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IEEE 802.1AS Network Performance

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Acknowledgment

- The author would like to acknowledge Aaron Gelter, of Harman International, for having performed the tests of time transport over an 802.1AS network, and supplied the test results described here (slides 18 – 24)
- The author would like to acknowledge Lee Cosart, of Symmetricom, for having performed the wander generation tests and supplied the test results described here (slides 42 and 43; additional test results are contained in [18])
- Many of the slides in this presentation were taken or adapted from references [1] and [2]

Outline

- End-to-end application requirements
- 802.1AS network assumptions
- 802.1AS time-aware system (equipment) requirements
- Jitter/wander accumulation simulation studies and results
- Test results
- Summary

802.1AS Network Applications

- Audio/Video Bridging (AVB) applications include those described by the AVB profiles of IEEE 802.BA
  - Consumer A/V
  - Professional A/V
  - Industrial automation
  - Automotive
- Applications include (but are not limited to)
  - Uncompressed video
  - Compressed video
  - Uncompressed audio

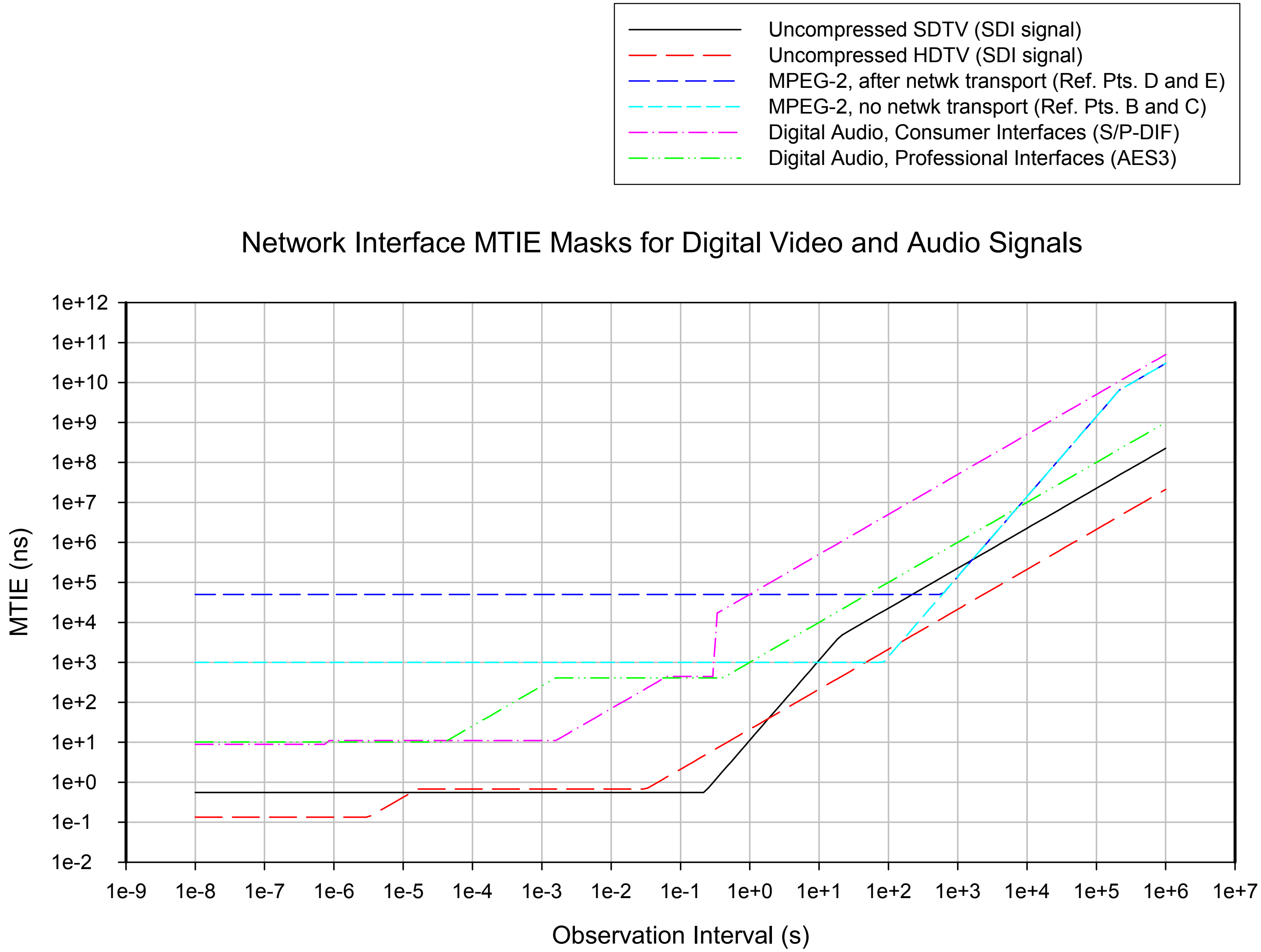
802.1AS Application Requirements – 1

- End-to-end time synchronization
  - Time synchronization relative to the grandmaster clock of ±500 ns or better (this implies no 2 time-aware systems differ in time by more than 1 μs)
- Jitter, frequency offset, and frequency drift requirements for AVB applications are given on the following slide
  - For convenience of comparison with simulation results and visualization, equivalent MTIE masks may be derived (given 2 slides following)
- See Appendix for background on requirements and additional remarks on uncompressed video requirements

802.1AS Application Requirements – 2

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

802.1AS Application Requirements – 3



802.1AS Network Assumptions

- All bridges and end-stations are time-aware systems, i.e., are 802.1AS-capable
  - No ordinary bridges or switches
  - Non-802.1AS bridges detected via peer delay mechanism
- Any two time-aware systems (bridges or end-stations) are separated by no more than 7 hops
- Full-duplex Ethernet links are 100 Mbit/s or faster
- 802.11 links are 100 Mbit/s (i.e., meet the requirements of IEEE 802.11n)
- 802.11 links support the localization features of 802.11v

Time –Aware System Requirements – 1

- ±100 ppm free-run accuracy for oscillator
  - Oscillator in bridge may be free-running; no requirement for PLL filtering in bridge
  - Any required filtering is at end station
- Oscillator frequency of at least 25 MHz (40 ns granularity)
- Oscillator meets respective jitter and wander generation requirements (see Appendix)
- Full-duplex Ethernet links are 100 Mbit/s or faster

Time –Aware System Requirements – 2

- 802.11 links are 100 Mbit/s (i.e., meet the requirements of IEEE 802.11n) and support the localization features of 802.11v
- All time-aware systems are two-step clocks
- Residence time and Pdelay turnaround time are less than or equal to 10 ms

Parameters for Simulation Case – 1

Parameter	Value
Number of nodes, including grandmaster	8 nodes (7 hops)
Sync interval	0.125 s
Pdelay interval	1.0 s
Free-running, local oscillator (in node) frequency tolerance	± 100 ppm (actual frequencies chosen randomly at initialization, from uniform distribution over this range)
Residence time	1 ms
Pdelay turnaround time	1 ms

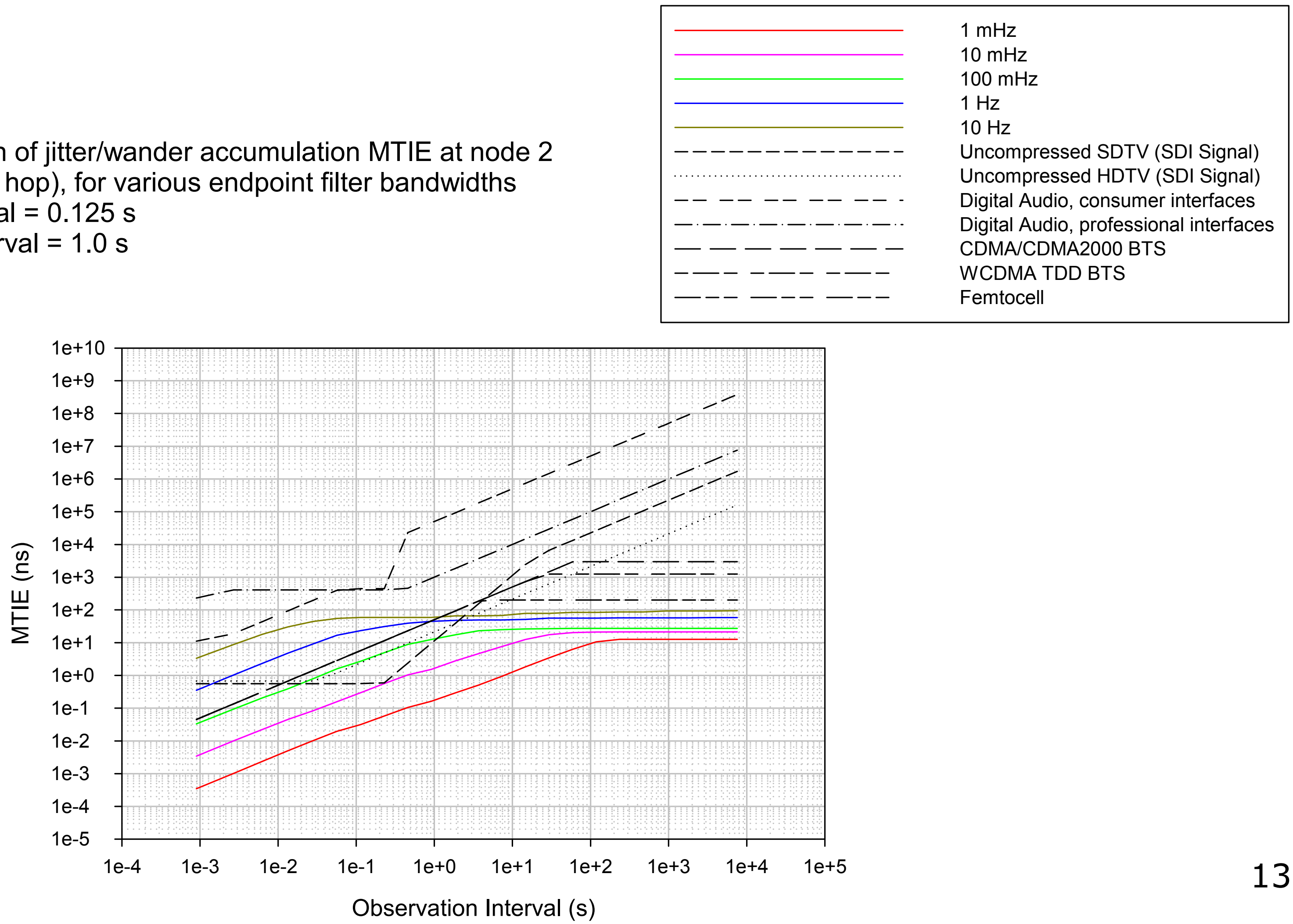
Parameters for Simulation Case – 2

Parameter	Value
Link propagation time	500 ns (assumed symmetric)
Phase measurement granularity of local oscillator	40 ns
Free-running oscillator noise jitter and wander generation	None modeled
Endpoint filter 3 dB bandwidth	1 mHz, 0.01 Hz, 0.1 Hz, 1 Hz, 10 Hz
Endpoint filter gain peaking	0.1 dB
Simulation time	10,010 s
Maximum time step	0.001 s

Note: Simulations are planned with jitter/wander generation of free-running oscillators modeled, and with residence time and Pdelay turnaround time ranging from 10 ms to 50 ms

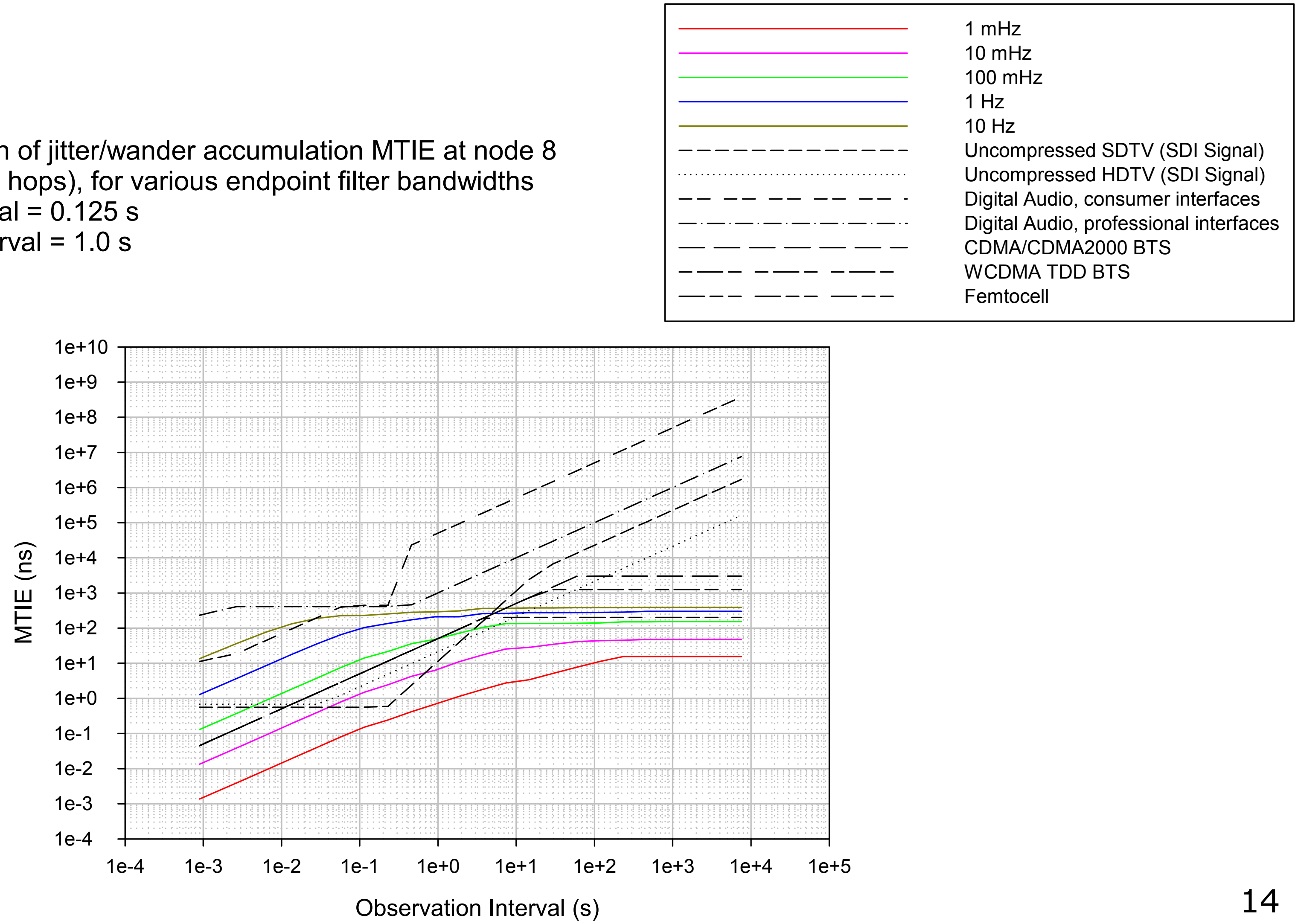
Jitter/Wander Simulation Results – Node 2 (1 Hop)

Comparison of jitter/wander accumulation MTIE at node 2 (i.e., after 1 hop), for various endpoint filter bandwidths
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s



Jitter/Wander Simulation Results – Node 8 (7 Hops)

Comparison of jitter/wander accumulation MTIE at node 8 (i.e., after 7 hops), for various endpoint filter bandwidths
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s



Simulation Results Summary – 1

- The MTIE masks on the previous slide were derived from the actual requirements (jitter, frequency offset, and frequency drift where applicable)
- For the single simulation run made here
  - All application requirements are met with a 1 mHz endpoint filter
  - All requirements except those for uncompressed SDTV are met with a 0.01 Hz endpoint filter
  - Professional and consumer audio requirements are met with a 1 Hz endpoint filter

Simulation Results Summary – 2

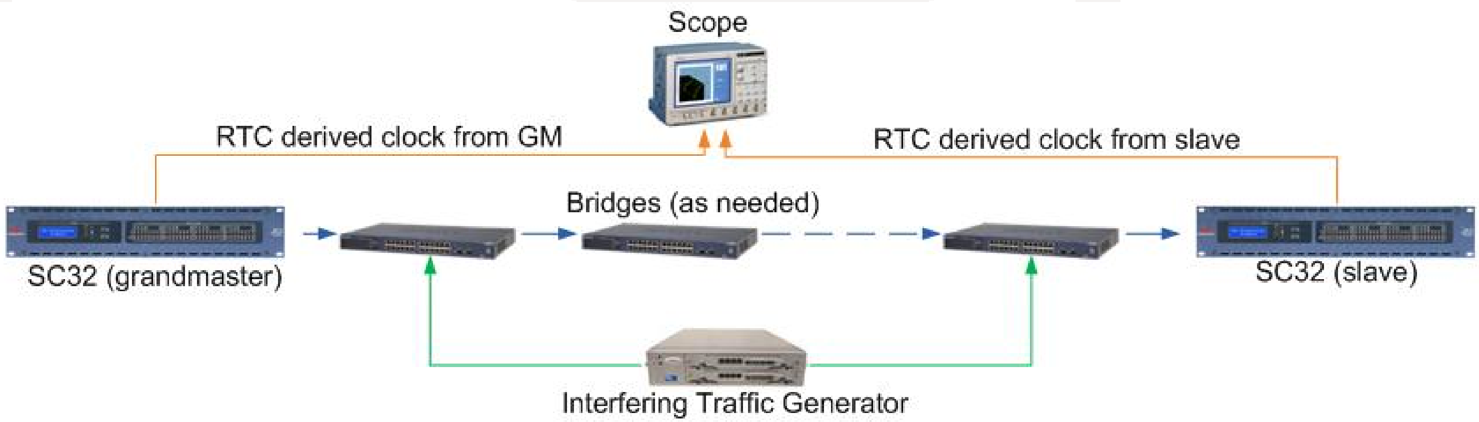
- For the single simulation run made here (cont.)
  - Professional audio requirements are met with a 10 Hz endpoint filter
    - Note that professional audio equipment is required to tolerate more jitter than consumer audio equipment, and therefore larger jitter accumulation is allowed
  - The requirements for several cellular technologies are shown for comparison; they are met with a 0.01 Hz endpoint filter

Simulation Results Summary – 3

- Note that very narrow-bandwidth endpoint filters are needed to meet the uncompressed video requirements
  - While the cost of the filter is borne by the application, this still implies higher cost for the uncompressed video display
  - As indicated earlier, a liaison has been sent to SMPTE asking for more background on these requirements

Test Configuration – 1

- The tests described on this and the following slides were performed by Aaron Gelter [1]
- 8 node (7 hop) configuration
  - Endpoints: 2 dbx® SC32 digital audio matrix processors with AVB Option Cards
  - Intermediate bridges: 6 Netgear®/BSS™ SW224 Prosafe 24 Port 10/100/1000 Mbps Smart Switches with AVB support
  - All links ran at 1 Gbit/s
- One SC32 was grandmaster, and the switches and second SC32 were slaves



Test Configuration – 2

- Each SC32 has a counter, i.e., real-time clock (RTC) that is incremented every 8 ns (i.e., local oscillator is 125 MHz)
  - The GM SC32 is free-running
  - The slave SC32 is adjusted with each Sync/Follow_Up it receives\
  - Adjustments are instantaneous, i.e., no endpoint filtering
  - Bit 20 of the RTC is used to form a 953.674 Hz square wave ($(1/2^{20})*10^9$ Hz)
- Square waves derived from the GM and slave SC32s were compared using a Tektronix DPO7245 oscilloscope with TDSJIT3 jitter analysis software
  - Note that only the SC32s could produce the square waves; separate tests were run for each desired number of hops, with the slave SC32 located that number of hops from the GM SC32
- For each test, cases were run with and without interfering traffic
  - Interfering traffic was introduced at the first bridge (closest to the GM) and last bridge (closest to the slave) and broadcast to all other bridges and the endpoints

Test Configuration – 3

- Interfering traffic (cont.)
  - Since the 802.1AS messages flow from GM to slave, traffic introduced at the last bridge interferes with 802.1AS traffic only on the link from the last bridge to the slave
  - Traffic introduced at the first bridge consisted of 1500 byte frames, and the load was close to 100%
  - Traffic introduced at the last bridge consisted of 1500 byte frames, and the load was close to 10%
  - Therefore, for cases with interfering traffic, the link between the last bridge and slave was possibly overloaded, and the other links had close to 100% load
  - For the case of 1 hop (no bridges), there was no background traffic

Test Results – 1

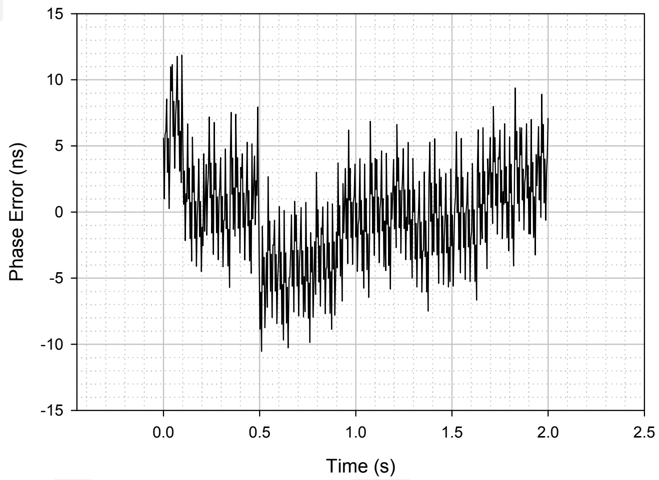
- Measurements were made for 0, 1, 2, 3, 4, 5, and 6 bridges between the slave and GM
- Due to limitations in the DPO7524 oscilloscope and TDSJIT3 software, the longest measurement interval attainable was 2 s

Peak-to-peak phase error (ns) for 2 s measurement interval

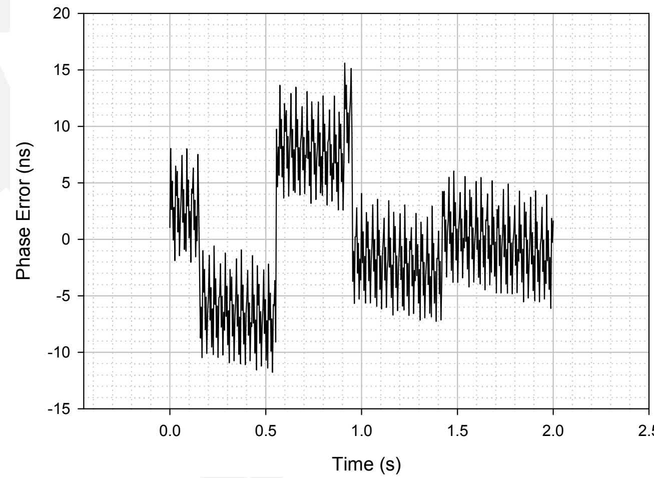
Number of hops	1	2	3	4	5	6	7
No background traffic	22.4	20.7	20.9	27.4	26.7	30.0	33.5
With background traffic	____	21.1	24.9	26.2	21.6	31.8	43.9

Test Results – No Background Traffic

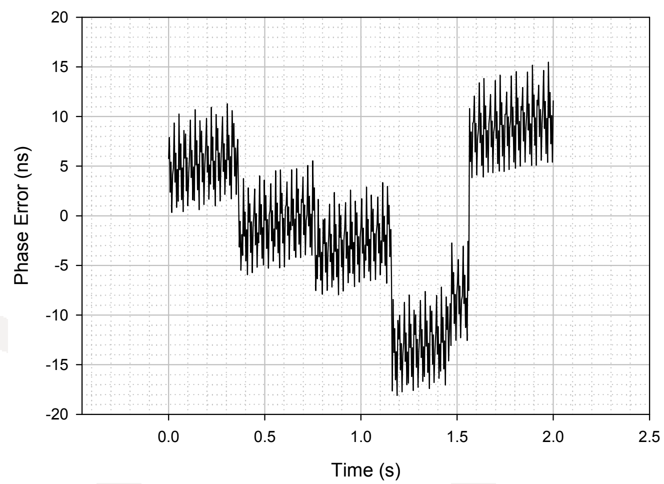
1 hop, no background traffic



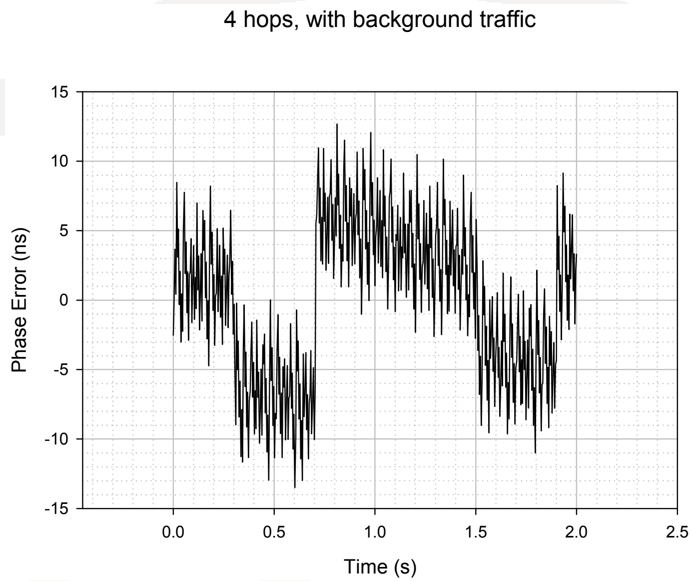
4 hops, no background traffic

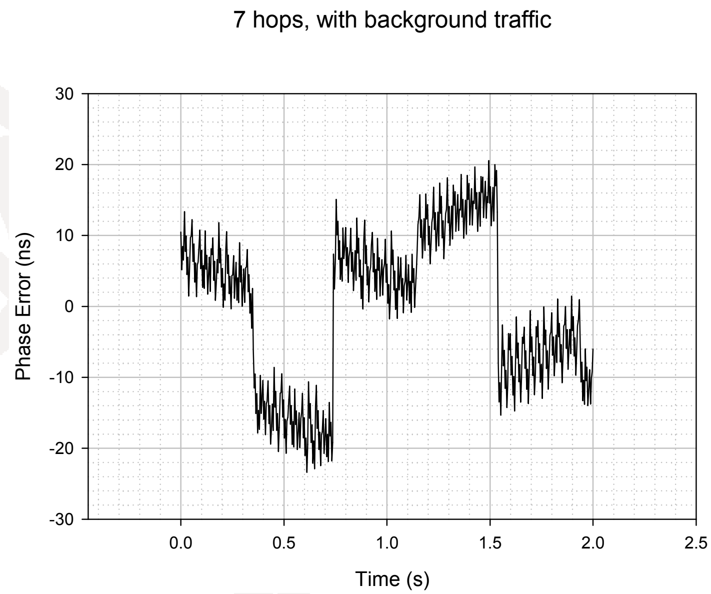


7 hops, no background traffic



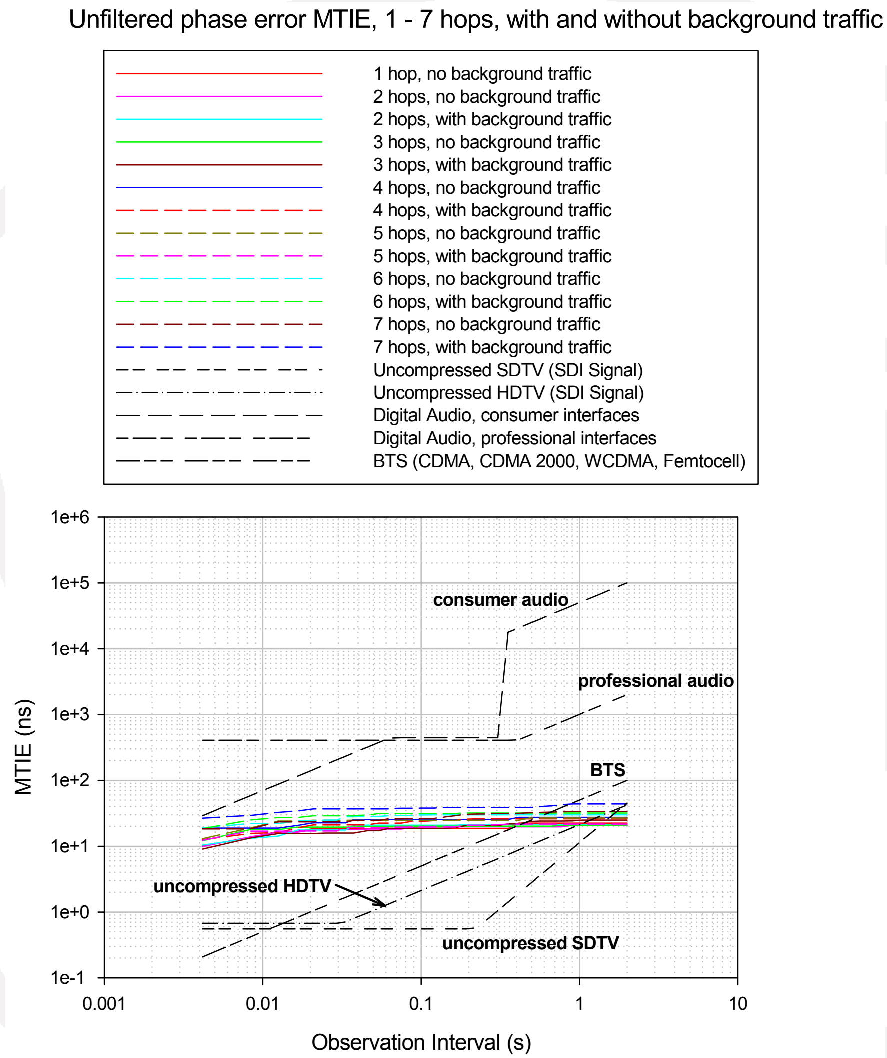
Test Results – With Background Traffic





- The time synchronization requirement of ±500 ns relative to the grandmaster is easily met
- The main component of phase error is due to the effect of the 8 ns phase measurement granularity in measuring propagation delay and residence time
- The 8 ns truncation can result in 4 ns jumps in the propagation delay measurement and 8 ns jumps in the residence time measurement
- The peak-to-peak phase error generally increases with the number of hops, as expected
- The background traffic does not have significant effect

Test Results – MTIE



- ❑The MTIE results meet the requirements for professional and consumer audio, for the range of observation intervals shown
  - •However, note that the jitter requirement is 10 ns for observation intervals less than 2.5 ms (200 Hz high-pass jitter measurement filter) for consumer audio and less than 62.5 μs (8 kHz measurement filter) for professional audio
- ❑The requirements for uncompressed video and cellular base stations are exceeded for shorter observation intervals
- ❑Endpoint filtering is needed to meet the application jitter requirements
  - •Consideration was given to filtering the measured data
    - ➢However, meeting the cellular base station and uncompressed video requirements requires narrow bandwidth filters (i.e., < 1 Hz)
    - ➢The 2 s of data collected for each case (the limit of the test equipment) is not sufficient duration for initial transients to decay

Summary

- Simulation results indicate that jitter/wander requirements are met for:
  - professional audio with a 10 Hz endpoint filter
  - consumer audio with a 1 Hz filter
  - cellular base stations and uncompressed HDTV with a 0.01 Hz filter
  - uncompressed SDTV with a 1 mHz filter
- Test results indicate that the time synchronization requirement of ±500 ns relative to the grandmaster, over 7 hops, is easily met
- The test results exceeded the jitter/wander requirements for the consumer and professional audio, cellular base station, and uncompressed video applications at shorter observation intervals because endpoint filtering was not performed

References – 1

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2. Geoffrey M. Garner, *Synchronization of Audio/Video Bridging Networks using IEEE 802.1AS*, presentation at 2010 NIST – ATIS – Telcordia Workshop on Synchronization in Telecommunication Systems (WSTS ‘10), March 9 – 11, 2010.
3. SMPTE 259M-1997, *10-Bit 4:2:2 Component and 4fSC Composite Digital Signals – Serial Digital Interface*, Society of Motion Picture and Television Engineers, 1997.
4. SMPTE 292M-1998, *Bit-Serial Digital Interface for High-Definition Television Systems*, Society of Motion Picture and Television Engineers, 1998.

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5. SMPTE 318M-1999 (Revision of SMPTE RP 154-1994), *Synchronization of 59.94- or 50-Hz Related Video and Audio Systems in Analog and Digital Areas – Reference Signals*, Society of Motion Picture and Television Engineers, 1999.
6. IEC 60958-1, *Digital Audio Interface – Part1: General*, International Electrotechnical Commission, Geneva, 2004.
7. IEC 60958-3, *Digital Audio Interface – Part3: Consumer Applications*, International Electrotechnical Commission, Geneva, 2003.
8. IEC 60958-4, *Digital Audio Interface – Part4: Professional Applications (TA4)*, International Electrotechnical Commission, Geneva, 2003.

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9. ISO/IEC 13818-1, *Information technology – Generic coding of moving pictures and associated audio information: Systems*, ISO/IEC, Geneva, 2000 (same as ITU-T Rec. H.222.0, ITU-T, Geneva, 2000).

10. ISO/IEC 13818-9, *Information technology – Generic coding of moving pictures and associated audio information: Extension for real-time interface for systems decoders*, ISO/IEC, Geneva, 1996.

11. Geoffrey M. Garner, *Description of ResE Video Applications and Requirements*, Samsung presentation to IEEE 802.3 ResE Study Group, May, 2005 (available at http://www.ieee802.org/3/re_study/public/200505/garner_1_rev1_0505.pdf)

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12. Geoffrey M. Garner, *Description of ResE Audio Applications and Requirements*, Samsung presentation to IEEE 802.3 ResE Study Group, May, 2005 (available at http://www.ieee802.org/3/re_study/public/200505/garner_2_0505.pdf)

13. Geoffrey M. Garner, *End-to-End Jitter and Wander Requirements for ResE Applications*, Samsung presentation to IEEE 802.3 ResE Study Group, May, 2005 (available at http://www.ieee802.org/3/re_study/public/200505/garner_3_0505.pdf)

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14. Geoffrey M. Garner and Yong Kim, *Comparison of 802.1AS D6.2 Jitter Generation Requirement with Specs for Inexpensive Oscillator Families used in 802 MAC/PHY Implementations*, Samsung and Broadcom presentation to IEEE 802.1 AVB TG, November 16, 2009 (available at http://www.ieee802.org/1/files/public/docs2009/as-garner-jitter-requirements-specs-1109.pdf).

15. Lee Cosart and Geoffrey M. Garner, Wander TDEV Measurements for Inexpensive Oscillator, Revision 1, Symmetricom and Samsung presentation to IEEE 802.1 AVB TG, November 2, 2009 (available at http://www.ieee802.org/1/files/public/docs2009/as-cosart-wander-tdev-measurements-1109-v01.pdf)

Appendix

802.1AS Application Requirements – Background

- References for application jitter, frequency offset, and frequency drift requirements and equivalent MTIE masks
  - The requirements for uncompressed video (SDTV and HDTV) are taken from [3] – [3]
  - The requirements for digital audio (consumer and professional) are taken from [6] – [8]
  - The requirements for MPEG-2 video are taken from [9] – [10]
  - The MTIE masks are derived from the requirements in [13]
  - See [11] – [13] for background on the A/V applications and their jitter/wander requirements

Remarks on Uncompressed Video Requirements – 1

- The uncompressed video requirements are very stringent, and will imply very narrow-bandwidth endpoint filters
  - For SDTV, the frequency drift requirement and the wide-band jitter requirement will give rise to a filter bandwidth on the order 1 mHz
  - For HDTV, the frequency offset requirement and the wide-band jitter requirement will give rise to a filter bandwidth on the order 0.01 Hz

Remarks on Uncompressed Video Requirements – 2

- Both IEEE 802.1 and ITU-T Q13/15 have sent liaisons to SMPTE asking for more background information on these requirements; in particular
  - Does the frequency drift requirement have to be met for digital SDTV, given that this requirement was originally intended to constrain the rate of change of frequency of the color subcarrier for analog, composite video
  - What is the purpose of the wide-band jitter requirement, with 10 Hz high-pass measurement filter, given there are no regenerators

Remarks on Uncompressed Video Requirements – 3

- A response liaison to IEEE 802.1 indicated:
  - The maximum frequency drift requirement does apply. The tight requirement is mainly due to the SMPTE 259M Level A specification (sampled analog NTSC video)
  - The wide-band jitter requirement does apply. The tight requirement is mainly due to the SMPTE 259M Level A specification
  - Since the SMPTE 259M specification was first put into place, most newer equipment uses SMPTE 259M Level C (270 Mbit/s component video), which is less sensitive to clock stability and jitter
  - Two current activities in SMPTE are looking at these issues

Remarks on Uncompressed Video Requirements – 4

- The potential narrow bandwidth required for the endpoint filter for uncompressed video is not an immediate concern for consumer A/V applications, because these signals are not used in consumer applications
  - At present, consumer bridges use 100 Mbit/s or 1 Gbit/s Ethernet
  - Uncompressed HD video signals have nominal rates of approximately 1.5 Gbit/s and 3 Gbit/s
  - Uncompressed SD video signals have nominal rates of approximately 145 Mbit/s, 177 Mbit/s, 270 Mbit/s, and 360 Mbit/s

Jitter Generation Requirement – 1

- The jitter generation of the free-running oscillator in a time-aware system shall not exceed 2 ns peak-to-peak, when measured over a 60 s measurement interval using a band-pass filter that consists of the following low-pass and high-pass filters:
  - High-pass filter: first-order characteristic (i.e., 0 dB gain peaking), 20 dB/decade roll-off, and 3 dB bandwidth (i.e., corner frequency) of 10 Hz
  - Low-pass filter: maximally-flat (i.e., Butterworth) characteristic, 60 dB/decade roll-off, and 3 dB bandwidth equal to the Nyquist rate of the oscillator (i.e., one-half the nominal frequency of the oscillator)

Jitter Generation Requirement – 2

- The 10 Hz high-pass measurement filter was chosen because some of the application requirements have wide-band jitter specifications with this or a similar jitter measurement filter
- Jitter generation and, where available, phase noise specifications were examined for a number of commercially-available, inexpensive oscillators used IEEE 802 MAC/PHY implementations [14]

Jitter Generation Requirement – 3

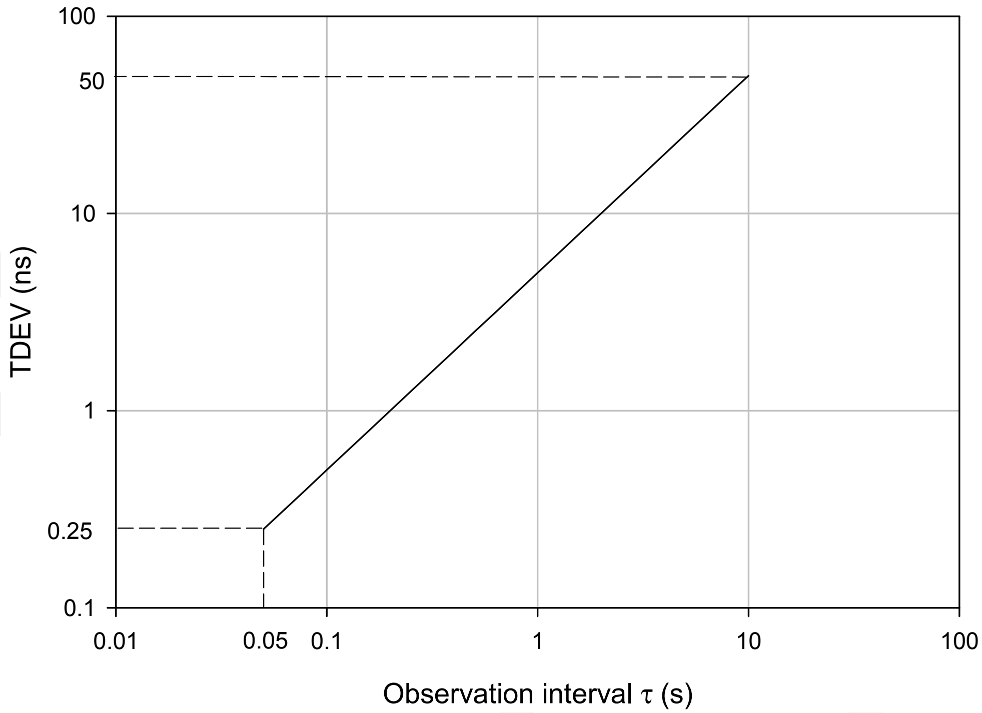
- It was found that all the specifications examined were consistent with the above jitter generation specification in the following sense
  - The above specification was derived from a phase noise power spectrum
  - In the case of those commercially-available oscillators for which power spectrum specifications were given, each respective specification was below the spectrum used to derive the jitter generation requirement
  - In the case of those commercially-available oscillators for which a jitter specification but not a full power spectrum was given, the jitter was generally not measured through a 10 Hz high-pass filter; however
    - The jitter computed from the assumed power spectrum exceeded the specification

Wander Generation Requirement – 1

- TDEV of the free-running oscillator in a time-aware system shall not exceed the TDEV mask on the next slide, when measured using
  - a measurement interval that is at least 120 s (i.e., at least 12 times the longest observation interval),
  - a low-pass filter with 3 dB bandwidth of 10 Hz, first-order characteristic, and 20 dB/decade roll-off,
  - a sampling interval that does not exceed 1/30 s.

Wander Generation Requirement – 2

Wander generation TDEV mask

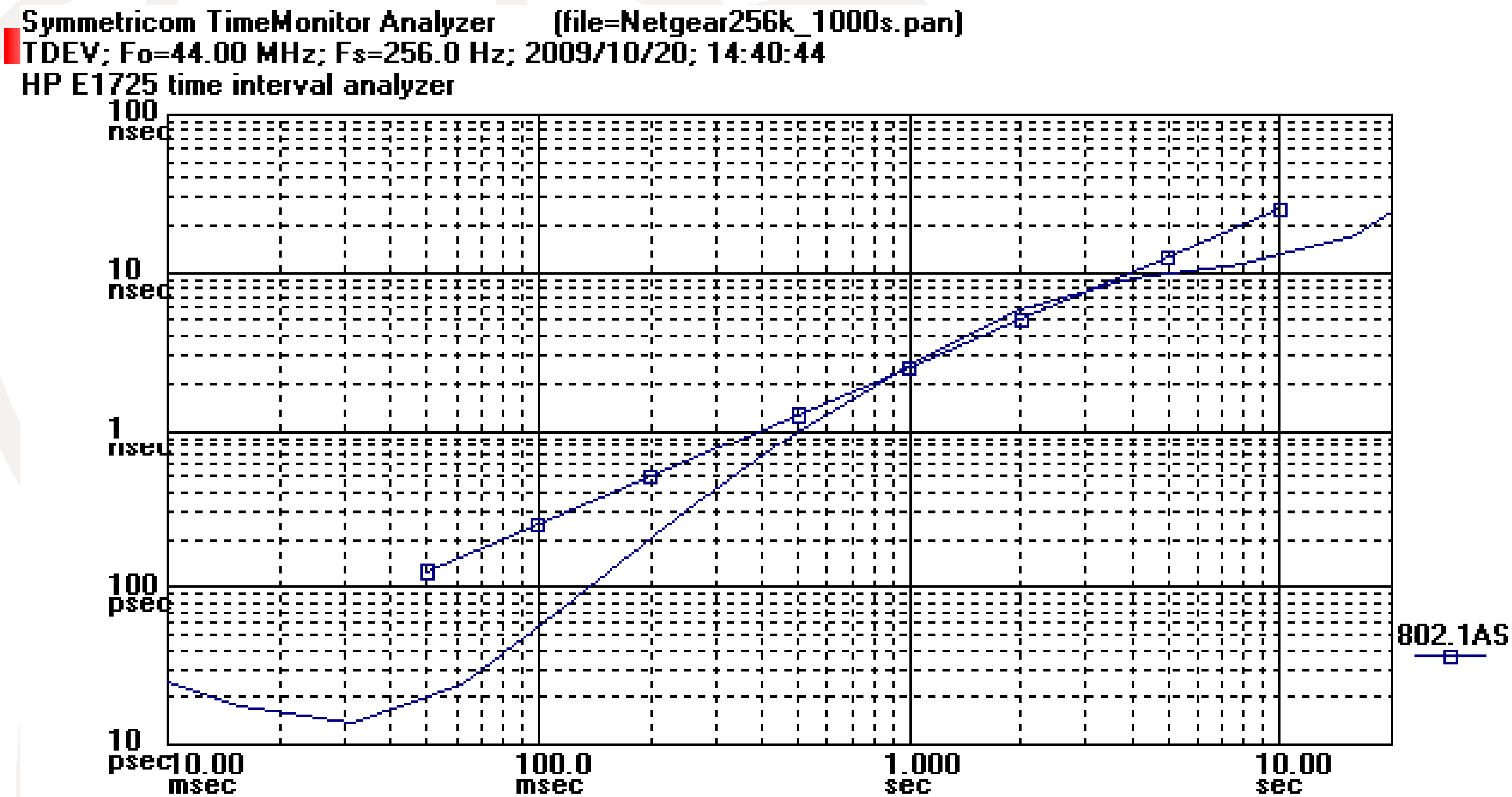


Observation Interval τ	TDEV
$\tau < 0.05$ s	No requirement
0.05 s $\leq \tau \leq$ 10 s	5τ ns
$\tau > 10$ s	No requirement

Wander Generation Measurements

- TDEV measurements were performed in [18] for one sample of an inexpensive oscillator used in a consumer-grade wireless router
- Results [15] indicate that the TDEV mask on the next slide is met for temperature variations in the lab of 4 deg C
  - The test results were actually compared with a TDEV mask whose level was one-half that of the mask on the previous slide, and the results slightly exceeded the mask for some observation intervals
  - As a result of the tests, the TDEV requirement was increased by a factor of 2 to allow margin
  - Sample result is given on the following slide, and additional results and test details are given in [15])

Sample Wander Generation Test Results



Brief Description of Simulator – 1

- Model is discrete-event based
- For simplicity, the clocks are modeled as one-step (this results in modeling of fewer events)
- Events include sending and receiving of Sync, Pdelay_Req, and Pdelay_Resp
- On each event, an event handler function runs, and then schedules the next event
- The events are stored in chronological order, in a linked list

Brief Description of Simulator – 2

- A fixed time step between events is used to integrate endpoint filters
- Endpoint filter model is linear, second-order, with 20 dB/decade roll-off
  - Specify filter bandwidth and gain peaking
- The simulator is implemented in C on a Linux system