Comparison of 802.1AS D6.2 Jitter Generation Requirement with Specs for Inexpensive Oscillator Families used in 802 MAC/PHY Implementations

Geoffrey M. Garner
SAMSUNG Electronics (Consultant)
gmgarner@comcast.net

Yong Kim
Broadcom Corporation
ybkim@broadcom.com

IEEE 802.1 AVB TG
2009.11.16

Introduction - 1

- The current jitter requirement in 802.1AS D6.2 is given in B.1.3.1 as
  - The jitter generation of the free-running LocalClock shall not exceed 1 ns peak-to-peak, when measured over a 60 s measurement interval. The jitter generation shall be measured through a band-pass filter that consists of the following high-pass and low-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 LocalClock entity (i.e., one-half the nominal frequency of the LocalClock entity)
- A portion of Reference [1] described the model that the above jitter requirement is based on, in conjunction with comment 80 of the 802.1AS D6.1 ballot
  - Comment 80 outlined several issues that had been raised offline, and Reference [1] provided background information on the specification and underlying model

Introduction - 2

- While the resolution of comment 80 at the September, 2009 AVB TG meeting was that the current jitter specification is reasonable and appropriate, there was at least one comment in the meeting that it would be advisable to compare the specification in 801AS with specifications for commercially-available inexpensive oscillators
- The present contribution makes this comparison
- Before making the comparison, the model and its relation to the 802.1AS jitter generation specification is reviewed
- As indicated in reference [1], the reason for limiting jitter here is to enable the jitter requirements for applications to be met with reasonable endpoint filtering
  - We are not trying to ensure clock recovery with acceptable BER (other jitter specs do that)
  - We are not trying to prevent buffer overflow in chains of clocks (at the physical layer) or regenerators (we don’t have these in 802.1AS)

Clock Noise Model - 1

- The clock noise model was taken from a model used in previous simulations in September and November, 2005
  - http://www.ieee802.org/3/re_study/public/200509/garner_1.pdf
  - http://www.ieee802.org/3/re_study/public/200511/20051114-garner-synch-simul.pdf
- Clock noise is modeled as a combination of 3 components:
  - White phase modulation (WPM, i.e., white phase noise)
  - Flicker phase modulation (FPM)
  - Flicker frequency modulation (FFM)

Clock Noise Model - 2

- Can characterize these noise processes by the respective one-sided power spectral density (PSD)

$$S_\varphi(f) = 4\int_0^\infty R_\varphi(\tau)\cos 2\pi f\tau \, d\tau$$

$$R_\varphi(\tau) = \int_0^\infty S_\varphi(f)\cos 2\pi f\tau \, df$$

$$R_\varphi(\tau) = E[\varphi(t)\varphi(t+\tau)]$$

$$R_\varphi(0) = E[\varphi^2(t)]$$

where

$\varphi(t) =$ phase noise process (units are usually rad, deg, or UI)

$S_\varphi(f) =$ power spectral density (units are usually $\mathrm{rad}^2/\mathrm{Hz}$ or $\mathrm{UI}^2/\mathrm{Hz}$)

$R_\varphi(\tau) =$ autocorrelation function (units are usually rad^2 or UI^2)

$R_\varphi(0) =$ mean square (= variance for zero mean process, units are usually rad^2 or UI^2)

Clock Noise Model - 3

- For the above noise processes, the PSDs are
  - FFM: $S(f) = A/f^3$
  - FPM: $S(f) = B/f$
  - WPM: $S(f) = C$
- In the above, A, B, and C are constants.
- Note that for both WPM and FPM a noise bandwidth must be specified (because the integral over frequency diverges as $f \to \infty$
- The actual PSD was taken from the document: *Jitter and Signal Noise in Frequency Sources*, Raltron, Application Note, available at http://www.raltron.com/
  - In this document, PSD is specified using the related 2-sided spectrum $L(f)$
  - $S_\varphi(f) = 2L(f)$ (units of $L(f)$ are usually $\mathrm{dBc/Hz}$)
- The spectrum is given on the following slide

Clock Noise Model - 4

Frequency (Hz), from carrier	$L(f)$, in dBc/Hz	$S_\varphi(f)$ in rad^2/Hz
10	-40	2×10^{-4}
100	-70	2×10^{-7}
1000	-100	2×10^{-10}
10000	-120	2×10^{-12}

To match this, we take:

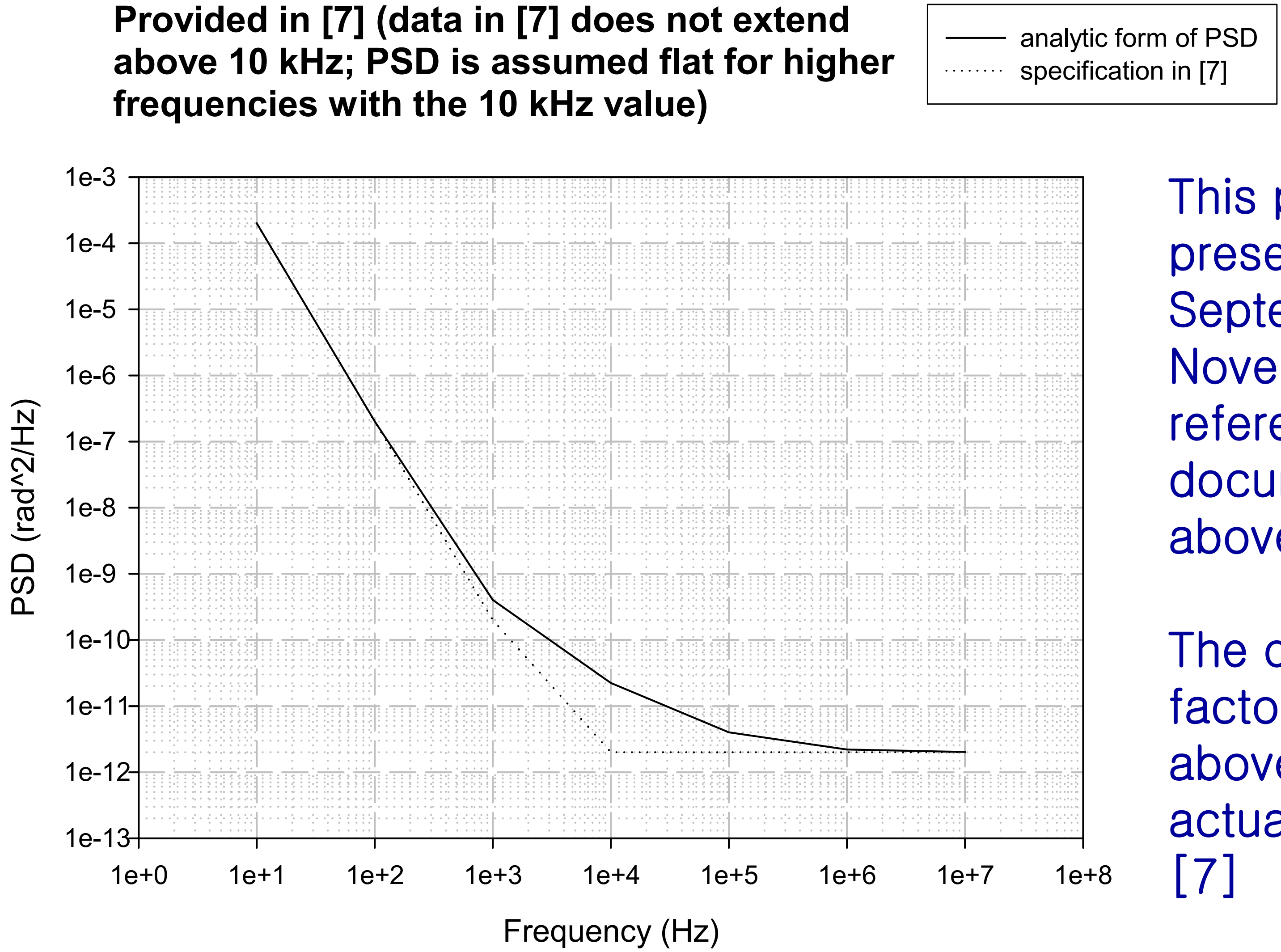
$A = 0.2$ rad^{2}Hz^2 (i.e., the FFM term matches the PSD at 10 Hz)
$B = 2 \times 10^{-7}$ rad^2 (i.e., the FPM term matches the PSD at 1000 Hz
$C = 2 \times 10^{-12}$ rad^2/Hz (i.e., the WPM term matches the PSD at 10 kHz

The full PSD is plotted on the following slide

Note: $L(f) = 10 * \log_{10} [S(f)/2]$

Clock Noise Model - 5

Example Clock Phase Noise Specification Provided in [7] (data in [7] does not extend above 10 kHz; PSD is assumed flat for higher frequencies with the 10 kHz value)



This plot is taken from presentations of September and November, 2005; reference [7] is the document cited above.

The dotted line is a factor of 10 or more above the data for actual oscillators of [7]

Clock Noise Model - 6

- Note that in this model, the FFM component dominates at low frequencies, i.e., in the wander region
  - This is typical for oscillators
  - The wander generation requirement of B.1.3.2 covers frequencies below 10 Hz
  - It is stated in terms of TDEV (with corresponding ADEV and PTPDEV shown as well)
    - These are given for observation intervals of 0.05 s and longer
    - If a 10 Hz anti-aliasing filter has been used to remove frequency components in the jitter region (i.e., > 10 Hz), then 10 Hz becomes the Nyquist rate, and the corresponding sampling interval is 0.05 s
  - For FFM (τ = observation interval)
    - TDEV is proportional to τ^1
    - ADEV is proportional to τ^0
    - PTPDEV is proportional to τ^1
- In the following slides, we focus on jitter, because that was the focus of this comment

RMS Jitter Computation - 1

- In B.1.3, jitter is measured through a 10 Hz high-pass measurement filter
- For a 25 MHz oscillator (ν_0 = 25 MHz), the Nyquist rate is 12.5 MHz
- The mean-square jitter is given by

$$\sigma^2 = \int_{10}^{\nu_0/2} S_\varphi(f)\,df$$

- The plot on slide 21 indicates that, between 10 Hz and 12.5 MHz, the FFM is the dominant noise component
- The comment indicates that the jitter was incorrectly computed using the WPM component
  - The resulting rms jitter was considerably less than 1 ns; this was rounded to 1 ns, which is still very small compared to the 40 ns phase measurement granularity
- In any case, the above is incorrect; we now compute the jitter due to each component

RMS Jitter Computation - 2

❑FFM component

$$\sigma^2 = \int_{10}^{\nu_0/2} \frac{A}{f^3} df = -\frac{A}{2f^2}\bigg|_{10}^{\nu_0/2} \cong \frac{A}{200\text{Hz}^2} = 10^{-3}\,\text{rad}^2 = \frac{10^{-3}}{(2\pi)^2}\text{UI}^2 = 2.53\times10^{-5}\,\text{UI}^2$$

$$\sigma(\text{rms}) \cong 5\text{ mUI} = 0.2\text{ ns}$$

❑FPM component

$$\sigma^2 = \int_{10}^{\nu_0/2} \frac{B}{f} df = B\ln f\big|_{10}^{\nu_0/2} = B\ln\frac{\nu_0}{20} = B\ln(1.25\times10^6) = 2.81\times10^{-6}\,\text{rad}^2 = \frac{2.81\times10^{-6}}{(2\pi)^2}\text{UI}^2 = 7.11\times10^{-8}\,\text{UI}^2$$

$$\sigma(\text{rms}) \cong 0.27\text{ mUI} = 10.8\text{ ps}$$

❑WPM component

$$\sigma^2 = \int_{10}^{\nu_0/2} C\,df = C\left(\frac{\nu_0}{2} - 10\right) \cong 2.5\times10^{-5}\,\text{rad}^2 = \frac{2.5\times10^{-5}}{(2\pi)^2}\text{UI}^2 = 6.3\times10^{-7}\,\text{UI}^2$$

$$\sigma(\text{rms}) \cong 0.8\text{ mUI} = 32\text{ ps}$$

RMS Jitter Computation - 3

- The above indicate that the FFM component gives the largest contribution to jitter measured from 10 Hz
- The rms jitter due to all 3 components is obtained by taking the square root of the sum of the mean-square jitter for each component, i.e.,

$$\sigma(\mathrm{rms,\,total}) = \sqrt{(0.2\ \mathrm{ns})^2 + (0.0108\ \mathrm{ns})^2 + (0.032\ \mathrm{ns})^2} = 0.203\ \mathrm{ns}$$

Peak-to-Peak and RMS Jitter - 1

- Next, the relation between rms and peak-to-peak jitter must be considered. The above model assumes phase noise has an underlying probability distribution
  - In this case, the peak-to-peak would be taken as some number of standard deviations (i.e., some multiple of the rms jitter), and the value of the multiplier along with the distribution determine the particular quantile that the peak-to-peak value corresponds to
  - For example, for a Gaussian distribution
    - 3σ corresponds to 0.9973 quantile, or 2.7×10^{-3} probability of exceeding the peak-to-peak value (in either the positive or negative direction)
    - 6σ corresponds to 1.97×10^{-9} probability of exceeding the peak-to-peak value (in either the positive or negative direction)
    - 7σ corresponds to 2.56×10^{-12} probability of exceeding the peak-to-peak value (in either the positive or negative direction)
    - 9σ corresponds to 2.26×10^{-19} probability of exceeding the peak-to-peak value (in either the positive or negative direction)
    - 14σ corresponds to 1.56×10^{-44} probability of exceeding the peak-to-peak value (in either the positive or negative direction)

Peak-to-Peak and RMS Jitter - 2

- In considering the relation between peak-to-peak and rms jitter, note that the jitter measurement is made over 60 s
- For a minimum frequency oscillator of 25 MHz, this corresponds to $(25 \times 10^6 \text{ Hz})(60 \text{ s}) = 1.5 \times 10^9$ samples
- For a 125 MHz oscillator, this corresponds to $(125 \times 10^6 \text{ Hz})(60 \text{ s}) = 7.5 \times 10^9$ samples
- This and the quantiles of the Gaussian distribution on the previous slide indicate that, for measurement of the jitter generation of a 25 MHz oscillator over 60 s, the relation between peak-to-peak and rms jitter is between 6σ and 7σ
- For the above model, 7σ corresponds to (7)(0.203 ns) = 1.42 ns
  - Note that this is slightly larger than the requirement in B.1.3.1 of 802.1AS
    - This means that even if the above noise model and rms jitter value (0.203 ns) are correct, the requirement for peak-to-peak likely needs more margin
    - 2 ns for the peak-to-peak limit would provide the needed margin, assuming the above noise model and rms jitter are correct, i.e., are representative of inexpensive oscillators

Peak-to-Peak and RMS Jitter - 3

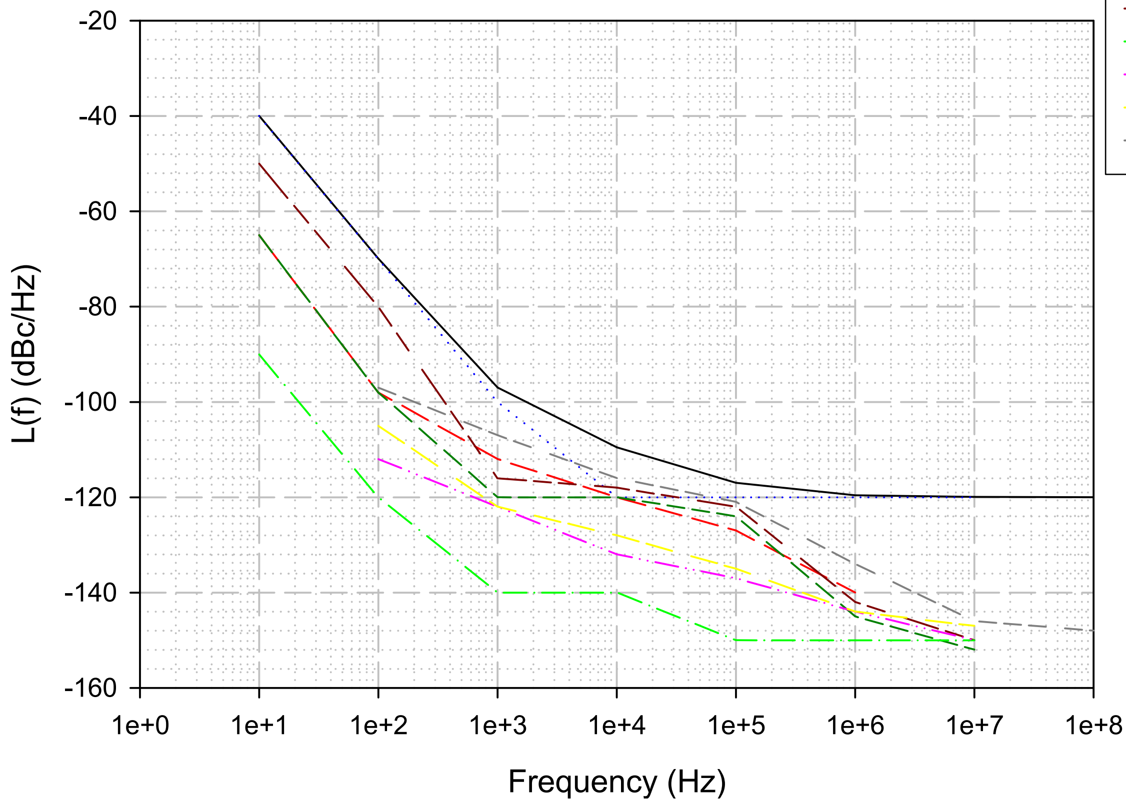
- The results show that, for the above noise model, the peak-to-peak jitter will certainly not exceed 1.42 ns (i.e., just over 7σ), which is still small compared to the 40 ns phase measurement granularity
- Note: the phase measurement granularity and jitter/wander are separate quantities
  - Phase measurement granularity refers to the 40 ns spacing of the clock edges
    - An event that we want to timestamp must be referred to the most recent edge, which means that the error can be as much as 40 ns
  - Jitter and wander refer to the deviation of the clock edges from their ideal positions in time
    - This gives rise to an additional error in a timestamp, because the most recent clock edge does not occur at its ideal time
- It remains to consider whether the above noise model and rms jitter are representative of inexpensive oscillators; this is done on the following slides

Jitter Specifications for Commercially Available, Inexpensive Oscillators - 1

- Specifications were obtained for the following oscillators (these are all inexpensive and obtained from public web sites):
  1) Fox Xpress0 FXO-HC73 Series
  2) Wipro NewLogic 40 MHz oscillator available IP Core
  3) Ecliptek EC26 Series
  4) Ecliptek EB17E2 Series
  5) Silicon Labs Si532
  6) SaRonix-eCera Legacy S1614 Series
  7) SaRonix-eCera Legacy S1642 Series
  8) Pericom (various oscillators)
     a) CMOS crystal oscillators, series FN, SX, FD, FK, FJ
     b) Differential crystal oscillators, series PX, LN, SH, SN, PN, PB, SD
- For (1), (2), and (5), phase noise power spectra were given
- For (1) and (3) – (8), rms jitter measured through a specified bandpass filter was given

- Comparison of phase noise power spectra of oscillators with model used to derive jitter specification in B.1.3.1

Phase noise spectra for various inexpensive oscillators and comparison with model that 802.1AS, Annex B, B.1.3.1 specification is based on



The model (solid black line) is above all the data

rms jitter specifications – 1

- A range in the frequency column indicates that a variety of products are available, with frequencies in the stated range

Oscillator	Frequency	Jitter measurement filter	Rms jitter specification (ps)
1) Fox Xpress0 FXO-HC73	0.75 – 250 MHz	12 kHz – 20 MHz	0.93 (62.5 MHz), 0.86 (106.25 MHz), 0.75 (125 MHz), 0.77 (156.25 MHz)
3) Ecliptek EC26 Series	1.544 – 200 MHz	12 kHz – 20 MHz	1
4) Ecliptek EB17E2 Series	1.8432 – 50 MHz	12 kHz – 20 MHz	1

Jitter Specifications for Commercially Available, Inexpensive Oscillators - 4

- rms jitter specifications – 2

Oscillator	Frequency	Jitter measurement filter	Rms jitter specification (ps)
5) Silicon Labs Si532	10 MHz – 1.4 GHz	12 kHz – 20 MHz	0.4 (500 – 1400 MHz), 0.5 (125 – 500 MHz)
6) SaRonix-eCera Legacy S1614 Series	1 – 166 MHz	10 kHz – 20 MHz	1
7) SaRonix-eCera Legacy S1642 Series	1 – 106.25 MHz	10 kHz – 20 MHz	1
8) Pericom (various oscillators)	1 – 800 MHz	PCI-Express 2.0 jitter filter (10 kHz – 1.5 MHz)	4 (note: this was the maximum of 26 products, 23 of which were 1 ps and 1 of which was 0.9 ps)

Jitter Specifications for Commercially Available, Inexpensive Oscillators - 5

- To compare the above rms jitter specifications with the model, we must re-compute the rms jitter using the jitter measurement filters in the tables above
- Each of the three integrals on slide 11 must be recomputed with lower and upper limits corresponding to the jitter measurement filter corner frequencies
- The computations are on the following slides

❑FFM component, 12 kHz – 20 MHz

$$\sigma^2 = \int_{12000}^{20\times10^6} \frac{A}{f^3}\,df = -\frac{A}{2f^2}\bigg|_{12000}^{20\times10^6} \cong \frac{A}{2.88\times10^8\,\mathrm{Hz}^2} = 6.944\times10^{-10}\,\mathrm{rad}^2 = \frac{6.944\times10^{-10}}{(2\pi)^2}\,\mathrm{UI}^2 = 1.759\times10^{-11}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 4.2\,\mu\mathrm{UI} = 0.17\ \mathrm{ps}$$

❑FPM component, 12 kHz – 20 MHz

$$\sigma^2 = \int_{12000}^{20\times10^6} \frac{B}{f}\,df = B\ln f\Big|_{12000}^{20\times10^6} = B\ln\frac{20\times10^6}{12000} = B\ln(1666.67) = 1.484\times10^{-6}\,\mathrm{rad}^2 = \frac{1.484\times10^{-6}}{(2\pi)^2}\,\mathrm{UI}^2 = 3.758\times10^{-8}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 0.194\ \mathrm{mUI} = 7.75\ \mathrm{ps}$$

❑WPM component

$$\sigma^2 = \int_{12000}^{20\times10^6} C\,df = C\left(20\times10^6 - 12000\right) \cong 3.998\times10^{-5}\,\mathrm{rad}^2 = \frac{3.998\times10^{-5}}{(2\pi)^2}\,\mathrm{UI}^2 = 1.103\times10^{-6}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 1.0\ \mathrm{mUI} = 40\ \mathrm{ps}$$

- The rms jitter due to all 3 components is obtained by taking the square root of the sum of the mean-square jitter for each component, i.e.,

$$\sigma(\mathrm{rms, total}) = \sqrt{(0.17\ \mathrm{ps})^2 + (7.75\ \mathrm{ps})^2 + (40\ \mathrm{ps})^2} = 40.7\ \mathrm{ps}$$

- This is well above the specifications for those oscillators above whose jitter measurement filter is a bandpass with corner frequencies of 12 kHz and 20 MHz (the largest such specification is 1 ps)
- **Note that it is not necessary to redo the integrals for the range 10 kHz to 20 MHz, because the result will be larger than 40.7 ps, and therefore is well above the specifications for those oscillators above whose jitter measurement filter is a bandpass with corner frequencies of 12 kHz and 20 MHz**

❑FFM component, 10 kHz – 1.5 MHz

$$\sigma^2 = \int_{10000}^{1.5\times10^6} \frac{A}{f^3}\,df = -\left.\frac{A}{2f^2}\right|_{10000}^{1.5\times10^6} \cong \frac{A}{2\times10^8\,\mathrm{Hz}^2} = 1.0\times10^{-9}\,\mathrm{rad}^2 = \frac{1.0\times10^{-9}}{(2\pi)^2}\,\mathrm{UI}^2 = 2.533\times10^{-11}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 5.03\ \mu\mathrm{UI} = 0.20\ \mathrm{ps}$$

❑FPM component, 12 kHz – 20 MHz

$$\sigma^2 = \int_{10000}^{1.5\times10^6} \frac{B}{f}\,df = B\ln f\Big|_{10000}^{1.5\times10^6} = B\ln\frac{1.5\times10^6}{10000} = B\ln(150) = 1.0\times10^{-6}\,\mathrm{rad}^2 = \frac{1.0\times10^{-6}}{(2\pi)^2}\,\mathrm{UI}^2 = 2.54\times10^{-8}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 0.159\ \mathrm{mUI} = 6.37\ \mathrm{ps}$$

❑WPM component

$$\sigma^2 = \int_{10000}^{1.5\times10^6} C\,df = C\left(1.5\times10^6 - 10000\right) \cong 2.98\times10^{-6}\,\mathrm{rad}^2 = \frac{2.98\times10^{-6}}{(2\pi)^2}\,\mathrm{UI}^2 = 7.55\times10^{-8}\,\mathrm{UI}^2$$

$$\sigma(\mathrm{rms}) \cong 0.275\ \mathrm{mUI} = 11\ \mathrm{ps}$$

Jitter Specifications for Commercially Available, Inexpensive Oscillators - 7

- The rms jitter due to all 3 components is obtained by taking the square root of the sum of the mean-square jitter for each component, i.e.,

$$\sigma(\text{rms, total}) = \sqrt{(0.2\text{ ps})^2 + (6.37\text{ ps})^2 + (11\text{ ps})^2} = 12.7\text{ ps}$$

- This is well above the specifications for those oscillators above whose jitter measurement filter is a bandpass with corner frequencies of 10 kHz and 1.5 MHz

Conclusions - 1

- It is shown on slide 17 that the phase noise power spectra for seven different commercially-available, inexpensive oscillators are below the model used to derive the rms jitter value that the peak-to-peak specification of B.1.3.1 is based on
- It is shown on slides 18-24 that the model produces rms jitter values that are below the rms jitter specifications of a number of commercially-available, inexpensive oscillators
- Therefore, the rms jitter value that the peak-to-peak specification of B.1.3.1 is based on is valid
- It is shown on slides 13 – 15 that the jitter measurement interval of 60 s (specified in B.1.3.1) and the minimum oscillator frequency of 25 MHz are consistent with a peak-to-peak of approximately 7σ , which corresponds to approximately 1.42 ns for the jitter measurement filter of B.1.3.1 (10 Hz to 12.5 MHz) and model used here
- This means that more margin is needed for the peak-to-peak jitter (i.e., the 1 ns peak-to-peak limit must be increased)
    - A limit of 2 ns peak-to-peak would provide the necessary margin

Conclusions - 2

- Some oscillator RMS jitter specifications that show 1 ps may be better than 1 ps but, so far, few main-stream applications require vendors to specify or test for a smaller number. However, there is value of specifying peak-to-peak jitter of 2 ns to accommodate a broad set of existing oscillators with published specifications.

References

1. Geoffrey M. Garner, Supporting Material for 802.1AS D6.1 Ballot Comments 35, 36, 37, and 80, Samsung presentation for September, 2009 IEEE 802.1 AVB TG meeting, Volterra, Italy, September 9, 2009.