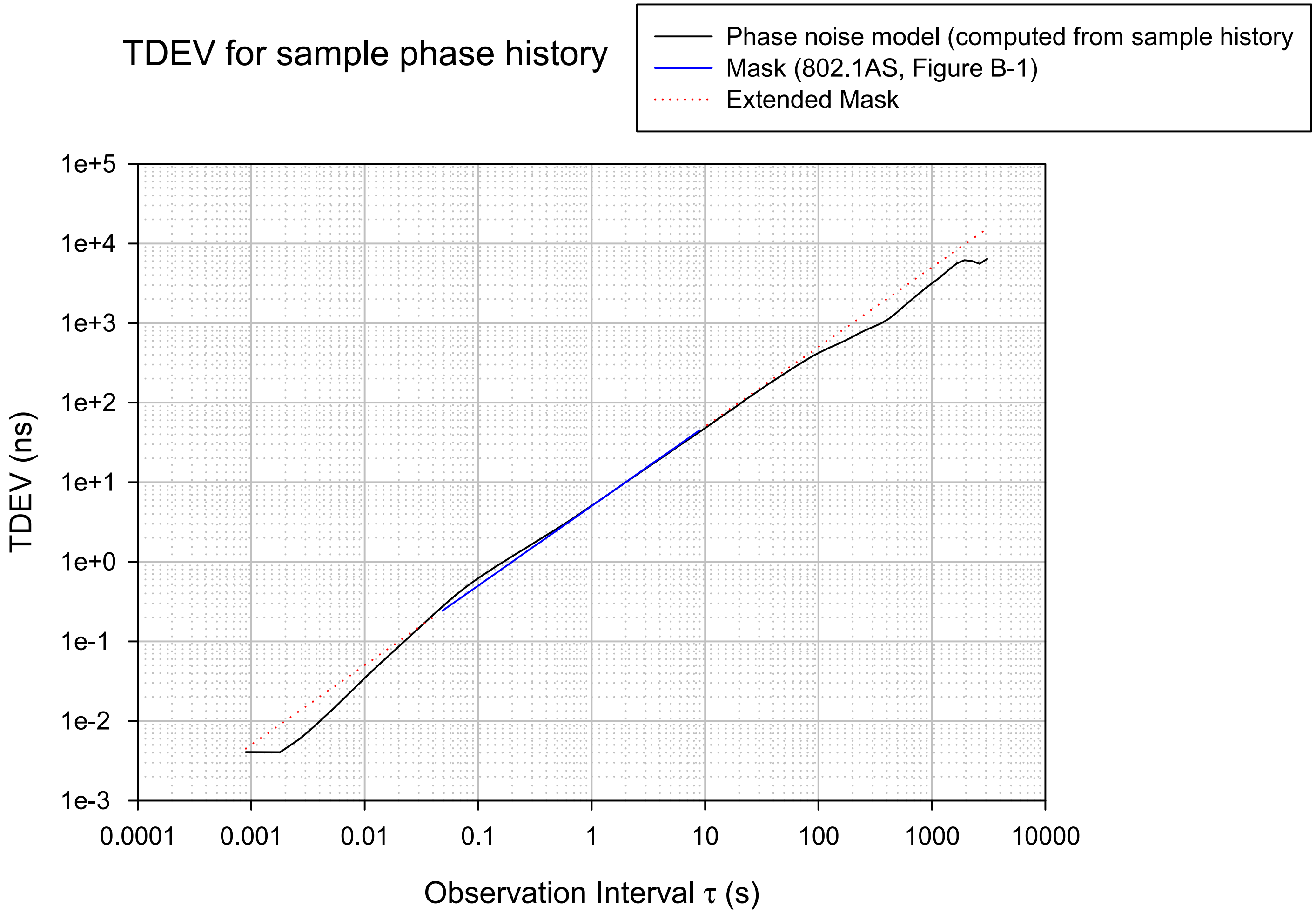
❑Sample local clock phase noise history (detail of 1199 – 1209 s)

Sample phase error history corresponding to 802.1AS Annex B, Figure B-1 TDEV mask
Detail of 1199 - 1209 s



Local Clock Wander Generation Model - 16

- TDEV for phase noise sample history, and comparison with 802.1AS Figure B-1 mask



Model Parameters Common to All Cases - 1

- Endpoint filter gain peaking = 0.1 dB
- Sync interval = 0.125 s
- Pdelay interval = 1.0 s
- Link propagation delay = 500 ns (fixed)
  - Links are symmetric
  - PHY latency is assumed symmetric
- Phase (time) measurement granularity = 40 ns
- Frequency measurement granularity = 2.328×10^{-10} (i.e., computations assumed to be done with 32-bit arithmetic)
- LocalClock entity frequency tolerance = $\pm$100 ppm
  - Frequencies of free-running oscillators in nodes are chosen randomly at initialization within their tolerance range (a uniform distribution is assumed)
- Number of time-aware systems = 8 (7 hops; see HRM on slide 7)
- Simulation time = 10 010 s
- Maximum time step = 0.001 s

Simulation Cases

Case	Residence time (ms)	Pdelay turnaround time (ms)	Local clock wander generation modeled (yes/no)	Endpoint filter bandwidths (each filter bandwidth is one subcase)
1	1	1	no	1 mHz, 10 mHz, 100 mHz, 1 Hz, 10 Hz
2	1	1	yes	1 mHz, 10 mHz, 100 mHz, 1 Hz, 10 Hz
3	10	10	yes	1 mHz, 10 mHz, 100 mHz, 1 Hz, 10 Hz
4	50	50	yes	1 mHz, 10 mHz, 100 mHz, 1 Hz, 10 Hz

Actual Frequency Offsets for Nodes 1 – 8

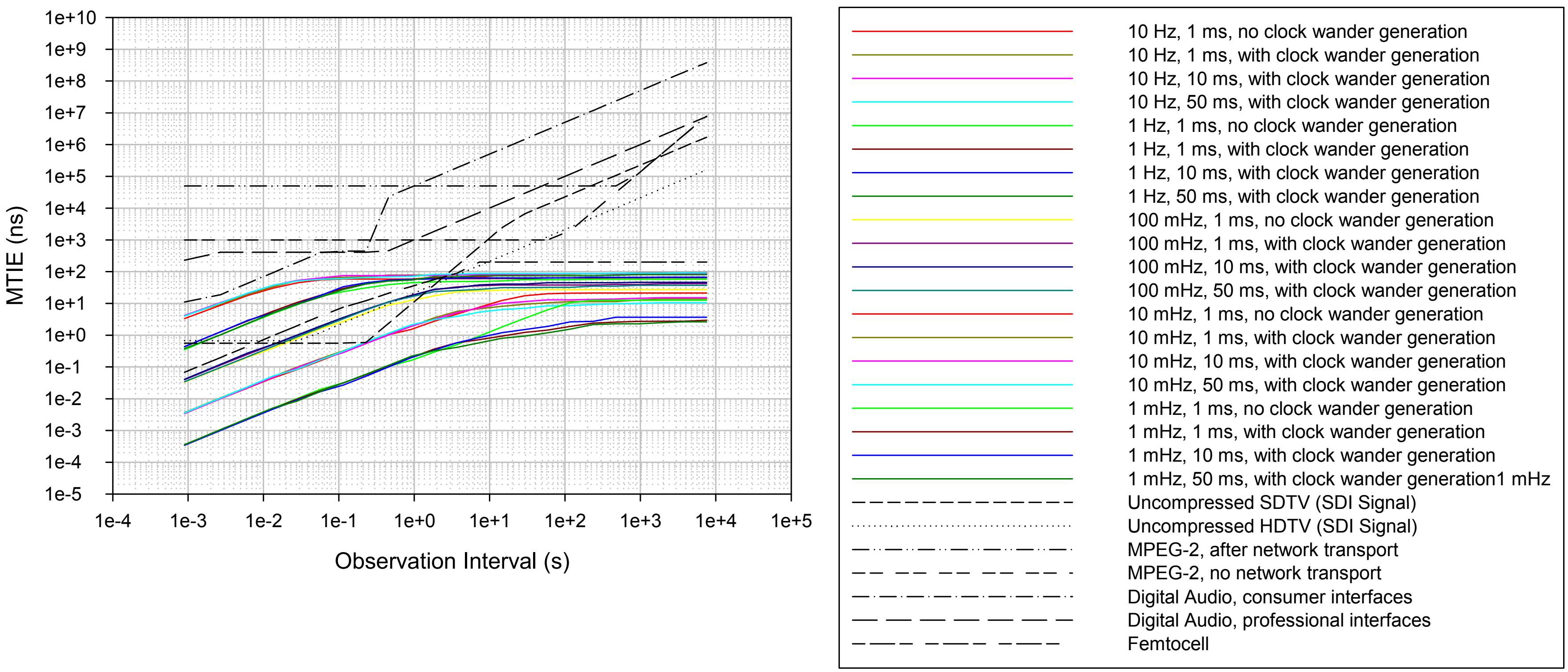
- The next slide gives the actual frequency offsets used in the simulation cases
  - They were chosen randomly at initialization from a uniform distribution over the tolerance range
  - Therefore, the values depended on the initial state (seed) of the random number generator
  - The same seed was used for all cases/subcases
- Note that the frequency offsets are the same as those for cases 1 and 3 of [1], and the cases of [2]

Actual Frequency Offsets for Nodes 1 – 8

Node	Frequency offset (ppm)
1	0 (GM)
2	6.4276
3	-55.714
4	32.295
5	-53.950
6	38.774
7	64.124
8	-83.231

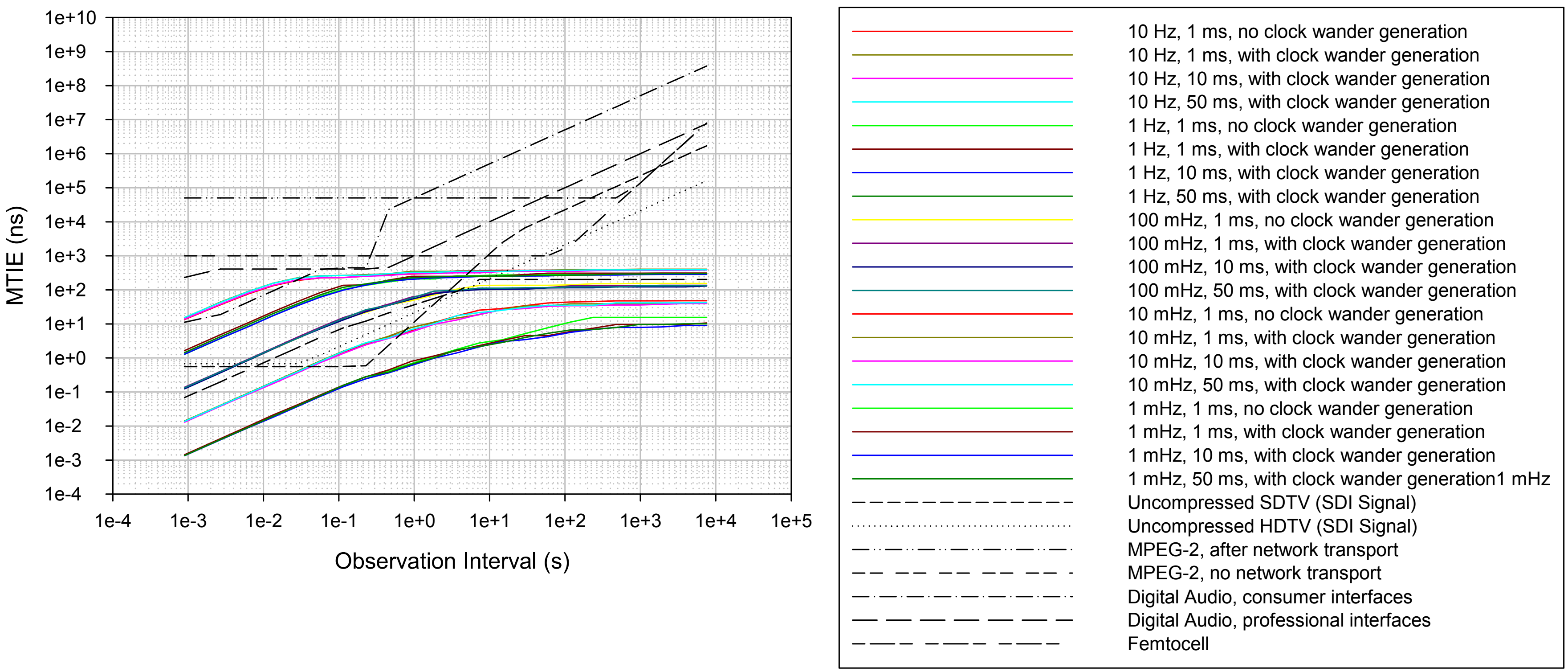
MTIE Results – Node 2

Comparison of jitter/wander accumulation MTIE at time-aware system (node) 2
10 Hz, 1 Hz, 100 mHz, 10 mHz, and 1 mHz endpoint filter bandwidths
1, 10, 50 ms residence time and Pdelay turnaround time (with clock wander generation)
1 ms residence time and Pdelay turnaround time (without clock wander generation
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s



MTIE Results – Node 8

Comparison of jitter/wander accumulation MTIE at time-aware system (node) 8
10 Hz, 1 Hz, 100 mHz, 10 mHz, and 1 mHz endpoint filter bandwidths
1, 10, 50 ms residence time and Pdelay turnaround time (with clock wander generation)
1 ms residence time and Pdelay turnaround time (without clock wander generation
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s



Discussion of Results - 1

- Note that case 1 corresponds to previous results, given in [1] and [2]
- Results indicate that addition of LocalClock wander generation at the level of the 802.1AS Annex B TDEV mask has negligible impact on the results
  - The reason for this is that the noise level represented by the wander generation, *over the 0.125 s Sync interval*, is small compared to the 40 ns phase measurement granularity
- Results also indicate that increasing the residence and Pdelay Turnaround times to 10 ms, and even to 50 ms, have negligible impact on the results

Discussion of Results - 2

- As in [1] and [2], the results indicate the following:
  - MTIE masks for all applications are met with a 1 mHz endpoint filter
  - MTIE masks for all applications except for uncompressed SDTV (SDI video) were met with a 10 mHz filter
  - MTIE masks for compressed video (MPEG) and digital audio were met with a 1 Hz filter
  - MTIE masks for compressed video (MPEG) and professional digital audio were met with a 10 Hz filter (this case must still be run)
    - Note that the MTIE mask for professional audio is less stringent than for consumer audio because the professional audio equipment is required to tolerate more jitter

Summary and Conclusions - 1

- Jitter/Wander accumulation simulation results have been presented based on current P802.1AS specifications [3]
- Results have been presented for
  - Previous assumptions, given in [1] and [2]
  - Previous residence and Pdelay turnaround times (1 ms), but with clock wander generation
  - Residence and Pdelay turnaround times of 10 ms, with clock wander generation
  - Residence and Pdelay turnaround times of 50 ms, with clock wander generation
- Simulation cases have considered
  - Endpoint filter bandwidths of 1 mHz, 10 mHz, 100 mHz, 1 Hz, and 10 Hz

Summary and Conclusions - 2

- Did not consider
  - Variability in sync interval, Pdelay interval, Pdelay turnaround time, residence time, and PHY latency
    - assumed that constant intervals at respective maximum values would be a worse case than intervals whose values vary but do not exceed respective maximum
  - Multiple replications to obtain statistics on MTIE

Summary and Conclusions - 3

- The results indicated
  - **No appreciable difference when local clock wander generation, at the level of the TDEV mask of Figure B-1 and Table B-1 of [3], is added**
  - **No appreciable difference when residence and Pdelay turnaround times are increased to 10 ms or 50 ms**
- Based on these results, the following conclusions, given in [1] and [2], hold here as well:
  - MTIE masks for all applications are met with a 1 mHz endpoint filter
  - MTIE masks for all applications except for uncompressed SDTV (SDI video) were met with a 10 mHz filter
  - MTIE masks for compressed video (MPEG) and digital audio were met with a 1 Hz filter
  - MTIE masks for compressed video (MPEG) and professional digital audio were met with a 10 Hz filter (this case must still be run)
    - Note that the MTIE mask for professional audio is less stringent than for consumer audio because the professional audio equipment is required to tolerate more jitter

Future Work

- Future work should consider multiple replications of each simulation case, to obtain estimates for a desired quantile of MTIE
  - For example, if 300 independent replications of a simulation case are run, a 99% confidence interval for the 0.95 quantile is obtained by placing the MTIE samples for each observation interval in ascending order
    - The 99% confidence interval extends from the 275th through the 294th sample
- Note that computation time and resource constraints may require some or all of the following
  - Shorter simulation times
  - Fewer replications, which could result in
    - Larger confidence intervals
    - Lower confidence levels
    - Lower quantile

References - 1

1. Geoffrey M. Garner, *Initial Simulation Results for 802.1AS Synchronization Transport with Longer Sync and Pdelay Intervals*, Samsung presentation to May, 2009 IEEE 802.1 AVB TG Meeting, Pittsburgh, PA, USA, May 18, 2006. Available at http://www.ieee802.org/1/files/public/docs2009/as-garner-simulation-results-longer-intervals.pdf
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