10GBASE-T PAM Scheme: Fixed Precoder for all Cable Types and Lengths

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Key points

One fixed precoding response, $h_{IIR}(D)$, suffices for all cable types & lengths.

$h_{IIR}(D)$ is designed for worst case conditions: maximum cable length + ANEXT + AWGN.

Decision-point SNR increases rapidly with shorter cable length despite precoder mismatch causing non-minimum colored noise.

Contents

- Assumed modulation and coding
- 10GBASE-T cable model extensions
- One pair model of PAM transmission scheme
- Choice of fixed precoding response $h_{IIR}(D)$
- SNR vs cable length with optimum precoding and with fixed $h_{IIR}(D)$, assuming ideal TX and RCV filters
- Practical TX and RCV filters
- SNR vs cable length with practical TX and RCV filters
- Feed-forward equalizer (FFE): required span
- Precoder simulation
- Conclusions

Assumed modulation and coding

1. **RS(255,239) + 8-PAM 4d 16st TCM**
   239/255 x 11/4 = 2.5775 bit/sym x 969.93 Mbaud = 2.5 Gbit/s per pair
   Minimal decision-point SNR required for BER ≤ 10^{-12}: SNR_{req} ≈ 20 dB

2. **RS(255,239) + 12-PAM 4d 16st TCM**
   239/255 x 13*/4 = 3.0461 bit/sym x 820.72 Mbaud = 2.5 Gbit/s per pair
   Minimal decision-point SNR required for BER ≤ 10^{-12}: SNR_{req} ≈ 23 dB

3. **RS(255,239) + 16-PAM 4d 16st TCM**
   239/255 x 15/4 = 3.5147 bit/sym x 711.30 Mbaud = 2.5 Gbit/s per pair
   Minimal decision-point SNR required for BER ≤ 10^{-12}: SNR_{req} ≈ 26 dB

Interleaving: NxI row-column interleaving of RS bytes + periodic interleaving of J TCM encoded symbol streams (N = 255, I = 4 - 8; J = 4 - 8).

*** 13 = floor($\log_2 (12^4/2)$)**

10GBASE-T cable models → variable-length cable models

Complex-valued cable-transfer function

$$G_C(f_{[Hz]}, \ell_{[m]}) = e^{-\underset{\substack{\uparrow \\ \text{propagation constant}}}{\ell\gamma(f)}} \times 10^{\underset{\text{4 connectors}}{-4\times 0.08\times\sqrt{f/10^6}/20}}\ ; \quad \gamma(f) = \sqrt{\frac{\overset{\text{skin effect}}{R_s\sqrt{jf/f_s}} + j2\pi fL}{\underset{\text{dielectric loss}}{R_d + 1/j2\pi fC}}}$$

$$f_s = 200\text{MHz};\ L = 0.5\text{mH/m}, C = 50\text{pF/m}:\ Z_0 \cong \sqrt{L/C} = 100\Omega,\ v = 1/\sqrt{LC} = 200\times 10^6\,\text{m/s}$$

Expected alien-NEXT squared magnitude function

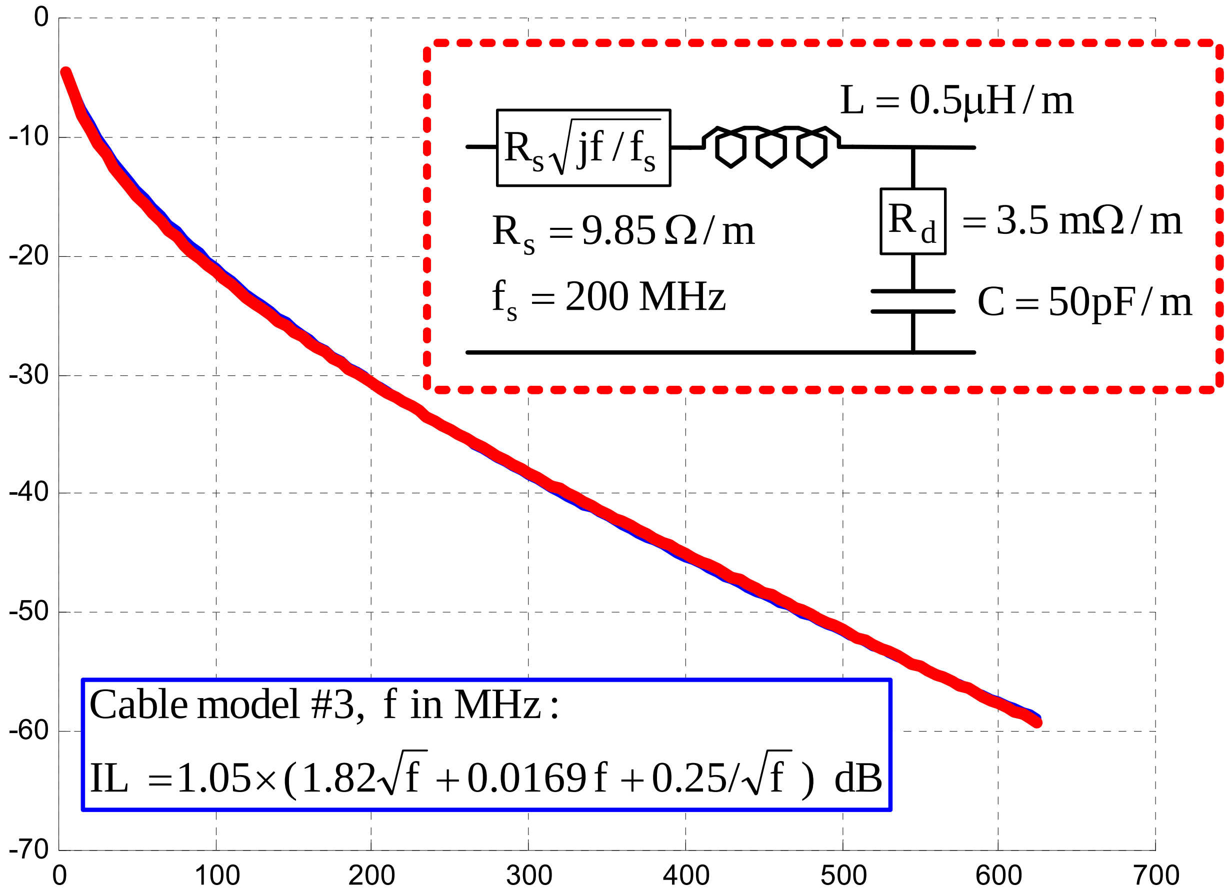
$$\left|G_A(f_{[Hz]}, \ell_{[m]})\right|^2 = 10^{-\underset{\text{NEXT attenuation [dB]}}{\left(X1+2.5-S\times\log_{10}\sqrt{f/10^8}\right)}/10} \times \underset{\text{dependence on length}}{\left(1-\left|G_C(f,\ell)\right|^4\right)};\ S = \begin{cases} 10\,, & f \le 10^8 \\ 15\,, & f \ge 10^8 \end{cases}$$

Model #1 (Cat 7, shielded) , 100 m → cabtyp **“ClassF”** : R_s=9.48 Ω/m, R_d=1.7 mΩ/m, X1=60 dB

Model #2 (Cat 6, unshielded) , 55 m → cabtyp **“ClassEu”** : R_s=9.85 Ω/m, R_d=3.5 mΩ/m, X1=47 dB

Model #3 (Cat 6, shielded) , 100 m → cabtyp **“ClassEs”** : R_s=9.85 Ω/m, R_d=3.5 mΩ/m, X1=62 dB

Fitting cable Model #3



Cable model #3, f in MHz:

$$IL = 1.05 \times (1.82\sqrt{f} + 0.0169f + 0.25/\sqrt{f}\ )\ dB$$

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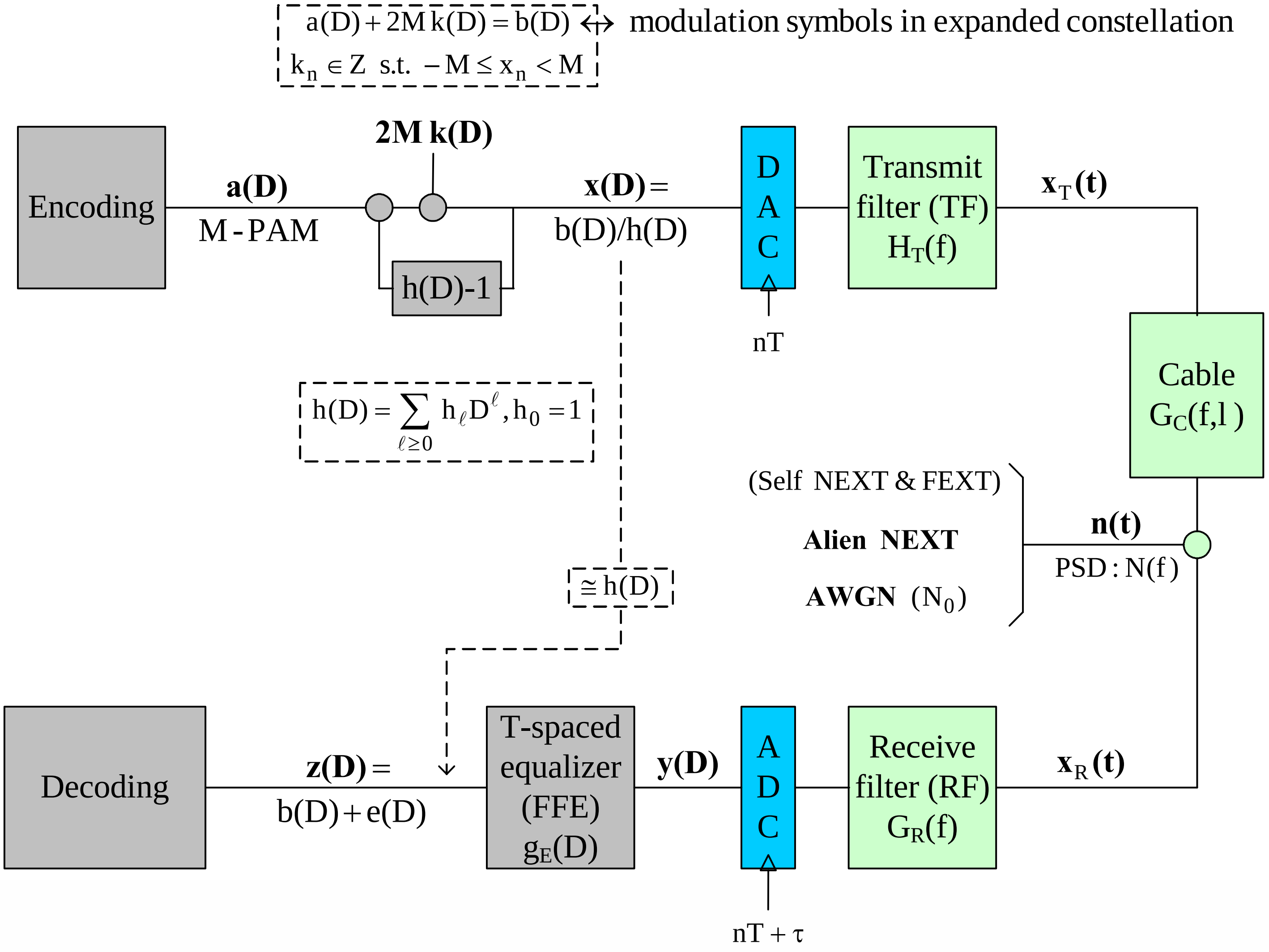
10GBASE-T PAM transmission model (one pair)



$a(D)+2M\,k(D)=b(D) \leftrightarrow$ modulation symbols in expanded constellation

$k_n \in Z \;\text{s.t.}\; -M \le x_n < M$

Encoding

a(D)

M-PAM

2M k(D)

h(D)-1

$\mathbf{x(D)} = b(D)/h(D)$

DAC

nT

Transmit filter (TF) $H_T(f)$

$\mathbf{x_T(t)}$

Cable $G_C(f,l)$

$h(D)=\sum_{\ell\ge 0} h_\ell D^\ell, h_0 = 1$

(Self NEXT & FEXT)

Alien NEXT

AWGN (N_0)

n(t)

PSD : N(f)

$\cong h(D)$

Decoding

$\mathbf{z(D)} = b(D)+e(D)$

T-spaced equalizer (FFE) $g_E(D)$

y(D)

ADC

$nT+\tau$

Receive filter (RF) $G_R(f)$

$\mathbf{x_R(t)}$

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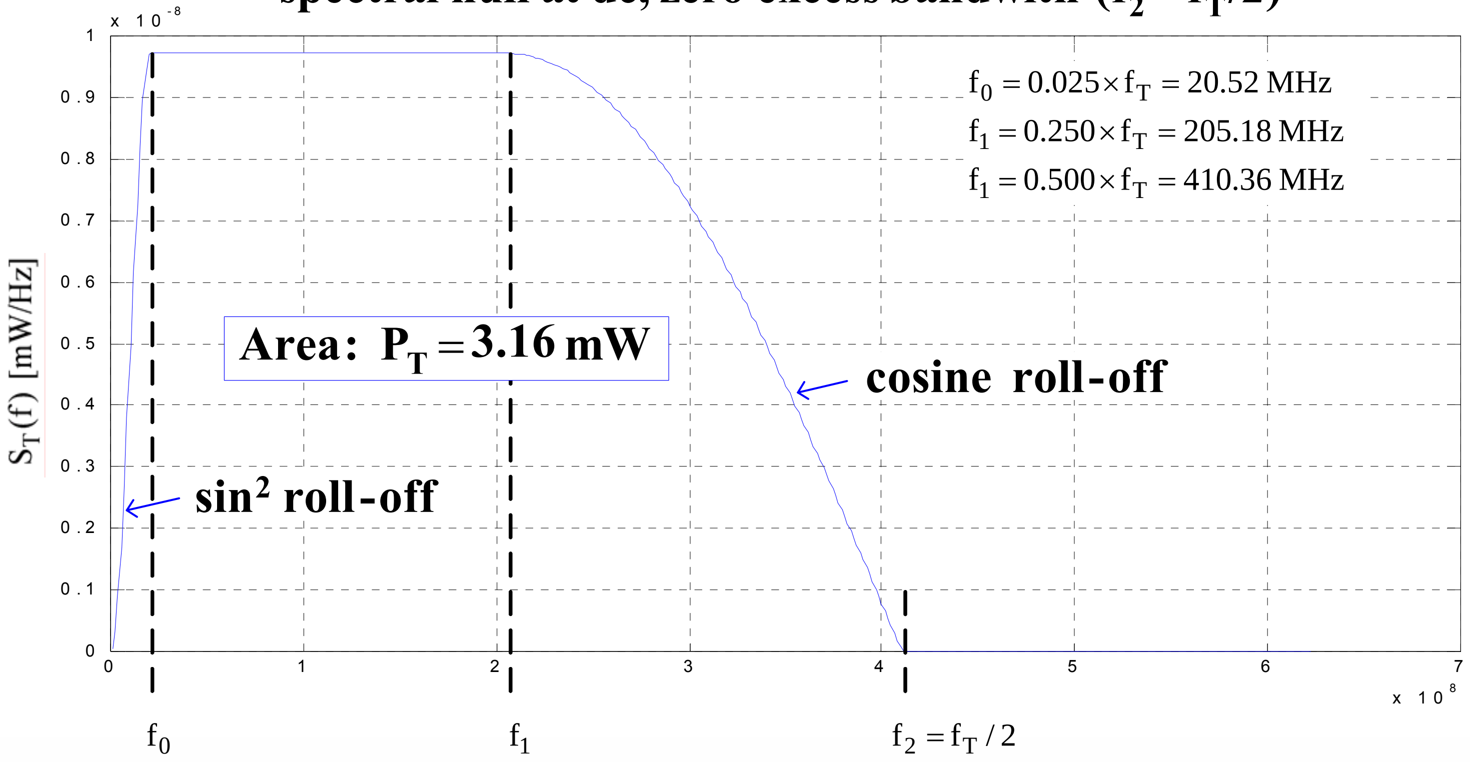
Transmit power spectral density (TX PSD)

Modulation rate f_T = 820.72 Mbaud, P_T = 5 dBm

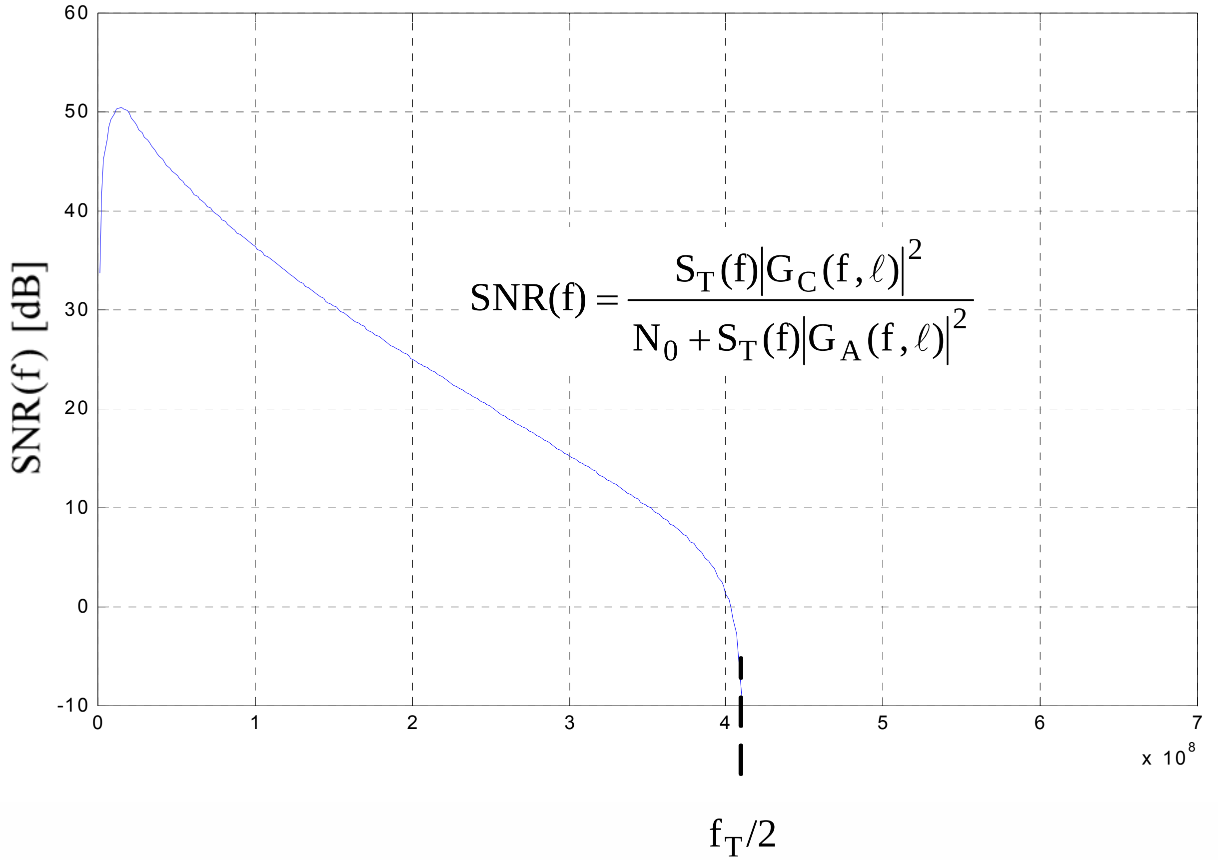
TX PSD from ideal TF: $S_T(f; 0.025,0.25,0.5)$

spectral null at dc, zero excess bandwith $(f_2 = f_T/2)$



Signal-to-noise ratio function SNR(f)

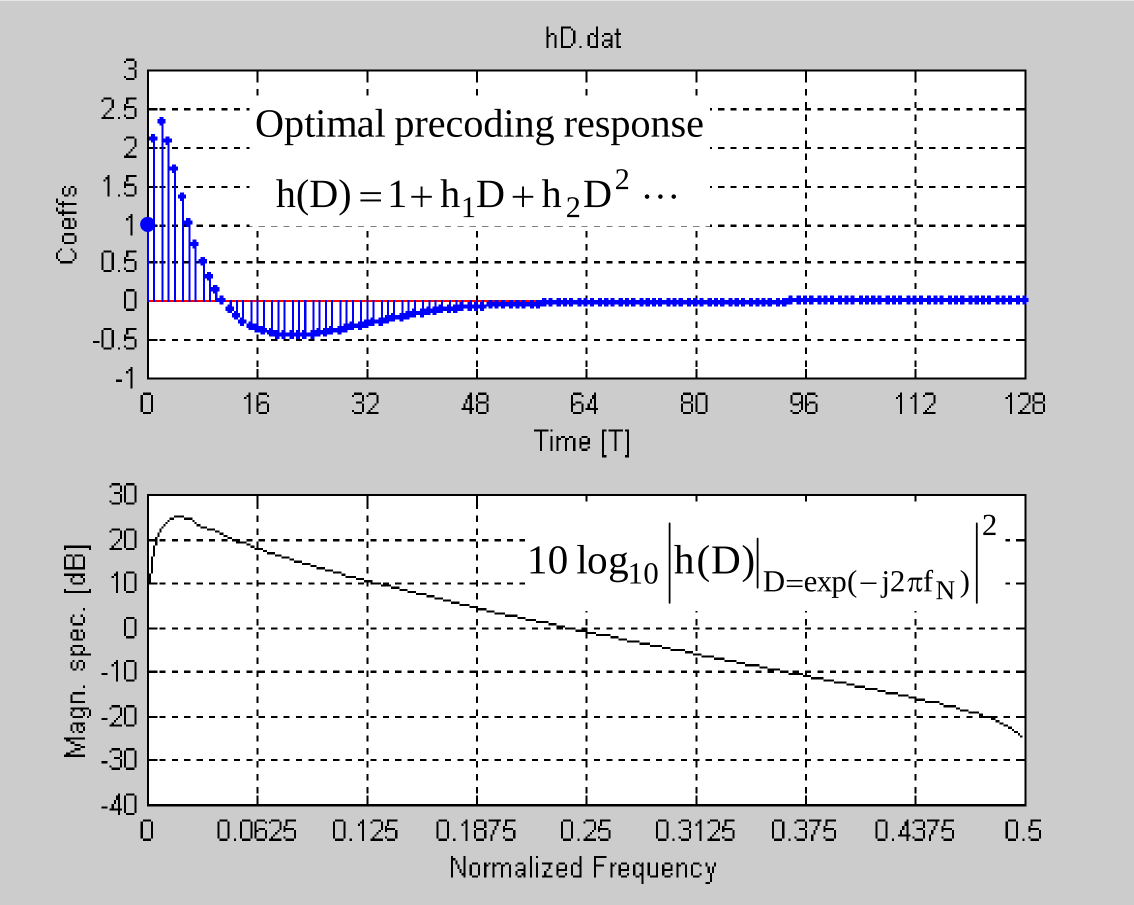
f_T = 820.72 Mbaud, PT = 5 dBm, ideal TF → S_T(f; 0.025,0.25,0.5)
cabtyp "ClassEs", cablen = 100m, ANEXT + AWGN (N_0 = -140 dBm/Hz)



$$\mathrm{SNR}(f) = \frac{S_T(f)\left|G_C(f,\ell)\right|^2}{N_0 + S_T(f)\left|G_A(f,\ell)\right|^2}$$

Optimal precoding response (=FBF coeffs of ideal DFE)

f_T = 820.72 Mbaud, P_T = 5 dBm, ideal TF → S_T(f; 0.025,0.25,0.5)
cabtyp "ClassEs", cablen = 100m, ANEXT + AWGN (N_0 = -140 dBm/Hz)



... optimal in MMSE sense for assumed TX filter, cable, noise ...

obtained by spectral factorization

$$SNR^*(f) + 1 = h(D^{-1}) A^2 h(D)$$

$$A^2 = SNR_{mmse-wmf}$$

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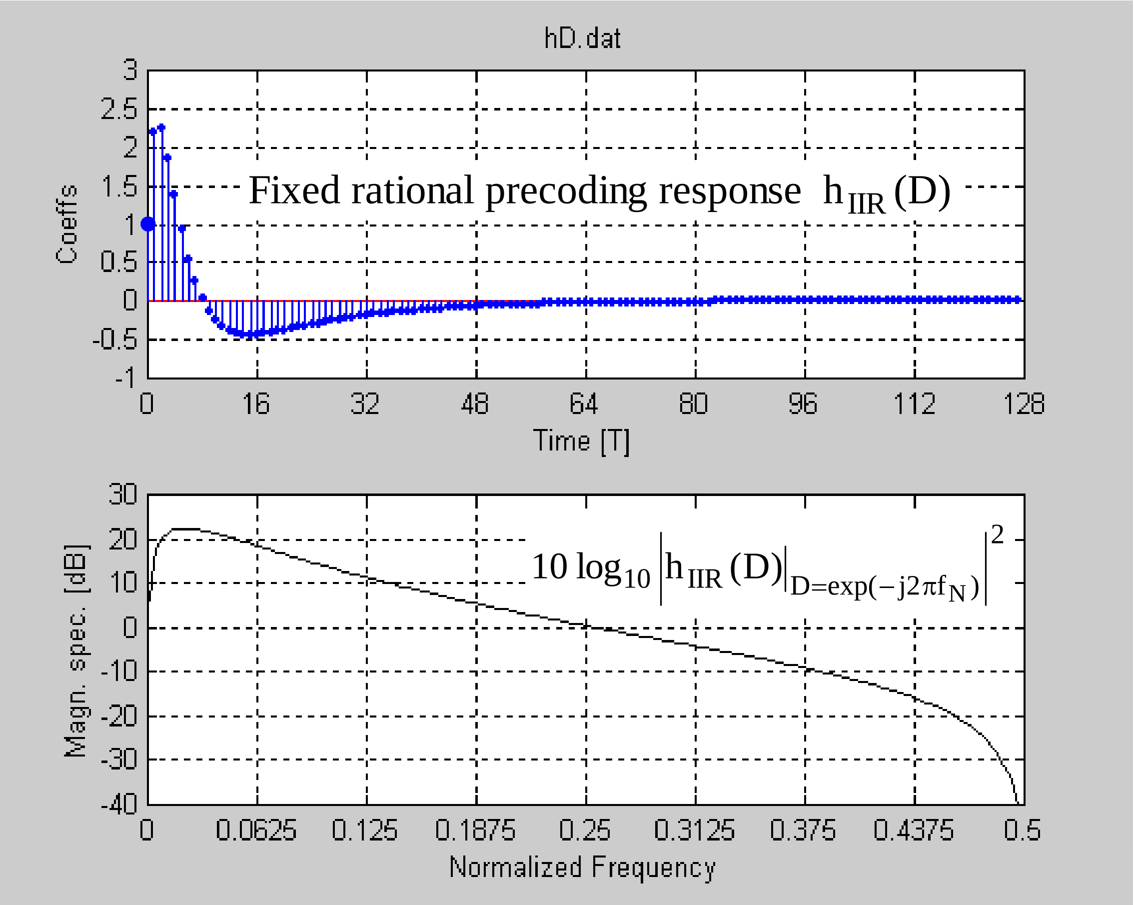
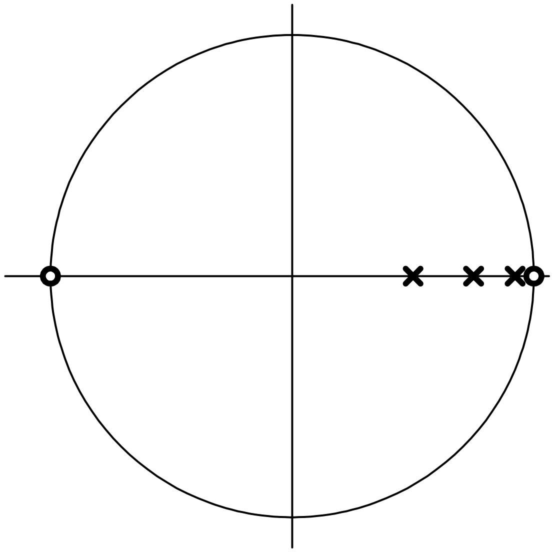
Fixed rational precoding response $h_{IIR}(D)$

$$h_{IIR}(D) = \frac{(1-D)(1+D)}{(1-0.9375D)(1-0.75D)(1-0.5D)}$$

zeroes: $\alpha_1 = +1$

$\alpha_2 = -1$





poles: $\beta_1 = +15/16$

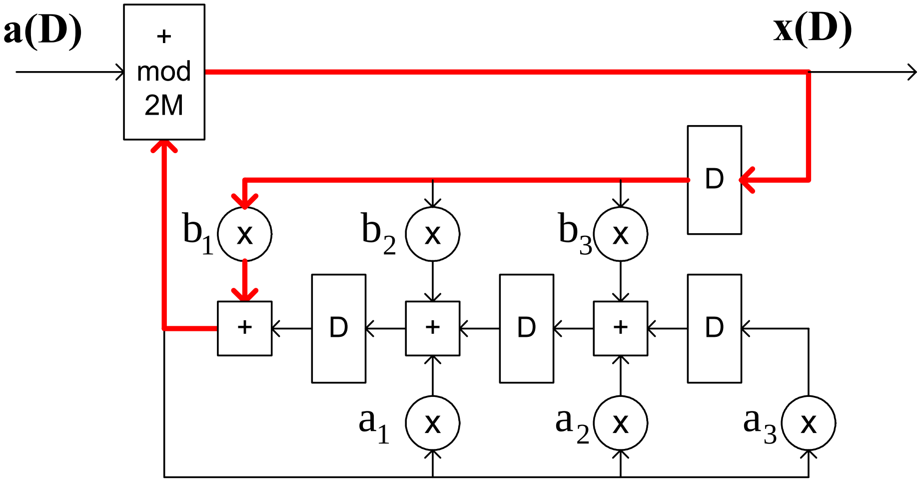
$\beta_2 = +3/4$

$\beta_3 = +1/2$

Precoder for rational precoding response $h_{IIR}(D)$

$$h_{IIR}(D)=\frac{(1-D)(1+D)}{(1-\frac{15}{16}D)(1-\frac{3}{4}D)(1-\frac{1}{2}D)}=\frac{1-D^2}{1-\frac{35}{16}D+\frac{99}{64}D^2-\frac{45}{128}D^3}$$

$$h_{IIR}(D)-1=\frac{\frac{35}{16}D-\frac{163}{64}D^2+\frac{45}{128}D^3}{1-\frac{35}{16}D+\frac{99}{64}D^2-\frac{45}{128}D^3}=\frac{b_1D+b_2D^2+b_3D^3}{1-a_1D-a_2D^2-a_3D^3}$$



$b_1 = \frac{35}{16} = 10.0011_2$

$b_2 = -\frac{163}{64} = -10.100011_2$

$b_3 = \frac{45}{128} = 0.0101101_2$

$a_1 = \frac{35}{16} = 10.0011_2$

$a_2 = -\frac{99}{64} = -1.100011_2$

$a_3 = \frac{45}{128} = 0.0101101_2$

Results on SNR vs cable length: next 5 slides

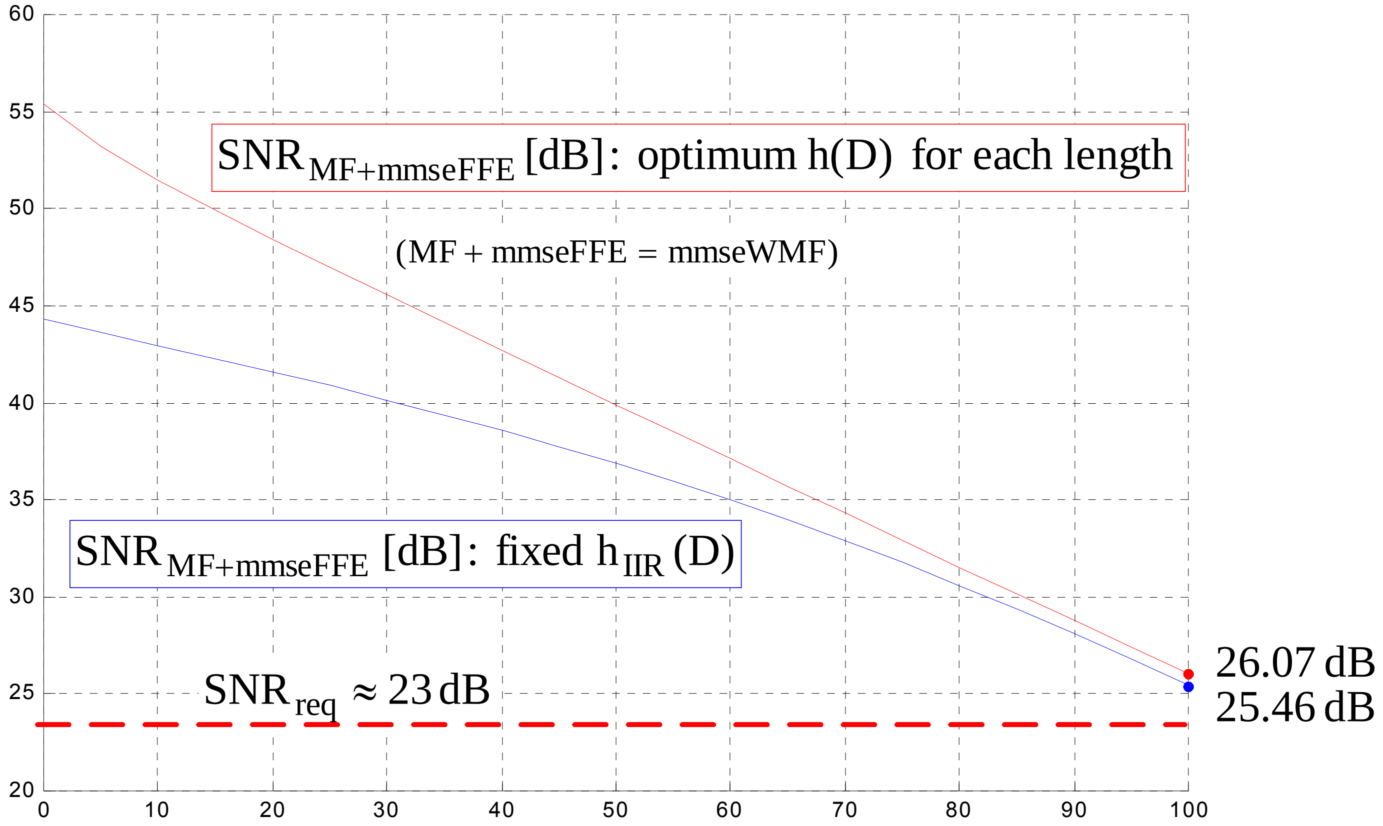
- Common assumptions
  - Ideal TF → $S_T(f; 0.025,0.25,0.5)$
  - P_T = 5 dBm; alien NEXT + AWGN (-140 dBm/Hz)
  - receiver equalization: MF + mmse FFE (T-spaced).

- Each slide showing two curves
  a) optimum h(D) for each cable length
  b) fixed $h_{IIR}(D)$

1. Cable type = "ClassF", f_T = 820.72 Mbaud (12-PAM)
2. Cable type = "ClassEu", f_T = 820.72 Mbaud (12-PAM)
3. Cable type = "ClassEs", f_T = 820.72 Mbaud (12-PAM)
4. Cable type = "ClassEs", f_T = 969.93 Mbaud (8-PAM)
5. Cable type = "ClassEs", f_T = 711.30 Mbaud (16-PAM)

SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

$$\textbf{Cable type} = \textbf{"ClassF"};\ \mathbf{f_T} = \mathbf{820.72\,MBaud\,(12\text{-}PAM)};\ \text{ideal TF} \rightarrow$$
$$S_T(f; 0.025, 0.25, 0.5);\ P_T = 5\,\text{dBm};\ \text{alien NEXT} + \text{AWGN}\ (\text{-}140\,\text{dBm/Hz})$$



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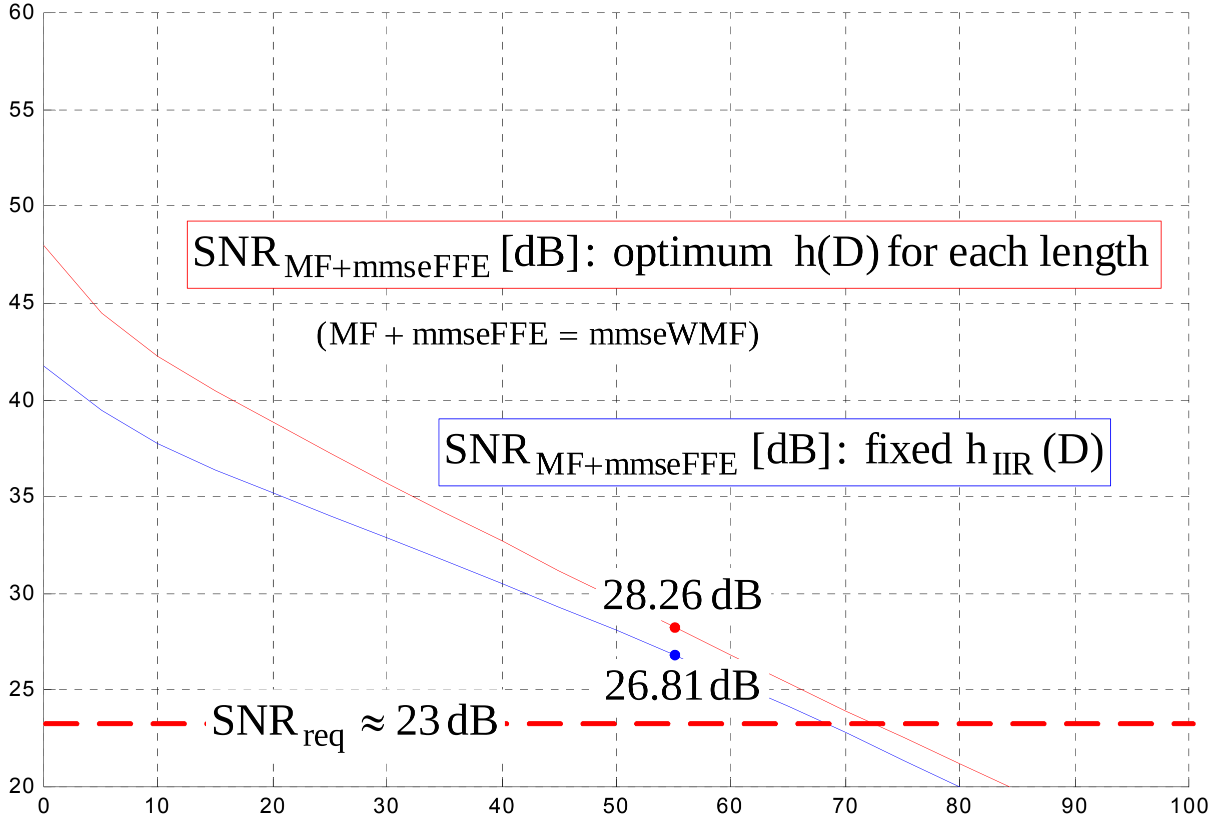
SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

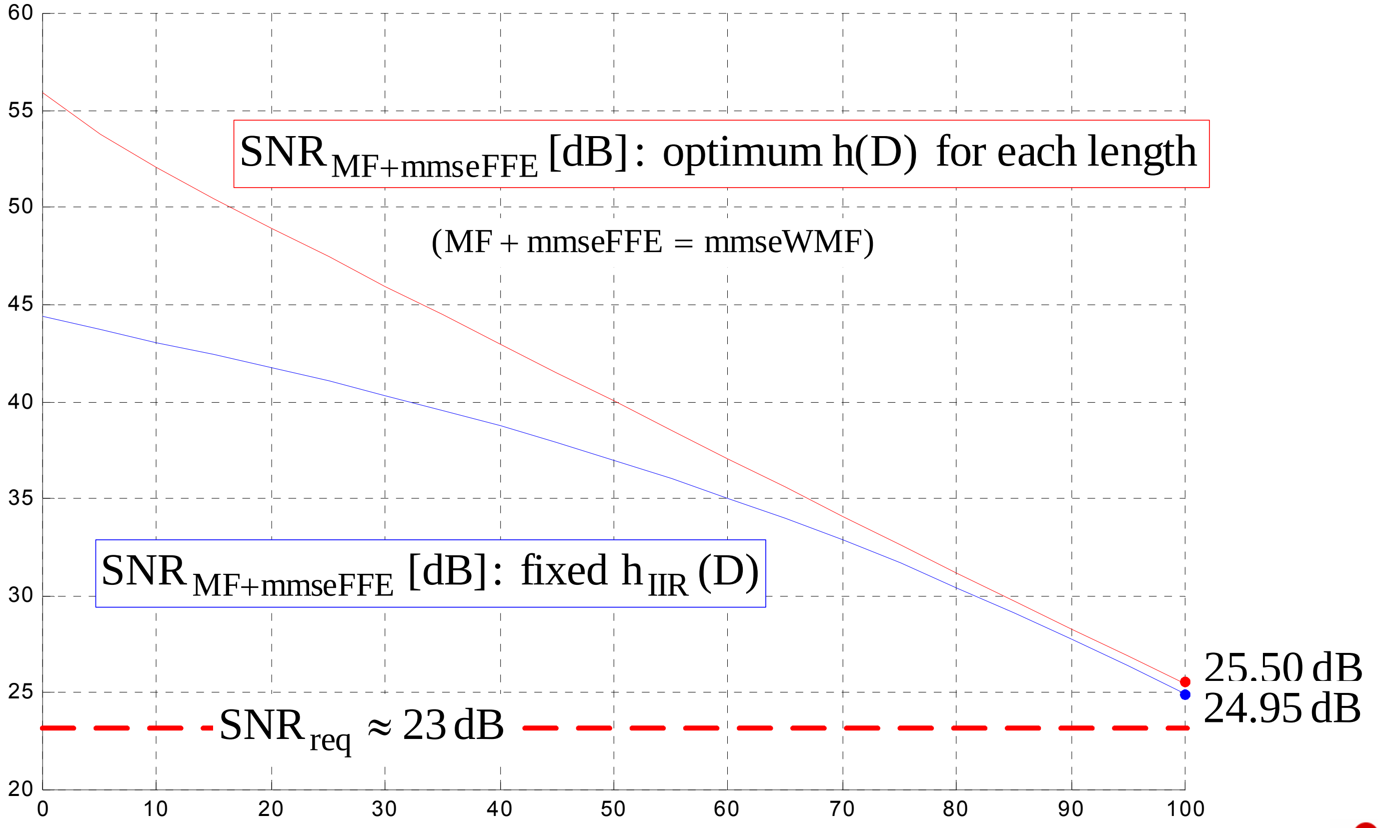
$\mathbf{Cable\ type = "ClassEu";\ f_T = 820.72\,MBaud\ (12\text{-}PAM);}$ ideal TF $\rightarrow$ $S_T(f; 0.025, 0.25, 0.5)$; $P_T = 5\,\mathrm{dBm}$; alien NEXT + AWGN (-140 dBm/Hz)



SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

$$\textbf{Cable type = "ClassEs"; } f_T = \textbf{820.72 MBaud (12-PAM); } \text{ideal TF} \rightarrow$$

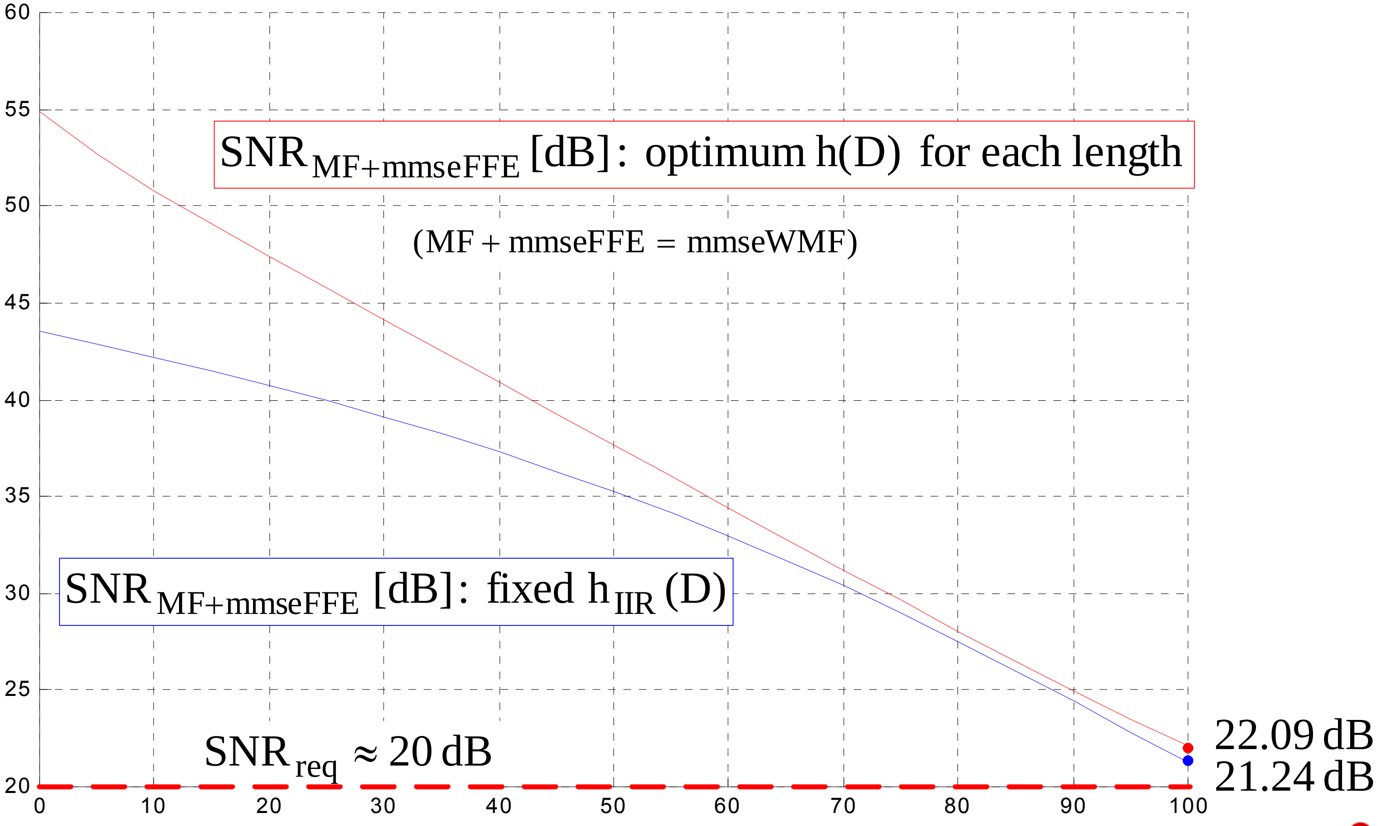
$$S_T(f; 0.025, 0.25, 0.5); \; P_T = 5\,\text{dBm}; \; \text{alien NEXT + AWGN (-140 dBm/Hz)}$$



SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

$$\textbf{Cable type ="ClassEs"; } f_T = \textbf{969.93 MBaud (8-PAM); } \text{ideal TF} \rightarrow$$

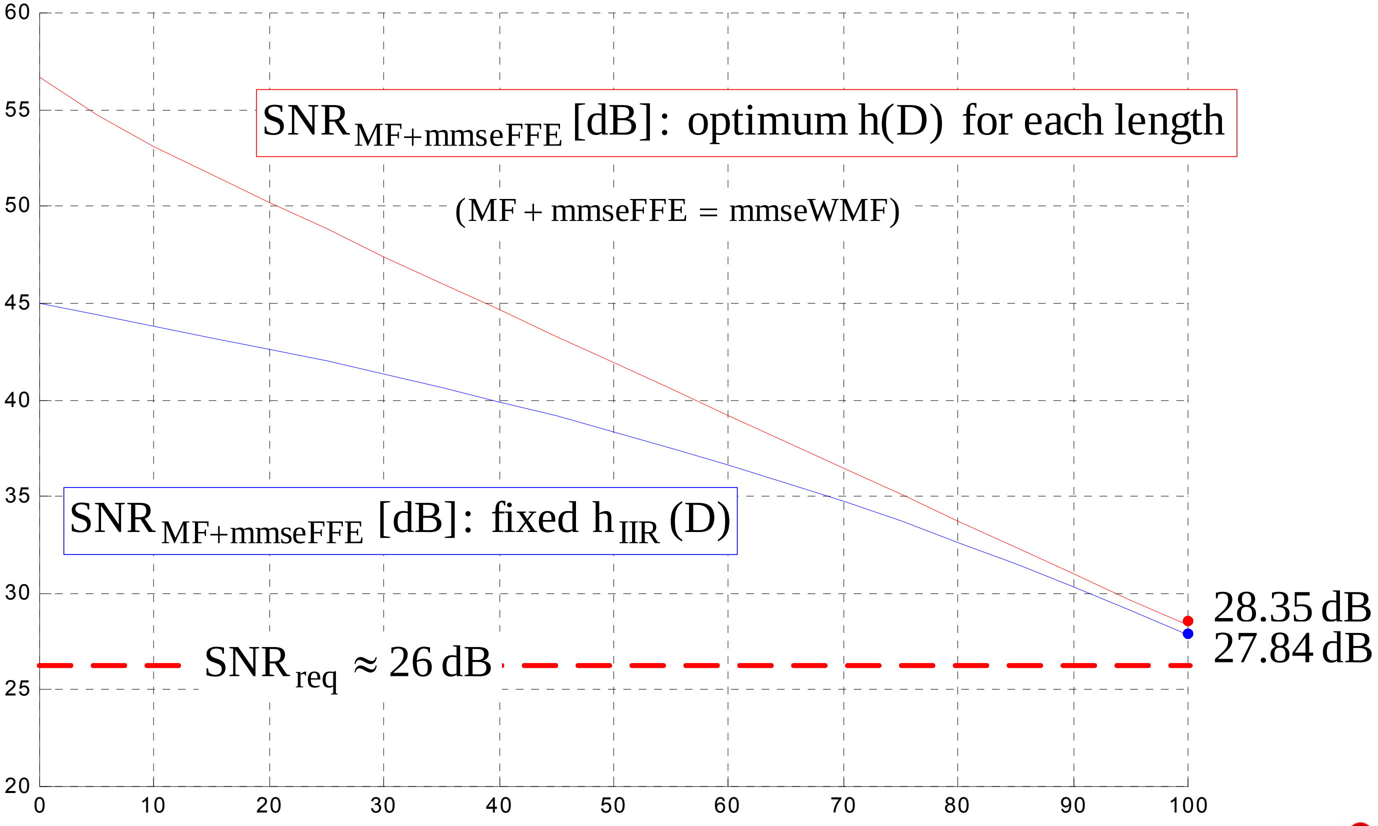
$$S_T(f; 0.025, 0.25, 0.5);\ P_T = 5\,\text{dBm};\ \text{alien NEXT + AWGN (-140 dBm/Hz)}$$



SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

$$\textbf{Cable type = "ClassEs"; } \mathbf{f_T = 711.30\,MBaud\,(16\text{-}PAM)};\ \text{ideal TF} \rightarrow$$

$$S_T(f; 0.025, 0.25, 0.5);\ P_T = 5\,\text{dBm};\ \text{alien NEXT + AWGN (-140 dBm/Hz)}$$



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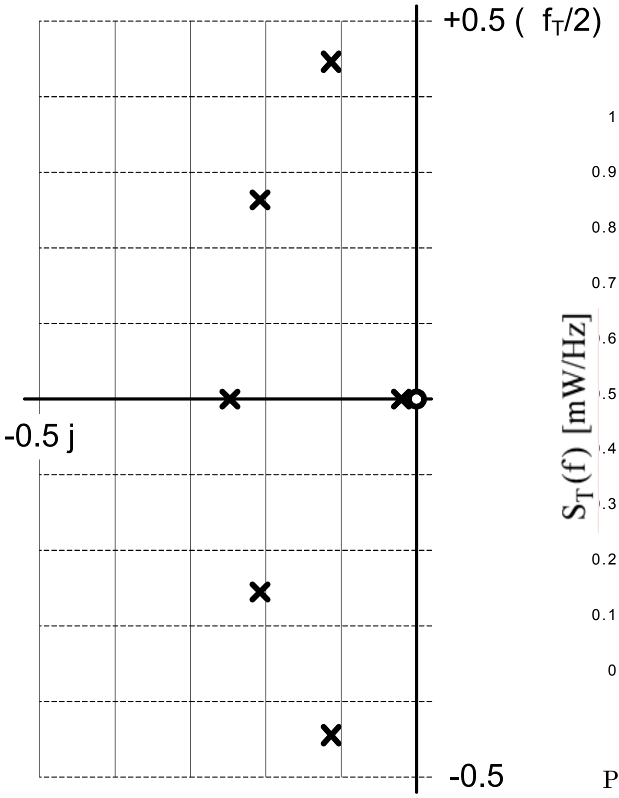
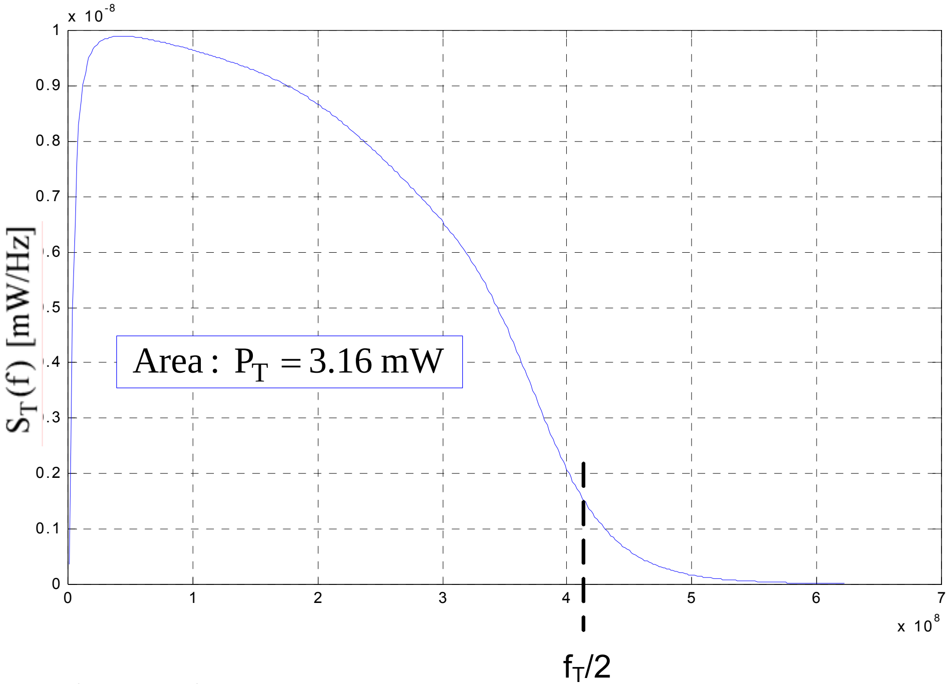
Practical continuous-time transmit filter (TF)

Modulation rate f_T = 820.72 Mbaud, P_T = 5 dBm
Modified 5th-order Butterworth filter with spectral null at dc



s_N-plane

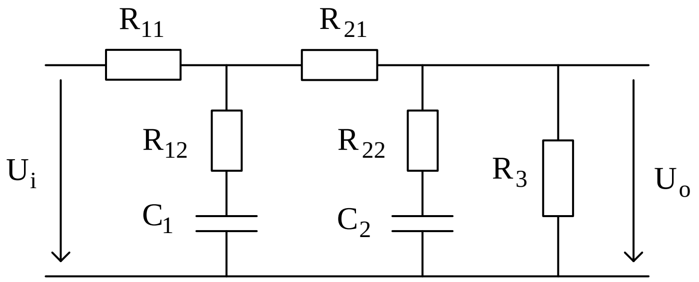
Zeroes in sN-plane:
b1= 0.00000+j 0.00000



Poles in sN-plane:
a1= -0.00500+j 0.00000
a2= -0.10644+j 0.45241
a3= -0.21108+j 0.26791
a4= -0.25000+j 0.00000
a5= -0.21108 -j 0.26791
a6= -0.10644 -j 0.45241

Practical continuous-time receive filter (pRF)

Receive filter: $G_R(f) \approx G_C(f,\ell = 50\text{m})$ of “ClassEs” cable



preliminary choice:

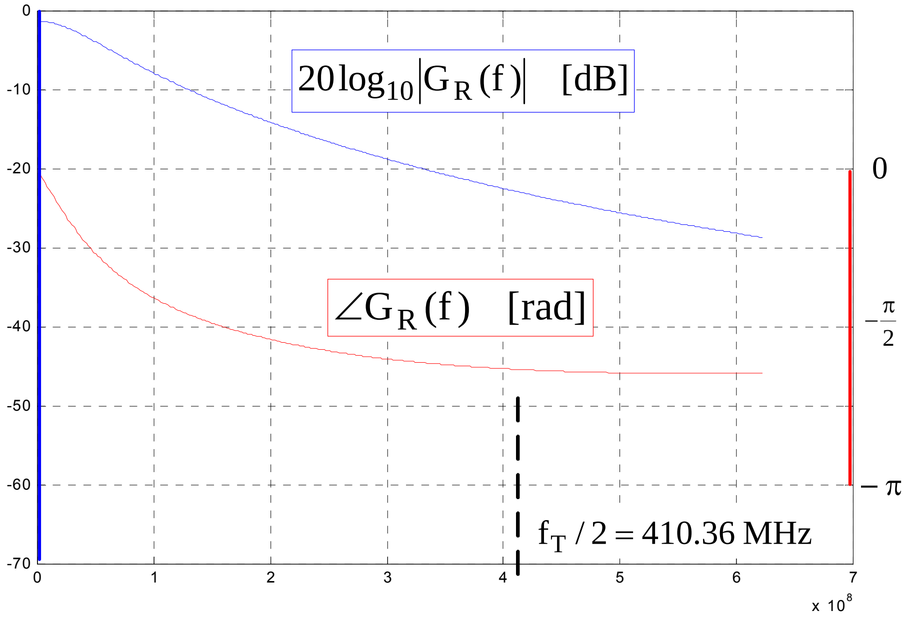
$R_{11} = R_{21} = 8\Omega$

$R_{12} = R_{22} = 0.5\Omega$

$R_3 = 100\Omega$

$C_1 = C_2 = 150\,\text{pF}$

$G_R(f) = U_o / U_i$



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Results on SNR vs cable length: next 2 slides

- Common assumptions
  - TF = modified 5-th order Butterworth filter with dc null
  - P_T = 5 dBm; alien NEXT + AWGN (-140 dBm/Hz)

- Each slide showing three curves

  a) optimum h(D) for each cable length; MF + mmse FFE = mmse WMF

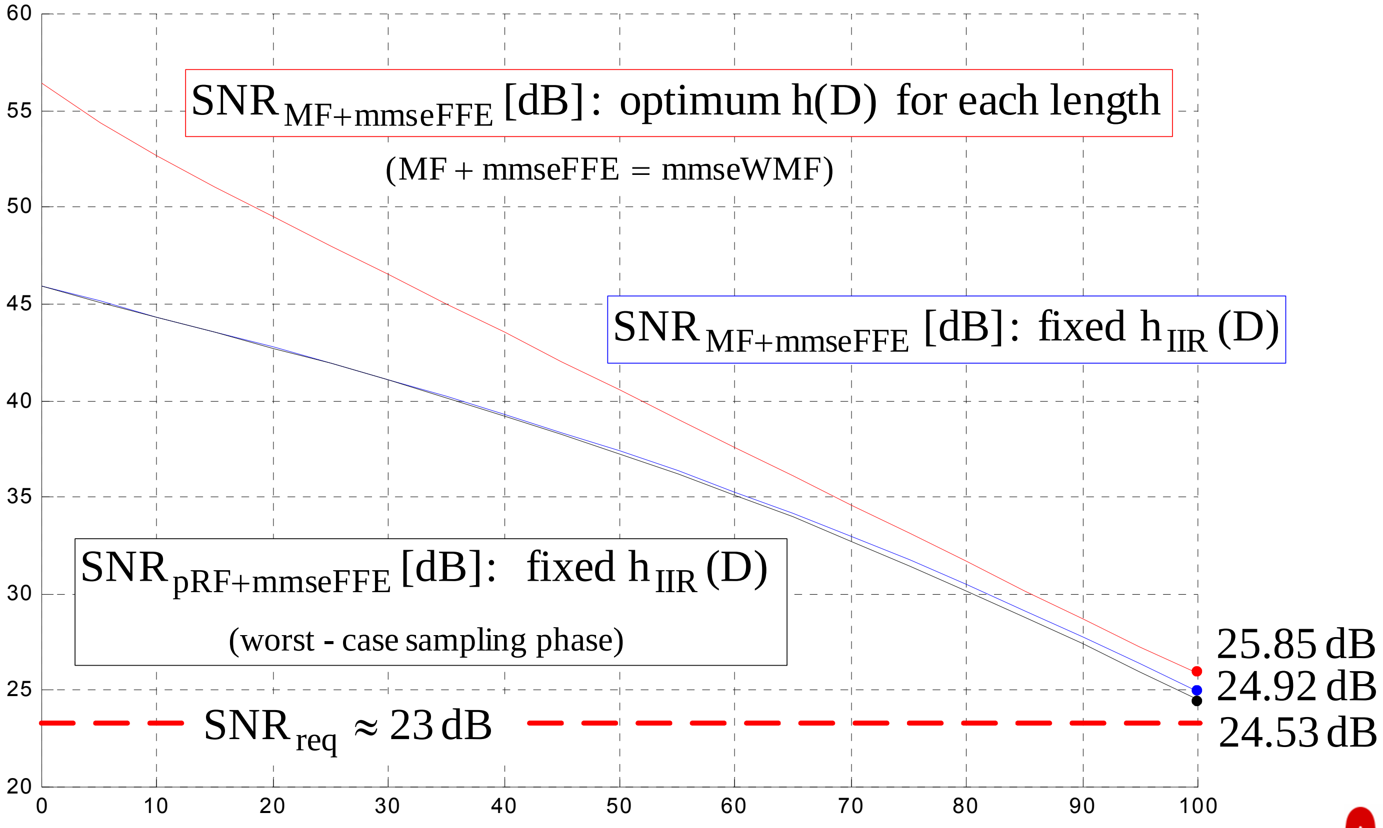
  b) fixed $h_{IIR}(D)$; MF + mmse FFE

  c) fixed $h_{IIR}(D)$; pRF + mmse FFE with worst-case sampling phase

1. Cable type = “ClassEs”, f_T = 820.72 Mbaud (12-PAM)
2. Cable type = “ClassEu”, f_T = 820.72 Mbaud (12-PAM)

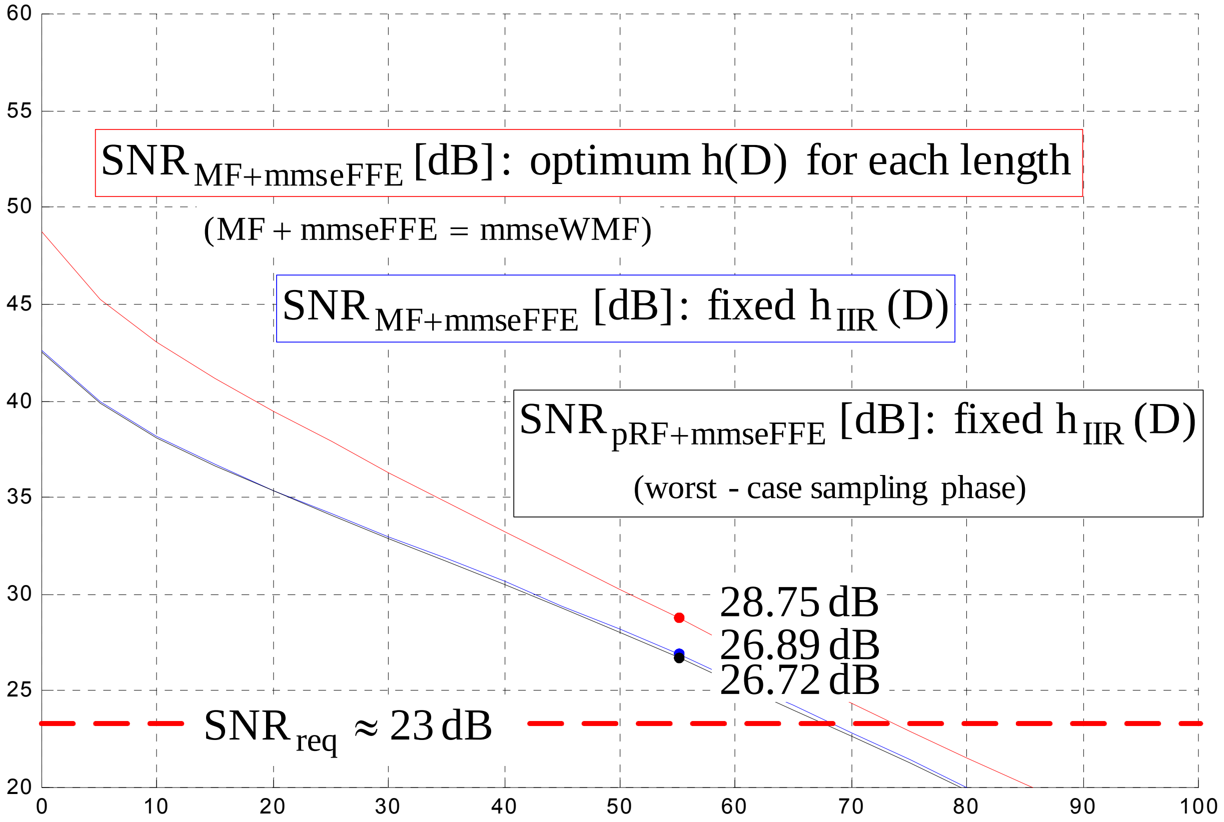
SNR vs cable length: optimal h(D) and fixed $h_{IIR}(D)$

Cable type ="ClassEs"; f_T = 820.72 MBaud (12-PAM); TF = modified BW filter with dc null; P_T = 5 dBm; alien NEXT + AWGN (-140 dBm/Hz)



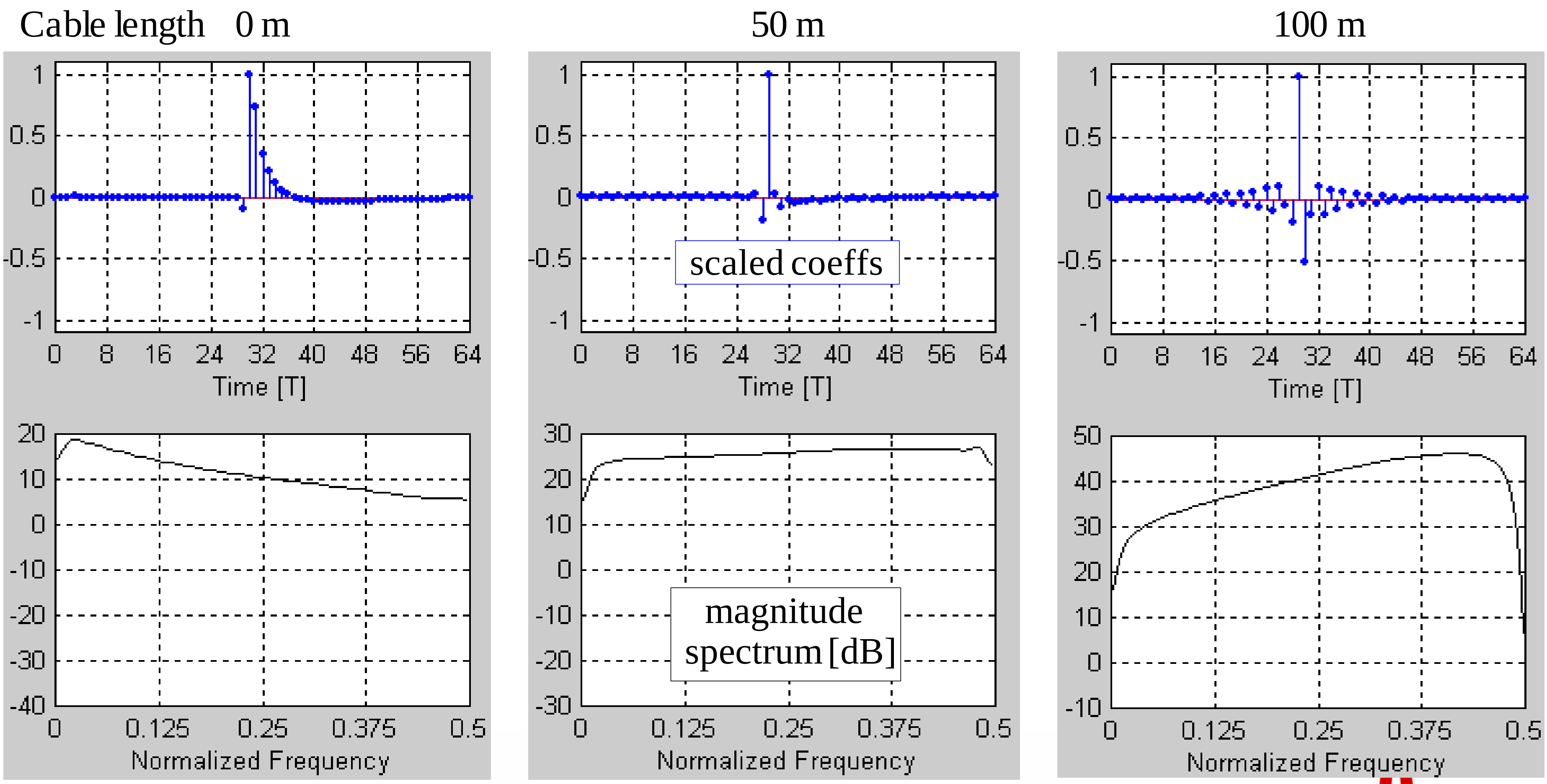
SNR vs cable length: optimal h(D) and fixed h_{IIR}(D)

Cable type ="ClassEu" ; f_T = 820.72 MBaud (12 - PAM); TF = modified BW filter with dc null; P_T = 5 dBm; alien NEXT + AWGN (-140 dBm/Hz)



Feed-forward equalizer (FFE): the only variable filter

Cable type = "Class E s"; f_T = 820.72 MBaud (12-PAM); P_T = 5 dBm;
alien NEXT + AWGN (-140 dBm/Hz); practical transmit and receive filters



Cable length 0 m

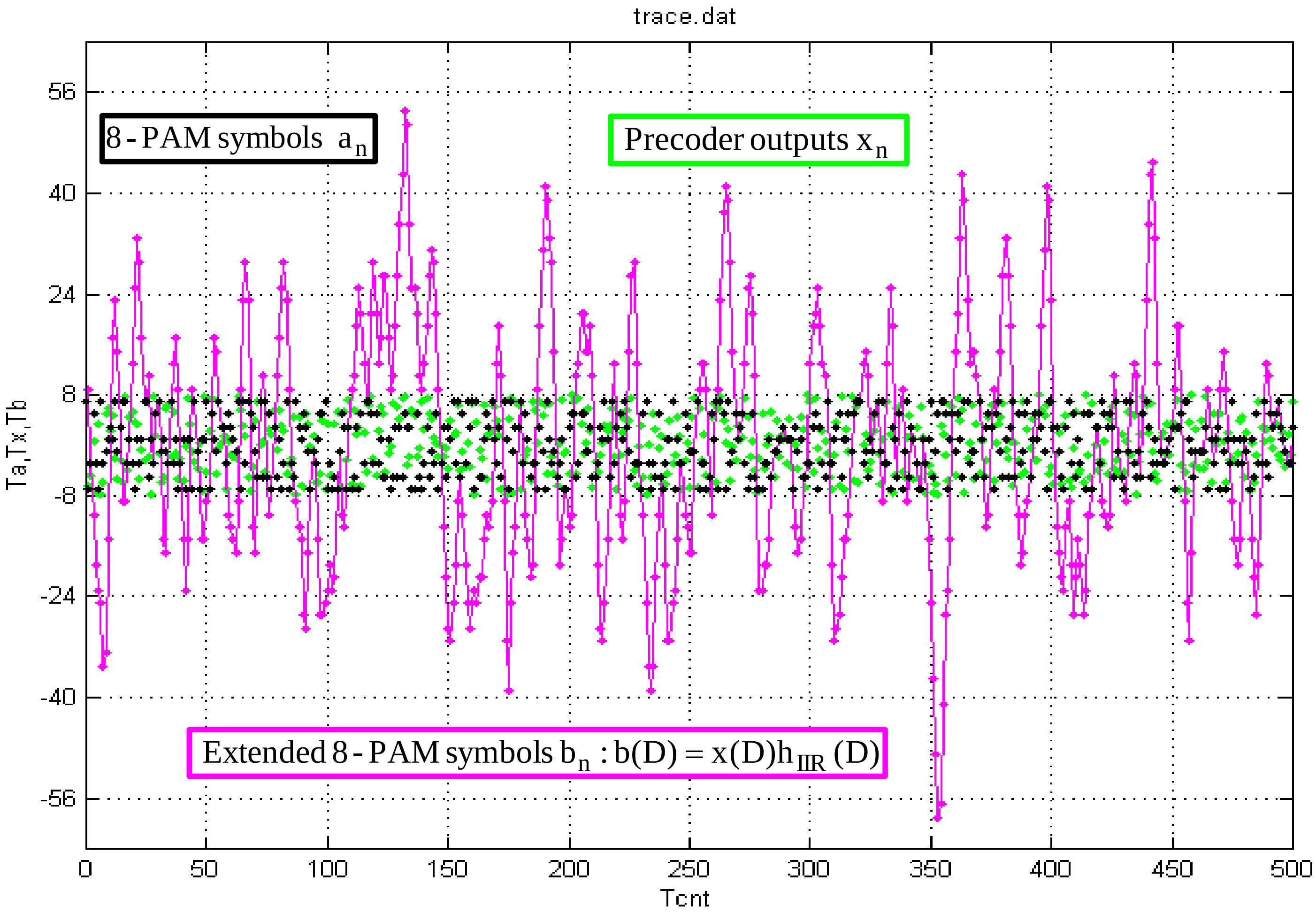
50 m

100 m

scaled coeffs

magnitude spectrum [dB]

Precoder simulation: 8-PAM using $h_{IIR}(D)$



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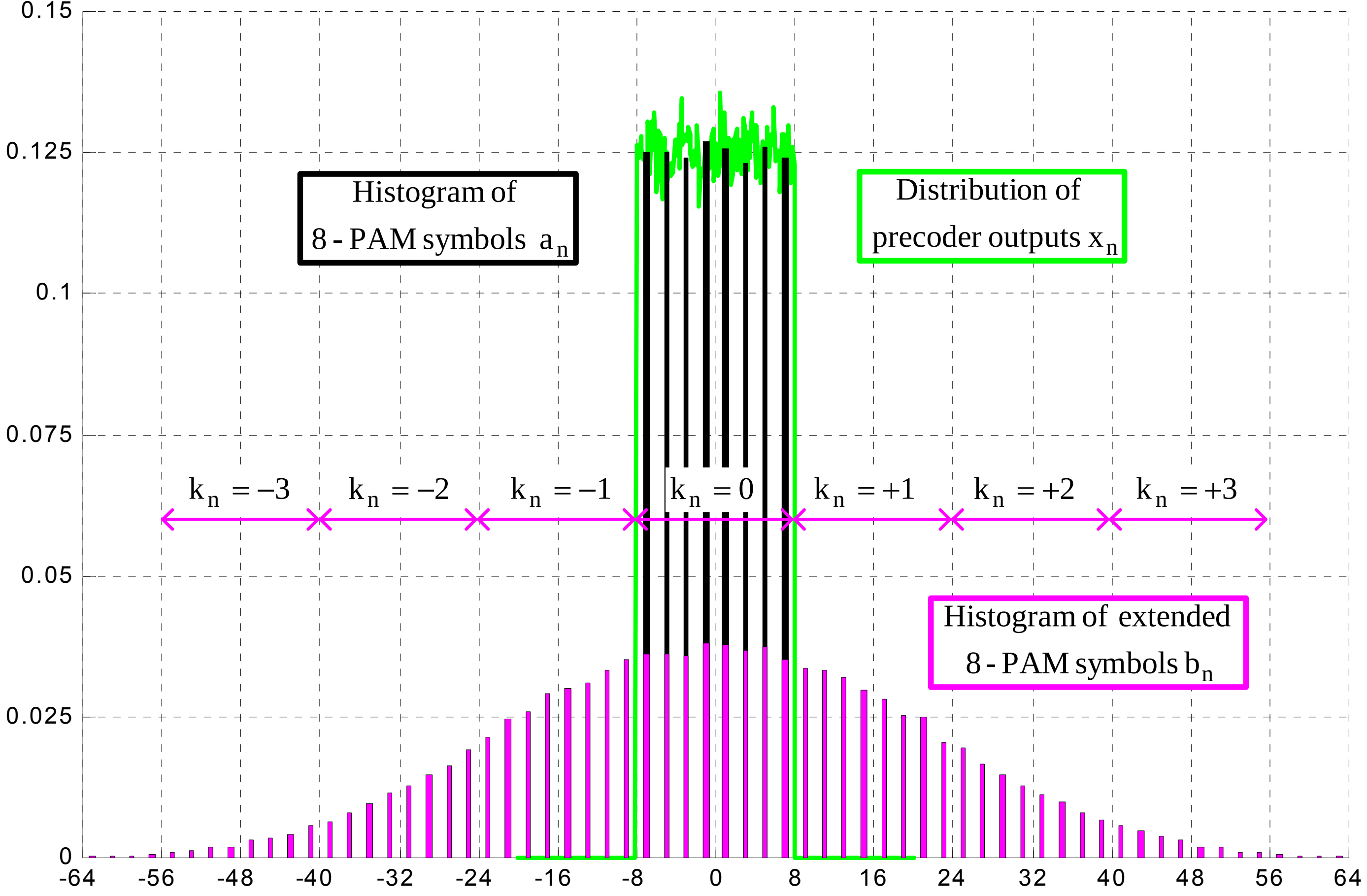
Precoder simulation: 8-PAM using $h_{IIR}(D)$

$a_n \in$ 8-PAM; $b_n = a_n + 2 \times 8 k_n$, $k_n \in \mathbf{Z}$ such that $-8 \le x_k < 8$,

Empirical distributions from 100'000 modulation intervals



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Conclusions

- One fixed precoding polynomial is sufficient for all cable types and length.
- Performance loss due to practical continuous-time TX and RCV filters is < 1 dB. Further optimization of initial filter designs may result only in small improvements.
- The only variable filter is the feed-forward equalizer (FFE), which requires a time span of 32 T to compensate for 0 – 100 m variations in cable length (for one pair).
- Additional FFE span will be needed to cope with delay skew and FEXT in a four-pair matrix FFE.