10GBASE-T
TxFE solutions, dpSNR vs length of precoding response, and PMA training

IEEE P802.3an Task Force
Austin, May 18-20, 2005

Gottfried Ungerboeck

Connecting everything™

BROADCOM®

Contents

- **Study of transmit front-end solutions**
  - **"Simple": no digital filtering, 800 Ms/s DAC, simple R//C signal smoothing (f_{3dB} = 300 MHz), 1:1 transformer → transmit PSD depends on inaccurate analog components, no designed spectral nulls at dc and 1/2T, poor return loss.**
  - **"Baseline": no digital filtering, 800 Ms/s DAC, signal smoothing by RLC front-end filter (f_{3dB} = 300 MHz) with constant output impedance, 1:1 transformer**
    → transmit PSD depends on inaccurate analog components, no designed spectral nulls at dc and 1/2T, good return loss.
  - **"Oversampled": digital filtering and interpolation, 1600 Ms/s DAC, simple R//C signal smoothing (f_{3dB} = 1 GHz), 1:1 transformer → transmit PSD exhibits well defined shape with spectral nulls at dc and 1/2T, good return loss.**

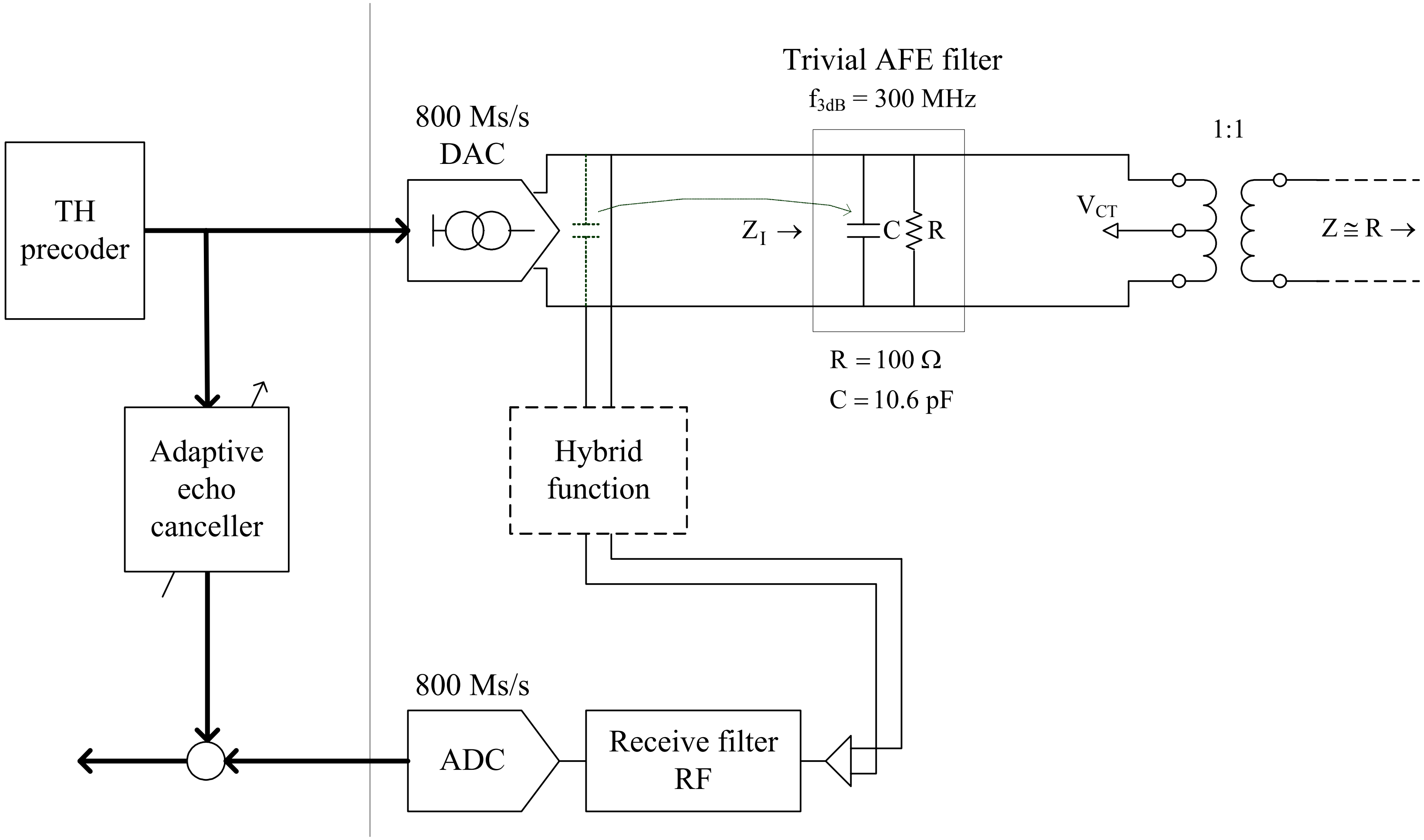
Contents

- Decision-point SNR vs. length of precoding response
  - Analysis: finite-length precoding response + infinite-length FFE optimized in MMSE sense.
  - Results obtained for “baseline” and “oversampled” transmit front-end, showning advantages of “oversampled” solution.
  - For worst case link characteristics, a programmable FIR precoding response of length L = 32 is found to be sufficient; L = 16 leads to small, but noticeable performance degradation.

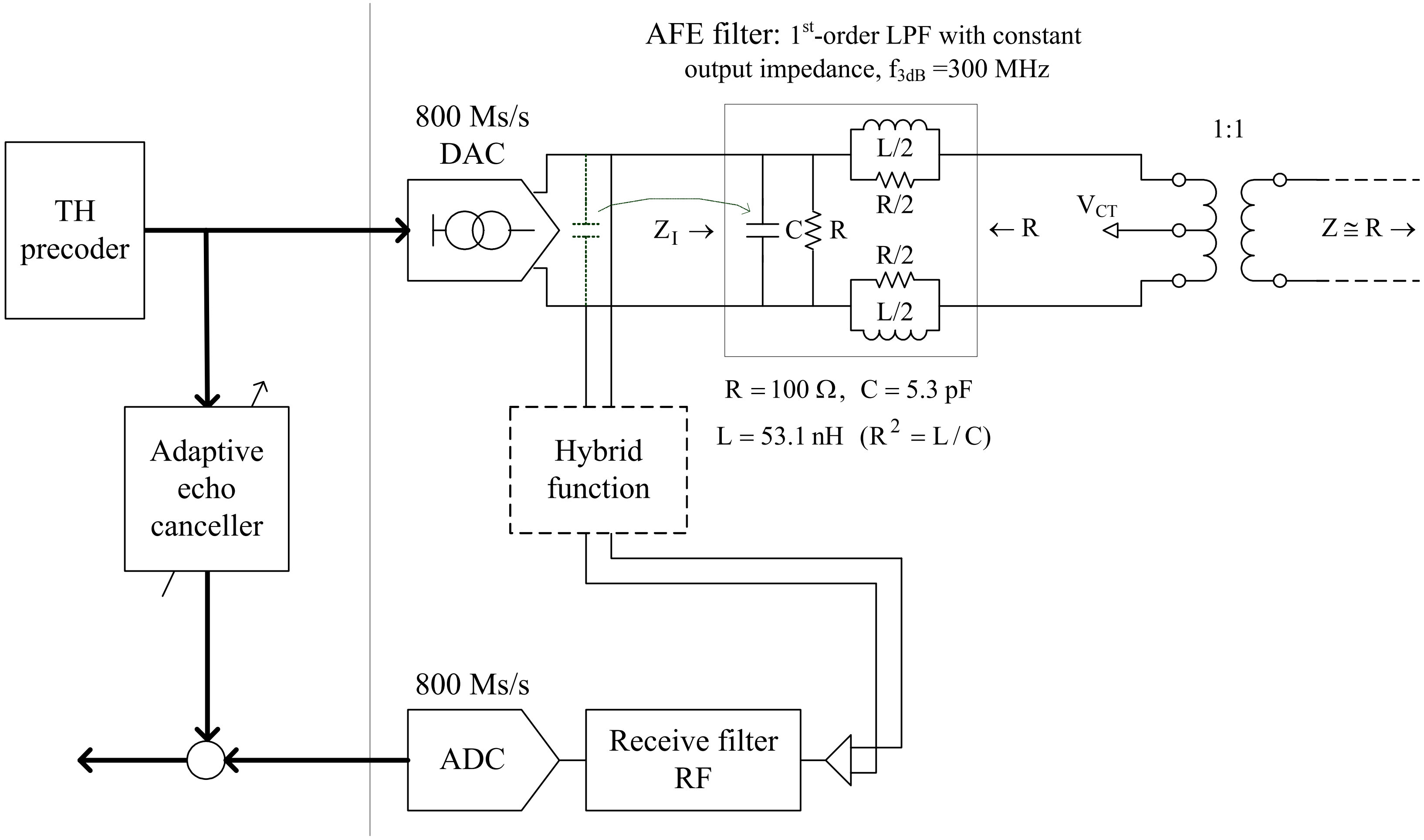
- PMA training issues
  - Generation of PMA training sequences: proposal for concise and unambiguous description.
  - … other points in preparation.

Study of transmit front-end solutions

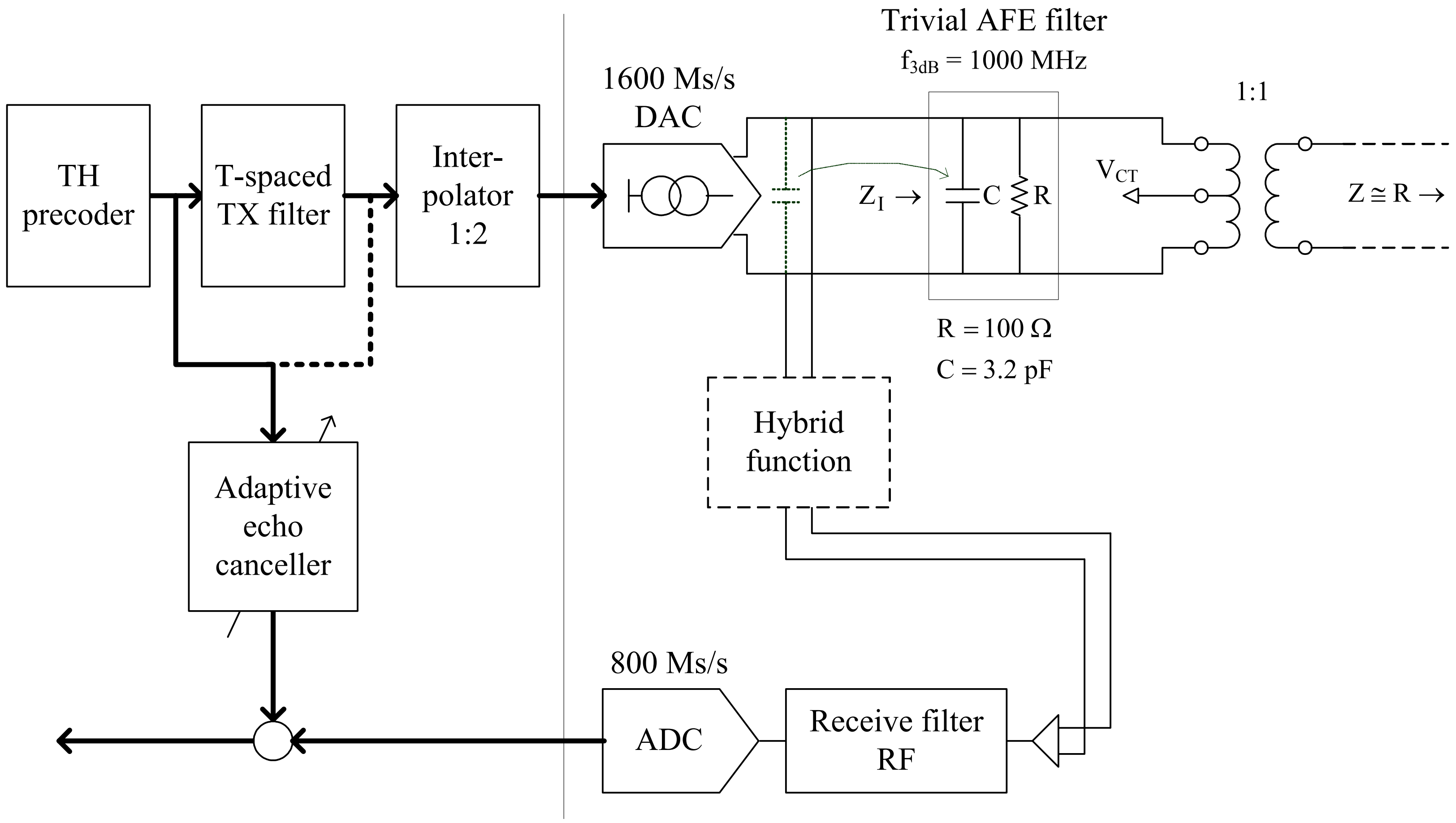
Transmitter front-end: “simple”



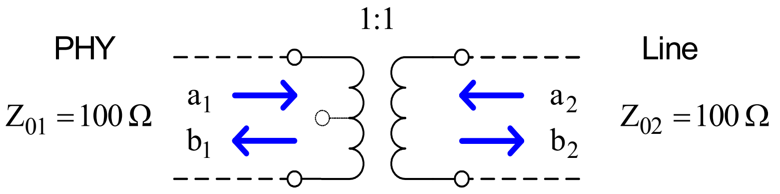
Transmitter front-end: "baseline"



Transmitter front-end: "oversampled"



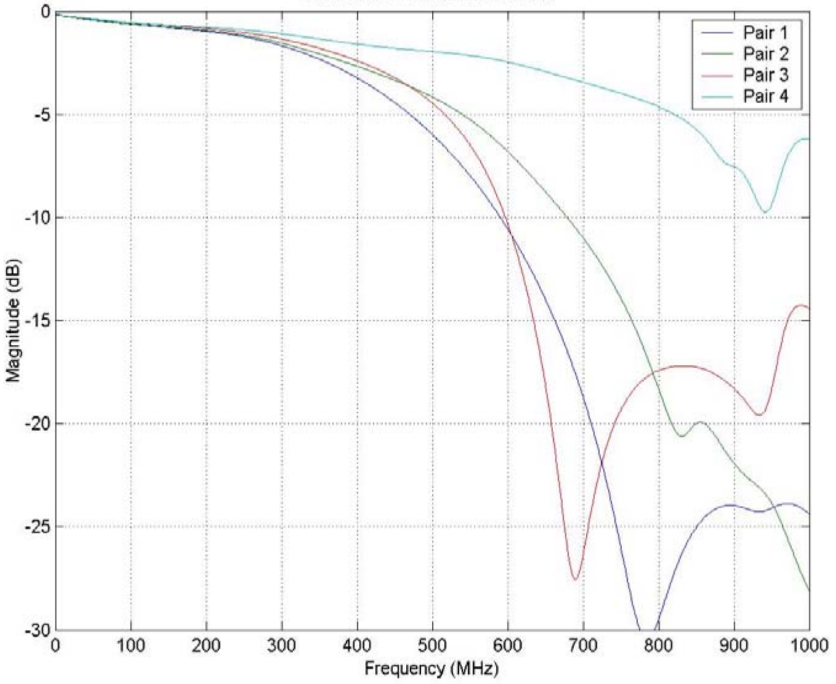
Measurements of sample 10G quad-transformer



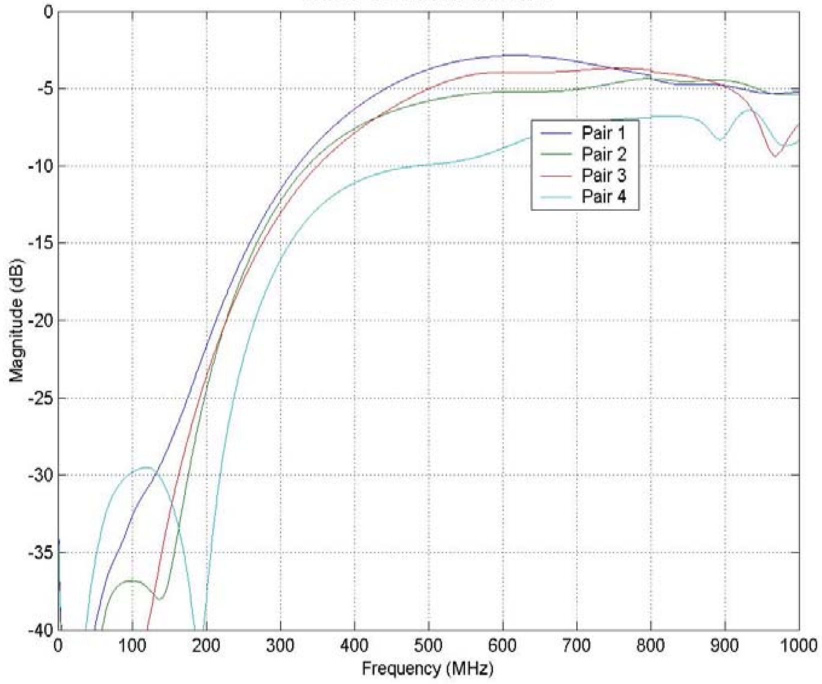
S parameters

$$b_1 = S_{11}\,a_1 + S_{12}\,a_2$$
$$b_2 = S_{21}\,a_1 + S_{22}\,a_2$$

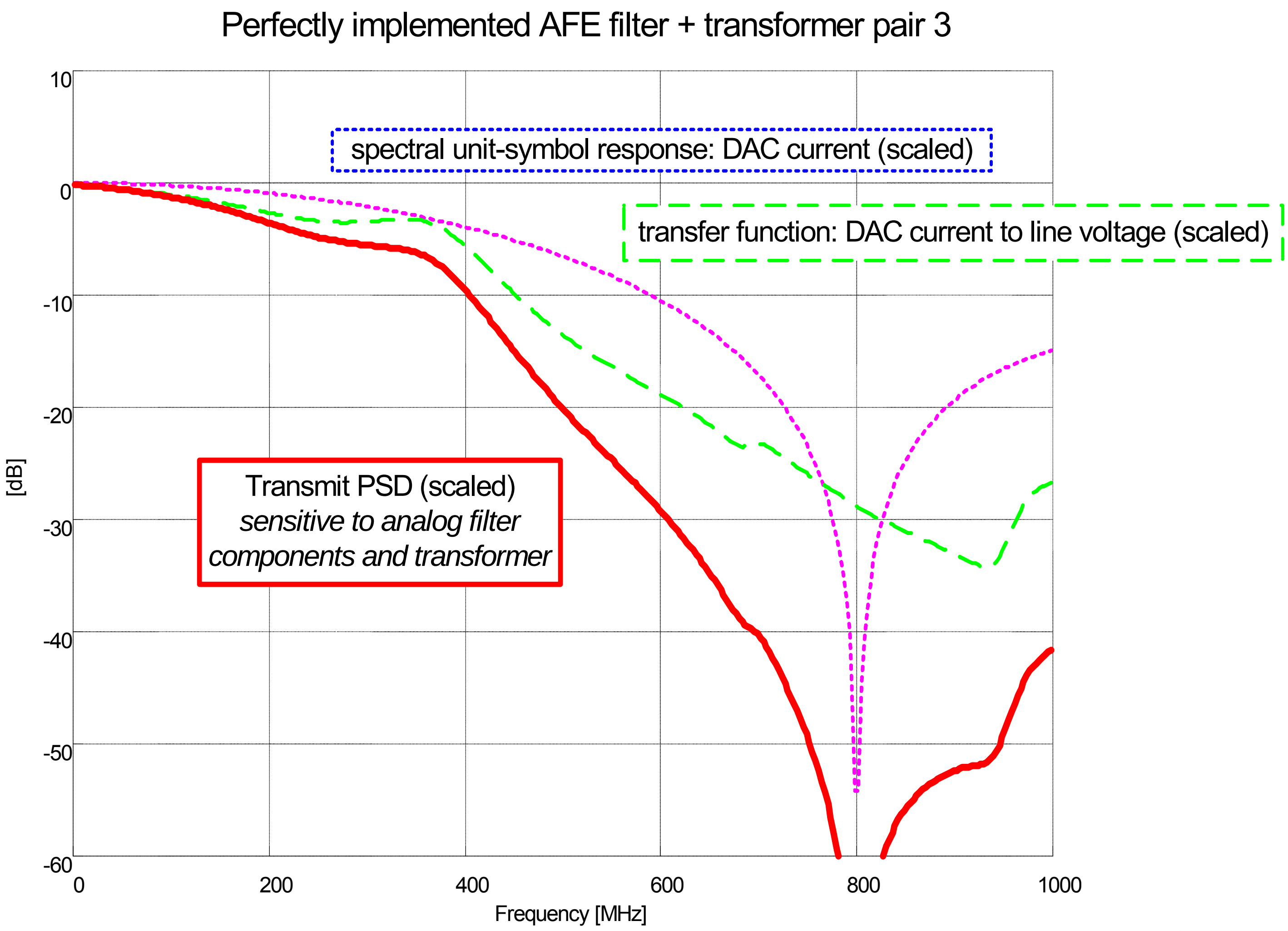
S_{21}: insertion loss PHY to Line (S_{12} is similar)



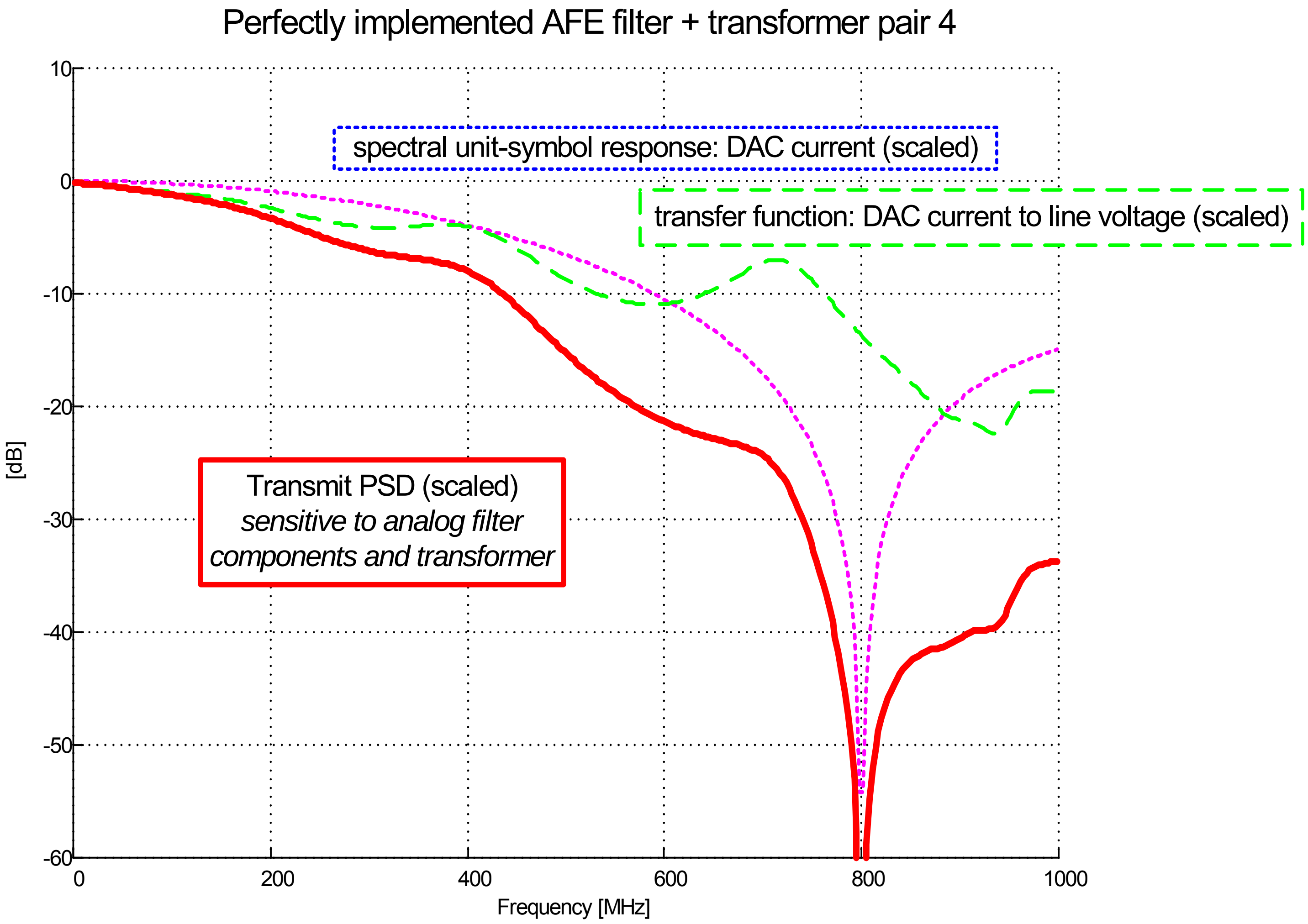
S_{22}: return loss Line to Line (S_{11} is similar)



Transmit PSD: “simple”



Transmit PSD: “simple”

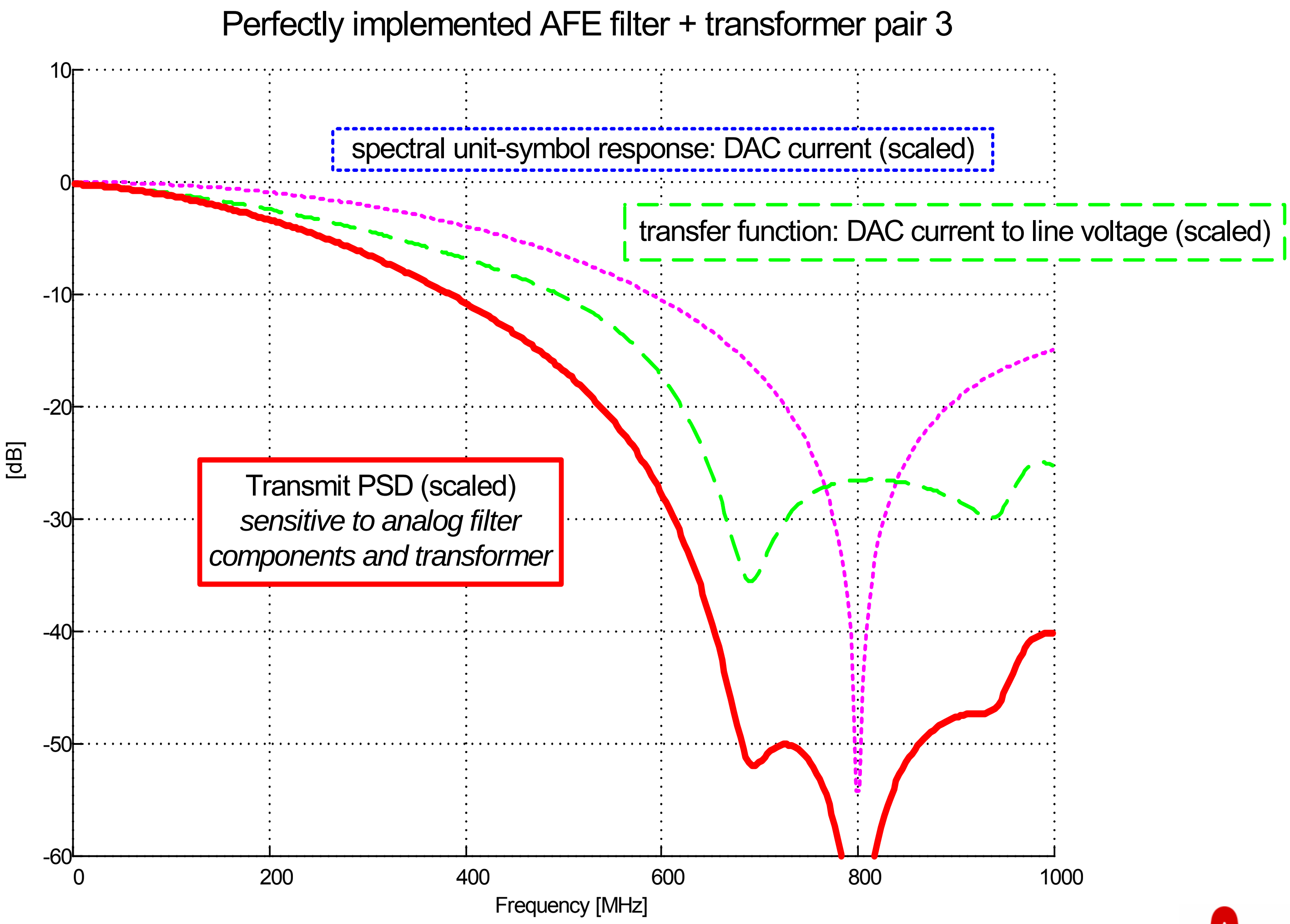


spectral unit-symbol response: DAC current (scaled)

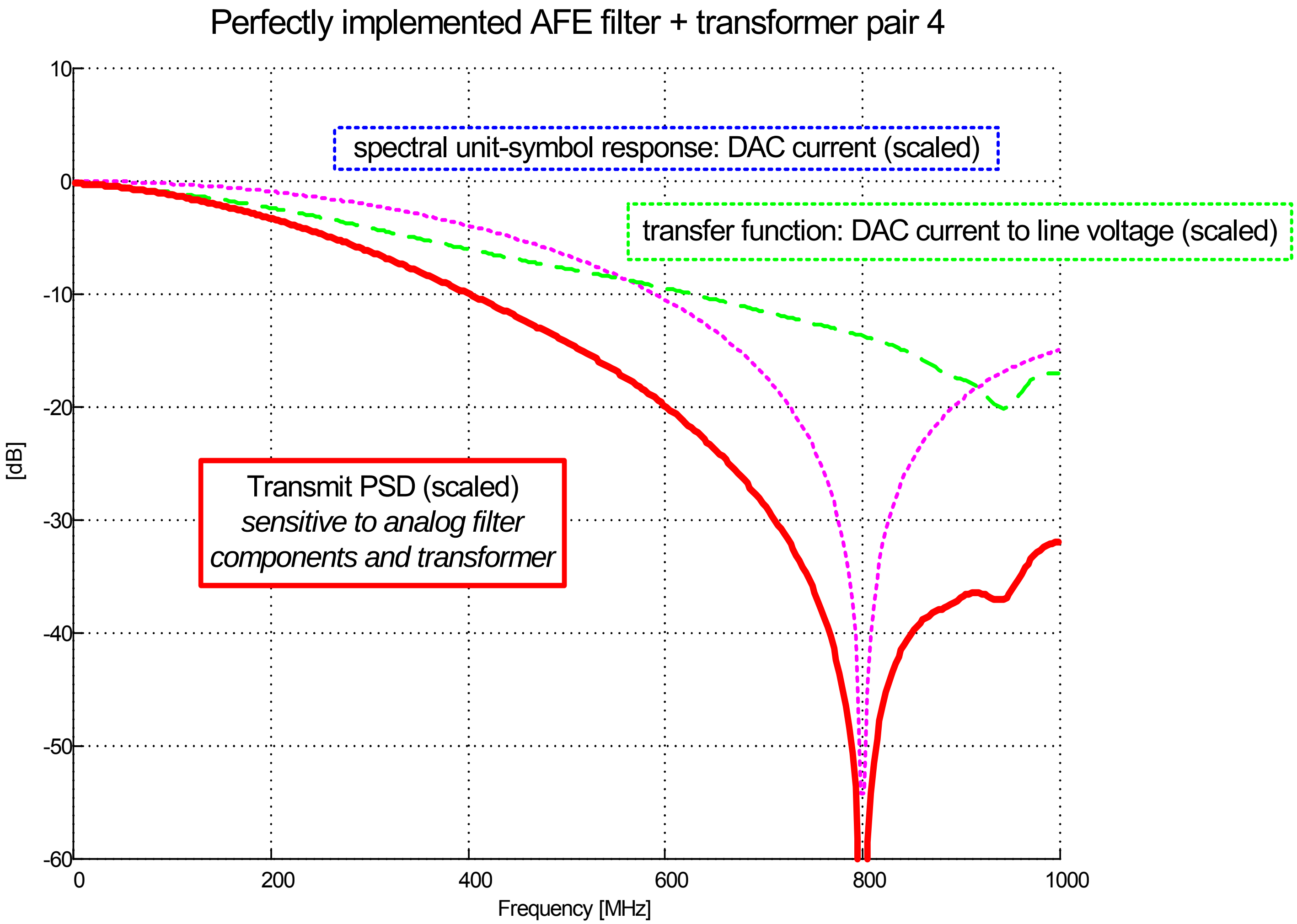
transfer function: DAC current to line voltage (scaled)

Transmit PSD (scaled)
sensitive to analog filter components and transformer

Transmit PSD: “baseline”



Transmit PSD: “baseline”



Perfectly implemented AFE filter + transformer pair 4

spectral unit-symbol response: DAC current (scaled)

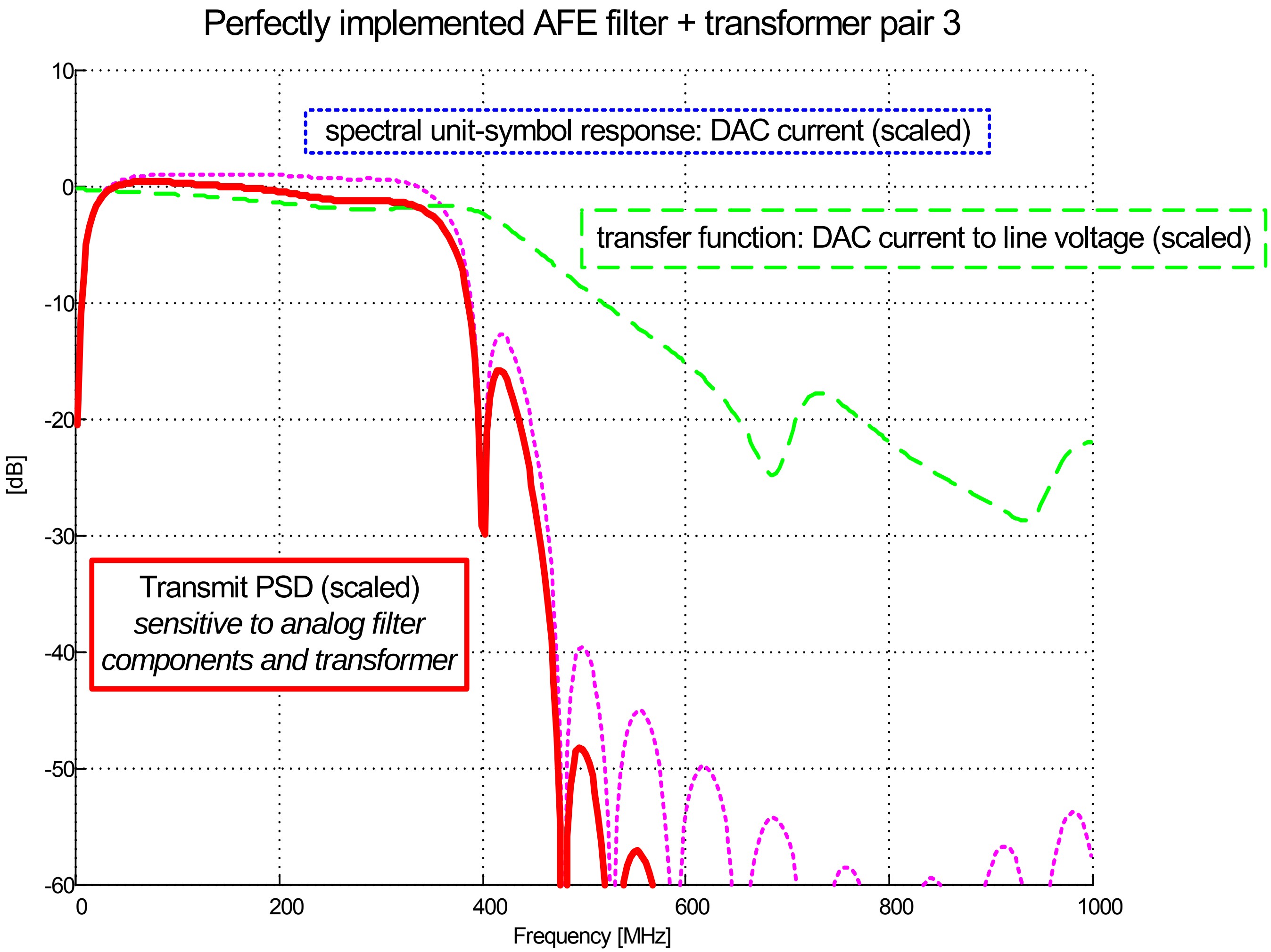
transfer function: DAC current to line voltage (scaled)

Transmit PSD (scaled)
sensitive to analog filter components and transformer

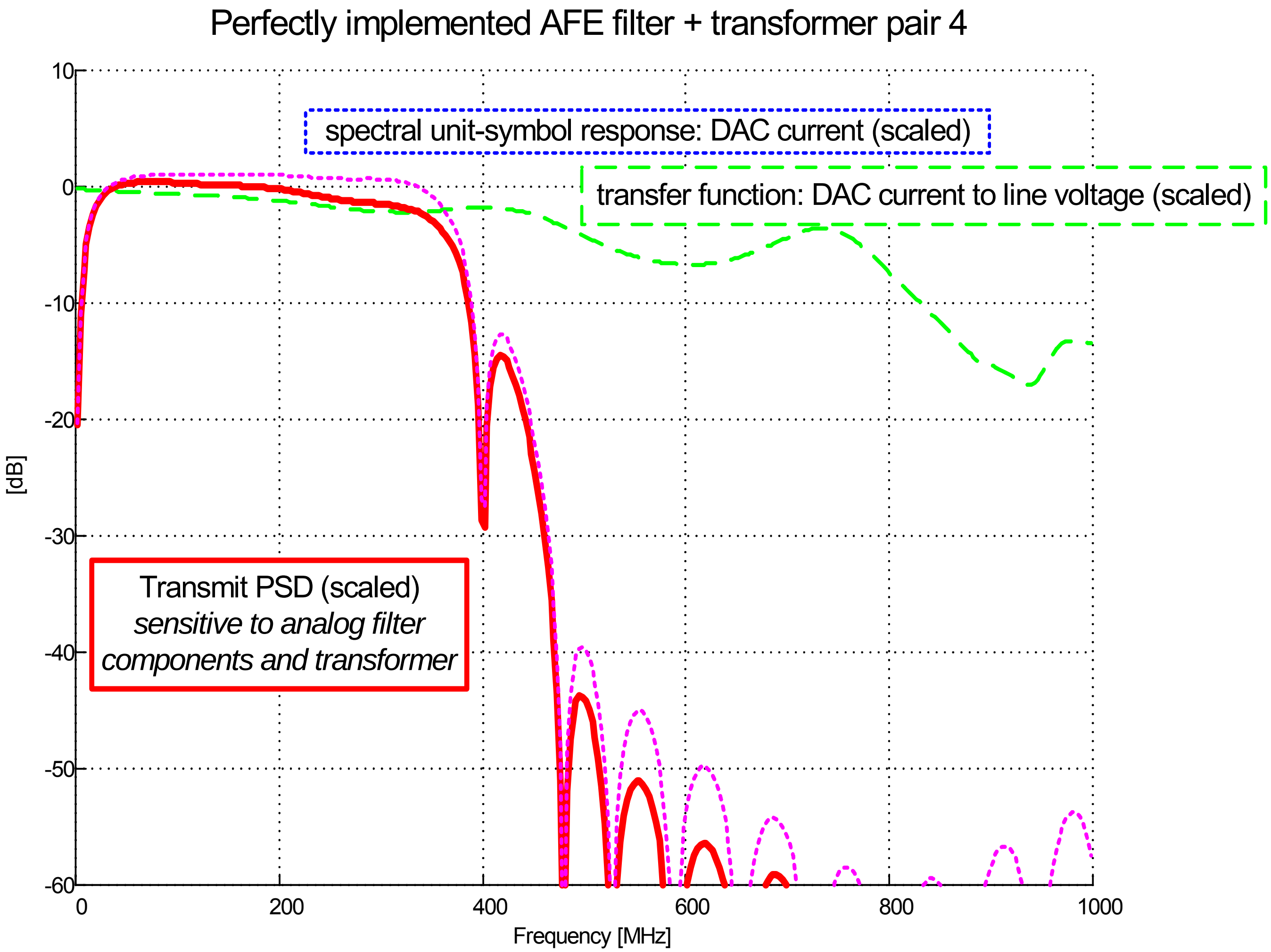
Connecting everything™

BROADCOM®

Transmit PSD: “oversampled”

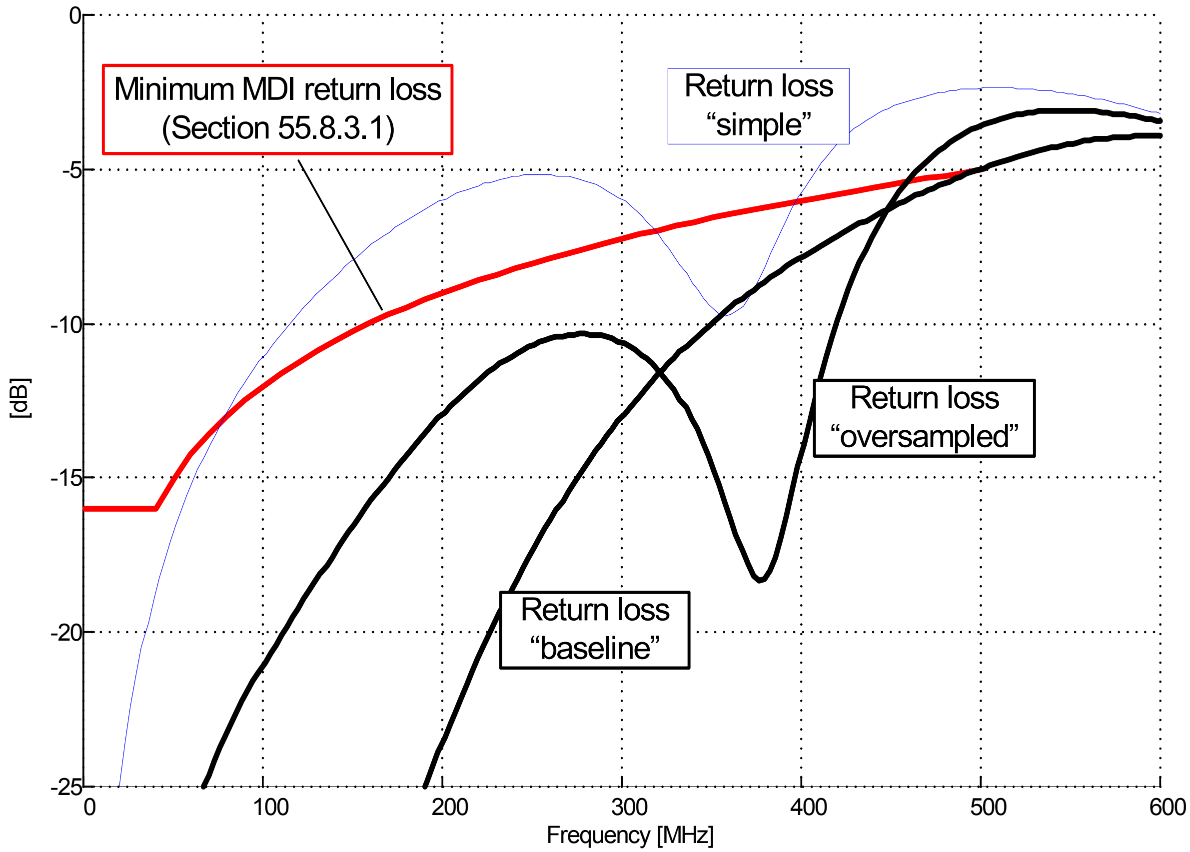


Transmit PSD: “oversampled”



MDI return loss

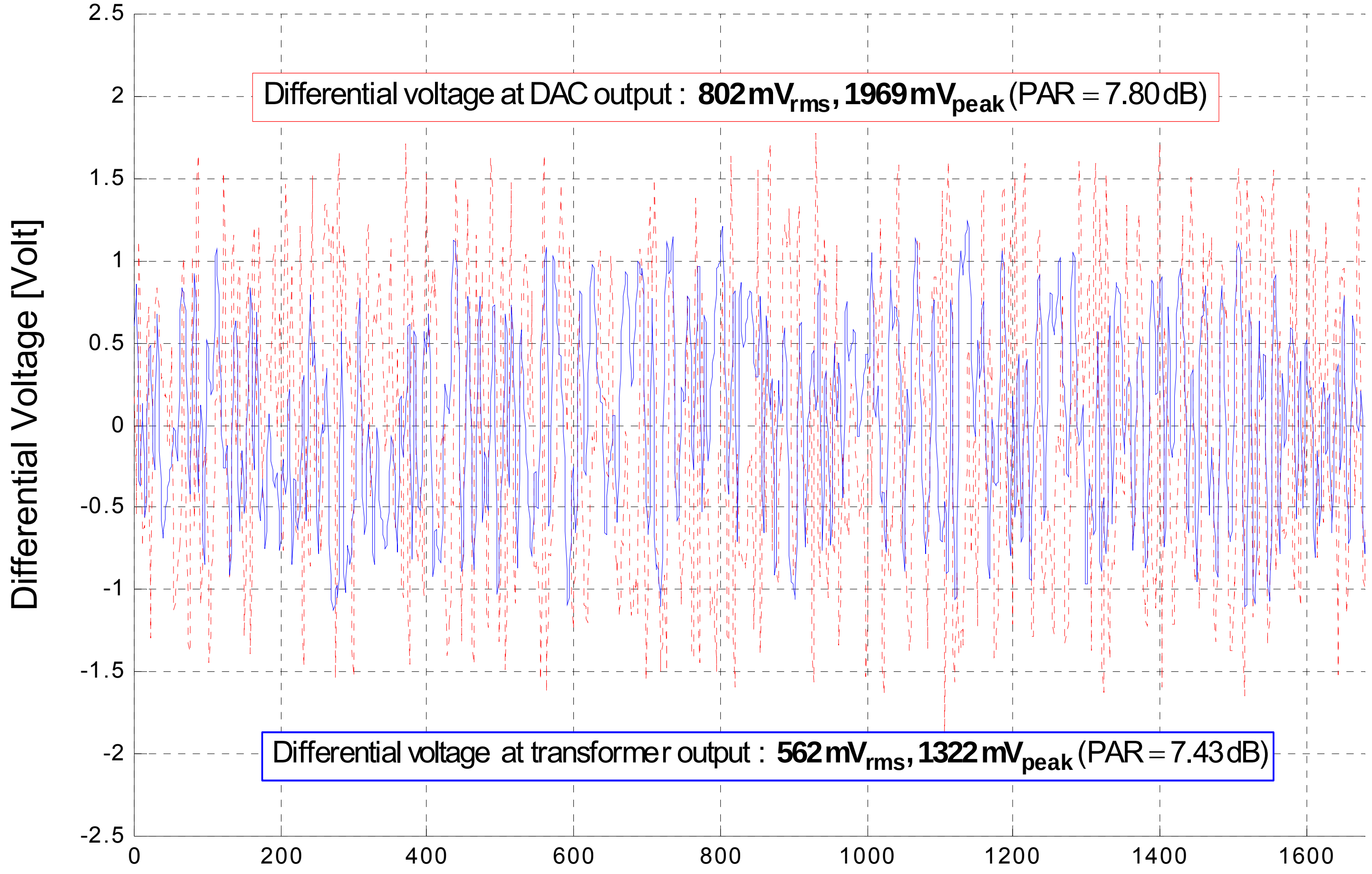
Perfectly implemented AFE filter + transformer pair 3



"Simple" solution does not meet MDI return loss spec: ruled out

Output voltages vs time: “baseline”

Simulated voltages at T/4-spaced time instances; rms and peak values determined in 1'000'000 T

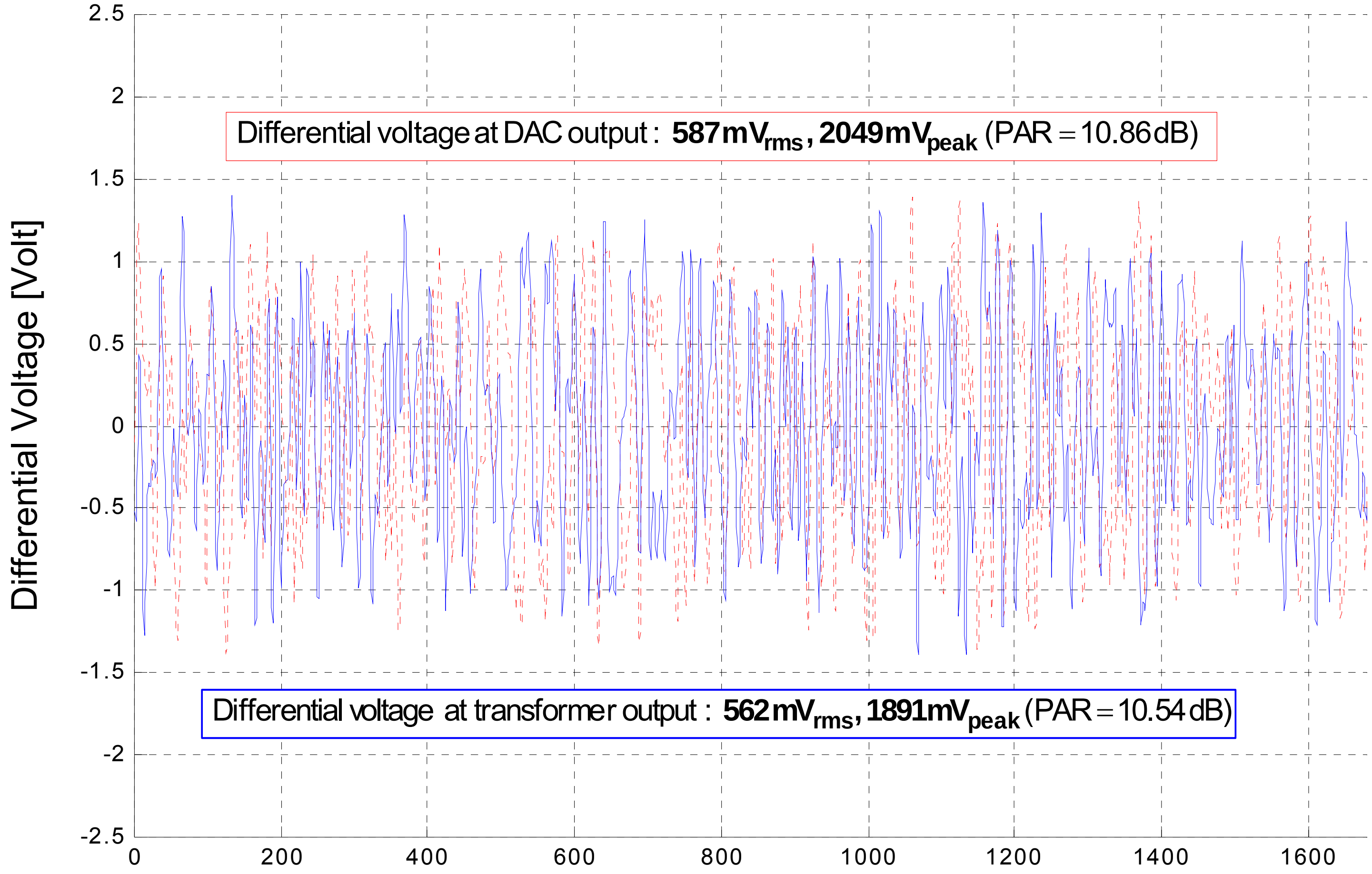


Perfectly implemented AFE filter + transformer pair 3

$P_T = 5$ dBm into 100 Ω ⇒ 562 mV$_{rms}$

Output voltages vs time: “oversampled”

Simulated voltages at T/4-spaced time instances; rms and peak values determined in 1'000'000 T



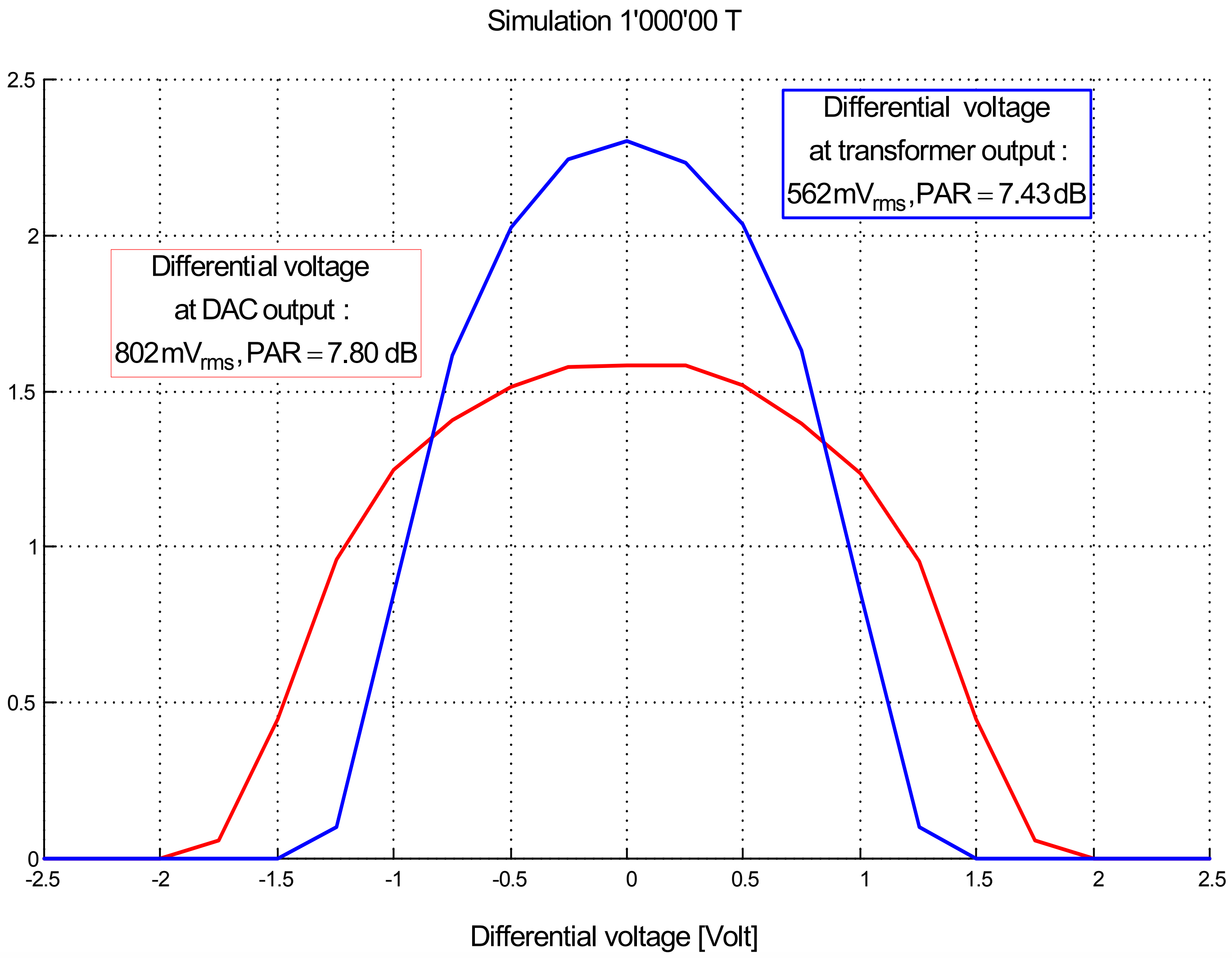
Perfectly implemented AFE filter + transformer pair 3

$P_T = 5\,\text{dBm into } 100\,\Omega \Rightarrow 562\,\text{mV}_{rms}$

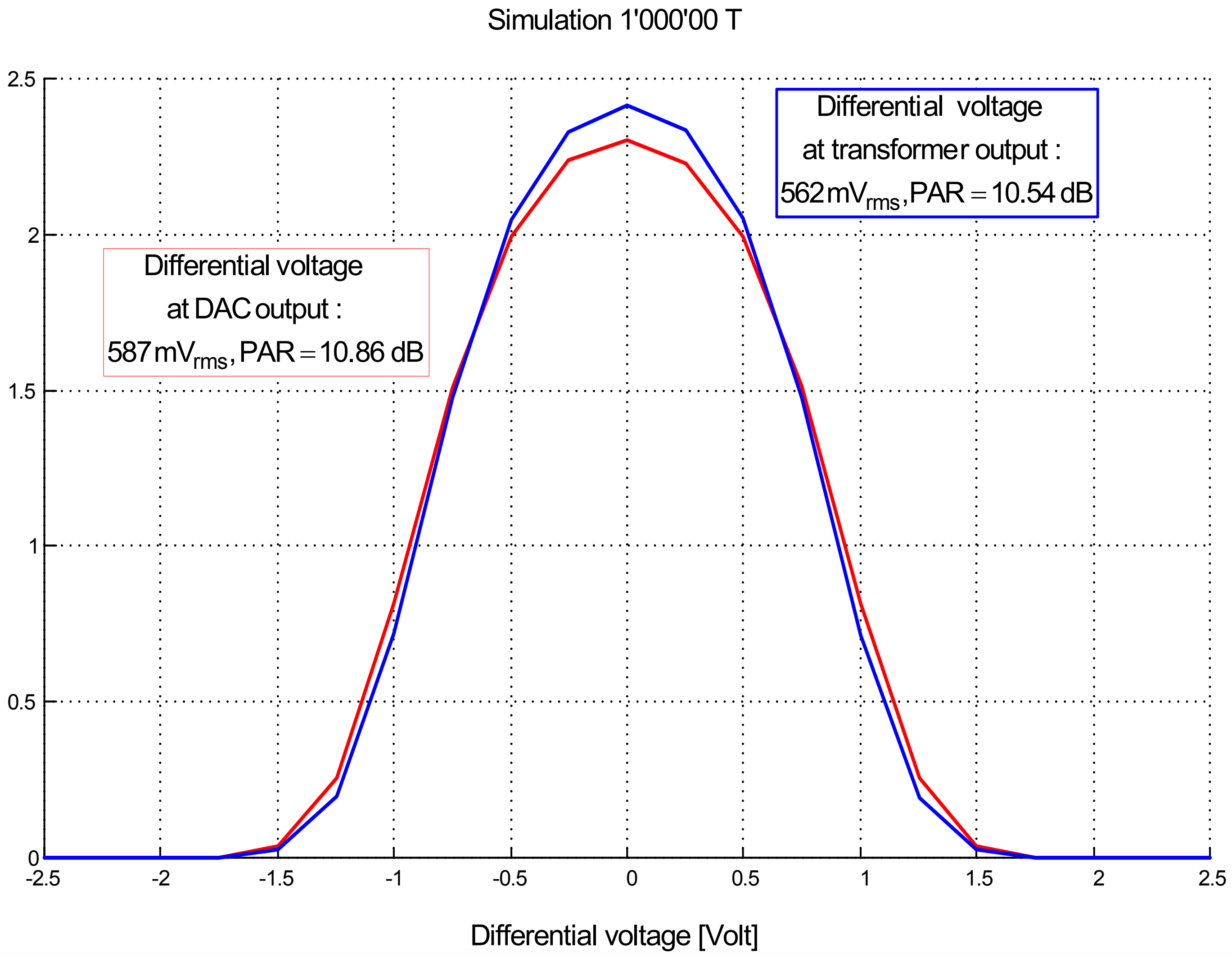
Connecting everything™

BROADCOM®

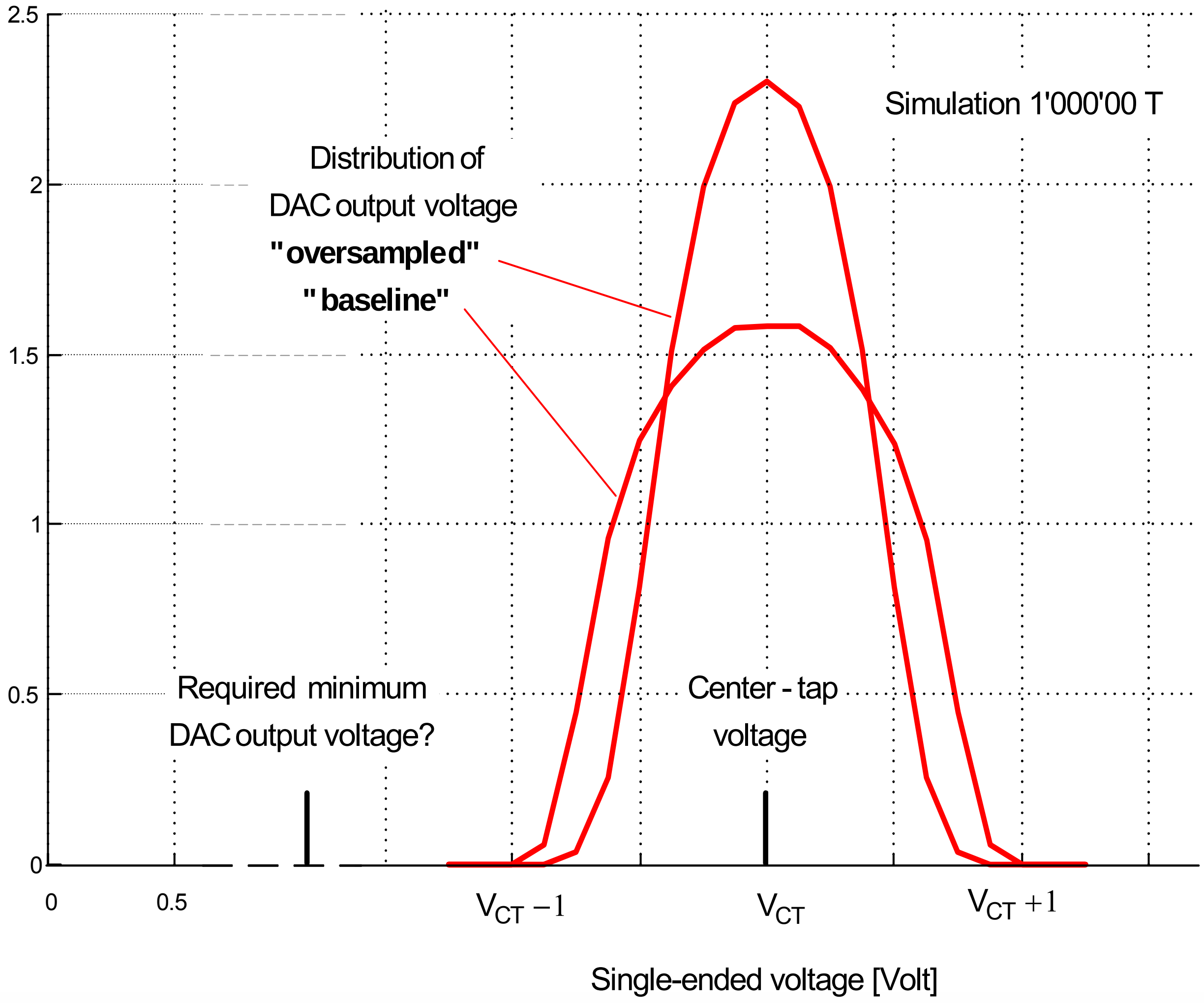
Voltage distributions: “baseline”



Voltage distributions: "oversampled"



Single-ended voltage distributions at DAC output



Study of transmit-front-end solutions: summary

“Simple” solution ruled out: fails to meet MDI return loss spec.

	“Baseline” solution	“Oversampled” solution
Digital filters	none	$(1-D^2)/(1-0.75\ D^2)$ + interpolator
DAC	800 Ms/s	1600 Ms/s
AFE filter	1-st order RLC LPF, f_{3dB}=300 MHz	Trivial R//C
rms and peak voltage at DAC output	higher rms, peak similar to “oversampled”	lower rms, peak similar to “baseline”
Excess bandwidth	substantial (→ sampling phase dependency in receiver)	sharp bandwidth limitation (EMI advantage)
Controlled spectral nulls	none	dc and 1/2T
Return loss	OK	OK
Transmit PSD shape	depends on analog components	digitally defined

Study of transmit-front-end solutions: conclusion

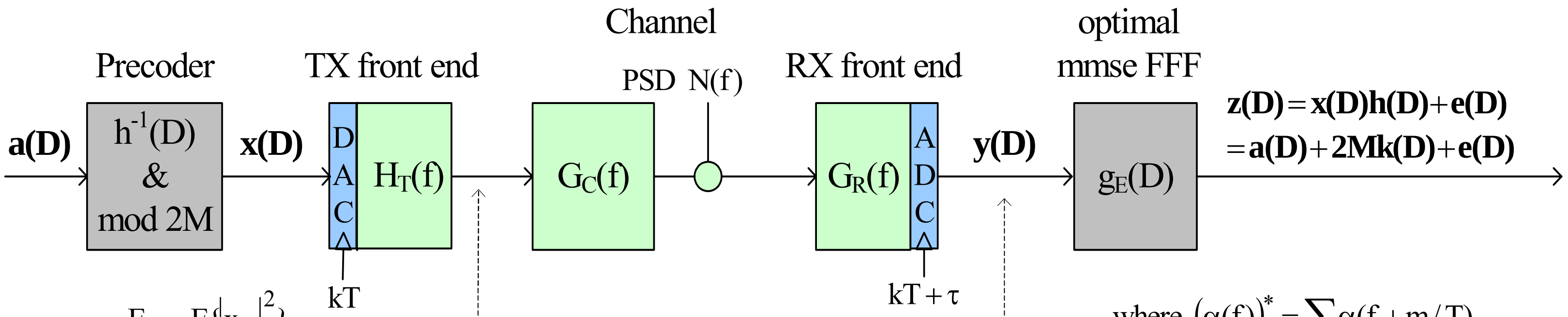
- **Peak voltages at DAC output for “oversampled” and “baseline” solutions are similar; higher PAR of “oversampled” is compensated for by lower rms voltage.**

- **Cost of digital filtering and oversampling DAC outweighs disadvantages of “baseline solution”**
  - o RLC AFE filter: two coils, concerns about balance, etc.
  - o PSD shape: substantial excess bandwidth, dependency on analog components, no controlled spectral nulls at dc and 1/2T
  - o hybrid function requires image impedances matching frequency-dependent input impedance of AFE filter.

Proposal: adopt well defined transmit PSD shape with sharp bandwidth limitation and spectral nulls at dc and 1/2T, as enabled by an “oversampled” transmit front-end solution.

Decision-point SNR vs. length of precoding response

Optimum precoding response and decision-point SNR



$$\mathbf{z(D) = x(D)h(D) + e(D)}$$
$$\mathbf{= a(D) + 2Mk(D) + e(D)}$$

$$E_x = E\{|x_k|^2\}$$

$$\text{PSD} \;\; S_T(f) = \frac{E_x}{T}|H_T(f)|^2$$

$$H_T(f)G_c(f)G_R(f) = H_A(f)$$
$$N(f)|G_R(f)|^2 = N_A(f)$$

$$\text{where } (\alpha(f))^* = \sum_m \alpha(f + m/T)$$

$$SNR_A^*(f) = \frac{E_x}{T}\left|\left(H_A(f)e^{j2\pi f\tau}\right)^*\right|^2 / \left(N_A(f)\right)^*$$

$$\tau_{\text{worst case}} \; : \; SNR_A^*(\pm 1/2T) = 0$$

Decision-point SNR for given $H_A(f)$, $N_A(f)$, τ, and precoding response $h(D)$

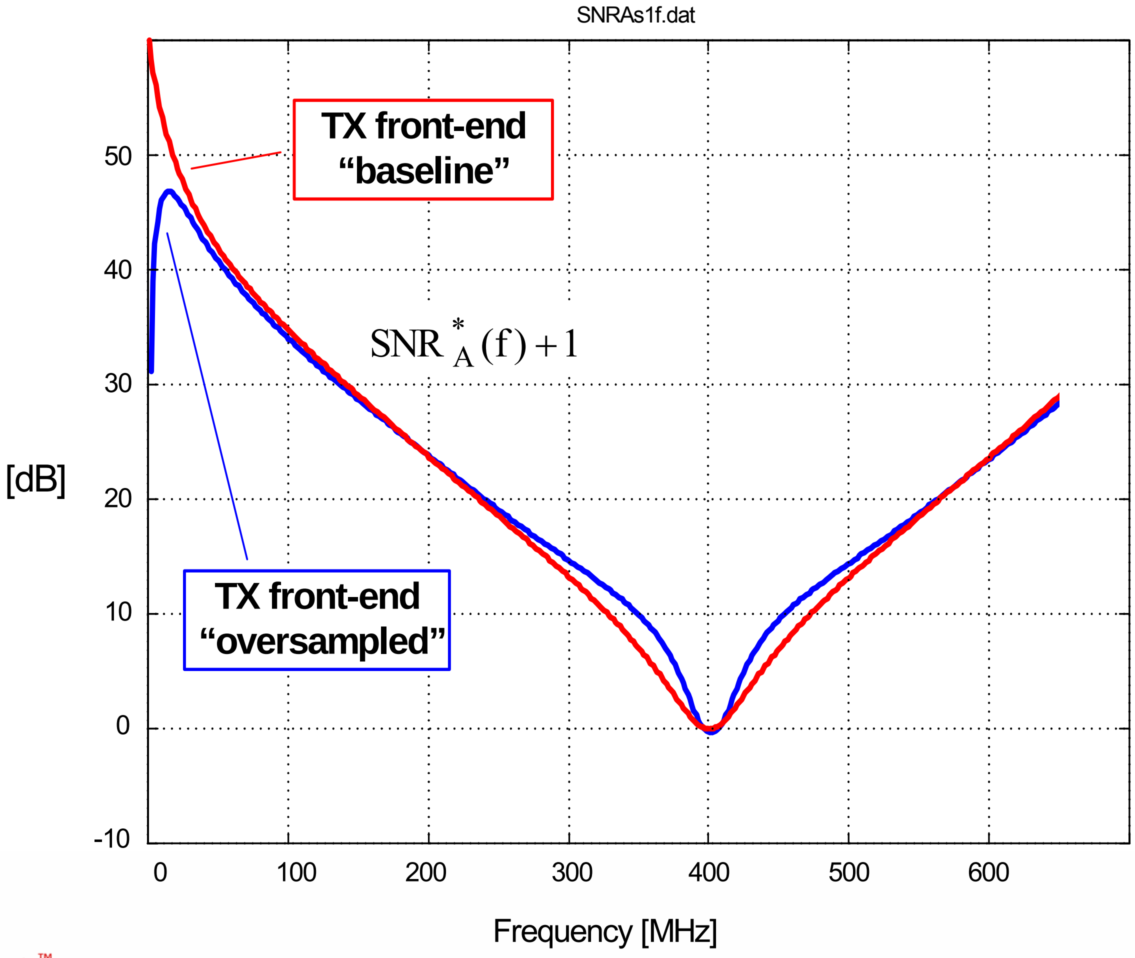
$$SNR_{mmse} = \left[T \int_{-1/2T}^{1/2T} \left| h(D = e^{-j2\pi fT}) \right|^2 / \left(SNR_A^*(f) + 1\right) df \right]^{-1}, \quad h(D) = 1 + \sum_{\ell=0}^{L} h_\ell D^\ell$$

For given $SNR_A^*(f) + 1$, determine (arg) $\max\limits_{h_1, h_2, \cdots h_L} SNR_{mmse}$.

Folded spectral SNR function +1

Class E cable, P_T = 5 dBm, l = 100m, AWGN = -140 dBm/Hz
PS_ANEXT and PS_AFEXT from P_T = 5 dBm, l = 100m

Fixed receive filter: 3rd-order BWF, f_{3dB}=300 MHz; worst-case sampling phase



Finite-length h(D) + infinite FFE, MMSE optimized

Class E cable, P_T = 5 dBm, ℓ = 100m, AWGN = -140 dBm/Hz, PS_ANEXT and PS_AFEXT from P_T = 5 dBm, ℓ = 100m
Fixed receive filter: 3rd-order BWF, f_{3dB} = 300 MHz; worst-case sampling phase

TX front-end: “baseline”

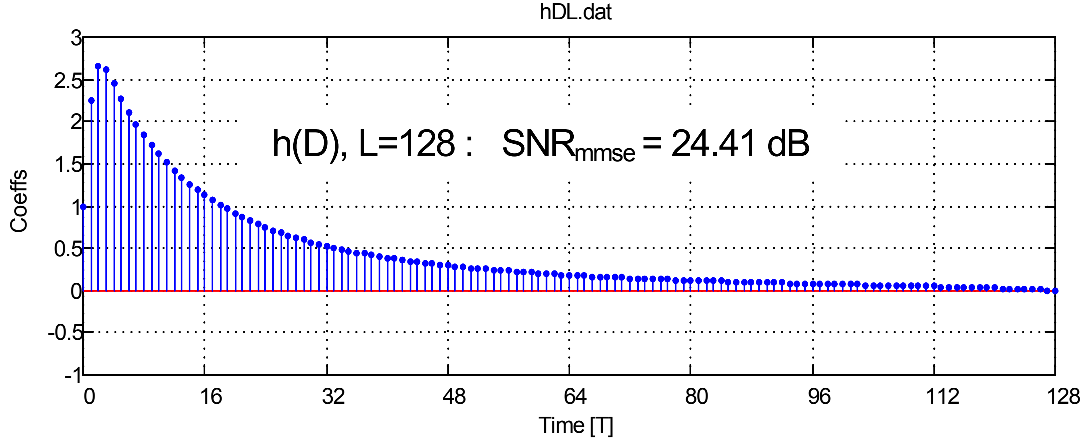
L	SNR_{mmse}	$\sum_{\ell=0}^{L}\|h_\ell\|$
4	23.50 dB	6.17
6	23.93 dB	9.15
8	24.11 dB	12.00
12	24.27 dB	17.32
16	24.34 dB	22.04
24	24.40 dB	29.81
32	24.41 dB	35.72
48	24.43 dB	43.79
64	24.43 dB	48.84
96	24.43 dB	54.51
128	24.43 dB	57.59
192	24.43 dB	60.73

TX front-end: “oversampled”

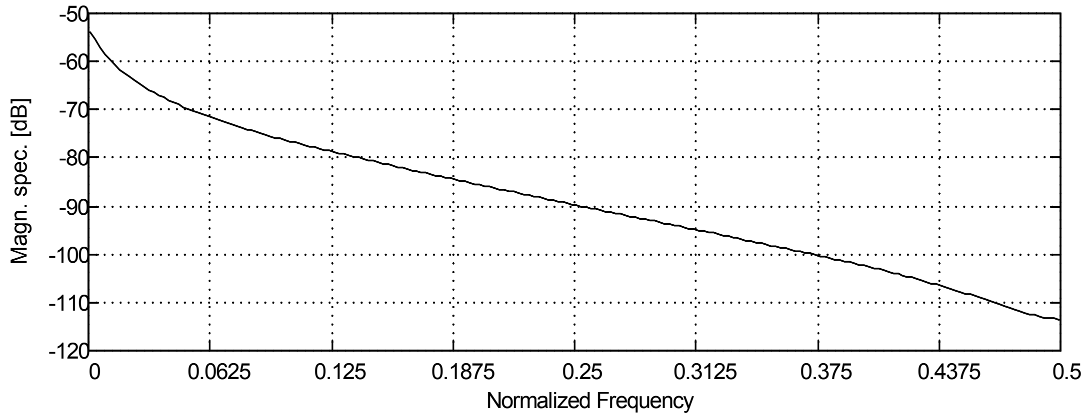
L	SNR_{mmse}	$\sum_{\ell=0}^{L}\|h_\ell\|$
4	24.21 dB	5.49
6	24.45 dB	7.36
8	24.48 dB	8.22
12	24.49 dB	8.59
16	24.55 dB	10.74
24	24.67 dB	15.26
32	24.73 dB	17.95
48	24.75 dB	19.75
64	24.76 dB	20.08
96	24.76 dB	20.17
128	24.76 dB	20.52
192	24.76 dB	21.09

Finite-length h(D) + infinite FFE , MMSE optimized

Class E cable, P_T = 5 dBm, l = 100m, AWGN = -140 dBm/Hz, PS_ANEXT and PS_AFEXT from P_T = 5 dBm, l = 100m
TX front-end: “baseline”; fixed receive filter: 3^{rd}-order BWF, f_{3dB} = 300 MHz; worst-case sampling phase

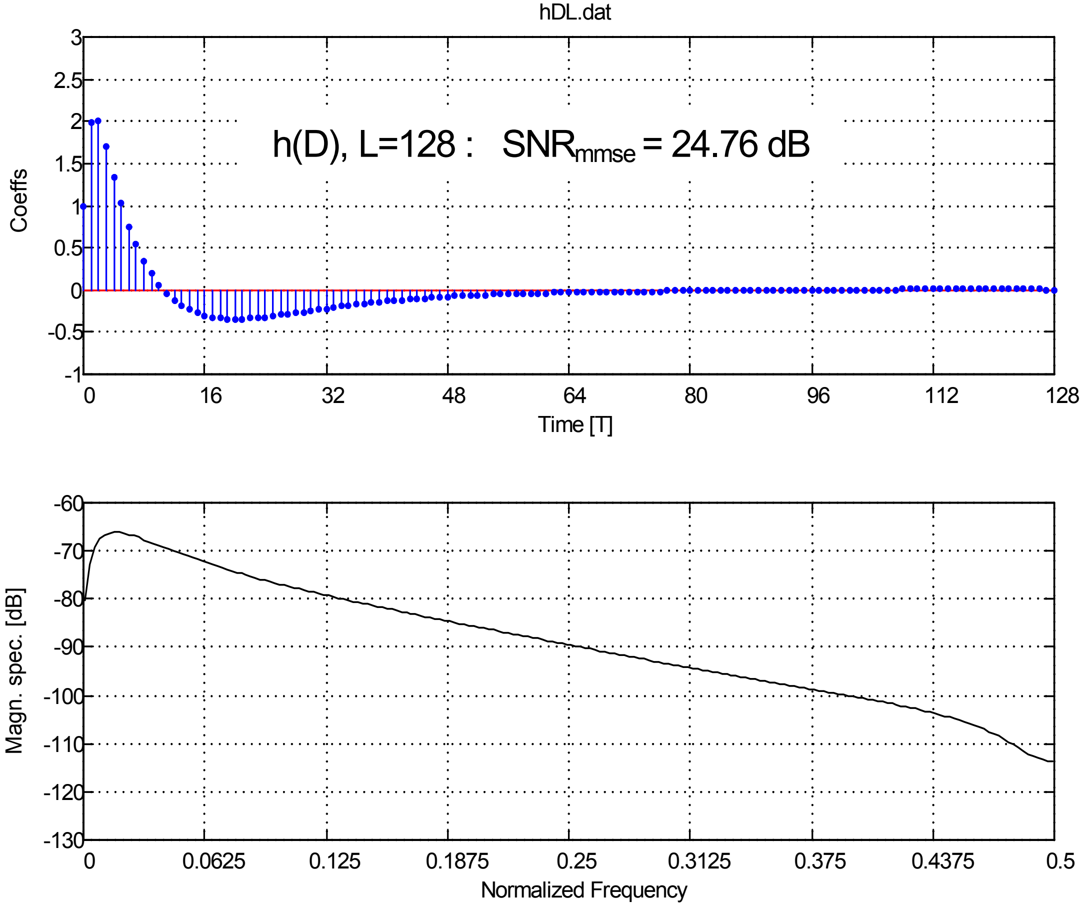


$$\sum_{\ell=0}^{L}|h_\ell| = 35.72$$



Finite-length h(D) + infinite FFE , MMSE optimized

Class E cable, P_T = 5 dBm, 1 = 100m, AWGN = -140 dBm/Hz, PS_ANEXT and PS_AFEXT from P_T = 5 dBm, 1 = 100m
TX front-end: “oversampled”; fixed receive filter: 3rd-order BWF, f_{3dB} = 300 MHz; worst-case sampling phase



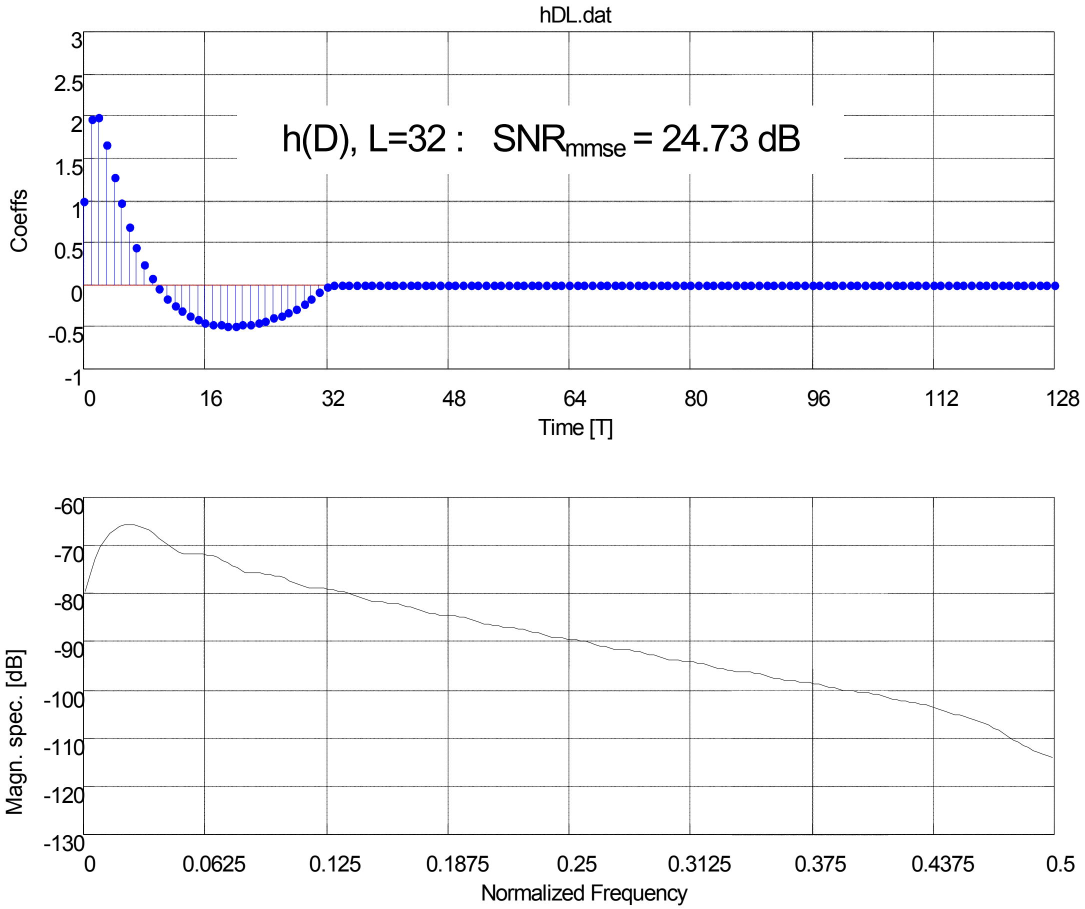
$$\sum_{\ell=0}^{L} |h_\ell| = 20.52$$

Connecting everything™

BROADCOM®

Finite-length h(D) + infinite FFE , MMSE optimized

Class E cable, P_T = 5 dBm, l = 100m, AWGN = -140 dBm/Hz, PS_ANEXT and PS_AFEXT from P_T = 5 dBm, l = 100m
TX front-end: "oversampled"; fixed receive filter: 3^{rd}-order BWF, f_{3dB} = 300 MHz; worst-case sampling phase

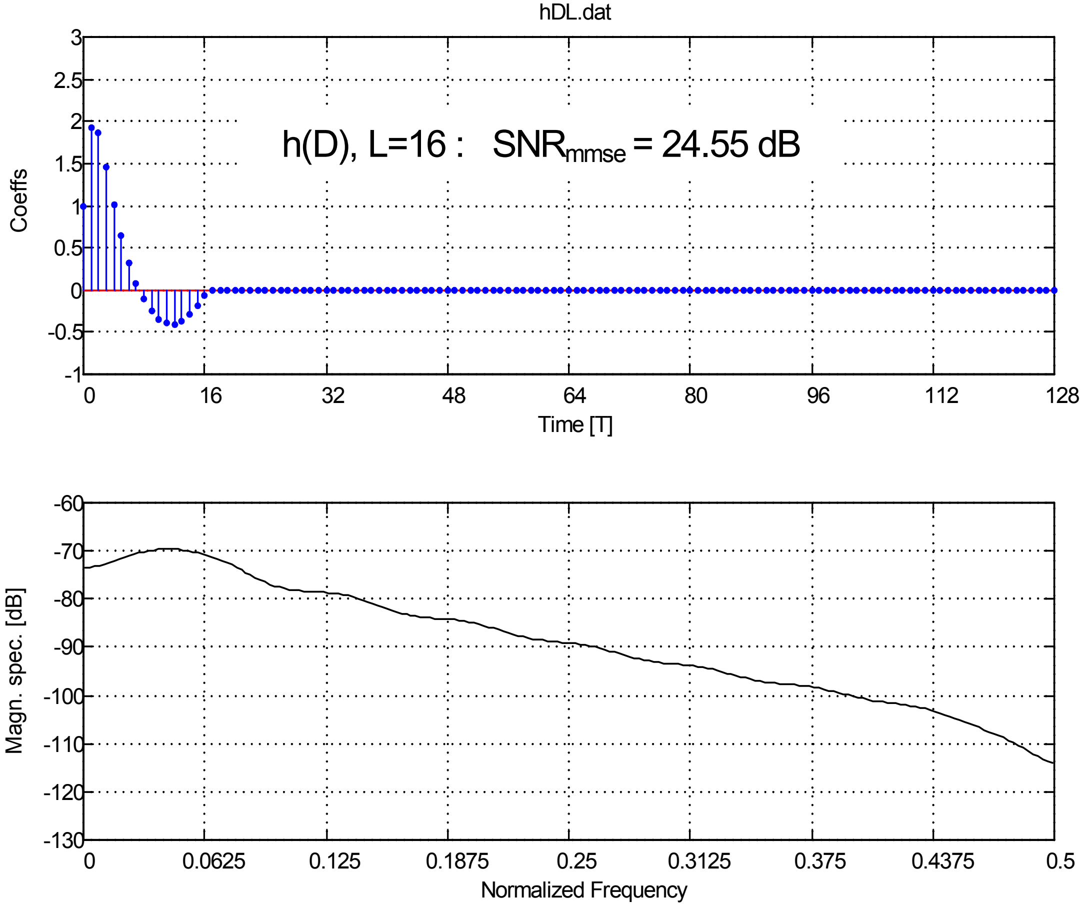


h(D), L=32 : SNR_{mmse} = 24.73 dB

$$\sum_{\ell=0}^{L} |h_\ell| = 17.95$$

Finite-length h(D) + infinite FFE , MMSE optimized

Class E cable, P_T = 5 dBm, ℓ = 100m, AWGN = -140 dBm/Hz, PS_ANEXT and PS_AFEXT from P_T = 5 dBm, ℓ = 100m
TX front-end: “oversampled”; fixed receive filter: 3rd-order BWF, f_{3dB} = 300 MHz; worst-case sampling phase



$$\sum_{\ell=0}^{L} |h_\ell| = 10.74$$

DP-SNR vs length of precoding response: conclusion

- **Decision-point SNR is insensitive to length L of precoding response; a programmable FIR precoding response with L = 32 is adequate. L = 16 leads to small, but noticeable performance degradation. L = 32 provides some headroom for dealing with non-smooth SNR(f).**

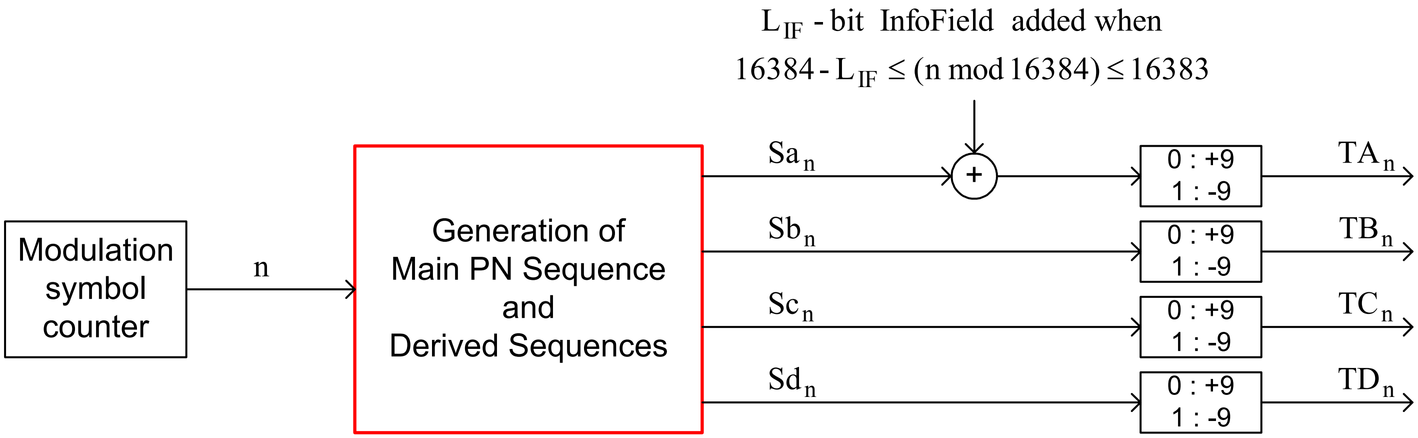
- **In addition, the results illustrate the benefits of the "oversampled" TX front-end:**
  - o Higher decision-point SNR due to better PSD shape
  - o SNR performance always insensitive to sampling phase due to stricter bandwidth limitation and spectral null at 1/2T
  - o Spectral null at dc reduces constellation expansion.

Proposal: adopt programmable FIR precoding with L = 32

Same response for all pairs, or four individual responses?

PMA training issues

Unambiguous generation of PMA training sequences



L_{IF} - bit InfoField added when

$16384 - L_{IF} \le (n \bmod 16384) \le 16383$

Modulation symbol counter

n

Generation of Main PN Sequence and Derived Sequences

Sa_n

Sb_n

Sc_n

Sd_n

\+

0 : +9
1 : -9

0 : +9
1 : -9

0 : +9
1 : -9

0 : +9
1 : -9

TA_n

TB_n

TC_n

TD_n

Main PN sequence

$$n \bmod 16384 = 0: \quad Scr_n[0:32] = 33 \text{ lsbs of } 0x15979A422 \quad (\text{periodic initialization})$$

$$n \bmod 16384 \neq 0: \quad Scr_n[1:33] = Scr_{n-1}[0:32]$$

$$Scr_n[0] = \begin{cases} Scr_n[20] \oplus Scr_n[33] & \text{if PMA\_CONFIG} = \text{MASTER} \\ Scr_n[13] \oplus Scr_n[33] & \text{if PMA\_CONFIG} = \text{SLAVE} \end{cases}$$

Derived sequences

$$Sa_n = \begin{cases} Scr_n[0] \oplus 1 & \text{if } n \bmod 256 = 0 \\ Scr_n[0] & \text{otherwise} \end{cases}$$

$$Sb_n = Scr_n[3] \oplus Scr_n[8]$$

$$Sc_n = Scr_n[6] \oplus Scr_n[16]$$

$$Sd_n = Scr_n[9] \oplus Scr_n[14] \oplus Scr_n[19] \oplus Scr_n[24]$$