Addition of Quantization Noise to COM

Additional Material for Comments Against Draft 2.0

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Introduction

- Contribution shakiba_3dj_01b_2505.pdf reemphasized effects of adding quantization noise to the COM reference receiver for channel compliance verification and provided comprehensive data and analysis for three test sets of 112 CR/KR, 110 C2C, and 208 C2M channels
- The contribution explained process of incorporating direct modeling method of quantization noise to the COM reference receiver as well as its example Matlab code implementation
- The contribution also demonstrated reasonable overhead in math and code implementation
- Follow-up contribution shakiba_3dj_elec_01_250626 presented a more specific proposal in support of comments against D2.0 to add a quantization noise term to the COM reference receiver and COM calculation flow
- The contribution offered four proposal options with option 3 having a stronger consensus
- This current contribution contains content for the changes resulting from quantization noise comments against draft D2.0

Description of Comments

- Comment row #6:
  - Page 777, after Section 178A.1.7.5
  - Add a new Section “178A.1.7.6 Quantization noise”

178A.1.7.6 Quantization noise

The power spectral density of the quantization noise at the input of the quantized time receiver equalizer is defined by Equation (178A-X0).

$$S_{qn}(\theta) = \sigma_q^2 / f_b \qquad (178\text{A} - \text{X}0)$$

where σ_q^2 is the power of the quantization noise at the output of the quantizer defined by Equation (178A-X1).

$$\sigma_q^2 = LSB^2/12 \qquad (178\text{A} - \text{X}1)$$

where LSB is the quantization step size defined by Equation (178A-X2).

$$LSB = 2\,CL/\left(2^{N_{qb}} - 1\right) \qquad (178\text{A} - \text{X}2)$$

Description of Comments

where CL is the quantization clip level defined by Equation (178A-X3).

$$CL = -P_{sig\_noise}^{-1}(P_{qc}/2) \qquad (178A-X3)$$

where P_{qc} is the quantization clip probability of the noisy signal, typically set by the target error ratio, and P_{sig_noise} is the cumulative distribution function of the noisy signal prior to quantization defined by Equation (178A-33) substituting $p_j(y)$ with p_{sig_noise}, probability density function of the noisy signal prior to quantization defined by Equation (178A-X4).

$$p_{sig\_noise}(y) = p_{sig}(y) * p_{noise}(y) \qquad (178A-X4)$$

Where

p_{sig} is the probability density function of the noiseless signal prior to quantization obtained by following the procedure defined in 93A.1.7.1 with pulse response $h(n)$ replaced by the pulse response from the input of the transmitter FFE to the input of the quantizer.

p_{noise} is the probability density function of the noise prior to quantization estimated by a Gaussian distribution* with a zero mean and a variance defined by Equation (178A-X5).

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* The actual noise probability distribution is not necessarily Gaussian. However, for the purpose of equalizer optimization a Gaussian assumption helps optimization algorithm run time by avoiding to calculate the noise PDF every time. The final COM will be based on the actual noise PDF.

Description of Comments

$$\sigma_{noise}^2 = \sigma_{rn}^2 + \sum_{k=1}^{K-1} {\sigma_{xn}^{(k)}}^2 + \sigma_{tn}^2 + \sigma_{jn}^2 + \sigma_{in}^2 \qquad (178\text{A} - \text{X5})$$

where each of the terms in the Equation (178A-X5) is calculated from the general Equation (178A-X6) using their corresponding power spectral densities obtained from sections 178A.1.7.1 to 178A.1.7.5.

$$\sigma^2 = \int_{-\pi}^{\pi} S(\theta) d\theta \qquad (178\text{A} - \text{X6})$$

Description of Comments

- Comment row #7:
  - Page 774, Section 178A.1.7, Figure 178A-7
  - Add quantization noise to the figure

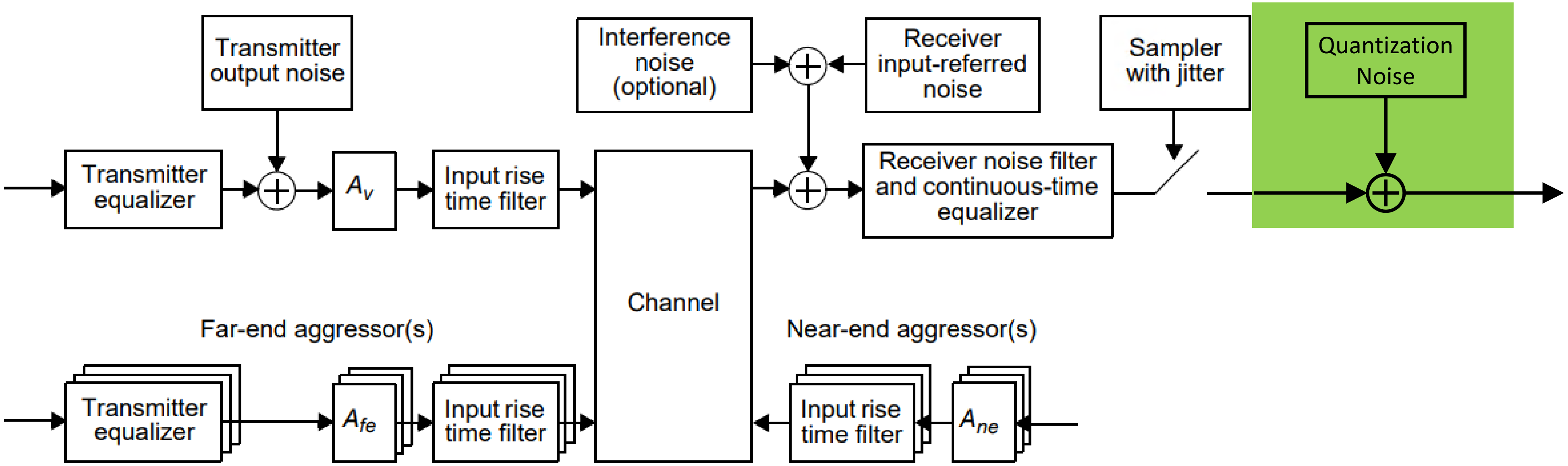

Figure 178A–7—Sources of noise considered in calculation of COM

Description of Comments

- Comment row #8:
  - Page 775, Section 178A.1.7, Table 178A-9
  - Add Noise-equivalent quantization bits and Quantization clip probability parameters to the table

Table 178A–9—Summary of noise parameters

Parameter	Symbol	Units
Number of signal levels	L	—
One-sided noise spectral density at receiver input	η_0	V^2/GHz
Transmitter signal-to-noise ratio	SNR_{TX}	dB
Random jitter, RMS	σ_{RJ}	UI
Dual-Dirac jitter, peak	A_{DD}	UI
Noise-equivalent quantization bits	N_{qb}	–
Quantization clip probability	P_{qc}	–

Description of Comments

- Comment row #9:
  - Page 775, Section 178A.1.7, Equation (178A-14)
  - Add Quantization Noise PSD

$$S_n(\theta) = S_{rn}(\theta) + \sum_{k=1}^{K-1} S_{xn}^{(k)}(\theta) + S_{tn}(\theta) + S_{jn}(\theta) + S_{in}(\theta) + S_{qn}(\theta) \qquad (178A\text{–}14)$$

where

θ	is normalized frequency in the range $[-\pi, \pi)$ where $\pi = f_b / 2$
$S_{rn}(\theta)$	is the receiver input-referred noise power spectral density defined in 178A.1.7.1
$S_{xn}{}^{(k)}(\theta)$	is the crosstalk power spectral density for signal path k defined in 178A.1.7.2
$S_{tn}(\theta)$	is the transmitter output noise power spectral density defined in 178A.1.7.3
$S_{jn}(\theta)$	is the power spectral density of the noise due to jitter defined in 178A.1.7.4
$S_{in}(\theta)$	is the interference noise power spectral density defined in 178A.1.7.5
$S_{qn}(\theta)$	is the quantization noise power spectral density defined in 178A.1.7.6

Description of Comments

- Comment row #10:
  - Page 774, Section 178A.1.7, Line 32

The sources of noise considered in the calculation of COM are illustrated in Figure 178A–7. Each source of noise is represented by its power spectral density at the output of the sampler. The parameters used to compute these power spectral densities are summarized in Table 178A–9.

quantizer

- Comment row #11:
  - Page 775, Section 178A.1.7, Line 15

The total noise power spectral density S_n at the sampler output is the sum of the individual noise power spectral densities as defined in Equation (178A–14).

quantizer

- Comment row #12:
  - Page 777, Section 178A.1.8.1, Line 43

The receiver discrete-time equalizer is illustrated in Figure 178A–9. It is composed of a feed-forward filter and a feedback filter. The input to the feed-forward filter is the output of the sampler. The input to the feedback filter is an estimate of the transmitted PAM-L symbol which is assumed to be correct. The impact

quantizer

Description of Comments

- Comment row #13:
  - Page 778, Section 178A.1.8.1, Figure 178A-9
  - Add quantization noise after sampler

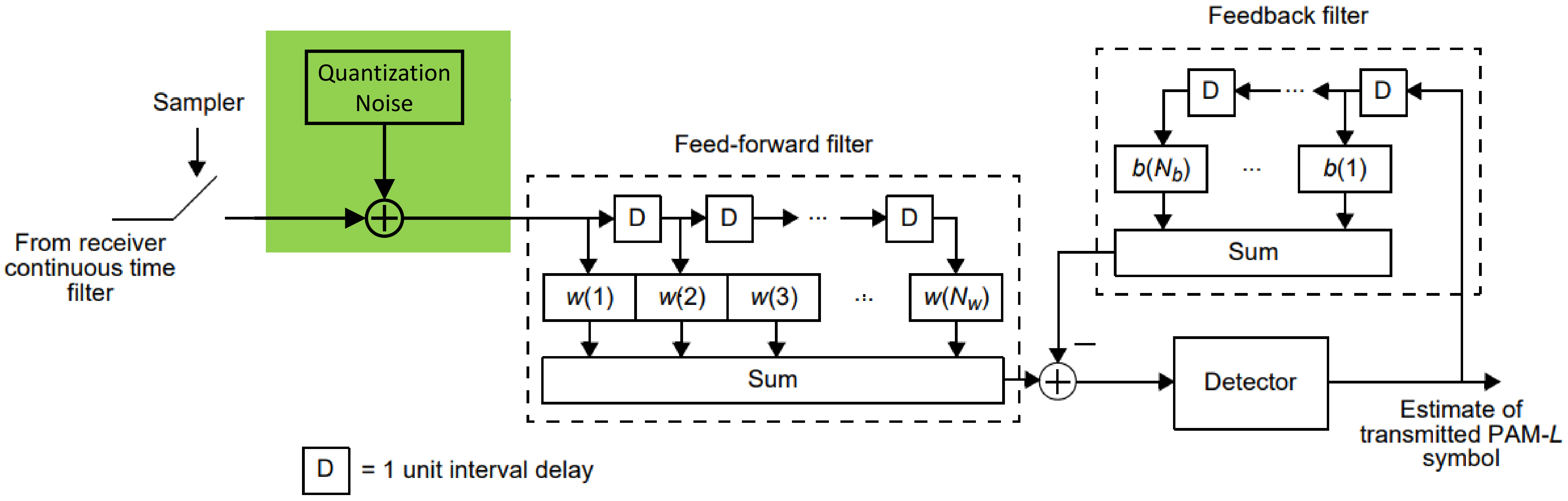

Figure 178A–9—Receiver discrete-time equalizer

Description of Comments

- Comment row #14:
  - Page 782, Section 178A.1.9.3, Line 17
  - Add the following text starting from line 17

The probability distribution function $f_{QN,in}(y)$ for quantization noise at its injection point (input of the feed-forward filter) is uniformly distributed over the range of $-LSB/2$ to $LSB/2$. The probability distribution function $f_{QN}(y)$ for quantization noise is computed by initializing $f_{QN}(y)$ to a Dirac-delta function and recursively convolving it with $f_{QN,in}(y)$, each time scaled by $w_{lim}(j)$ for integer values $j = 1$ to $j = N_w$, as defined by Equation (178A-X7).

$$f_{QN}(y) = f_{QN}(y) * f_{QN,in}\left(\frac{y}{w_{lim}(j)}\right) \quad , for\ j = 1\ to\ N_w \qquad (178A - X7)$$

where

$f_{QN,in}$ is the probability density function of the quantization noise at its injection point defined by Equation (178A-X8).

w_{lim} is the optimized vector of taps in the feed-forward filter of the receiver equalizer defined in 178A.1.8.1.

Description of Comments

N_w is the total number of taps in the feed-forward filter of the receiver equalizer defined in 178A.1.8.1.

LSB is defined by Equations (178A-X2) and (178A-X3) with substituting P_{sig_noise} with the actual cumulative distribution function of the noise prior to quantization and after optimization during execution of the equation.

$$p_{qi}(y) = \begin{cases} 1/LSB & -LSB/2 \leq y < LSB/2 \\ 0 & Otherwise \end{cases} \qquad (178A-X8)$$

Description of Comments

- Comment row #15:
  - Page 782, Section 178A.1.9.3, Equation (178A-36)
  - Add Quantization Noise PSD

$$\sigma_G^2 = f_b \int_{-\pi}^{\pi} [S_{tn}(\theta) + S_{jn}^{(RJ)}(\theta) + S_{rn}(\theta) + S_{in}(\theta) + S_{qn}(\theta)] \left|H_{rxffe}(\theta)\right|^2 d\theta \qquad (178A\text{–}36)$$

Description of Comments

- Comment row #16:
  - Page 783, Section 178A.1.10, Figure 178A-10
  - Add quantization noise after sampler

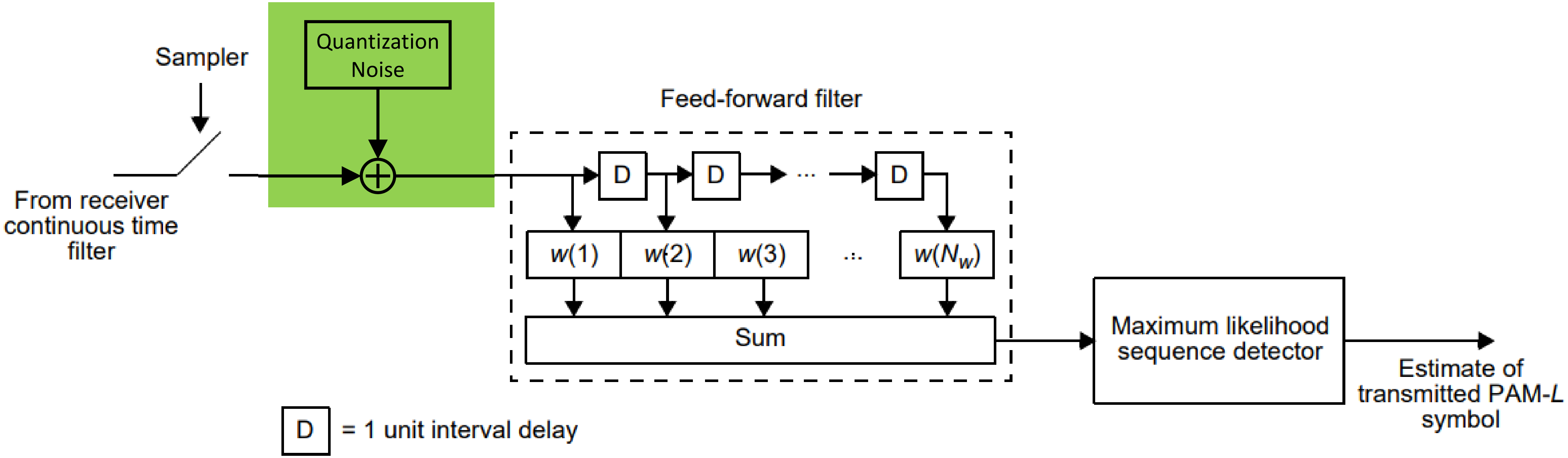

Figure 178A–10—Receiver discrete-time equalizer with MLSD

Description of Comments

- Comments rows #17 and #18:
  - Page 372, Section 178.10.1, Table 178-13
  - Change One-sided noise spectral density (Line 43) value from 10^{-8} to 5×10^{-9}
  - Add Noise-equivalent quantization bits and Quantization clip probability parameters with suggested values to the table

One-sided noise spectral density	η_0	5×10^{-9}	V^2/GHz
Transmitter signal-to-noise ratio	SNR_{TX}	33.5	dB
Random jitter, RMS	σ_{RJ}	0.01	UI
Dual-Dirac jitter, peak	A_{DD}	0.02	UI
Noise-equivalent quantization bits	N_qb	6	bits
Quantization clip probability	P_qc	$2 \times DER_0$	–

  - Suggested values may be updated based on outcomes of contribution shakiba_3dj_elec_01_250626.pdf

Description of Comments

- Comments rows #19 and #20:
  - Page 418, Section 179.11.7.1, Table 179-18
  - Change One-sided noise spectral density (Line 18) value from 10^{-8} to 5 X 10^{-9}
  - Add Noise-equivalent quantization bits and Quantization clip probability parameters with suggested values to the table

One-sided noise spectral density	η_0	5×10^{-9}	V^2/GHz
Transmitter signal-to-noise ratio	SNR_{TX}	33.5	dB
Random jitter, RMS	σ_{RJ}	0.01	UI
Dual-Dirac jitter, peak	A_{DD}	0.02	UI
Noise-equivalent quantization bits	N_qb	6	bits
Quantization clip probability	P_qc	$2 \times DER_0$	–

  - Suggested values may be updated based on outcomes of contribution shakiba_3dj_elec_01_250626.pdf

Description of Comments

- Comments rows #21 and #22:
  - Page 733, Section 176C.7.1, Table 176C-8
  - Change One-sided noise spectral density (Line 46) value from 10^{-8} to 5 X 10^{-9}
  - Add Noise-equivalent quantization bits and Quantization clip probability parameters with suggested values to the table

One-sided noise spectral density	η_0	5×10^{-9}	V^2/GHz
Transmitter signal-to-noise ratio	SNR_{TX}	33.5	dB
Random jitter, RMS	σ_{RJ}	0.01	UI
Dual-Dirac jitter, peak	A_{DD}	0.02	UI
Noise-equivalent quantization bits	N_qb	6	bits
Quantization clip probability	P_qc	$2 \times DER_0$	–

  - Suggested values may be updated based on outcomes of contribution shakiba_3dj_elec_01_250626.pdf

Description of Comments

- Comments rows #23 and #24:
  - Page 751, Section 176D.7.1, Table 176D-7
  - Change One-sided noise spectral density (Line 23) value from 10^{-8} to 5 X 10^{-9}
  - Add Noise-equivalent quantization bits and Quantization clip probability parameters with suggested values to the table

One-sided noise spectral density	η_0	5×10^{-9}	V^2/GHz
Noise-equivalent quantization bits	N_qb	6	bits
Quantization clip probability	P_qc	$2 \times DER_0$	–

  - Suggested values may be updated based on outcomes of contribution shakiba_3dj_elec_01_250626.pdf

Thank You ☺

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