10GBASE-T
PCS details and Precoding

with additions of 24Jan05

IEEE P802.3an Task Force
Vancouver, January 26-28, 2005

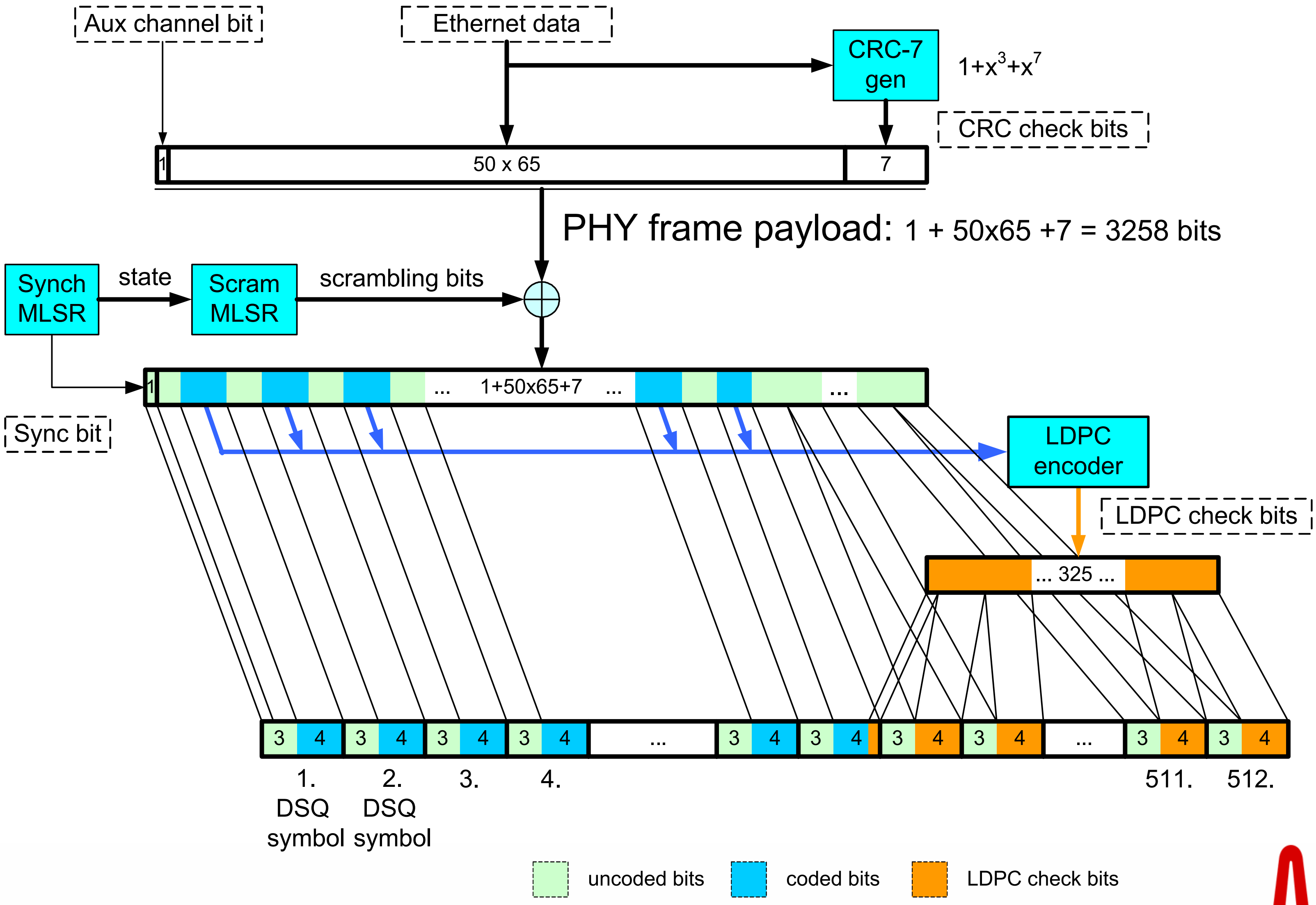
Gottfried Ungerboeck

CRC and Scrambling

- in which order?

- what type of scrambling?

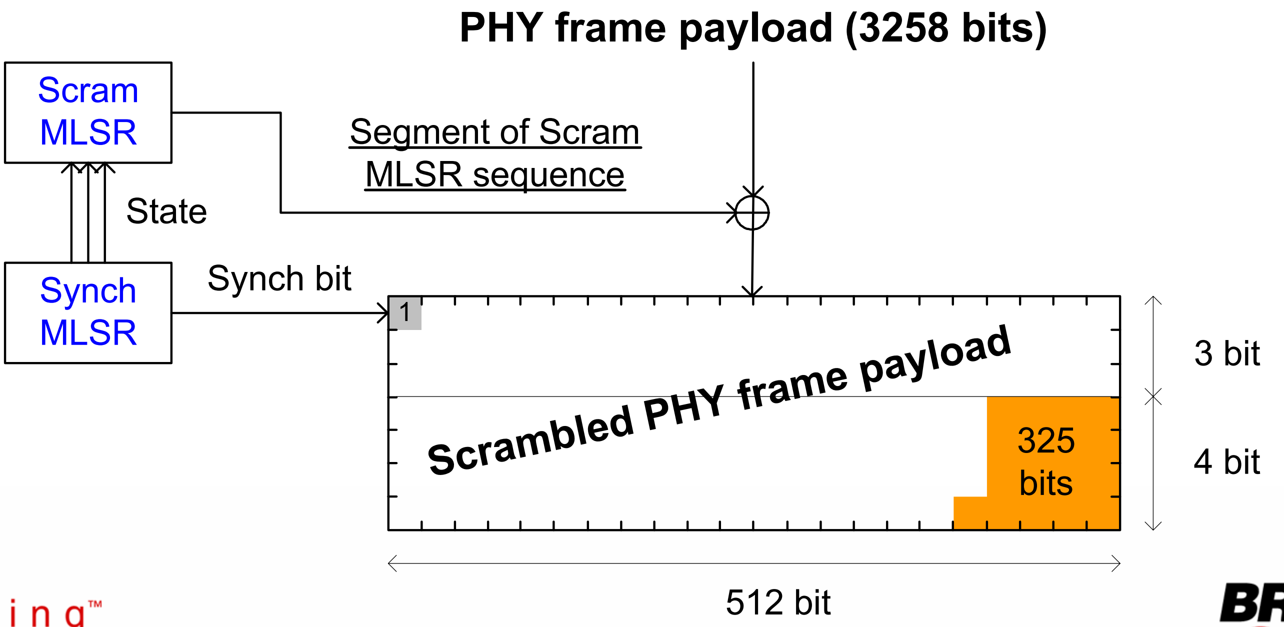
Composition of PHY frame: CRC, then cipher-stream scrambling



PHY frame payload: 1 + 50x65 +7 = 3258 bits

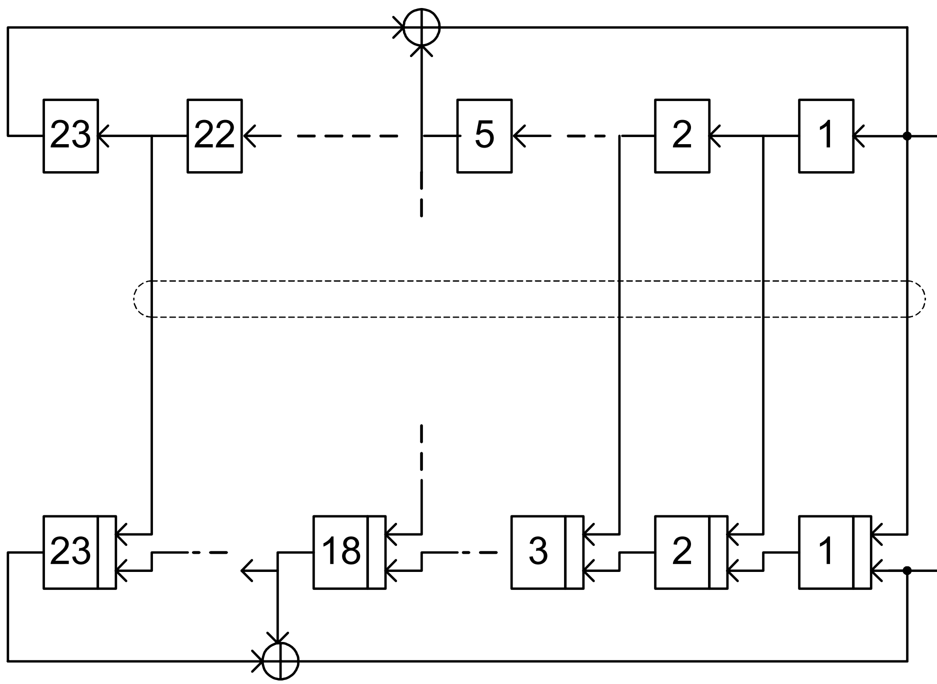
Synch bit and cipher-stream scrambling

- **Synch MLSR generates one synch bit per PHY frame and transitions to new n-bit state. The synch bit is inserted into the PHY frame.**
- **Scram MLSR is initialized with n-bit state of Synch MLSR and generates a segment of the Scram MLSR sequence for cipher-stream scrambling.**
- **By proper design, the segments of the Scram MLSR sequence start at pseudo-random locations.**



Synch MLSR and Scram MLSR generators

Synch MLSR $(1+x^5+x^{23})$



Synch bit of n - th PHY frame

$x_n = x_{n-5} \oplus x_{n-23}$

SCRAM PRNG initialization

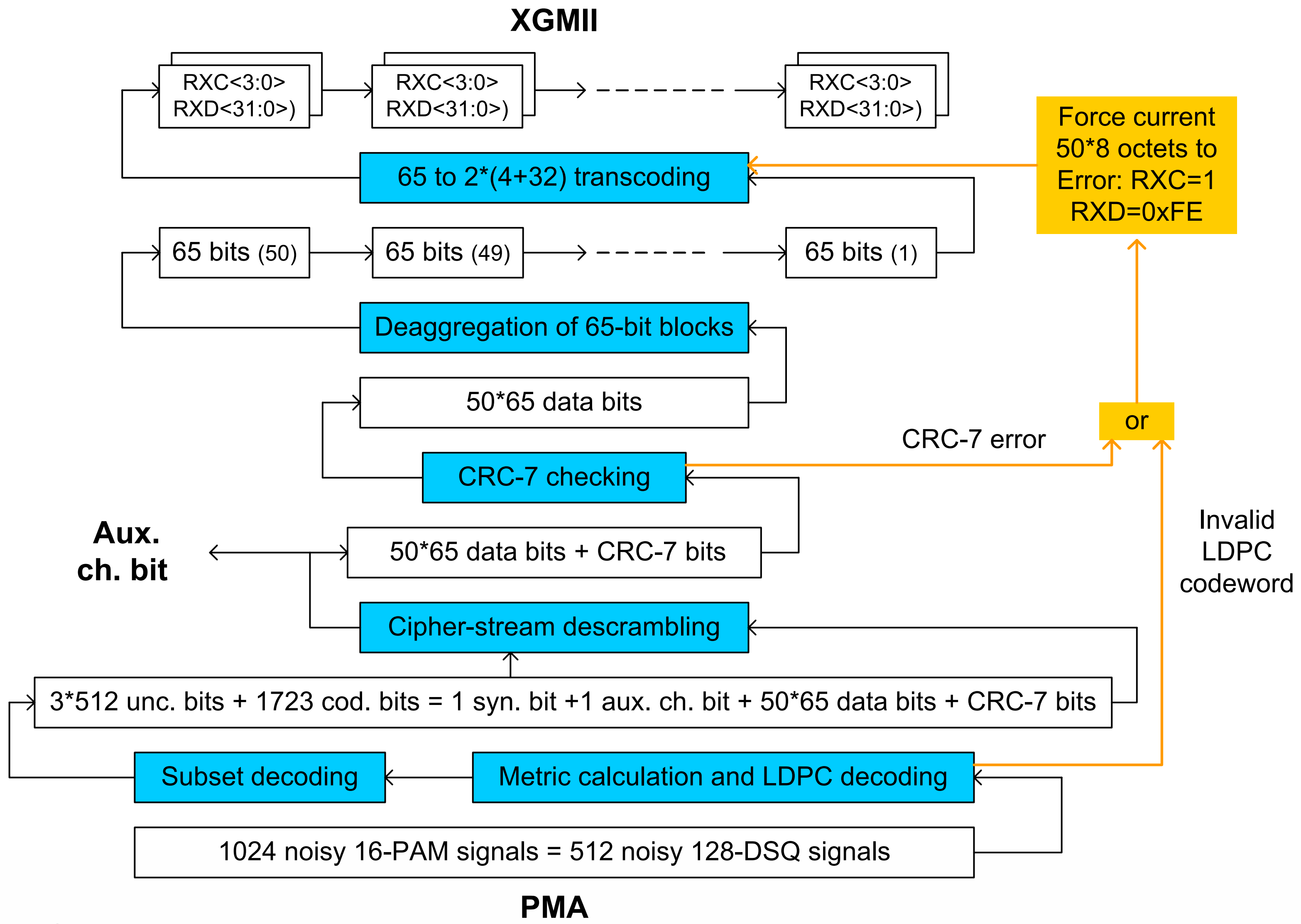
$y_n^{-23} = x_{n-22}, \ \cdots \ y_n^{-2} = x_{n-1}, \ y_n^{-1} = x_n$

Scrambling bit sequence for n - th PHY frame

$y_n^i = y_n^{i-18} \oplus y_n^{i-23}, \ \ i = 0, 1, 2 \ \cdots \ 3257$

Scram MLSR $(1+x^{18}+x^{23})$

Receiver PCS functions: cipher-stream descrambling, then CRC-7 checking



XGMII

RXC<3:0>
RXD<31:0>)

RXC<3:0>
RXD<31:0>)

RXC<3:0>
RXD<31:0>)

65 to 2*(4+32) transcoding

Force current 50*8 octets to Error: RXC=1 RXD=0xFE

65 bits (50)

65 bits (49)

65 bits (1)

Deaggregation of 65-bit blocks

50*65 data bits

or

CRC-7 error

CRC-7 checking

Aux. ch. bit

50*65 data bits + CRC-7 bits

Invalid LDPC codeword

Cipher-stream descrambling

3*512 unc. bits + 1723 cod. bits = 1 syn. bit +1 aux. ch. bit + 50*65 data bits + CRC-7 bits

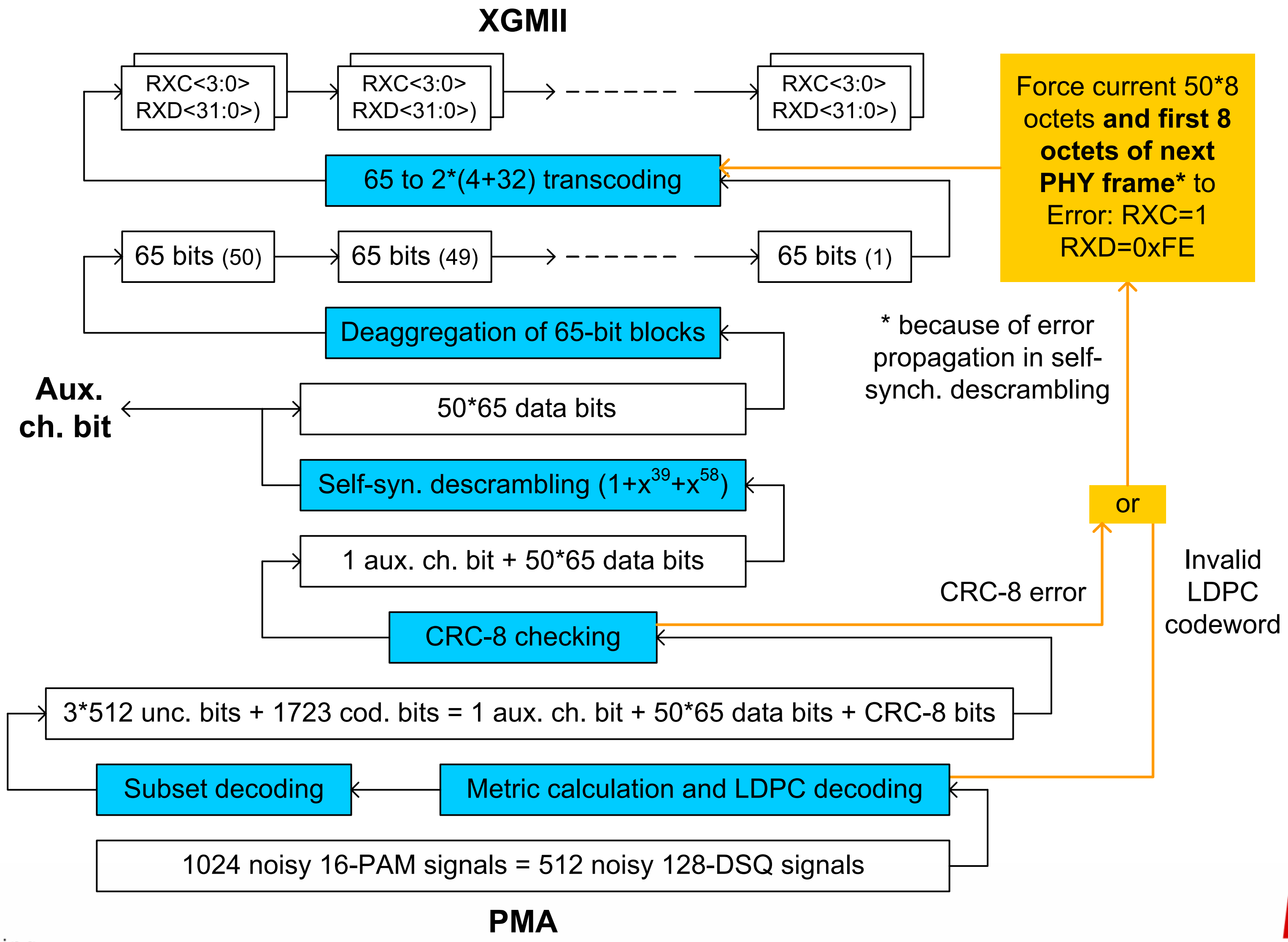
Subset decoding

Metric calculation and LDPC decoding

1024 noisy 16-PAM signals = 512 noisy 128-DSQ signals

PMA

Receiver PCS functions: CRC-8 checking, then self-synch descrambling



* because of error propagation in self-synch. descrambling

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CRC and scrambling: conclusions

Option 1: (in transmitter) **First CRC, then cipher-stream scrambling**

- ☺ When PHY frame error is detected in receiver, at XGMII all octets of current PHY frame must be replaced by ERROR octets
- ☹ Requires (?) one synch bit in PHY frame → 7 bits available for CRC.

Option 2: (in transmitter) **First self-synch scrambling, then CRC**

- ☺ No synch bit required → 8 bits available for CRC
- ☹ When PHY frame error is detected in receiver, at XGMII all octets of current PHY frame and a few octets at beginning of next PHY frame must be replaced by ERROR octets.

Differences in complexity are negligible.

(?) Cipher stream synchronization may be realized without synch bit by relying on PHY frame counting after start-up and/or signaling in auxiliary channel.

Precoding

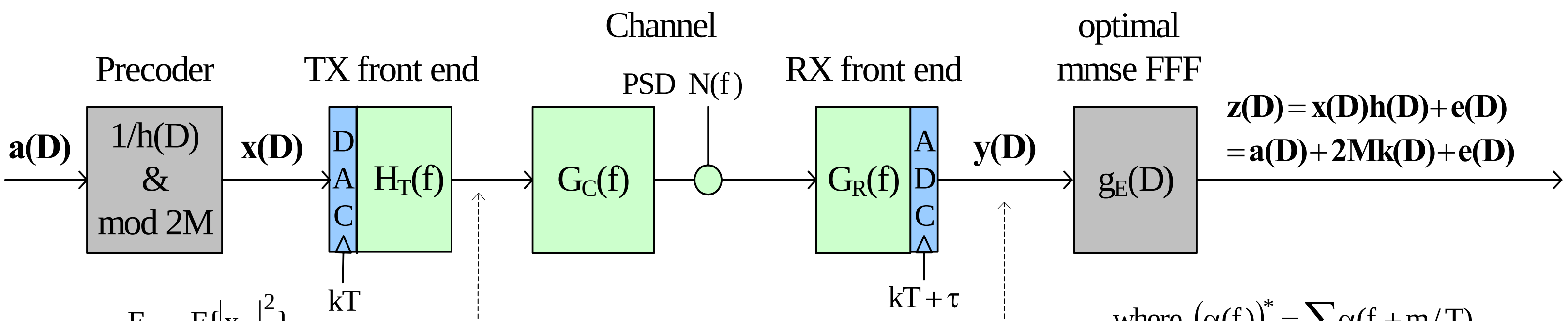
- analytic relations

- fixed transmit and receive filters

- set of IIR precoders

- SNR vs cable length for Cable Model #2

Optimum precoding response and decision-point SNR



Precoder

TX front end

Channel

RX front end

optimal mmse FFF

a(D)

1/h(D) & mod 2M

x(D)

DAC

$H_T(f)$

$G_C(f)$

PSD $N(f)$

$G_R(f)$

ADC

y(D)

$g_E(D)$

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

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

kT

$kT + \tau$

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

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

$H_T(f)G_c(f)G_R(f) = H_A(f)$

$N(f)|G_R(f)|^2 = N_A(f)$

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

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

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

Optimum precoding response h(D) for given $H_A(f)$, $N_A(f)$, and τ is obtained from

$$SNR_A^*(f) + 1 \overset{\text{spec.fac.}}{\Rightarrow} SNR_{mmse}\, \bar{h}(D^{-1})h(D)$$

h(D) causal, monic, $D = e^{-j2\pi fT}$

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

$$SNR_{mmse} = \left[T \int_{-1/2T}^{1/2T} \left|h(e^{-j2\pi fT})\right|^2 / \left(SNR_A^*(f) + 1\right) df \right]^{-1}$$

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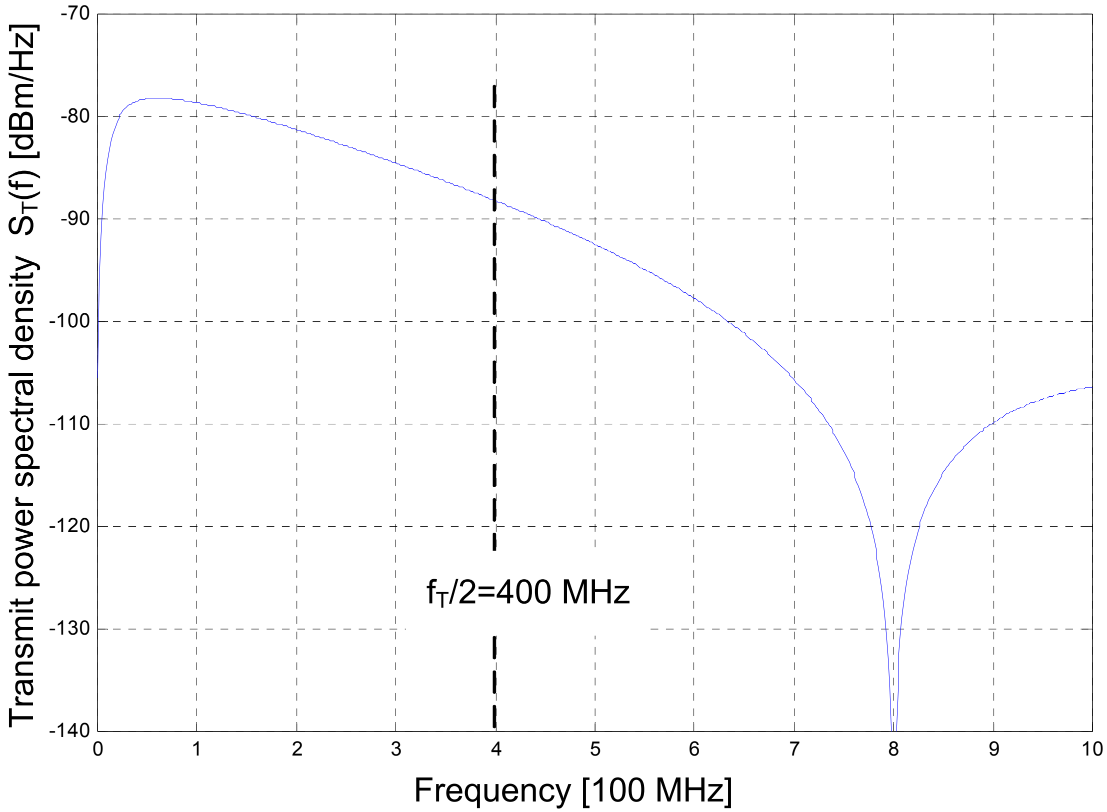
TX front-end filtering and PSD $S_T(f)$

Modulation rate f_T = 800 Mbaud, P_T = 5 dBm

$$H_T(f) \propto \frac{\sin(\pi f T)}{\pi f T} \times \frac{jf/f_0}{1+jf/f_0} \times \frac{1}{1+jf/f_1}, \quad f_0 = 20\text{ MHz}, f_1 = 200\text{ MHz}$$



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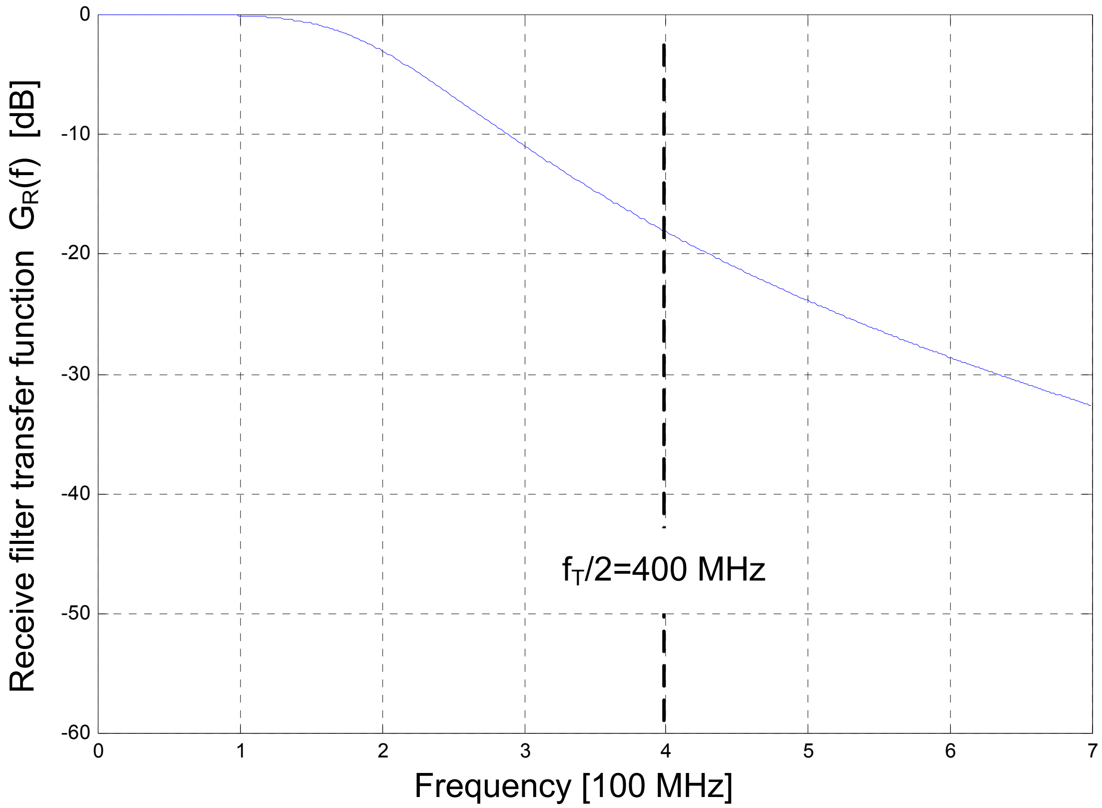
RX front-end filtering

Modulation rate f_T = 800 Mbaud, RF = 3rd order BWF

$$G_R(f) = \prod_{i=1}^{N} \frac{a_i}{a_i + jf/f_0}, \quad a_i = \exp\left(\frac{j\pi}{N}(i-(N+1)/2)\right), \quad N = 3, f_0 = 200\text{ MHz}$$



IIR precoding responses $h_{IIR}(D)$

$$h_{IIR}(D) = \frac{1-D^2}{1+q_1D+q_2D^2+q_3D^3} = 1 - \frac{q_1D+(q_2+1)D^2+q_3D^3}{1+q_1D+q_2D^2+q_3D^3}$$

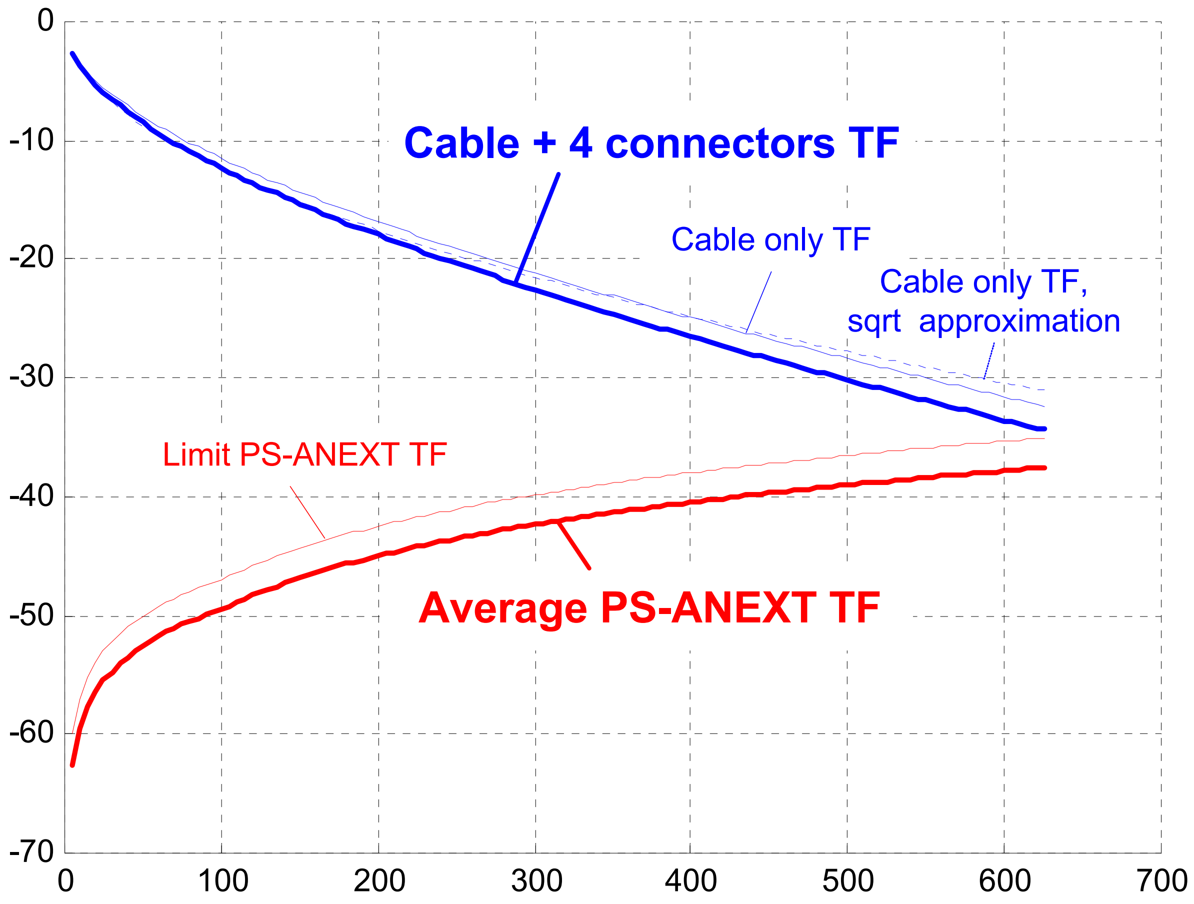
				Zeroes $\alpha_1=1, \alpha_2=-1$		
	Coeffs			Poles		
	q_1	q_2	q_3	β_1	β_2	β_3
THPF #1	$-141/64$	$104/64$	$-26/64$	0.8916	$0.6558+0.1600i$	$0.6558-0.1600i$
THPF #2	$-122/64$	$71/64$	$-12/64$	0.9309	0.6785	0.2969
THPF #3	$-98/64$	$36/64$	$0/64$	0.9195	0.6117	0
THPF #4	$-73/64$	$8/64$	$4/64$	0.9356	0.3805	-0.1755

THP filters designed for variable-length cable model #3 (Ungerboeck_1_0704, Portland)

#1: 100 m, #2: 70 m, #3: 40 m, #4: 10 m

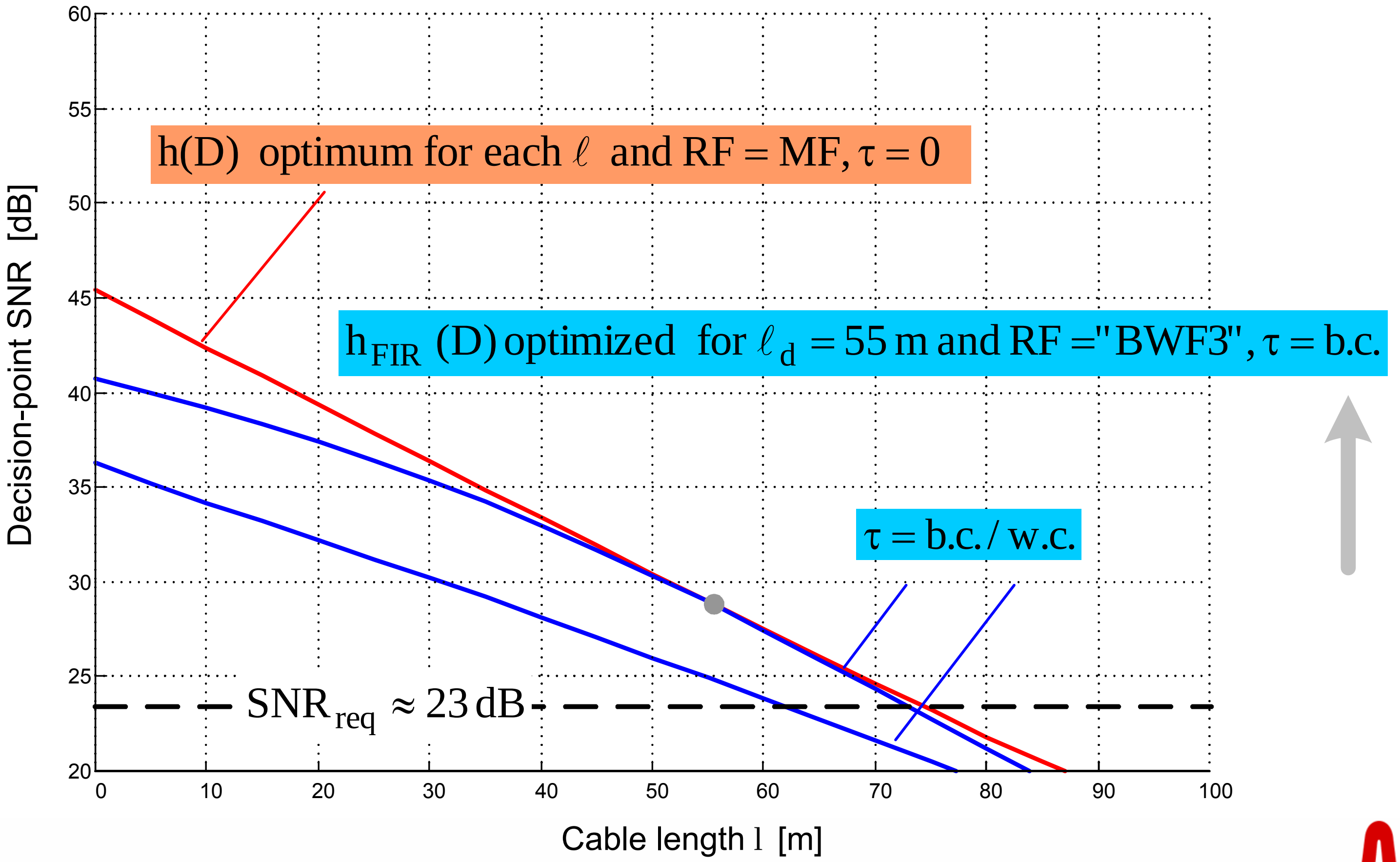
Decision-point SNR vs cable length shown for variable-length Cable Model #3 in ungerboeck_1_1104 (San Antonio). In the sequel we consider Cable Model #2.

Cable and PS-ANEXT transfer functions: Cable Model #2



SNR vs. cable length

Variable-length Cable Model #2; f_T = 800 Mbaud; TF = "Sinx/xf0f1"; P_T = 5 dBm; AWGN=-140 dBm/Hz; ANEXT (P_T=5dB,ℓ= 55m)



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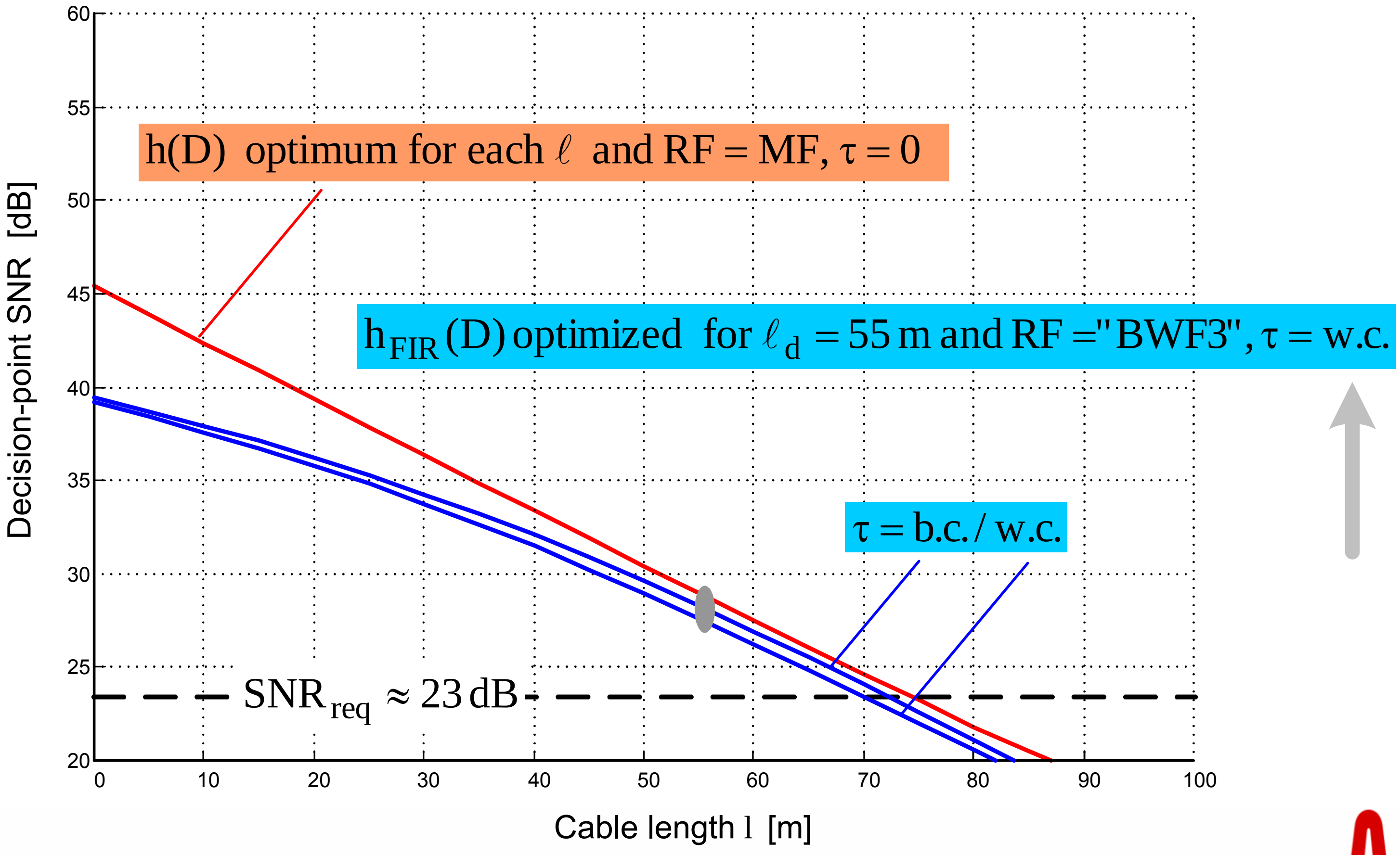

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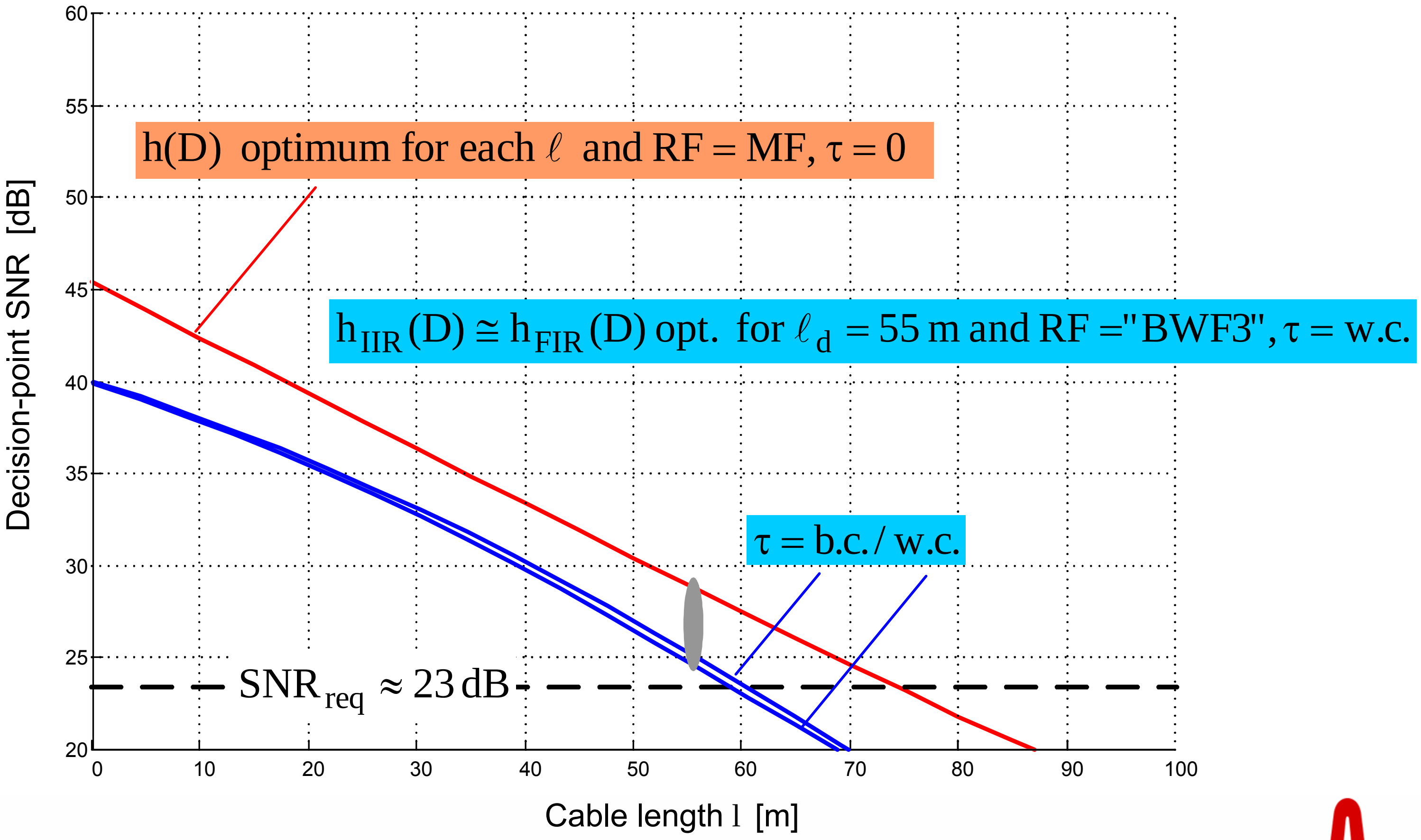
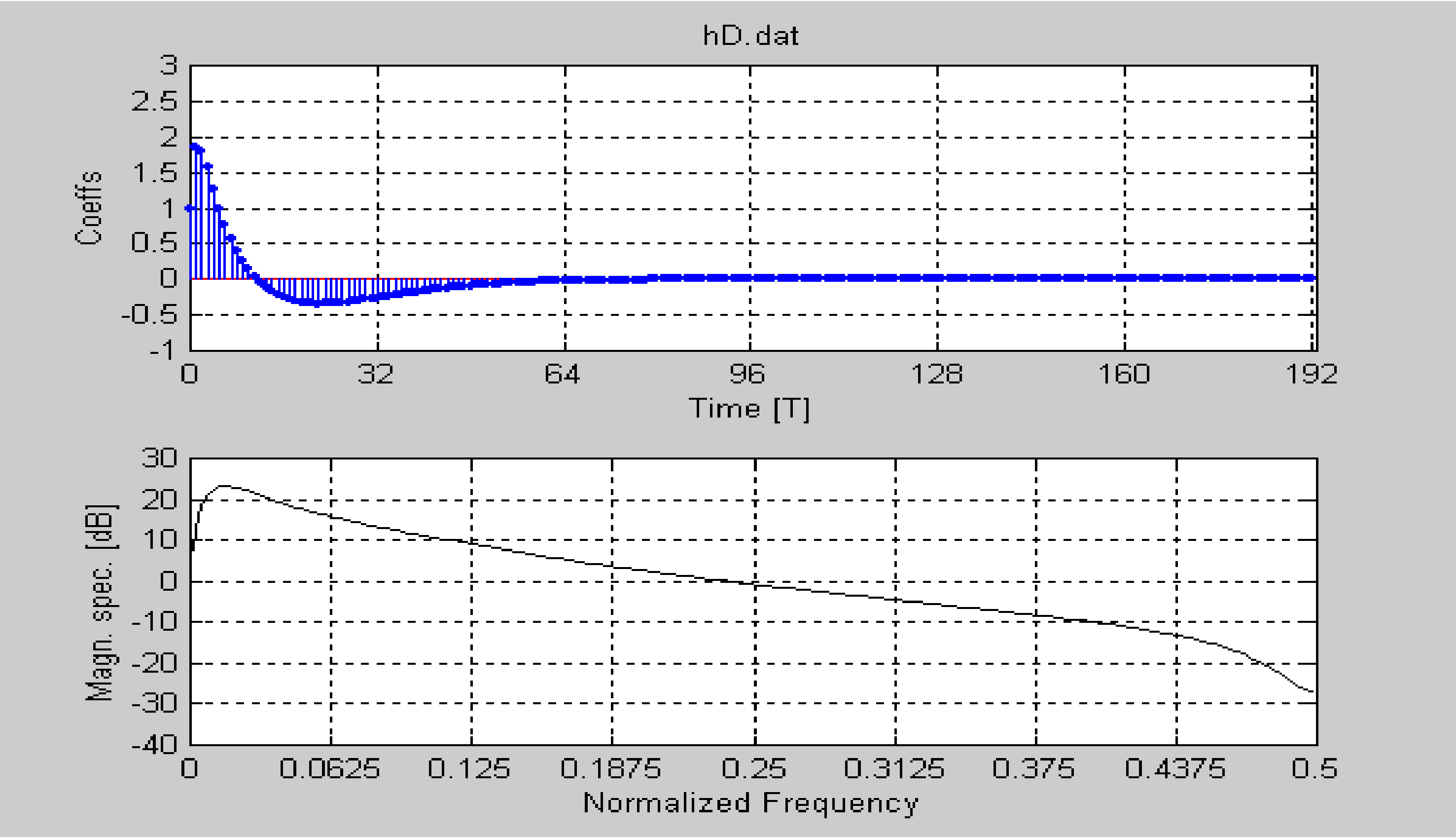


Fixed $h_{FIR}(D)$

Variable-length Cable Model #2; f_T = 800 Mbaud; TF = “sinx/xf0f1”;
P_T = 5 dBm; AWGN=-140 dBm/Hz; ANEXT (P_T=5dB,ℓ= 55m)

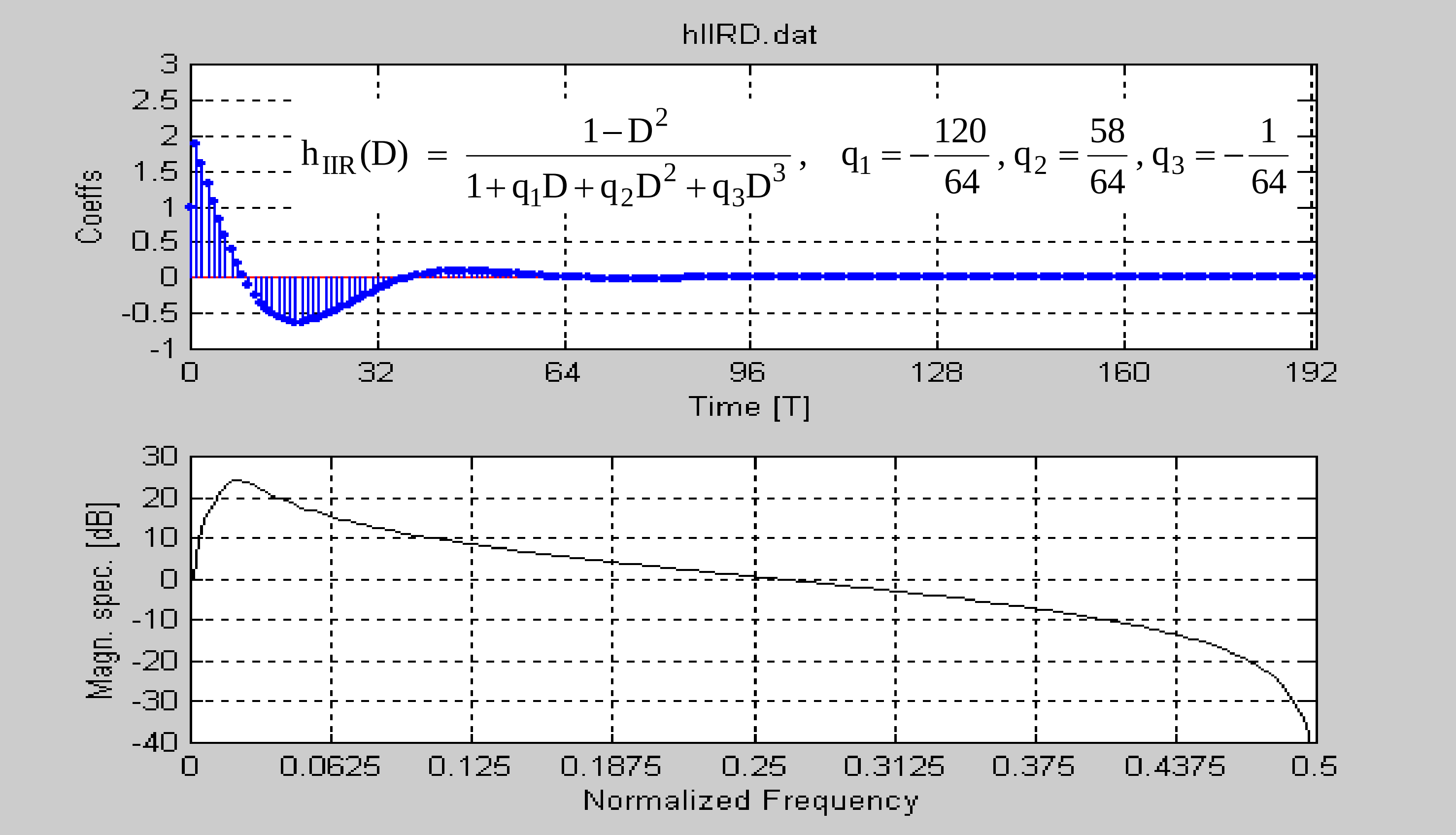
$h_{FIR}(D)$ optimized for $\ell_d = 55$ m and RF = "BWF3", τ = w.c.



Fixed $h_{IIR}(D)$

Variable-length Cable Model #2; f_T = 800 Mbaud; TF = "sinx/xf0f1"; P_T = 5 dBm; AWGN=-140 dBm/Hz; ANEXT (P_T=5dB,ℓ= 55m)

$$h_{IIR}(D) \cong h_{FIR}(D) \text{ optimized for } \ell_d = 55\,\text{m and RF} = \text{"BWF3"}, \tau = \text{w.c.}$$



$$h_{IIR}(D) = \frac{1-D^2}{1+q_1 D + q_2 D^2 + q_3 D^3}, \quad q_1 = -\frac{120}{64}, q_2 = \frac{58}{64}, q_3 = -\frac{1}{64}$$

Precoding: conclusions

- There exists sufficient evidence that a small number (3 - ?) of fixed precoding responses suffices to achieve near optimum performance for all cable types and lengths relevant for 10GBASE-T.
- Precoding responses should have spectral nulls at f = 0 and f = 1/2T.
- Approximation of known good FIR responses by IIR responses with low degrees of the numerator and denominator polynomials requires further study.

Backup slides

Variable-length 10GBASE-T cable models (ungerboeck_1_0704.pdf)

Complex-valued cable-transfer function

skin effect

$$G_C(f_{[Hz]},\ell_{[m]}) = e^{-\ell\gamma(f)} \times 10^{-4\times0.02\times\sqrt{f/10^6}\,/20}\;; \quad \gamma(f) = \sqrt{\frac{R_s\sqrt{jf/f_s} + j2\pi fL}{R_d + 1/j2\pi fC}}$$

propagation constant

4 connectors

dielectric loss

$$f_s = 200\text{MHz};\ L = 0.5\text{mH/m}, C = 50\text{pF/m}:\ Z_0 \cong \sqrt{L/C} = 100\Omega,\ v = 1/\sqrt{LC} = 200\times10^6\text{m/s}$$

Expected alien-NEXT squared magnitude function

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

NEXT attenuation

dependence on length

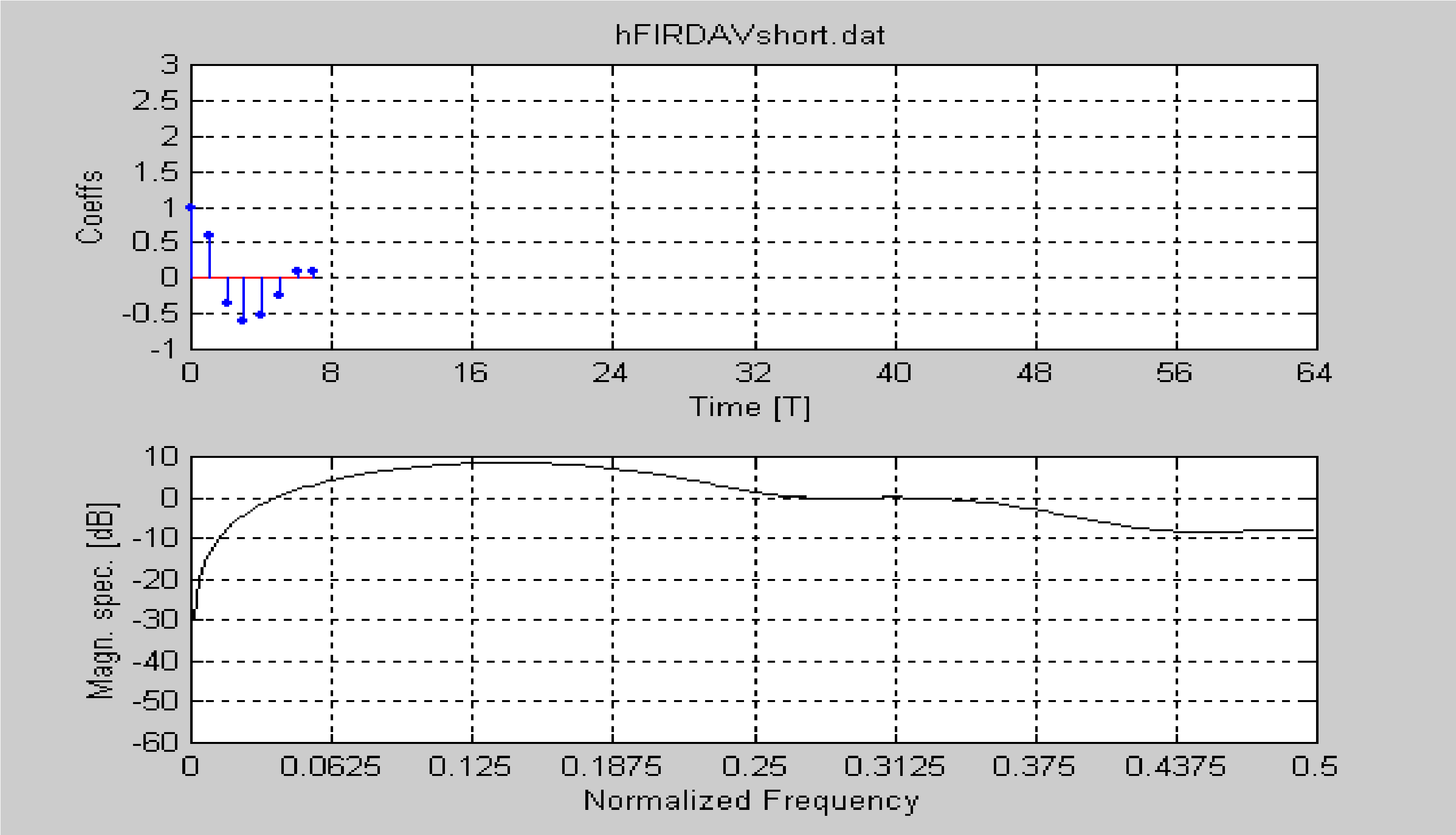
Model #1 (Cat 7, shielded) , 100 m → cabtyp **“ClassF”** : R_s=9.48 Ω/m, R_d=1.7 mΩ/m, X1=60 dB

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

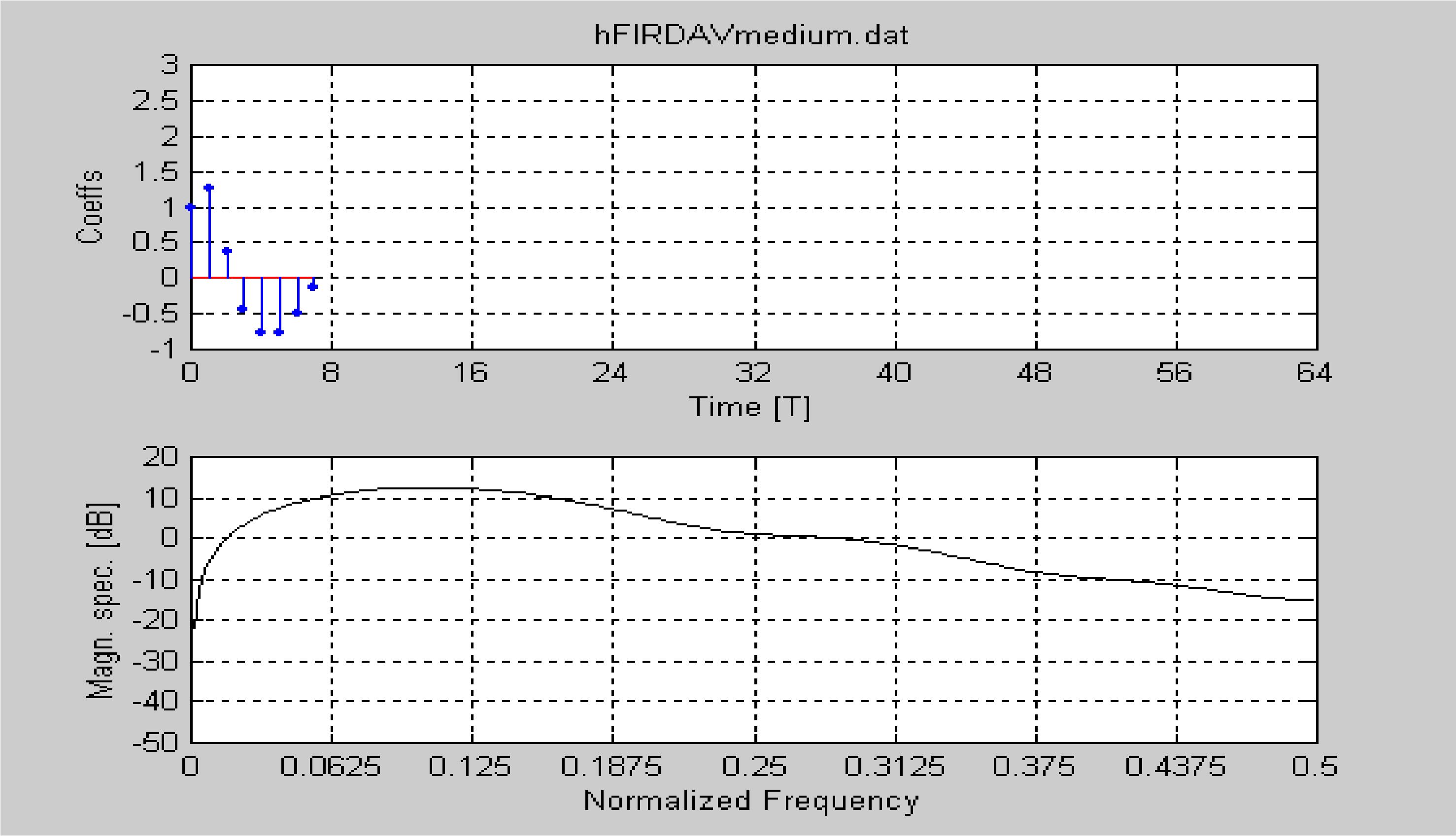
Model #3 (Cat 6, shielded) , 100 m → cabtyp **“ClassEs”** : R_s=9.85 Ω/m, R_d=3.5 mΩ/m, X1=62 dB

Typo corrected (was $S\times\log_{10}\sqrt{f/10^8}$)

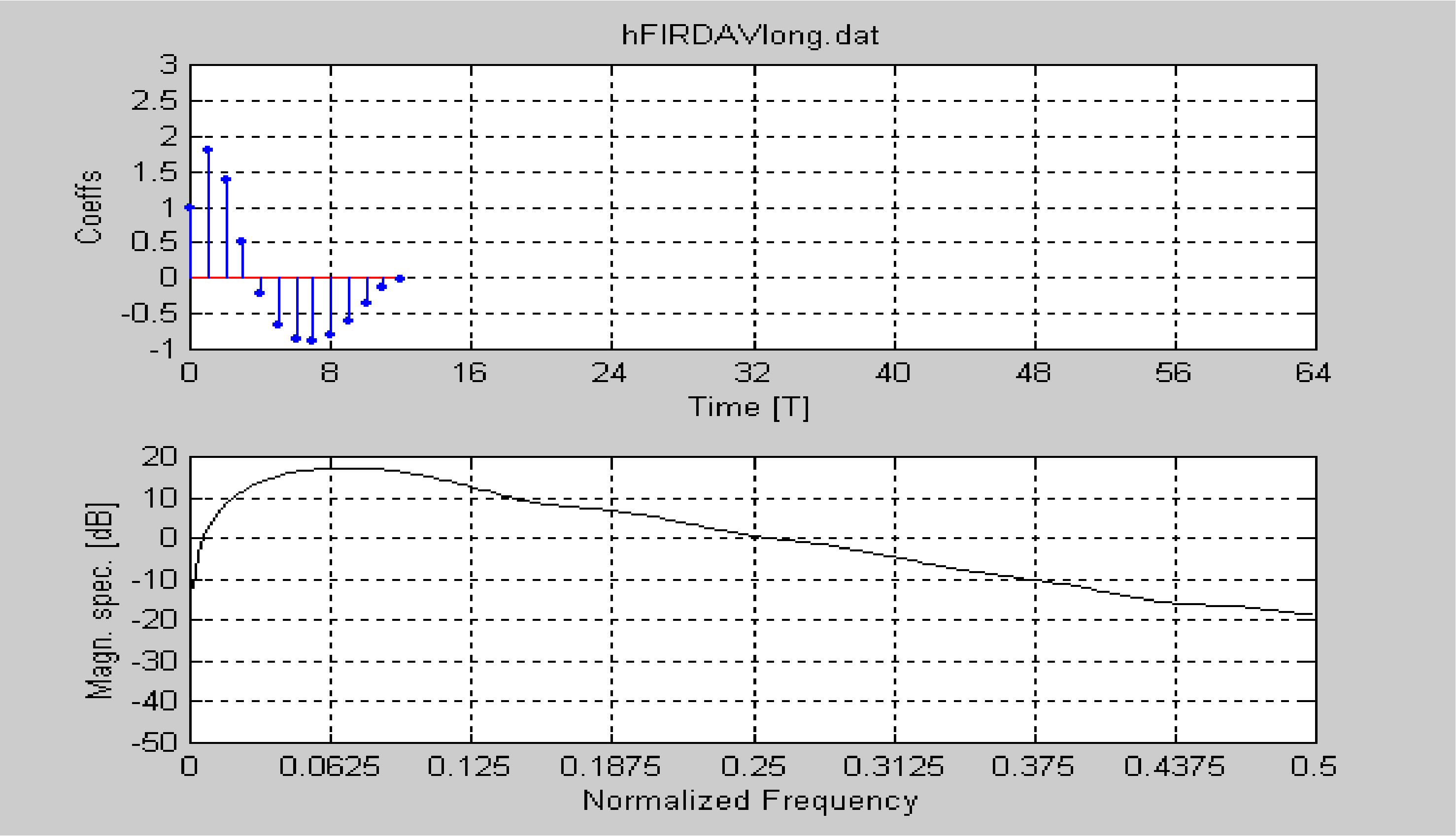
Fixed $h_{FIR}(D)$: Albert Vareljian's "SHORT" (<45 m)



Fixed h_{FIR}(D): Albert Vareljian's "MEDIUM" (45 – 80 m)



Fixed h_{FIR}(D): Albert Vareljian's "LONG" (80 – 100 m)



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