TECHNICAL UNIVERSITY OF CATALONIA
DEPARTMENT OF SIGNAL THEORY AND COMMUNICATIONS

COHERENT & NON-COHERENT COMMUNICATIONS IN THE WIDEBAND-REGIME

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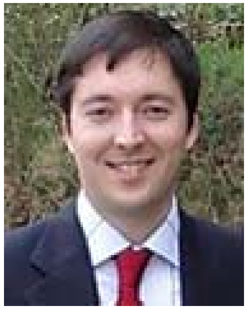

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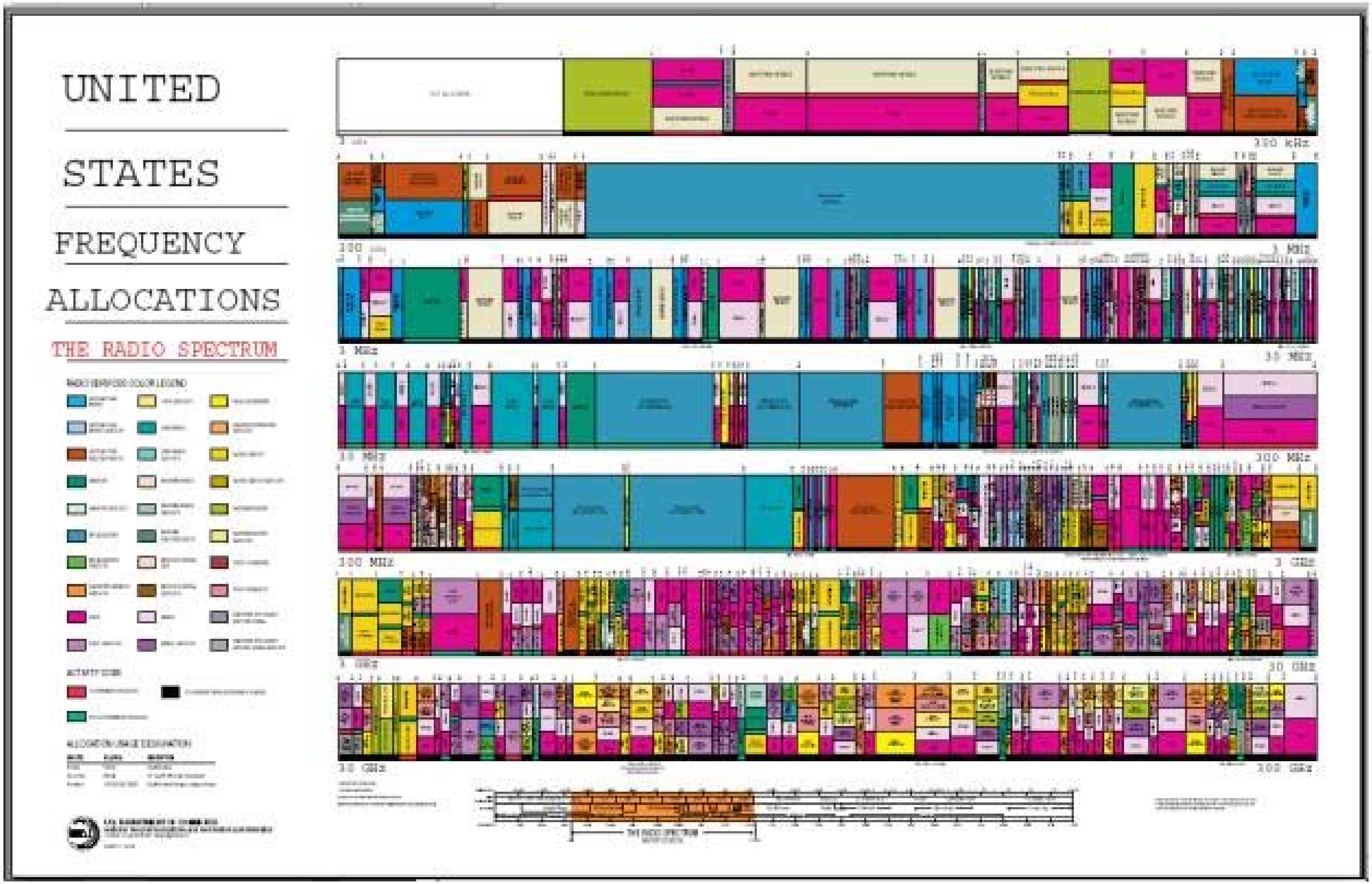
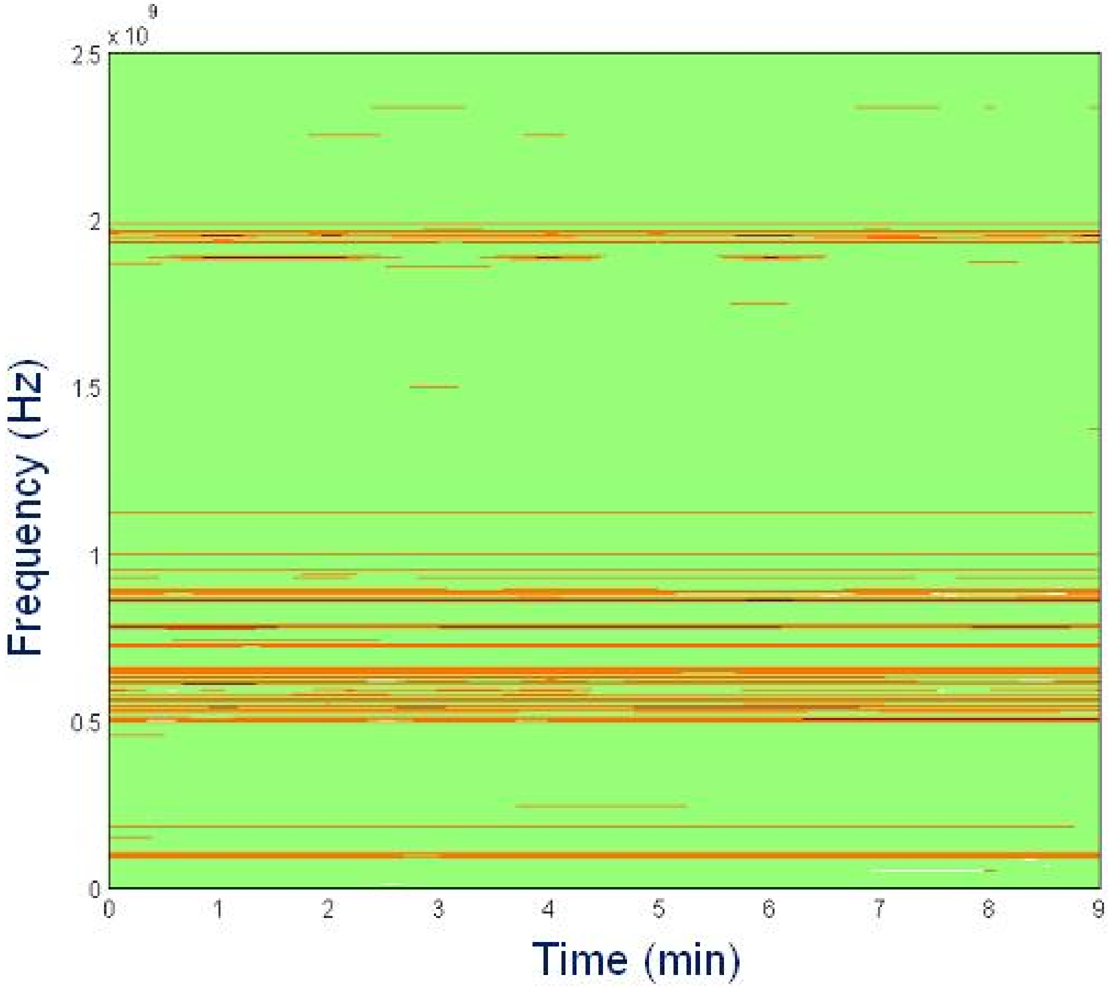
OUTLINES

- INTRODUCTION: UWB CONCEPT.
- THE WIDEBAND AND THE LOW-SNR REGIMES.
- GENERAL SIGNAL MODEL
- SPECTRAL-EFFICIENCY
- NON-COHERENT DETECTION
- FRAME-SYNCHRONIZATION/WAVEFORM ESTIMATION



about the scarcity of spectrum

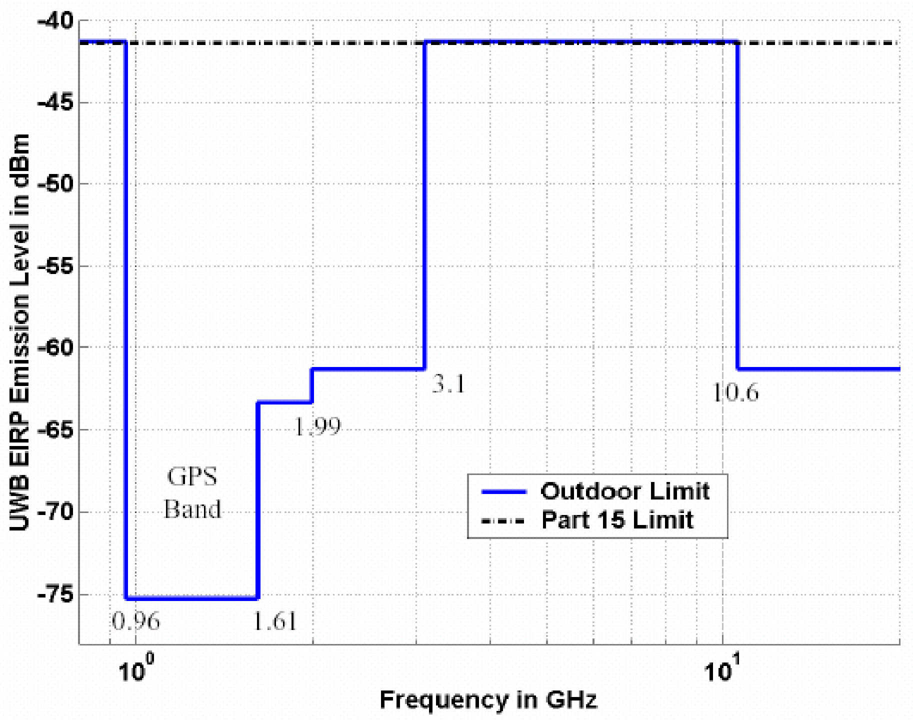
http://bwrc.eecs.berkeley.edu/Research/Cognitive/images/usage.JPG

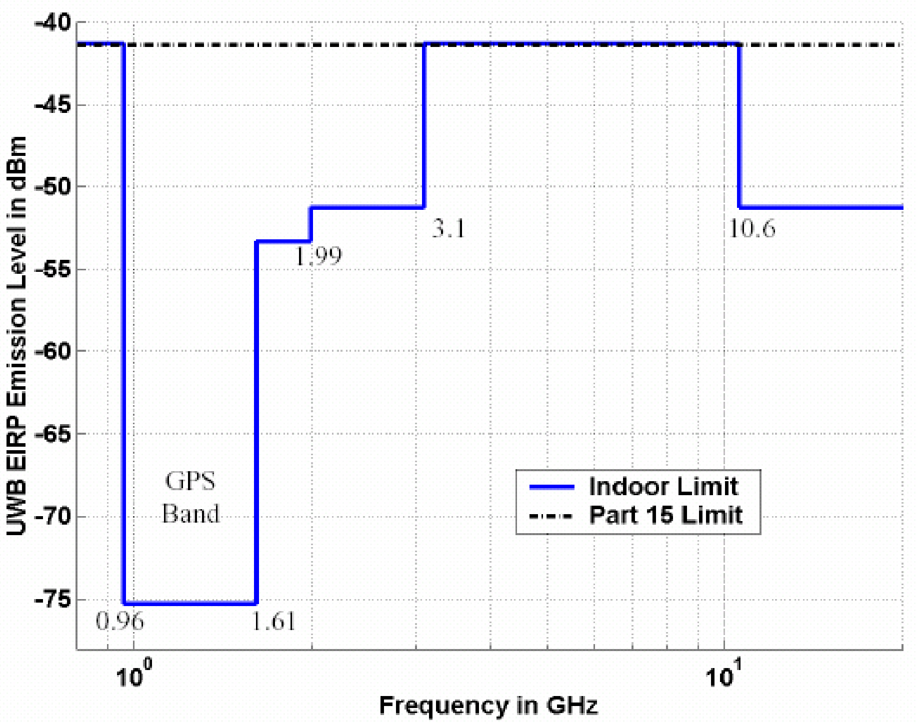


10 sec. test

UWB EIRP (per MHz) SPECTRAL MASKS (FCC)

$$W_{frac} = 2\frac{f_H - f_L}{f_H + f_L} > 0.25 \quad [DARPA/1990]$$





6 up to 8.5 for EU (-10 up to -20 dB)

STANDARDIZATION

- **IEEE 802.15.3a**

  Study group for wireless high data-rates (WPAN)

  - **100 Mbps (range 10 meters)**
  - **480 Mbps (range 2 meters)**

- **IEEE 802.15.4**

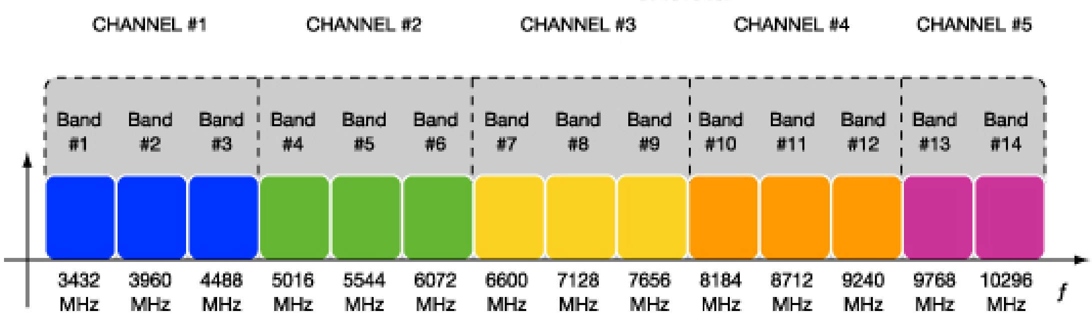
  Study group for low-complexity/low-data rates applications

- **DS-UWB**

  Pure impulsive-radio on traditional CDMA multiple-access

- **MB-OFDM**

  Multiband (>500 MHz) OFDM

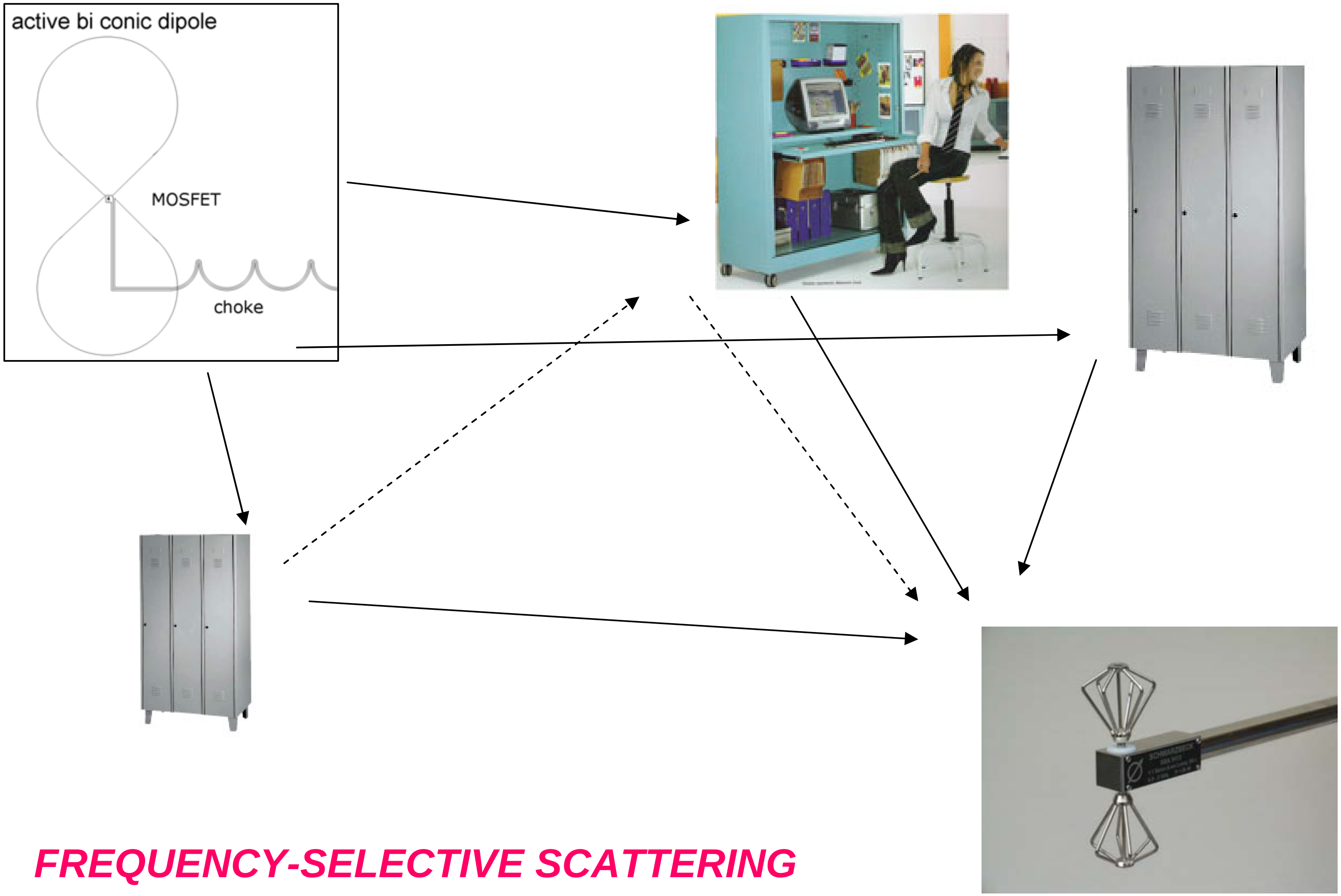


KEY FEATURES

- **HIGH DATA-RATES FOR SHORT-/MEDIUM-RANGE.**
- **LOW-COMPLEXITY/LOW-COST EQUIPMENTS.**
- **LOW PSD TRANSMISSION and NOISE-LIKE SPECTRUM.**
- **MULTIPATH and INTERFERENCE IMMUNITY:**
  - Use of spectral diversity.
  - High multipath resolution.
- **“HIGH PENETRATION” CAPABILITIES (LOW BANDS).**
- **ADEQUATE FOR “COGNITIVE-RADIO”.**
- **PULSE DISTORTION (TRANSMISSION AND PROPAGATION).**

(UNKNOWN) PULSE DISTORTION

DIRECTION-DEPENDENT ANTENNA RESPONSE



FREQUENCY-SELECTIVE SCATTERING

(UNKNOWN) PULSE DISTORTION (II)

- **PULSE DISTORTION DUE TO:**
  - ASYMMETRICAL (DIRECTIONAL) GEOMETRY OF THE TX/RX ANTENNAE.
  - HIGHLY FREQUENCY-SELECTIVE SCATTERING.

- **CONTROVERSIAL ON THE STATIONARITY:**
  - STATIONARY ENVIRONTMENT >> ESTIMATION OF THE WAVEFORMS.
  - WAVEFORM IS ALWAYS UNKNOWN.

- **CONTROVERSIAL ON THE CHANNEL MODEL:**
  - RICHNESS (HIGHLY-DENSE) OF THE MULTIPATH PROPAGATION.
  - DOMINANT "*LOS*" DIRECTION.

- **CONTROVESIAL ON THE ADOPTED SCHEMES:**
  - PILOT-BASED (TRAINING) SCHEMES >> COHERENT COMMUNICATIONS.
  - *NDA*-BASED SCHEMES >> NON-COHERENT COMMUNICATIONS.

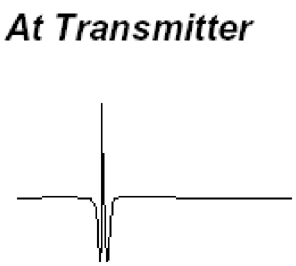
SIGNALING FORMATS

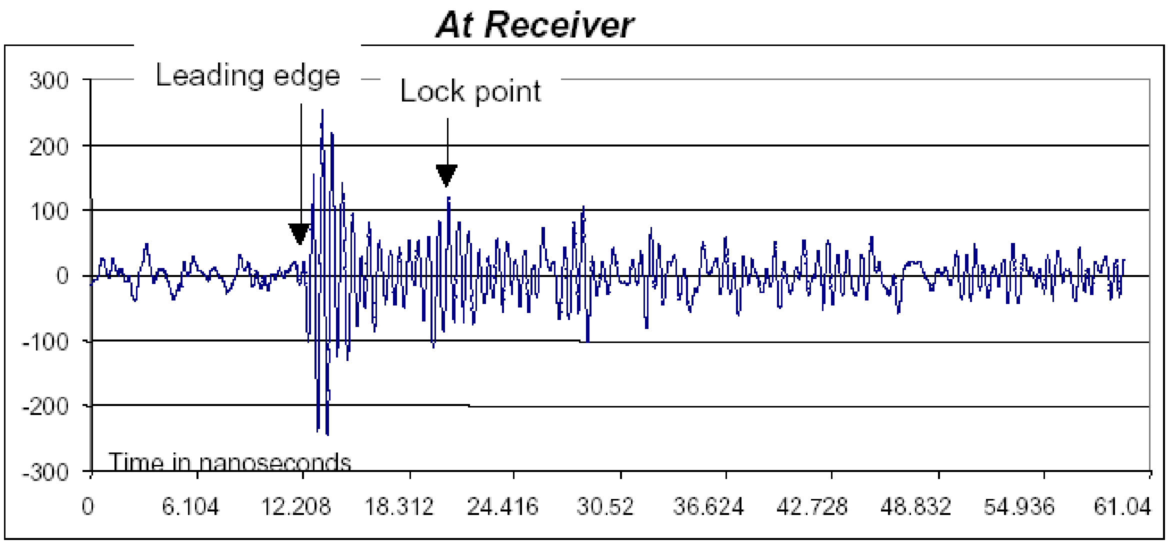
- **PULSE-AMPLITUDE MODULATION (*PAM*)**
  - NEED OF THE CHANNEL-STATE INFORMATION (*CSI*).
- **PULSE-POSITION MODULATION (*PPM*)**
  - ROBUST TO PARTIAL *CSI*.
  - STILL CAPABLE TO OPERATE WITHOUT *CSI*.
  - DETECTION GAIN BECAUSE ORTHOGONAL SIGNALLING.
  - EASY IMPLEMENTATION.
- **PULSE-POSITION AND AMPLITUDE MODULATION (*APPM*)**
- **MULTICARRIER/MULTIBAND TRANSMISSION**
  - FROM WIDEBAND TO NARROWER BAND MULTIPLE SCHEMES.
  - HIGHER COMPLEXITY.
  - ‘PEAK-TO-AVERAGE’ SIGNAL IMPAREMENTS.

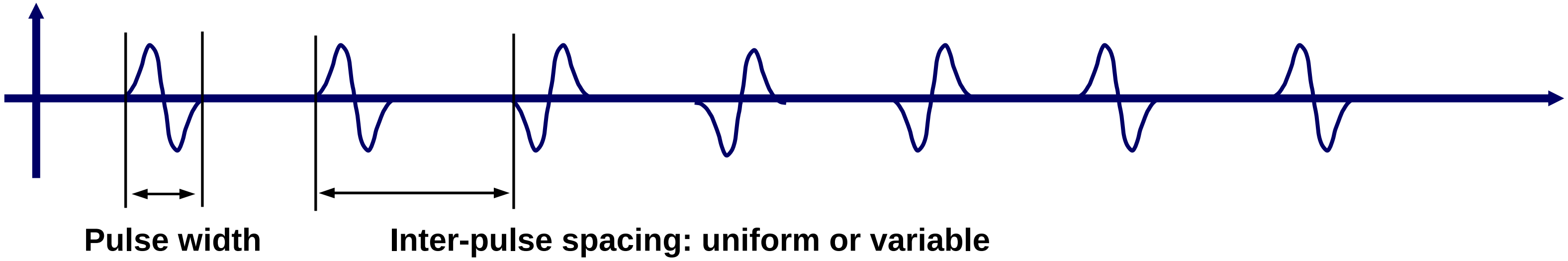
Channel model	LOS/NLOS	Distance TX/RX (meters)
CM1	LOS	0-4
CM2	NLOS	0-4
CM3	NLOS	4-10
CM4	NLOS	Very high multipath

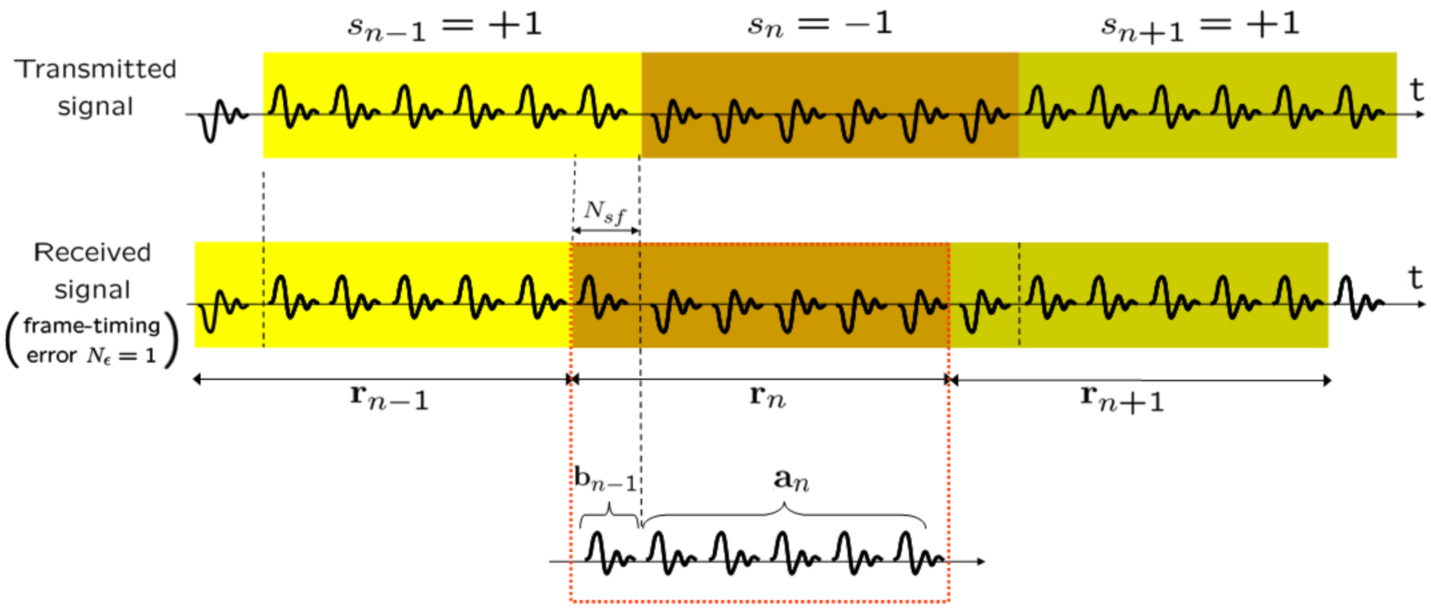
IEEE 802.15.3a

IEEE 802.15.4: Residential (LOS/NLOS), Office (LOS/NLOS), Outdoor (LOS/NLOS), Industrial (LOS/NLOS), "Body-Area-Networks" (NLOS-body diffraction).


At Transmitter

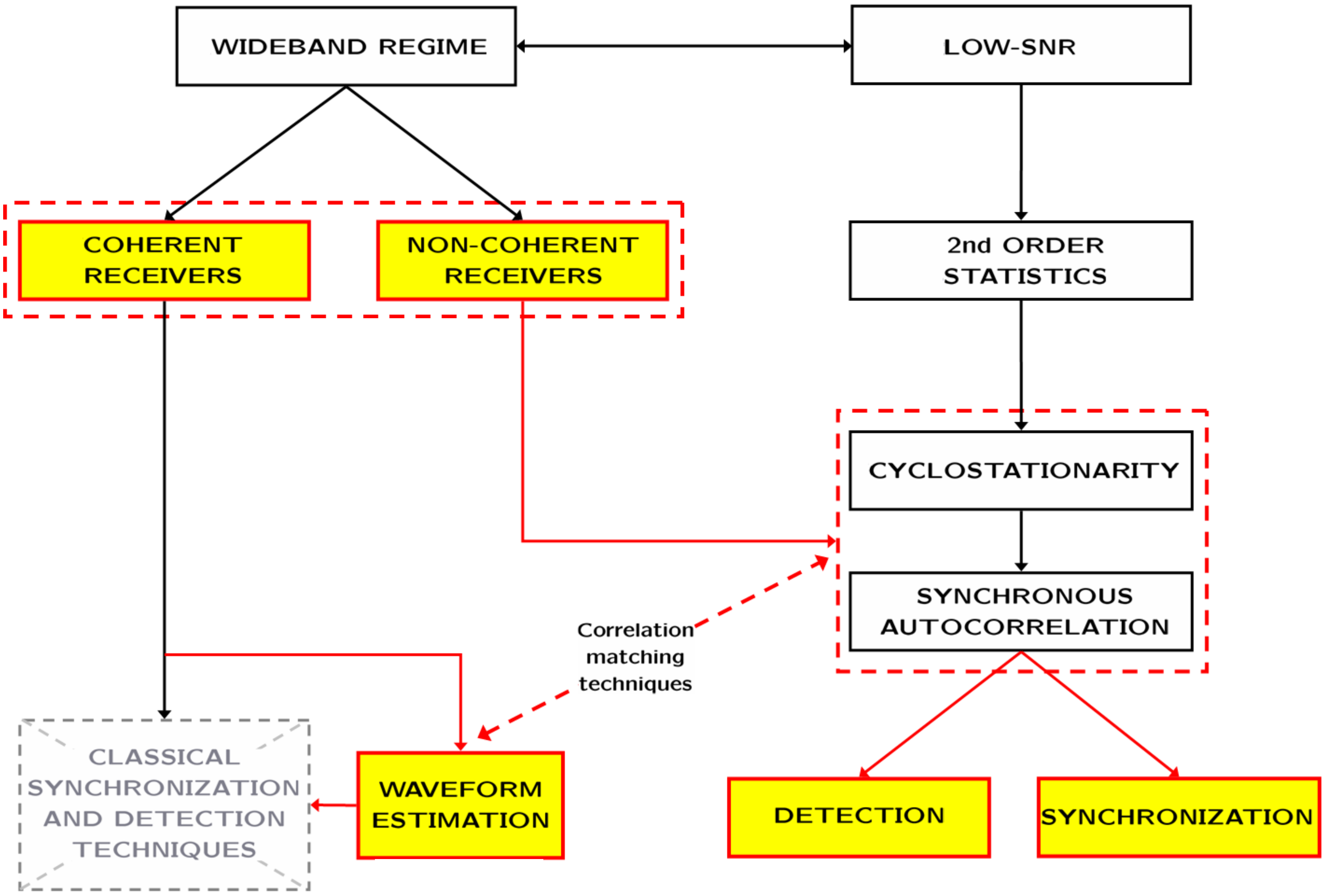

At Receiver
Leading edge
Lock point
300
200
100
0
-100
-200
-300
Time in nanoseconds
0
6.104
12.208
18.312
24.416
30.52
36.624
42.728
48.832
54.936
61.04


Pulse width
Inter-pulse spacing: uniform or variable



$s_{n-1} = +1$
$s_n = -1$
$s_{n+1} = +1$
Transmitted signal
t
N_{sf}
Received signal
(frame-timing error $N_\epsilon = 1$)
t
$\mathbf{r}_{n-1}$
$\mathbf{r}_n$
$\mathbf{r}_{n+1}$
$\mathbf{b}_{n-1}$
$\mathbf{a}_n$

GENERAL WORKING SCHEME



$$\mathbf{r} = \mathbf{H}(\underline{\boldsymbol{\theta}})\mathbf{x} + \mathbf{w}$$

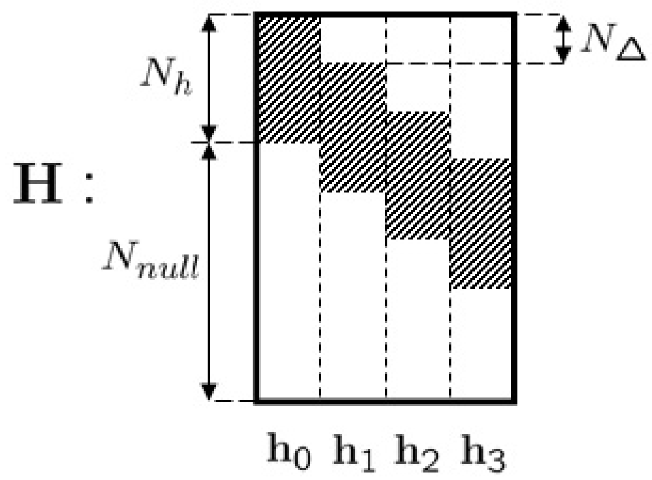
!

$$\mathbf{H}(\underline{\boldsymbol{\theta}}) = \left[\mathbf{H}_0(\underline{\boldsymbol{\theta}})\ \mathbf{H}_1(\underline{\boldsymbol{\theta}}) \ldots \mathbf{H}_{J-1}(\underline{\boldsymbol{\theta}})\right]$$

SHAPING MATRIX

$$\mathbf{x} = \left[\mathbf{x}_0^T\ \mathbf{x}_1^T \ldots \mathbf{x}_{J-1}^T\right]^T$$

NUISANCE PARAMETERS



- **STATISTIC' (LIKELIHOOD-FUNCTION):**

$$\Lambda(\mathbf{r}/\underline{\boldsymbol{\theta}}) = C\exp\left(-\frac{1}{\sigma^2}q(\mathbf{r}/\underline{\boldsymbol{\theta}})\right)$$

$$q(\mathbf{r}/\underline{\boldsymbol{\theta}}) = \left\|\mathbf{r} - \mathbf{H}(\underline{\boldsymbol{\theta}})\mathbf{x}\right\|^2$$

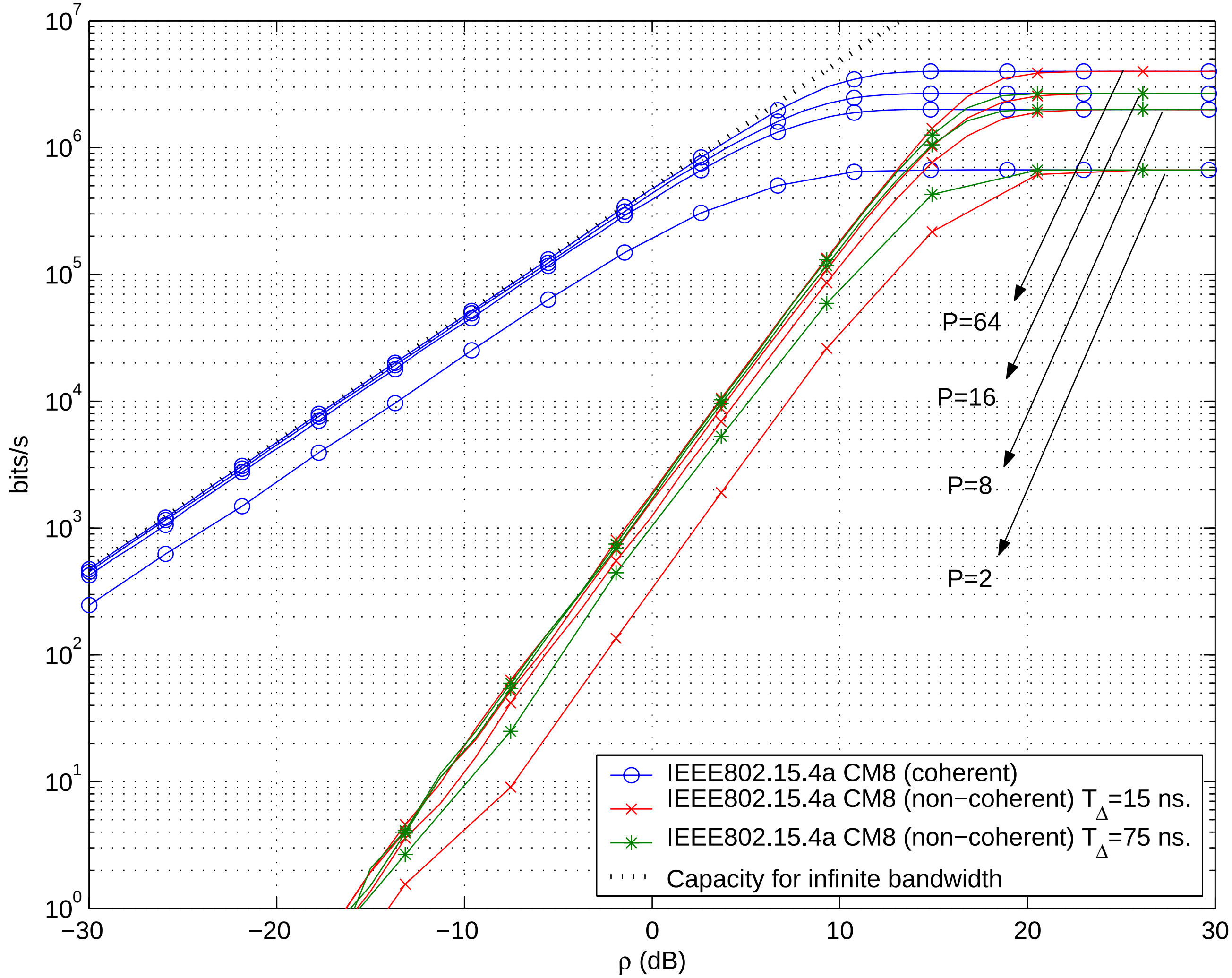
↓

UML: $$\Lambda(\mathbf{r}/\underline{\boldsymbol{\theta}}) = E_{\mathbf{x}}\left[\Lambda(\mathbf{r}/\mathbf{x},\underline{\boldsymbol{\theta}})\right]$$ **?**

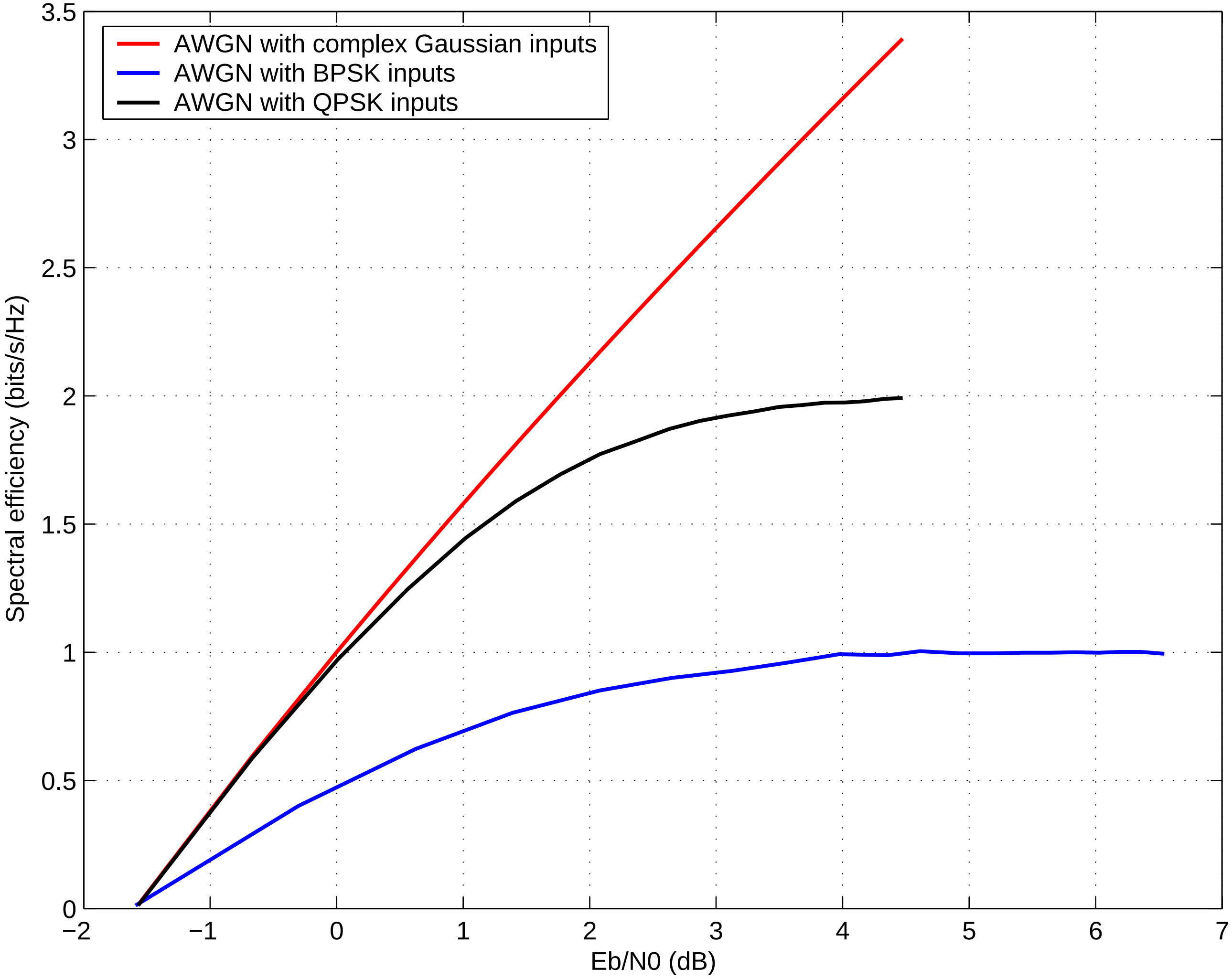
$$\Lambda(\mathbf{r}/\mathbf{x},\underline{\boldsymbol{\theta}}) \approx 1 - \frac{1}{\sigma^2}q(\mathbf{r}/\mathbf{x},\underline{\boldsymbol{\theta}}) + \frac{1}{2\sigma^4}q^2(\mathbf{r}/\mathbf{x},\underline{\boldsymbol{\theta}})$$

SPECTRAL EFFICIENCY

ACHIEVABLE DATA-RATES (W = 1 GHz)



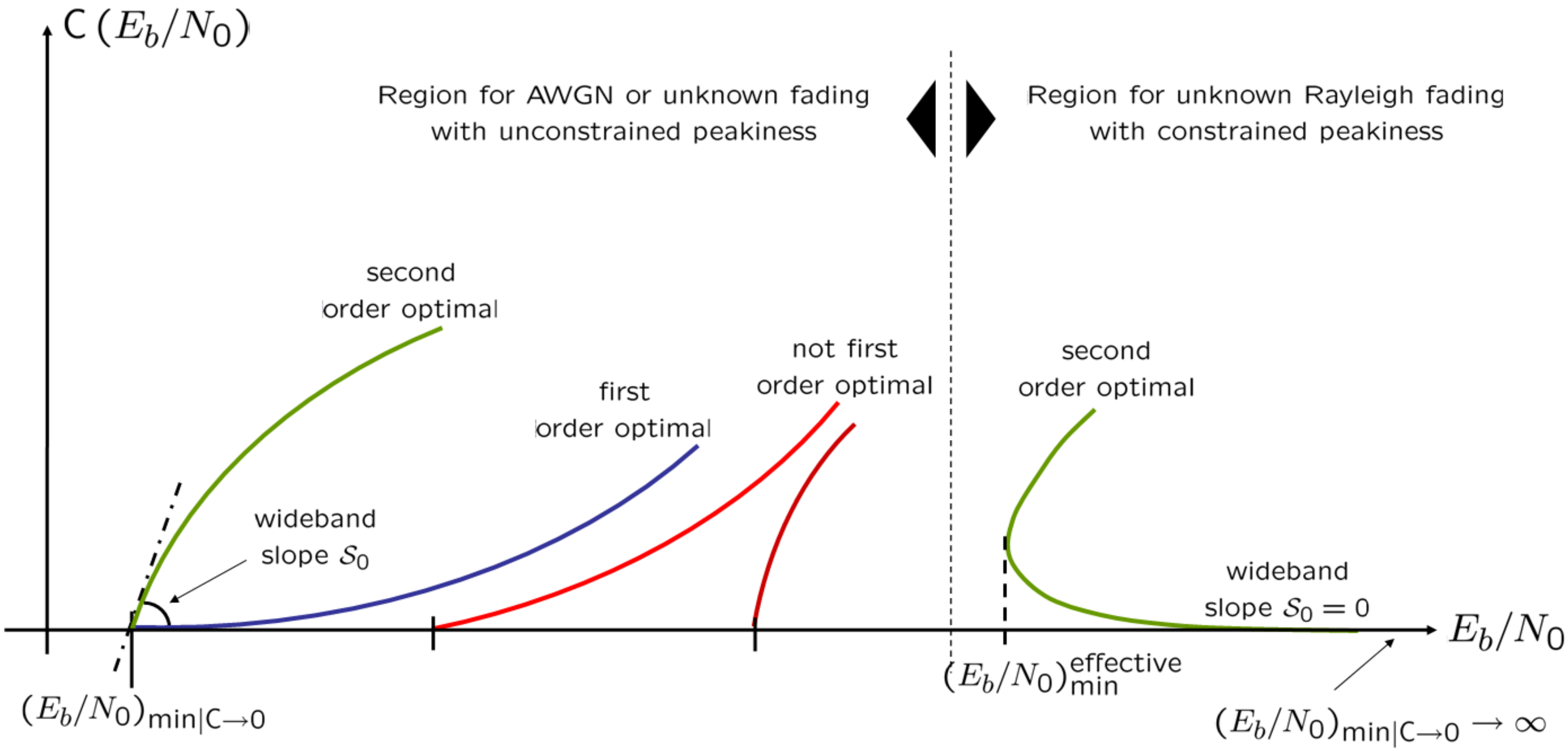
- **SNR vs Eb/No (Spectral Efficiency)**



$$\frac{E_b}{N_o} = \frac{W}{R} SNR$$

$$\left(\frac{E_b}{N_o}\right)_{\min} = \left(\frac{E_b}{N_0}\right)_{R=C_\infty} = \lim_{SNR \to 0} \frac{SNR}{C(SNR)}$$

$$C(SNR) = C'(0) SNR + \frac{1}{2} C''(0) SNR^2 + o(SNR^2)$$



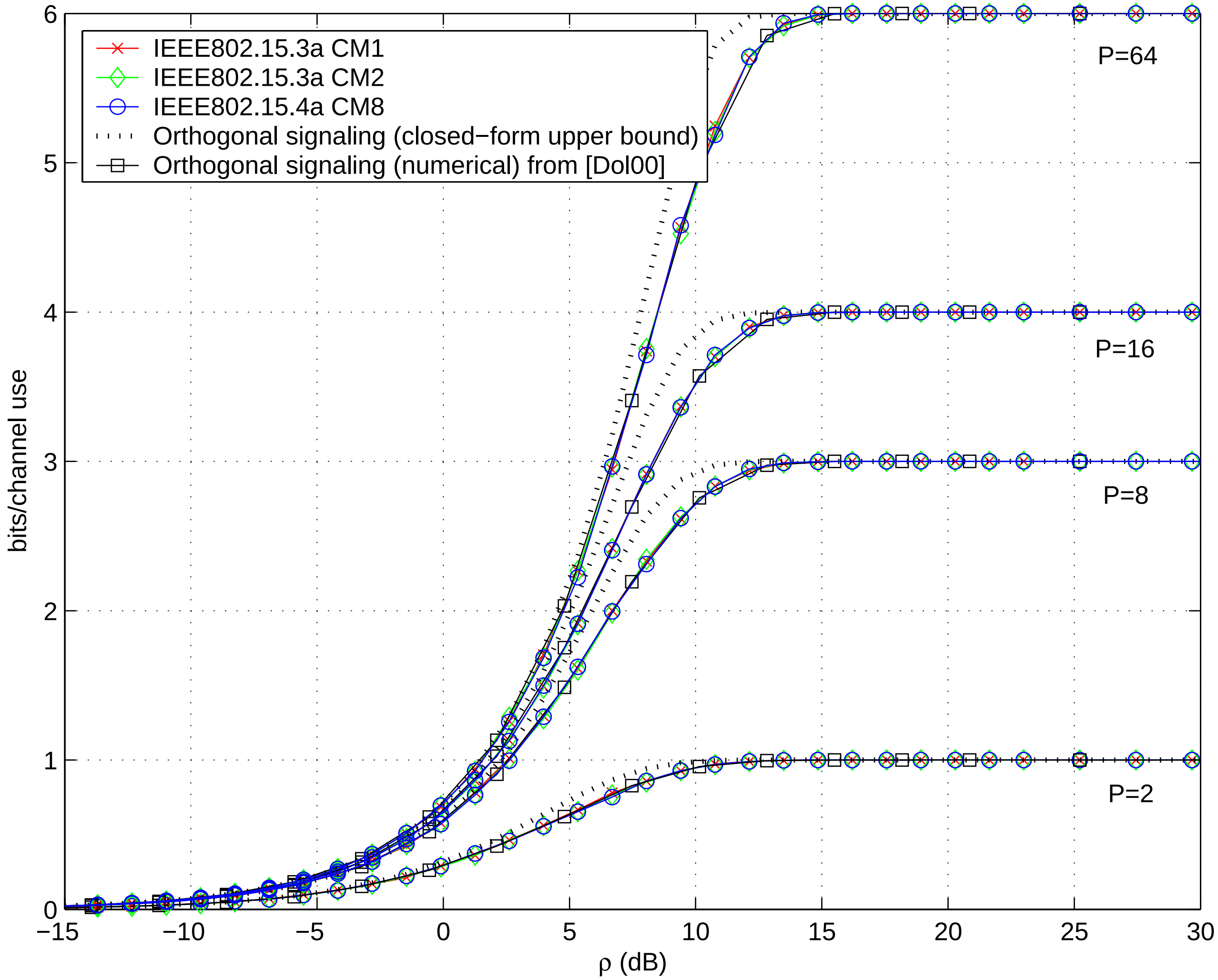
C (E_b/N_0)
Region for AWGN or unknown fading
with unconstrained peakiness
Region for unknown Rayleigh fading
with constrained peakiness
second
order optimal
first
order optimal
not first
order optimal
second
order optimal
wideband
slope $\mathcal{S}_0$
wideband
slope $\mathcal{S}_0 = 0$
E_b/N_0
$(E_b/N_0)_{\min|C\to 0}$
$(E_b/N_0)^{\text{effective}}_{\min}$
$(E_b/N_0)_{\min|C\to 0} \to \infty$

- Values for $(E_b/N_0)_{min}$ and $\mathcal{S}_0$ under peakiness constraints:

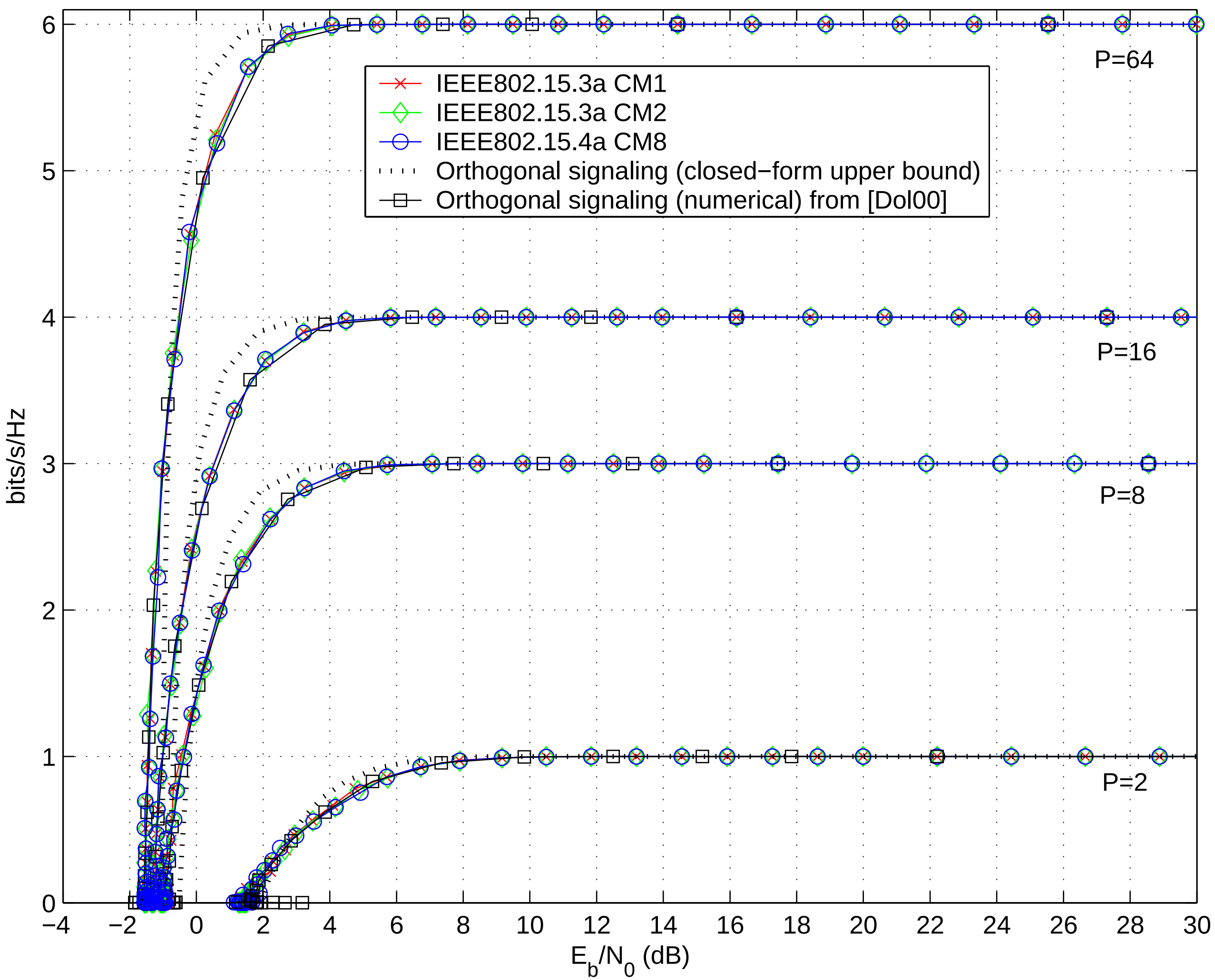
		$(E_b/N_0)_{\min}$	$\mathcal{S}_0$
Unconstrained peakiness	AWGN	$\log 2$	2
	Unknown Rayleigh or Rice fading	$\log 2$	0
Constrained peakiness	AWGN	$\log 2$	2
	Unknown Rayleigh fading	∞	0
	Unknown Rice fading†	$\left(1+\frac{1}{K}\right)\log 2$	$\frac{2K^2}{(1+K)^2-\kappa}$

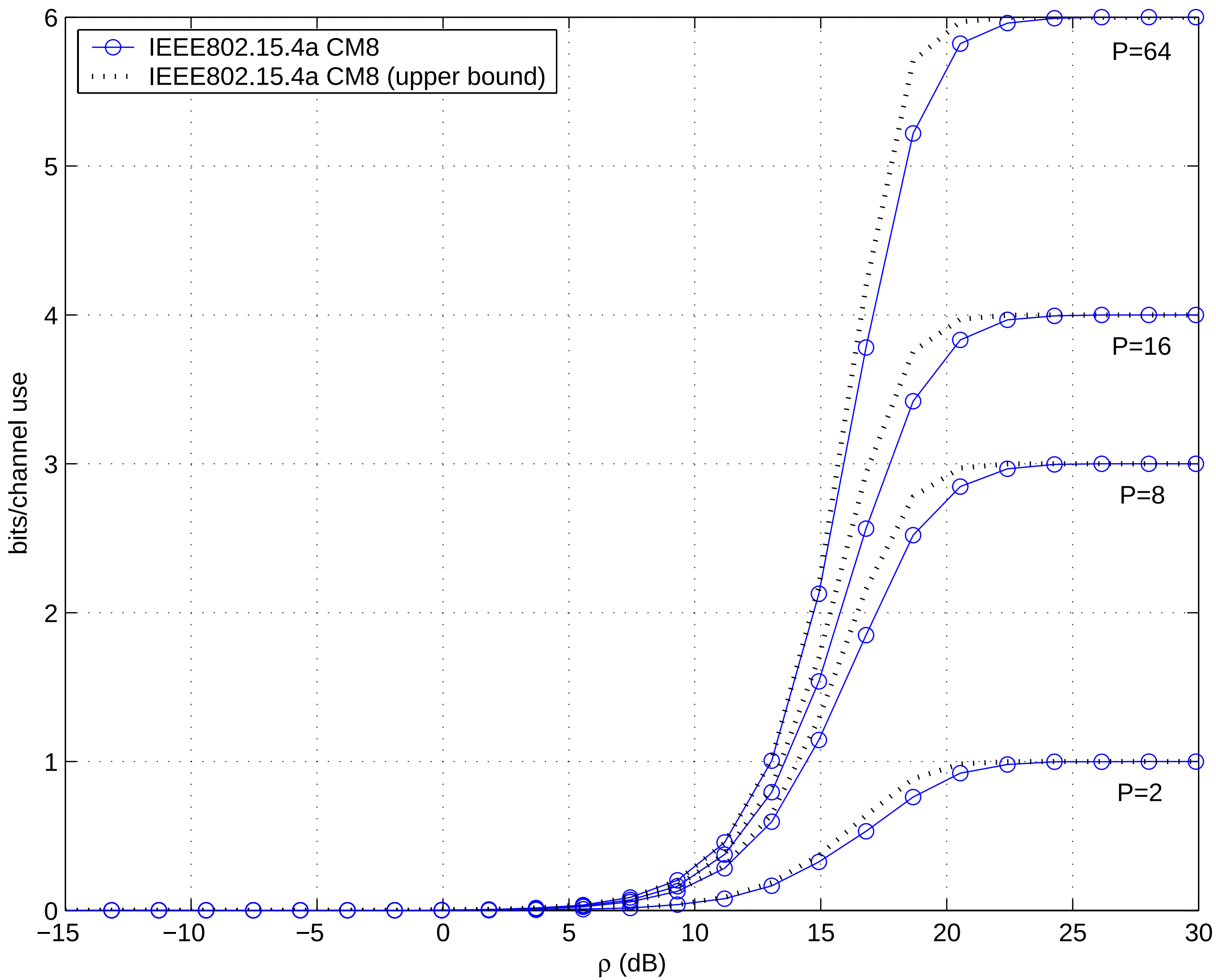
† Assuming a finite and known specular component. The Ricean factor is indicated by K and κ stands for the peak-to-average constraint.

CONSTELLATION CONSTRAINED CAPACITY: COHERENT RX

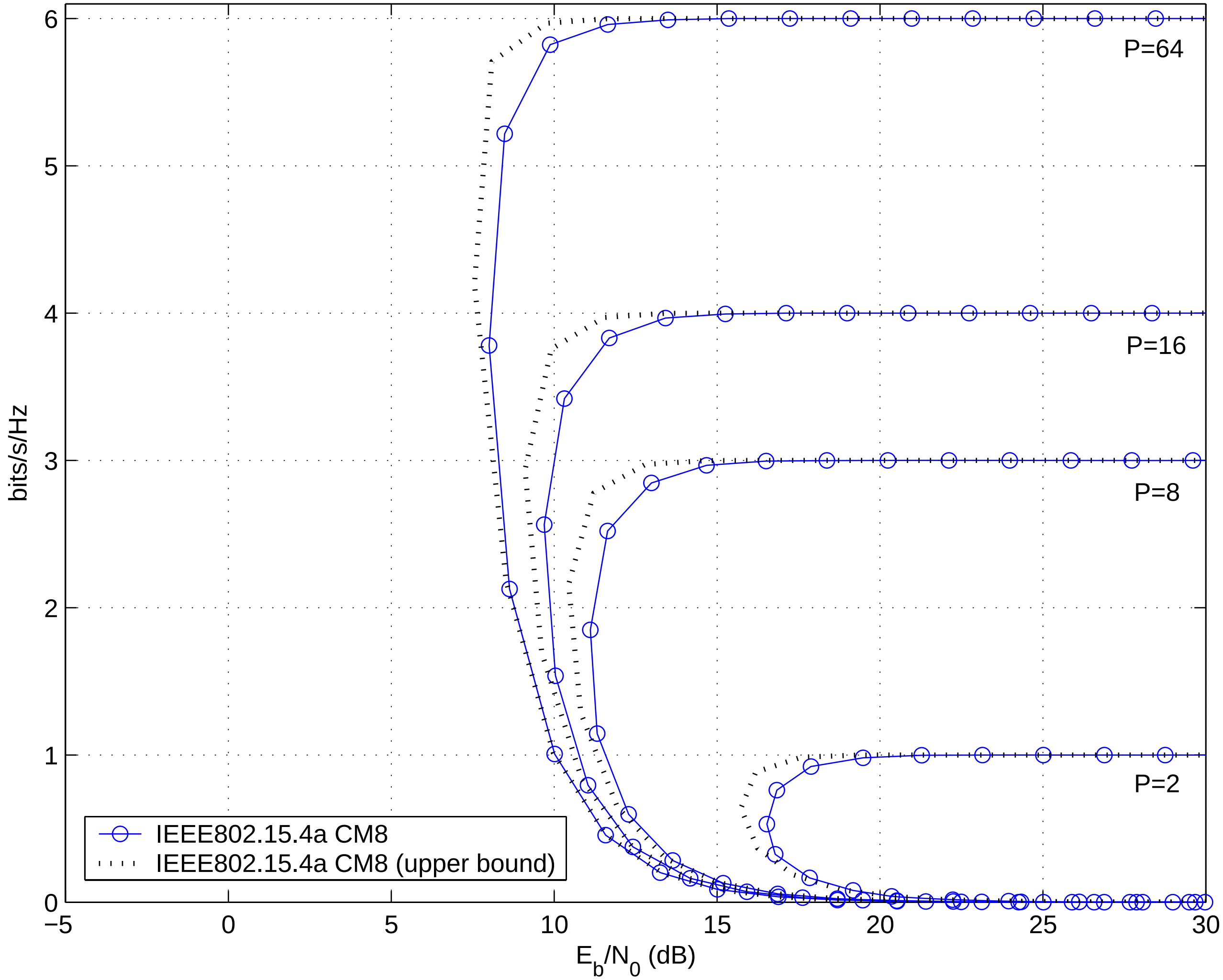


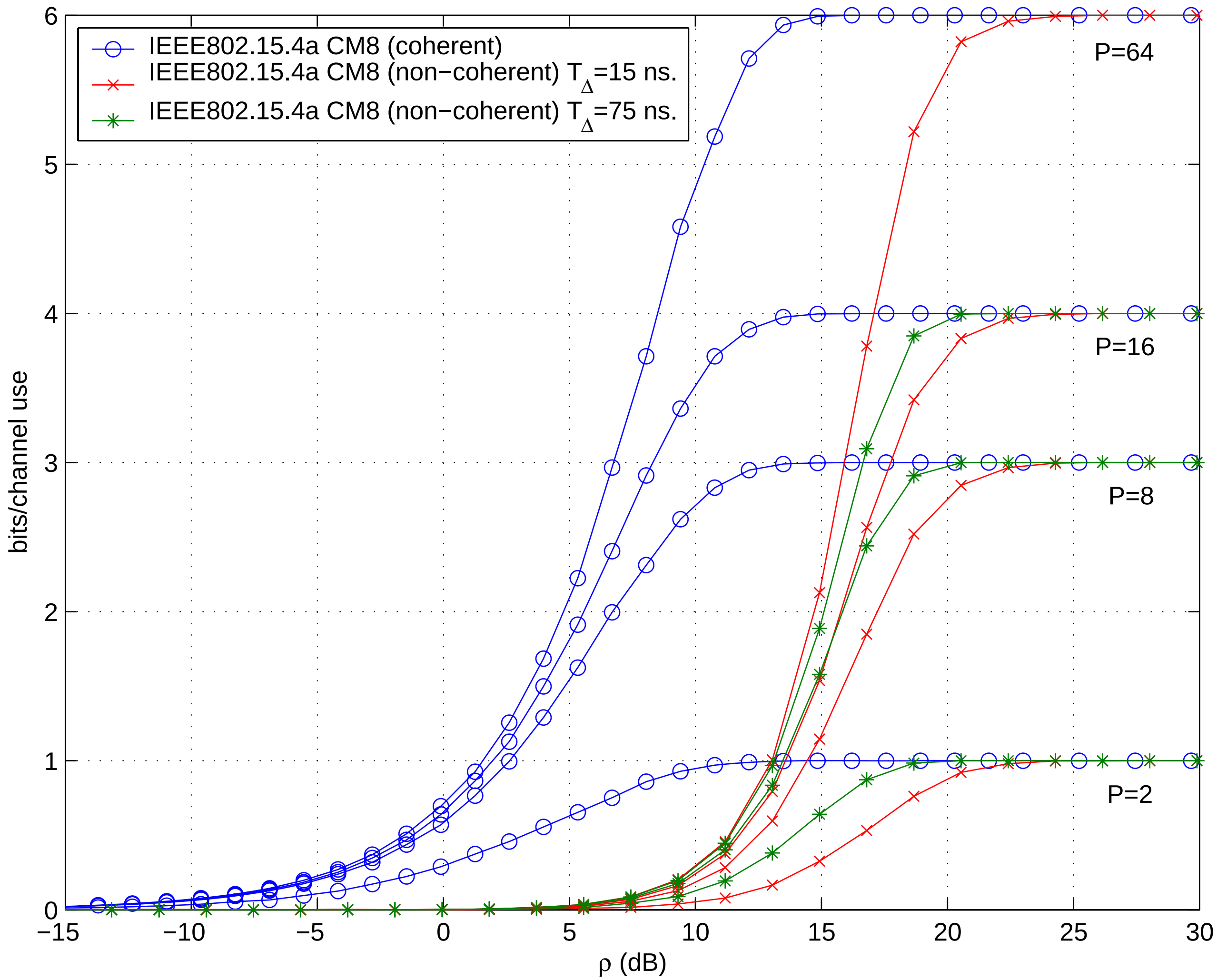
SPECTRAL EFFICIENCY: COHERENT RX

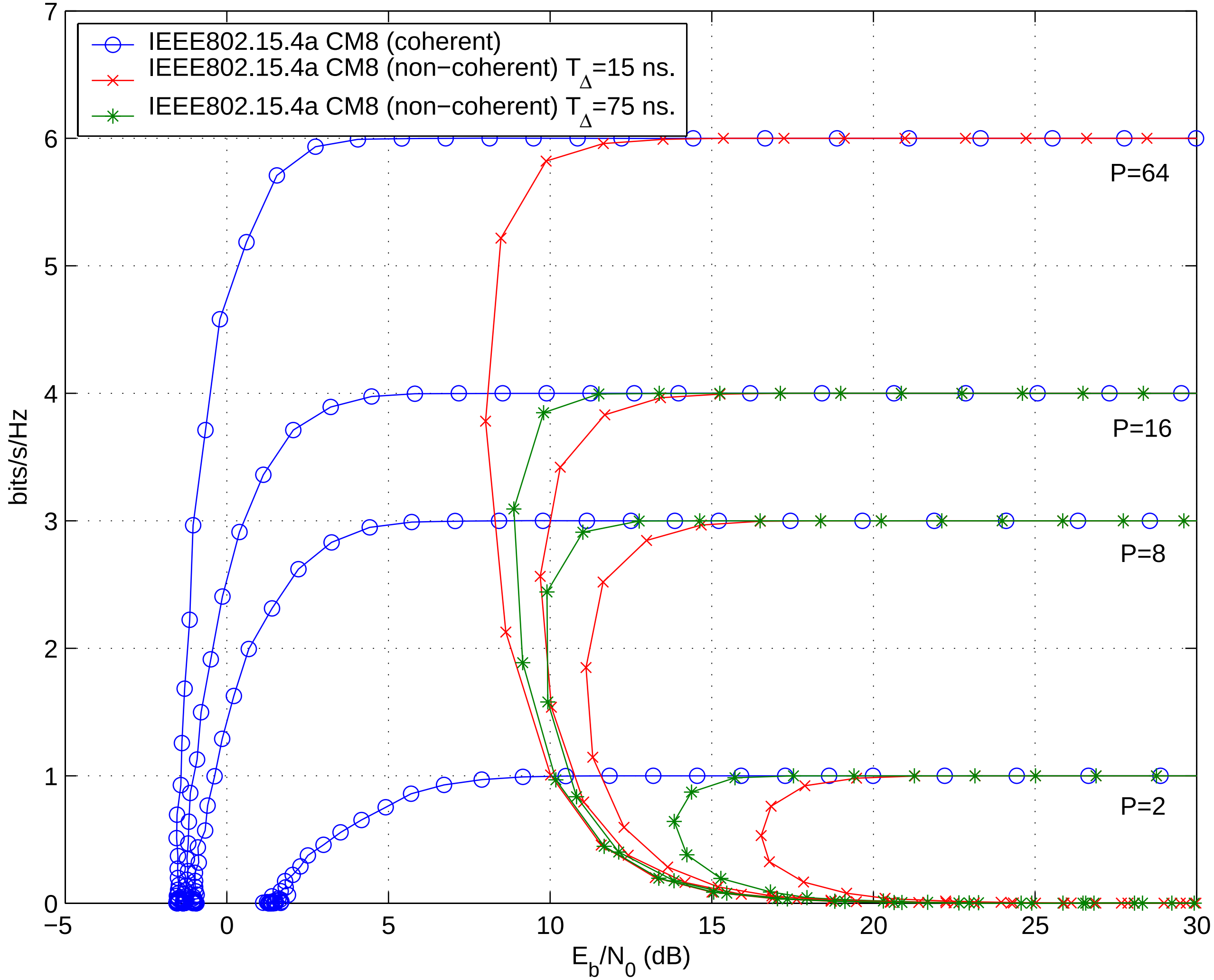



IEEE802.15.4a CM8
IEEE802.15.4a CM8 (upper bound)
P=64
P=16
P=8
P=2
bits/channel use
ρ (dB)
0
1
2
3
4
5
6
−15
−10
−5
0
5
10
15
20
25
30

SPECTRAL EFFICIENCY: NON-COHERENT RX




IEEE802.15.4a CM8 (coherent)
IEEE802.15.4a CM8 (non−coherent) T_Δ=15 ns.
IEEE802.15.4a CM8 (non−coherent) T_Δ=75 ns.
P=64
P=16
P=8
P=2
bits/channel use
ρ (dB)
6
5
4
3
2
1
0
−15
−10
−5
0
5
10
15
20
25
30



IEEE802.15.4a CM8 (coherent)
IEEE802.15.4a CM8 (non−coherent) T_Δ=15 ns.
IEEE802.15.4a CM8 (non−coherent) T_Δ=75 ns.
P=64
P=16
P=8
P=2
bits/s/Hz
E_b/N_0 (dB)
0
1
2
3
4
5
6
7
−5
0
5
10
15
20
25
30

NON-COHERENT DETECTION

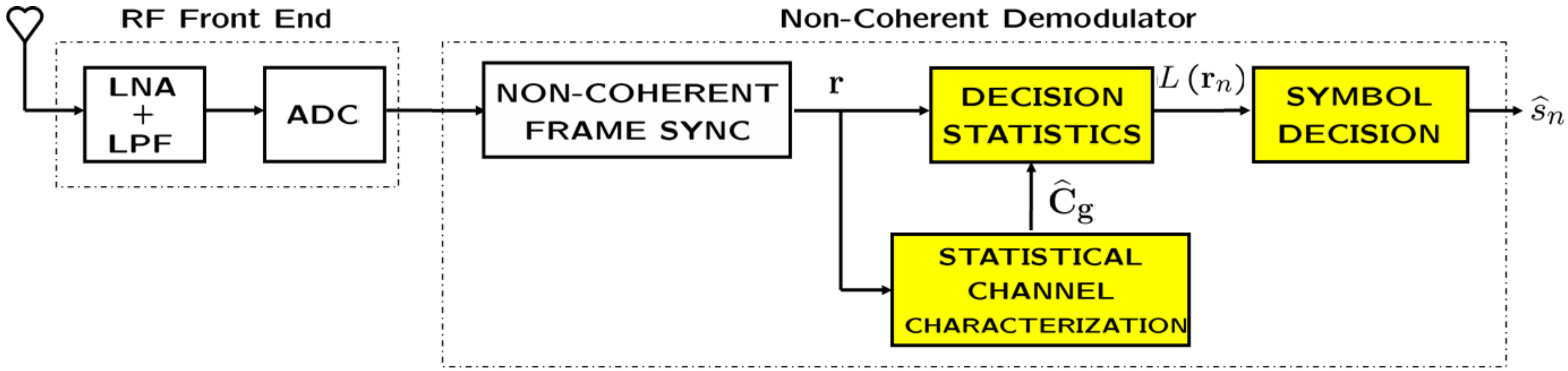
UNKNOWN WAVEFORM

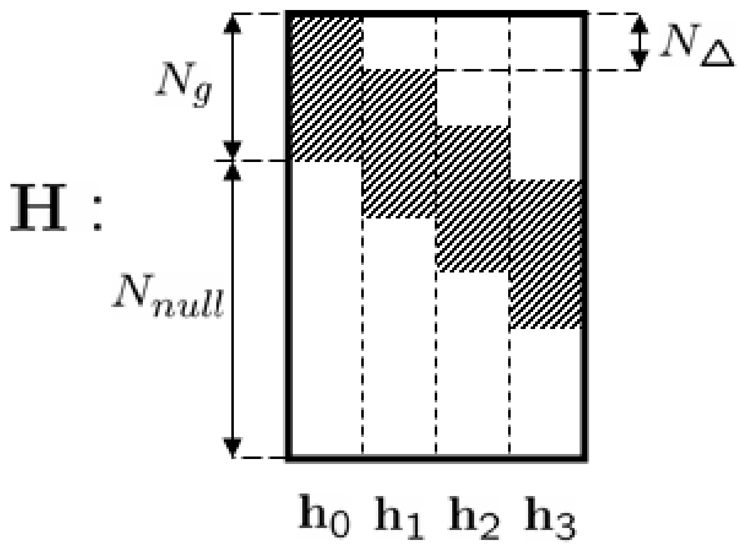
- **CONVENTIONAL APPROACH >> ENERGY DETECTION**

- **PARTIAL/UNCOMPLETE KNOWLEDGE ON:**
  - THE RECEIVED MONOCYCLES WAVEFORMS.
  - THE CHANNEL RESPONSE.
  - THE NOISE+INTERFERENCE SPD.

- **SIDE-INFORMATION:**
  - SIGNAL MODEL OF THE PPM UWB SIGNAL.
  - THE LOW-SNR OPERATING CONDITION.
  - THE CYCLOSTATIONARY STRUCTURE OF THE DATA.
  - STATISTICAL MODEL?

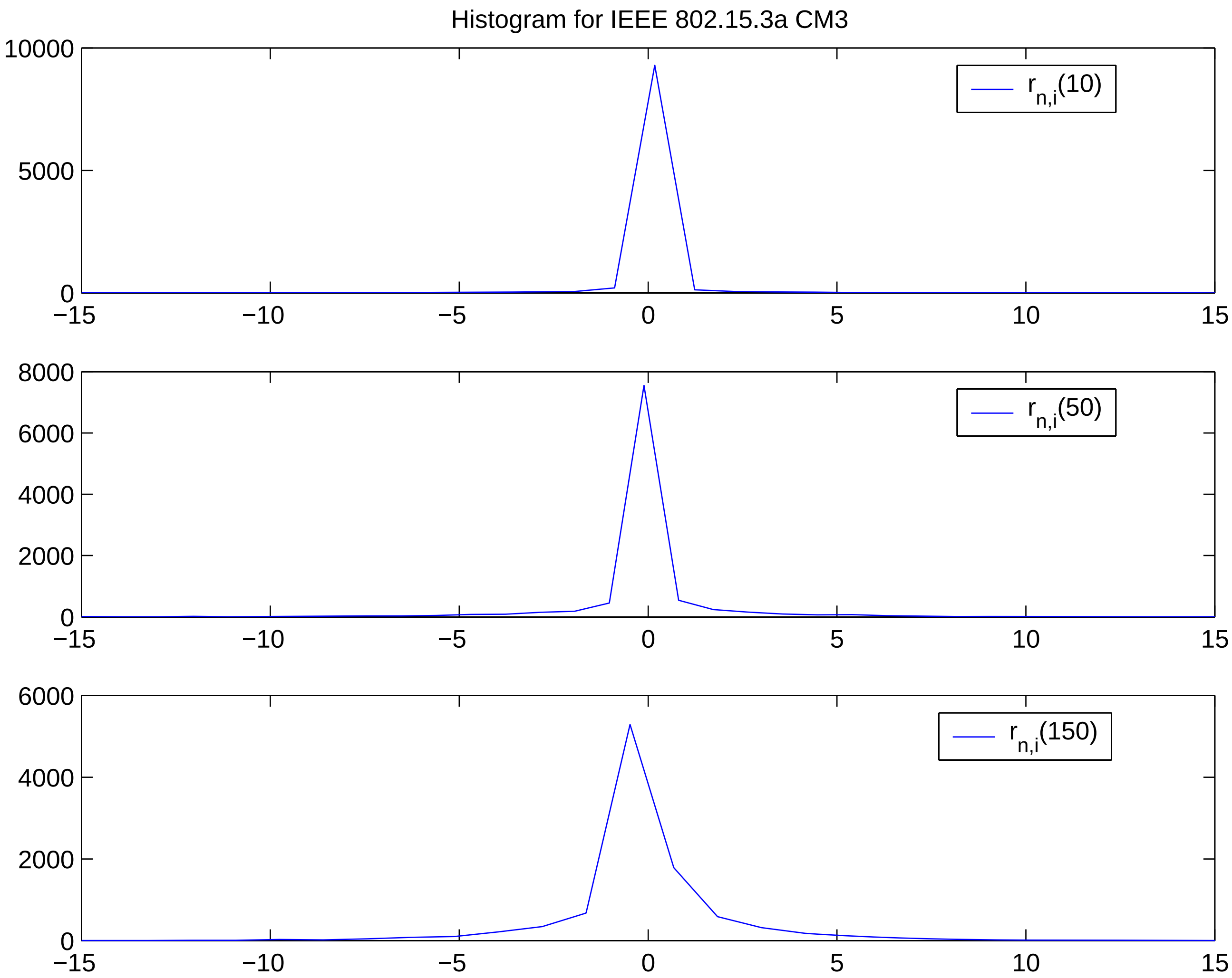
STATISTICAL APPROACH



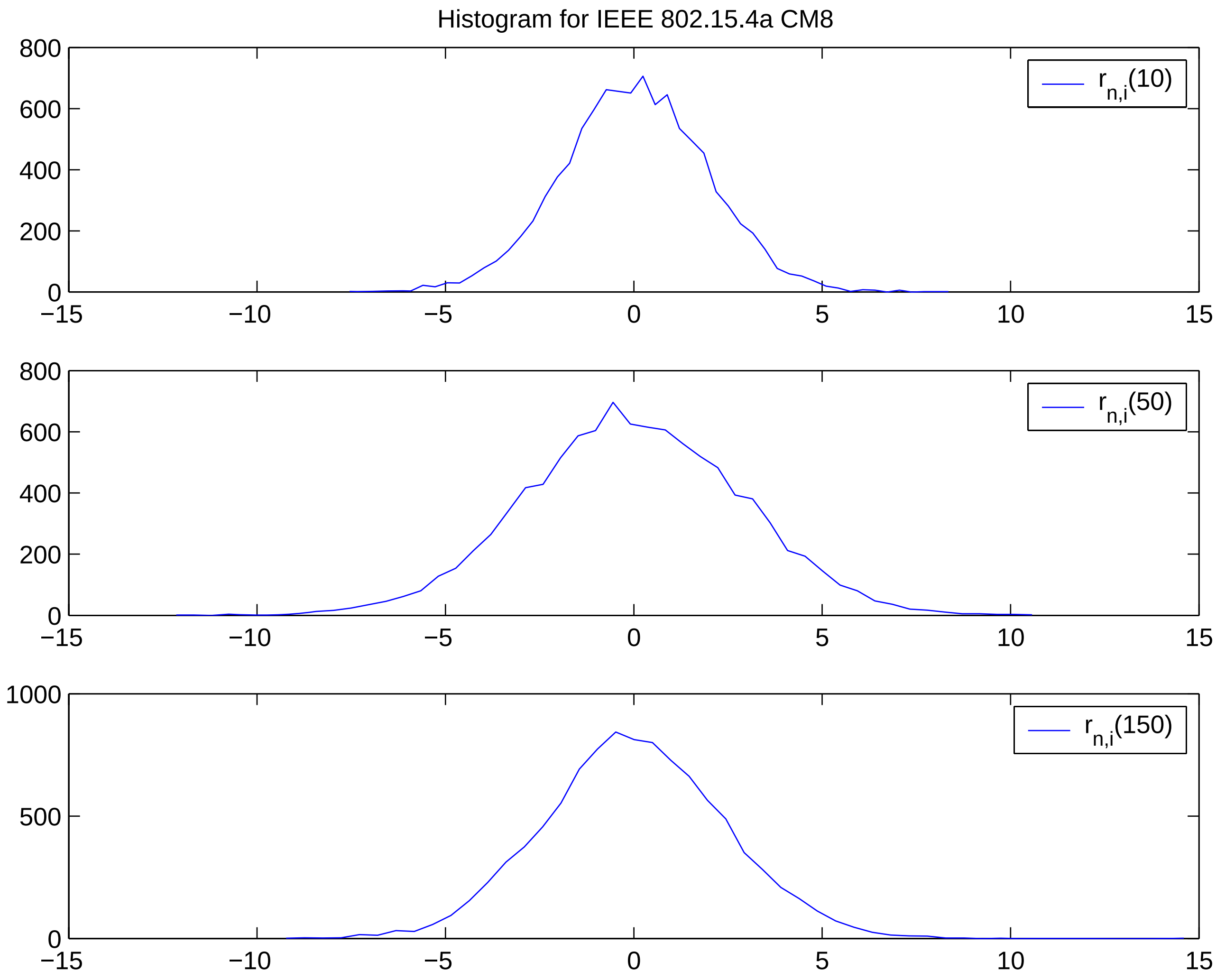


$$\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

IEEE 802.15.3a CM3 (NLOS)



IEEE 802.15.4 (INDUSTRIAL NLOS)



$$f\left(\mathbf{r}_n / H_\pm ; \mathbf{C}_\mathbf{g}\right) = \prod_{i=0}^{N_f-1} \frac{1}{(2\pi)^{N_{sf}/2} \det^{1/2}\left(\mathbf{C}_\pm + \mathbf{C}_N\right)} \exp\left(-\frac{1}{2}\mathbf{r}_{n,i}^T \left(\mathbf{C}_\pm + \mathbf{C}_N\right)^{-1} \mathbf{r}_{n,i}\right)$$

$$\mathbf{C}_N = \sigma_w^2 \mathbf{I} + \mathbf{C}_I$$

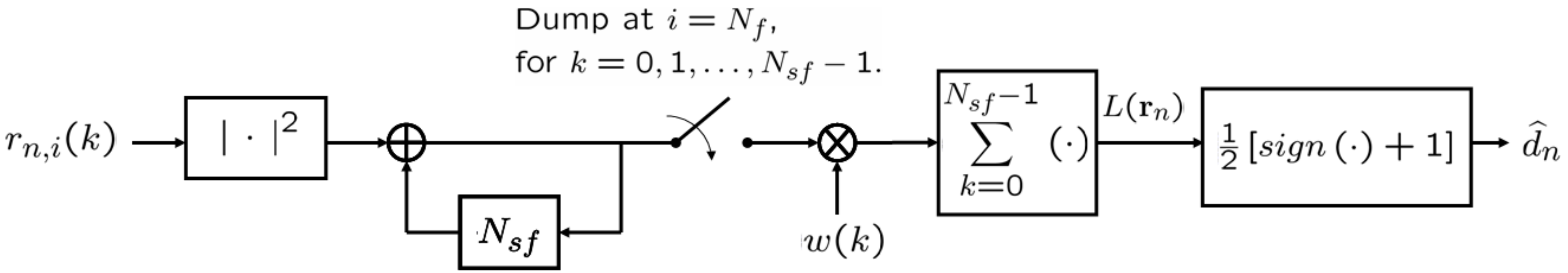
$$\boxed{L\left(\mathbf{r}_n / \mathbf{C}_g\right) = Tr\left[\left(\mathbf{C}_+ - \mathbf{C}_-\right)\hat{\mathbf{R}}_n\right]}$$

$$\hat{\mathbf{R}}_n = \frac{1}{N_f} \sum_{i=0}^{N_f-1} \mathbf{r}_{n,i} \mathbf{r}_{n,i}^T$$

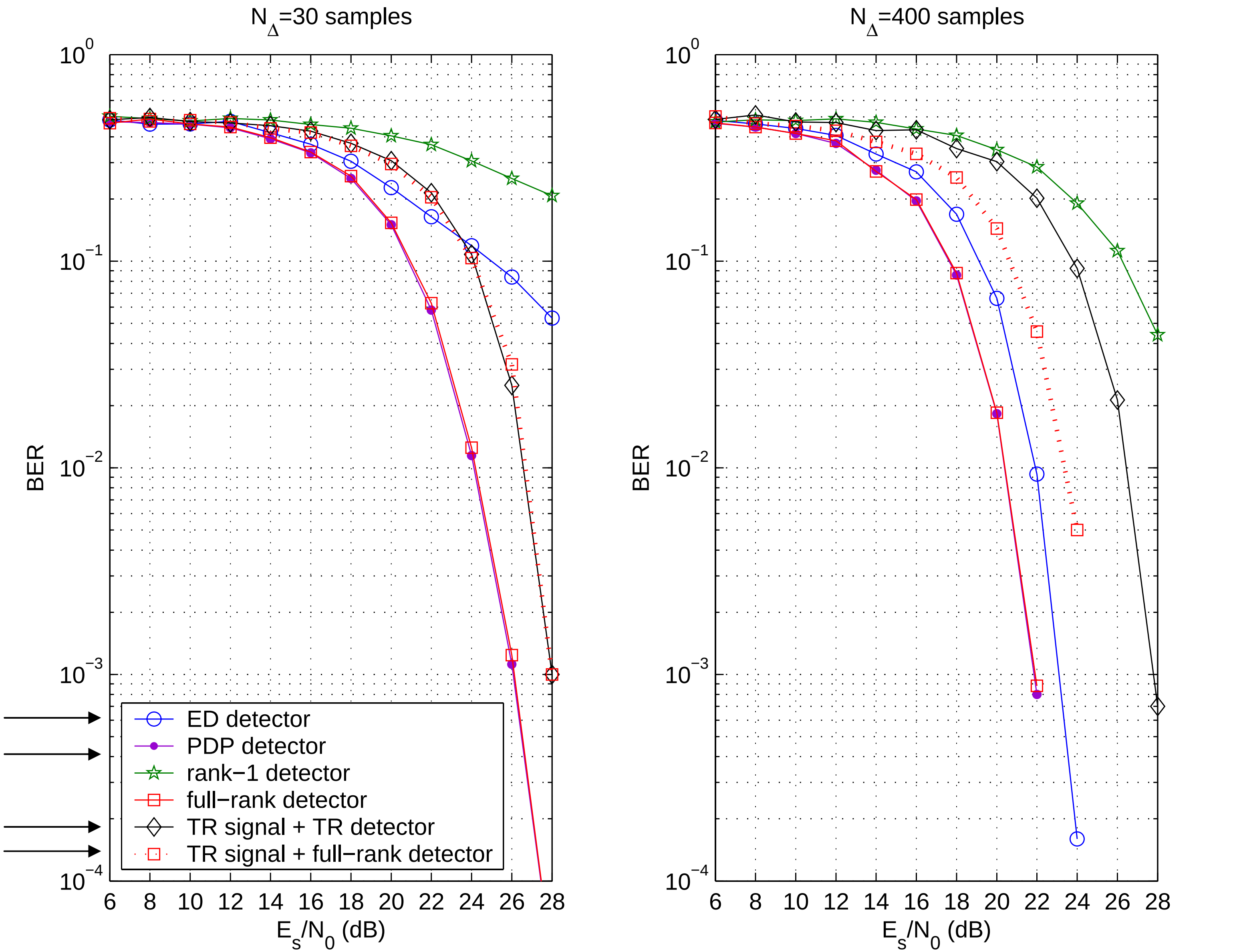
UNCORRELATED SCATTERING

$$\mathbf{C_g} = diag[\boldsymbol{\gamma}]$$

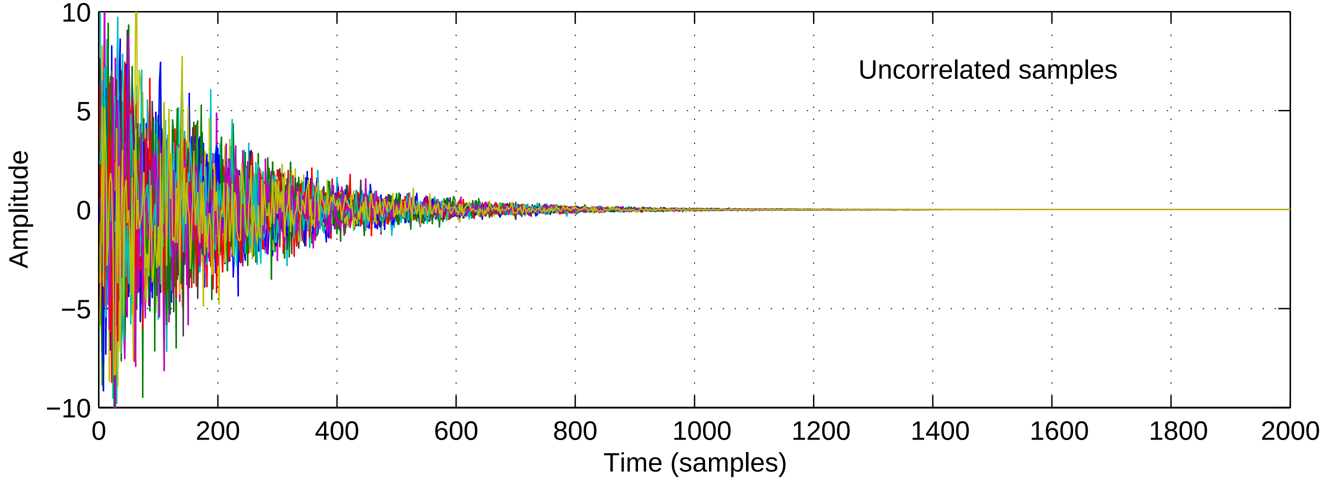
$$\boldsymbol{\gamma} = [\gamma(0), \gamma(1), \ldots, \gamma(N_g)]^T$$

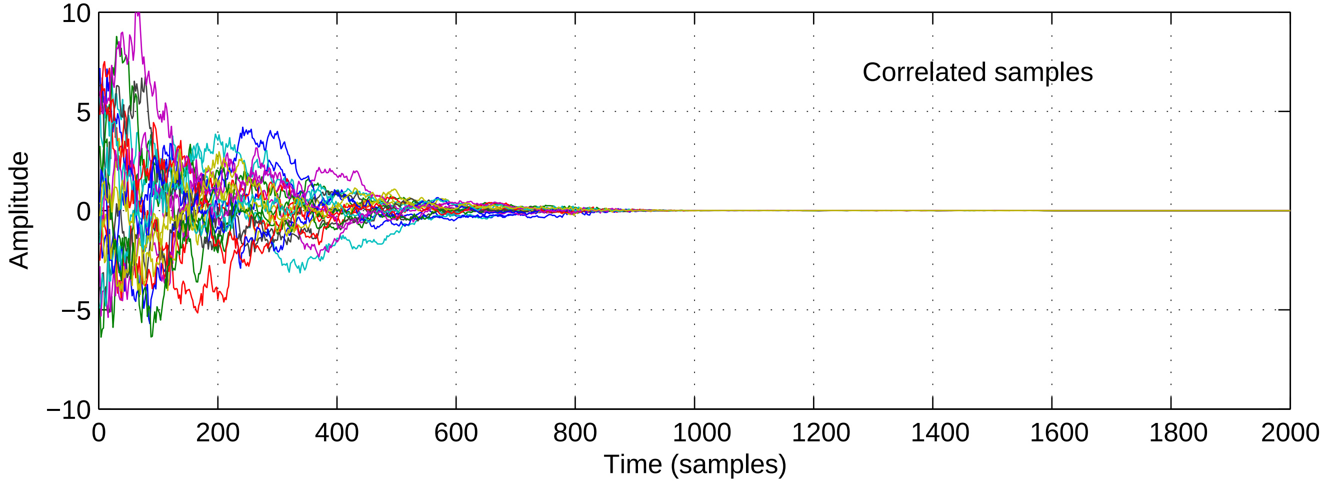


BER: UNCORRELATED-SCATTERING

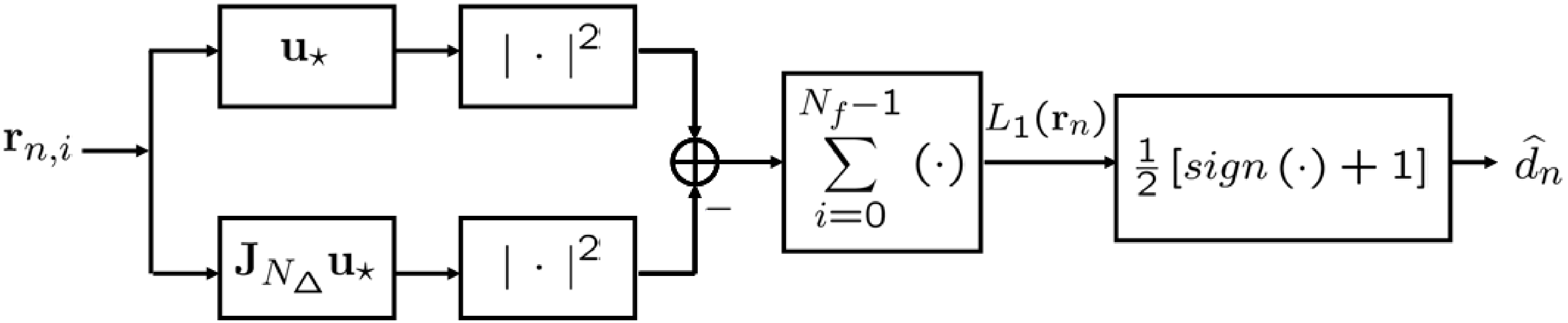


1000


Uncorrelated samples
Amplitude
Time (samples)
10
5
0
−5
−10
0
200
400
600
800
1000
1200
1400
1600
1800
2000

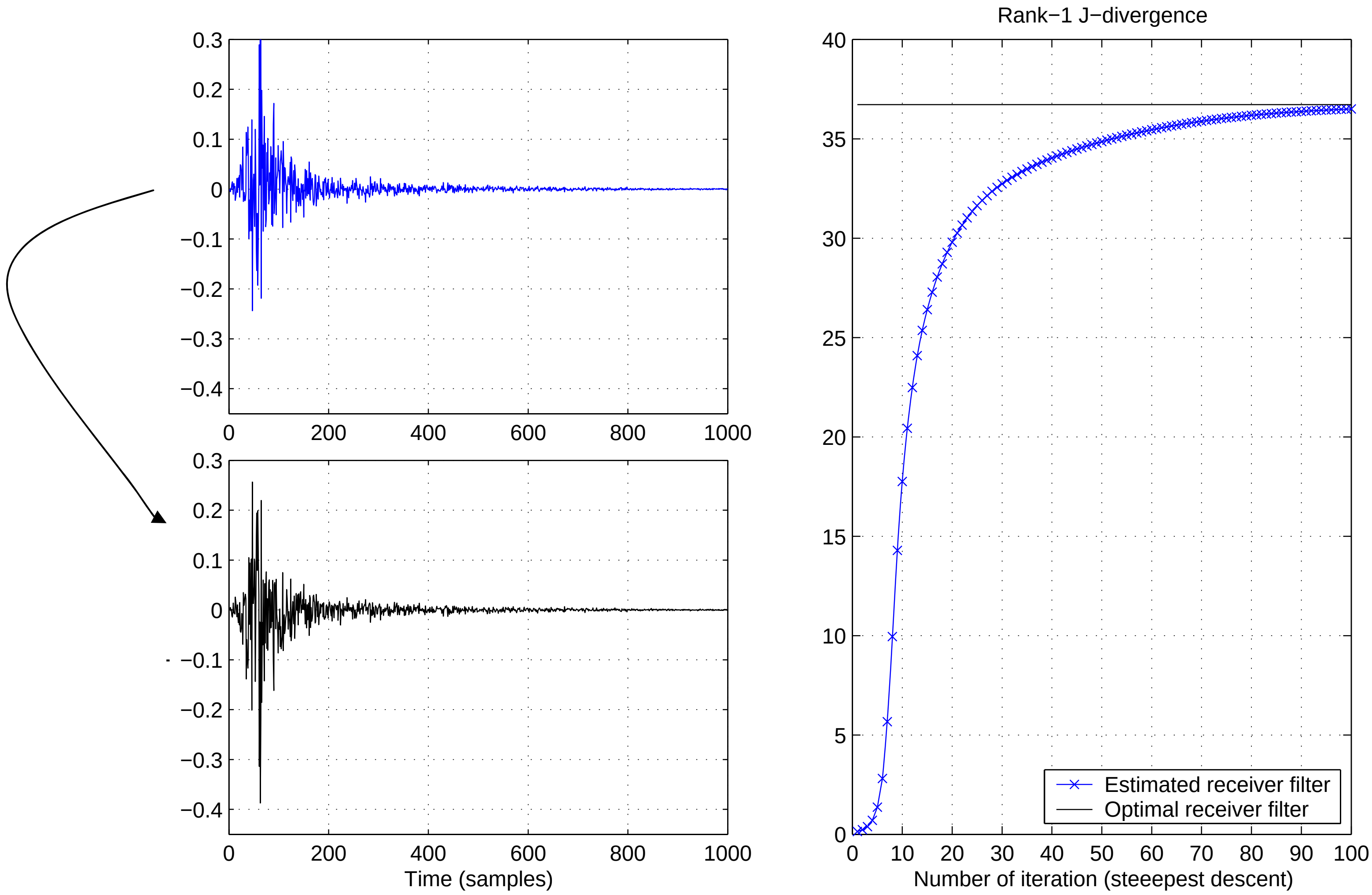

Correlated samples
Amplitude
Time (samples)
10
5
0
−5
−10
0
200
400
600
800
1000
1200
1400
1600
1800
2000

- **ORTHOGONAL PPM vs OVERLAPPED PPM**

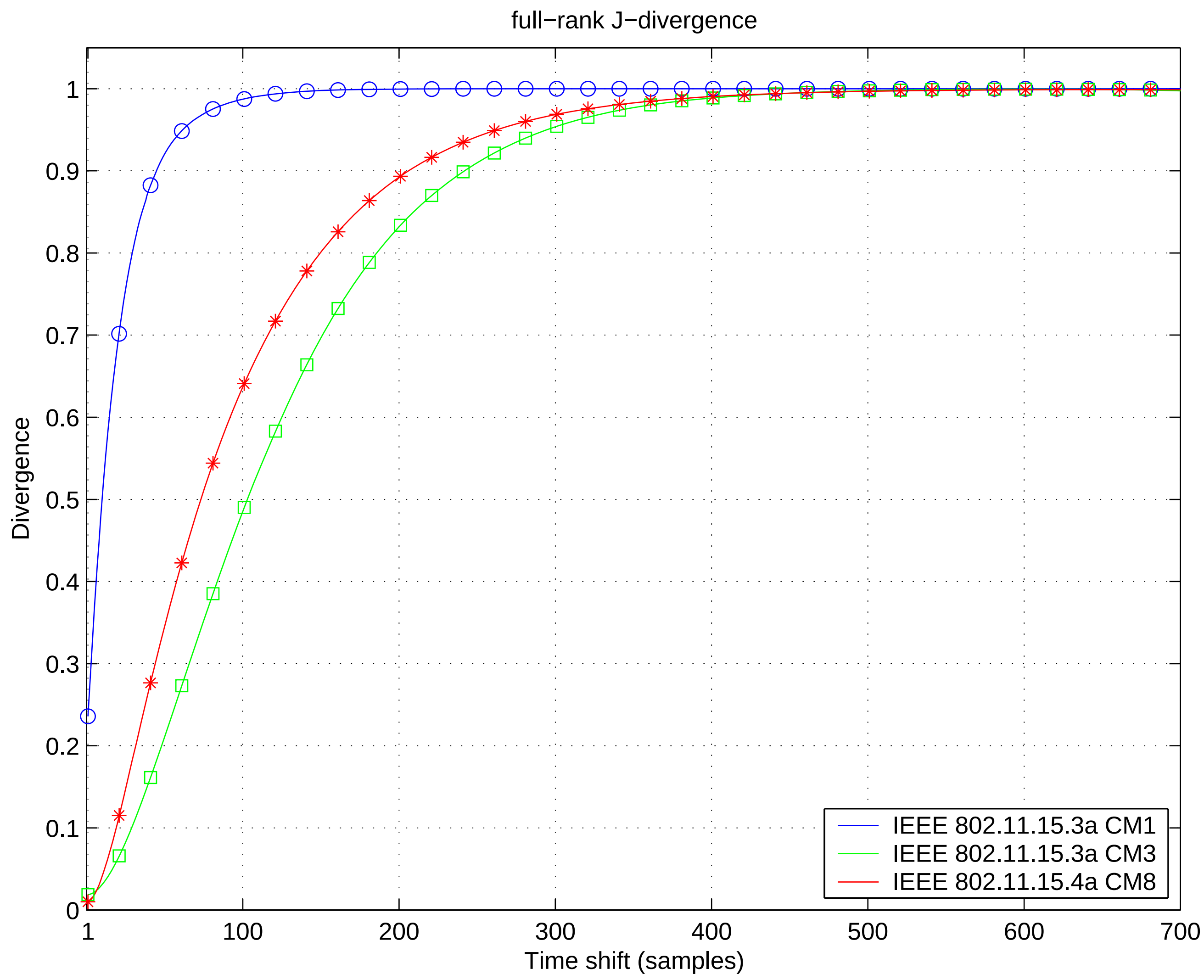


$$\mathbf{u}_* = \arg\max_{\mathbf{u}_m} J_1(\mathbf{u}_m) \Rightarrow \begin{cases} J_1(\mathbf{u}_m) = \lambda_m^2\left[1-\left(\mathbf{u}_m^T \mathbf{J}_{N_\Delta}\mathbf{u}_m\right)^2\right] \\ \lambda_m = \dfrac{\mathbf{u}_m^T \mathbf{C}_+ \mathbf{u}_m}{\mathbf{u}_m^T \mathbf{u}_m} \end{cases}$$

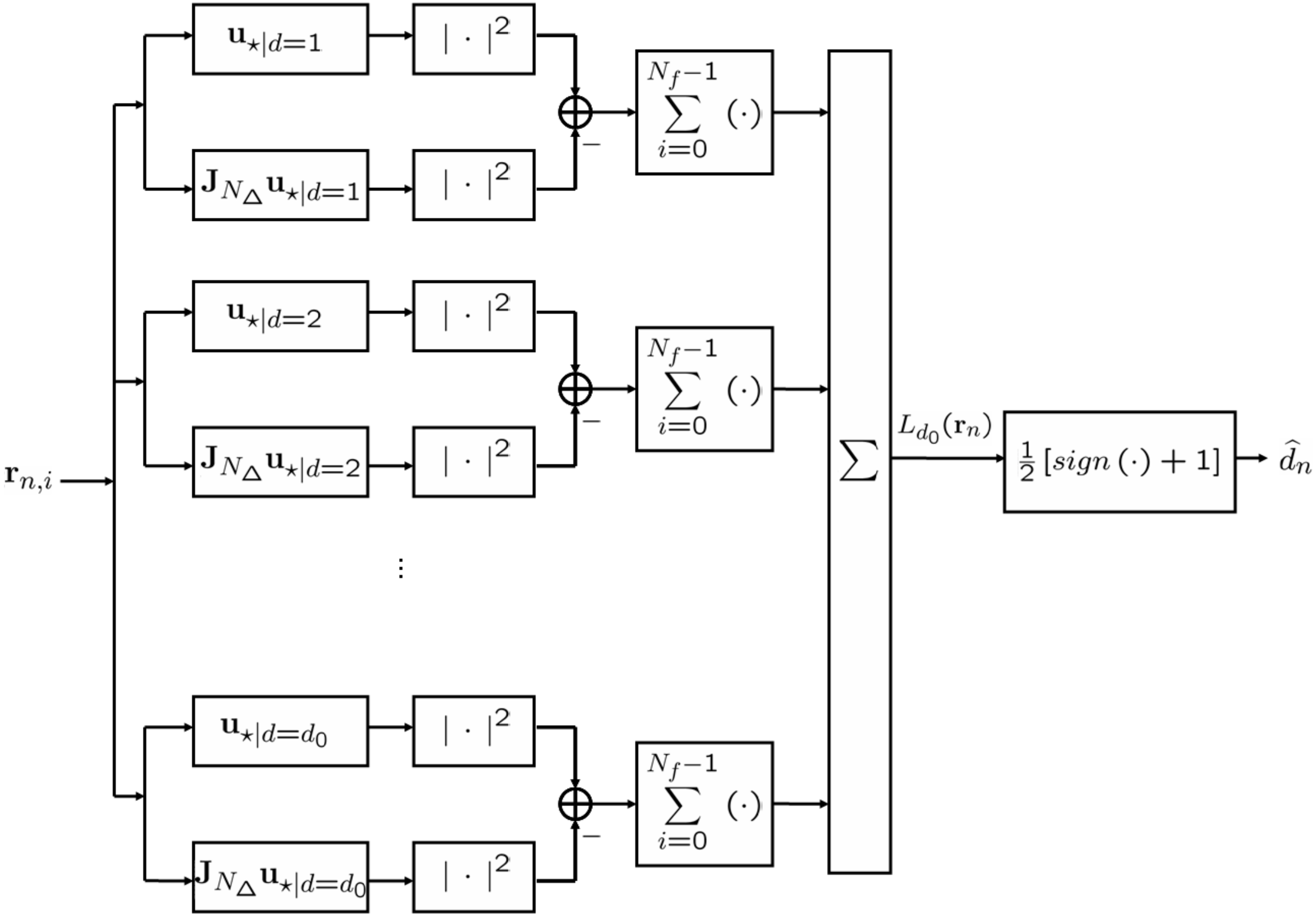
- **A MEASSURE OF THE DIFFICULTY WHEN DISCRIMINATING BETWEEN TWO HYPOTHESIS.**



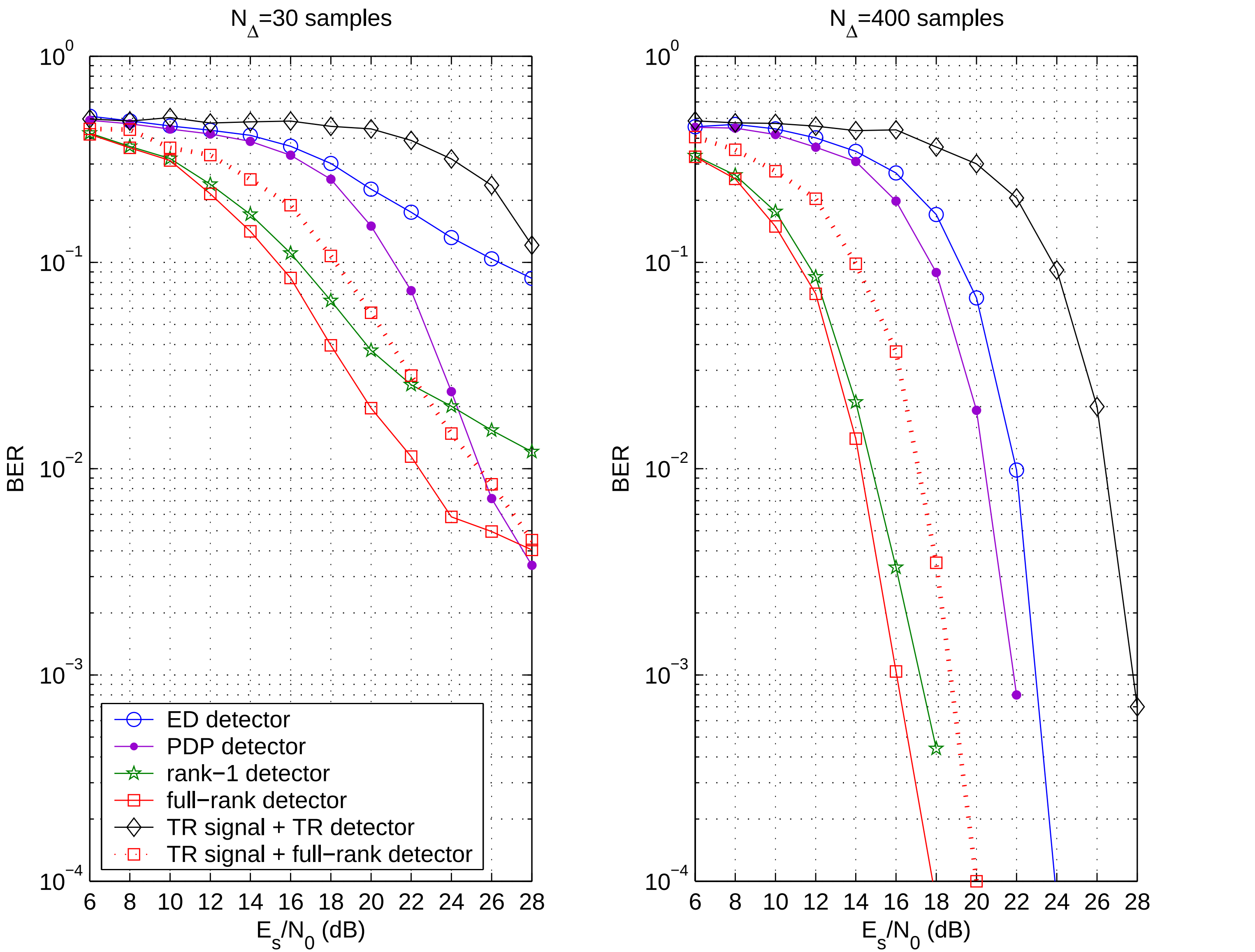
UWB WAVEFORM HISTOGRAM



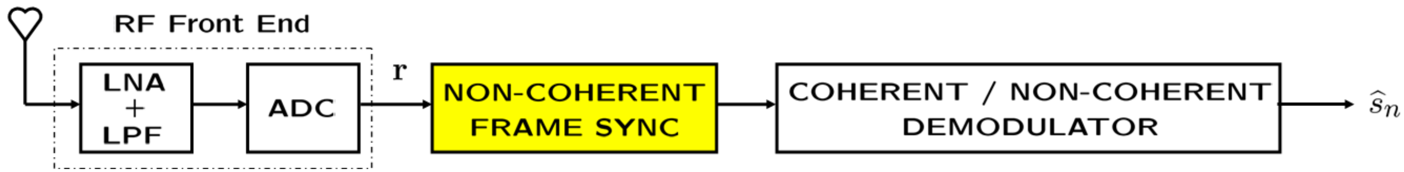
CORRELATED-SCATTERING: RANK-d_o



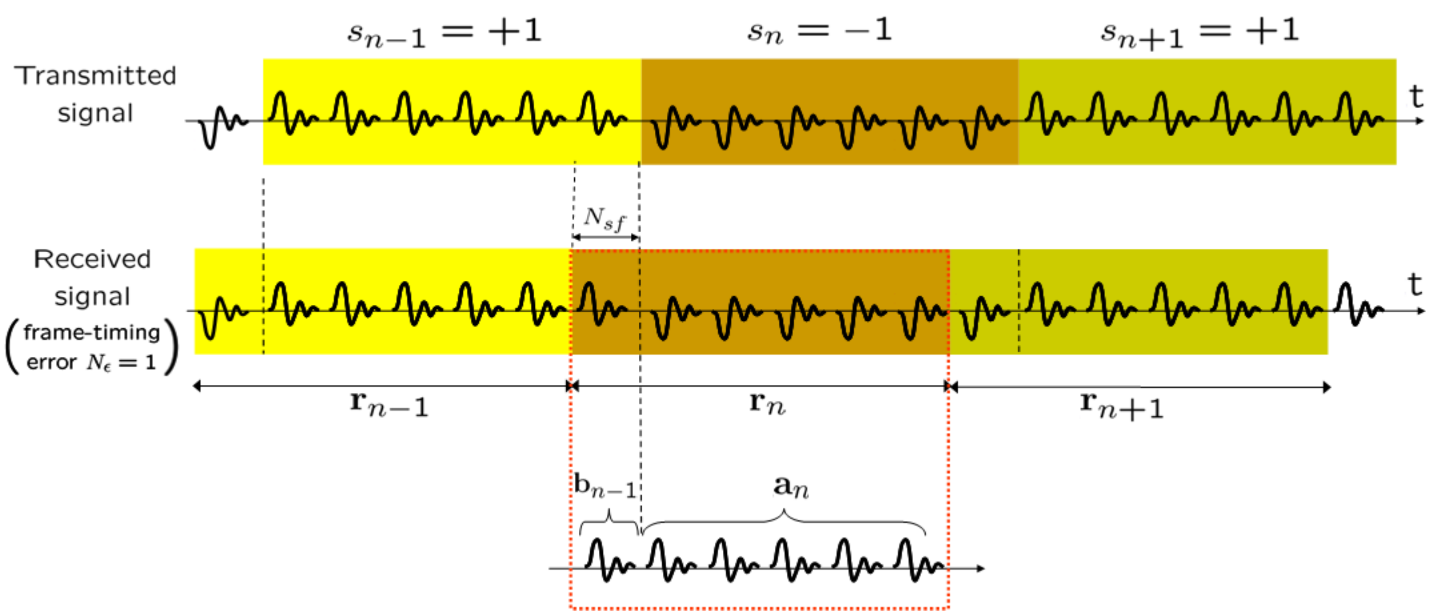
BER: CORRELATED SCATTERING



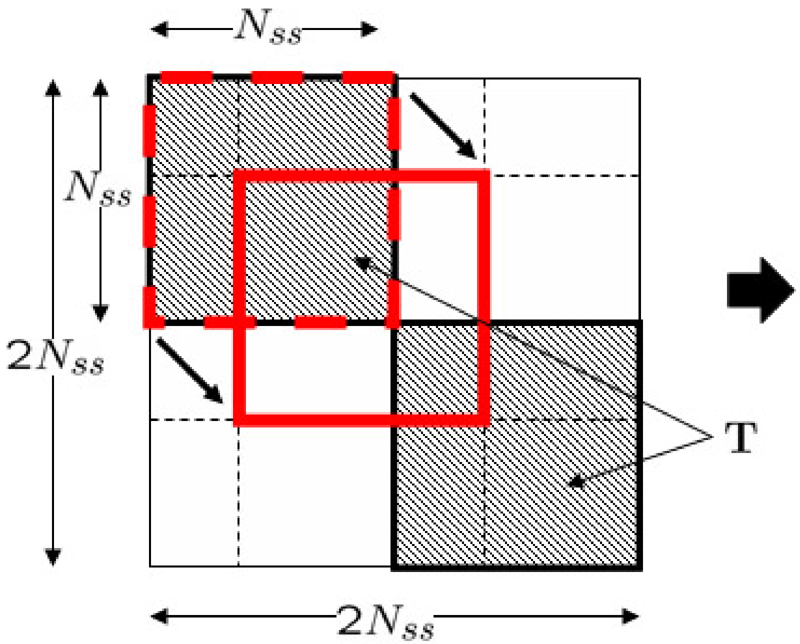
NON-COHERENT FRAME-TIMING ACQUISITION



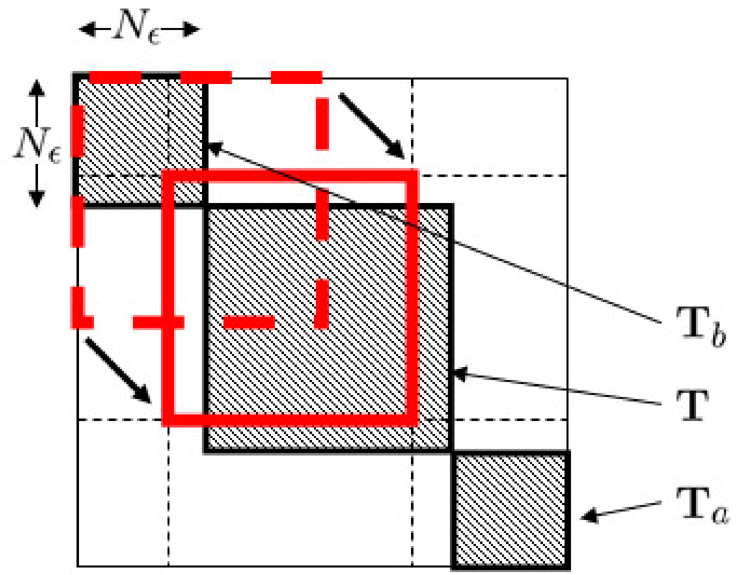
RF Front End
LNA + LPF
ADC
r
NON-COHERENT FRAME SYNC
COHERENT / NON-COHERENT DEMODULATOR
$\hat{s}_n$



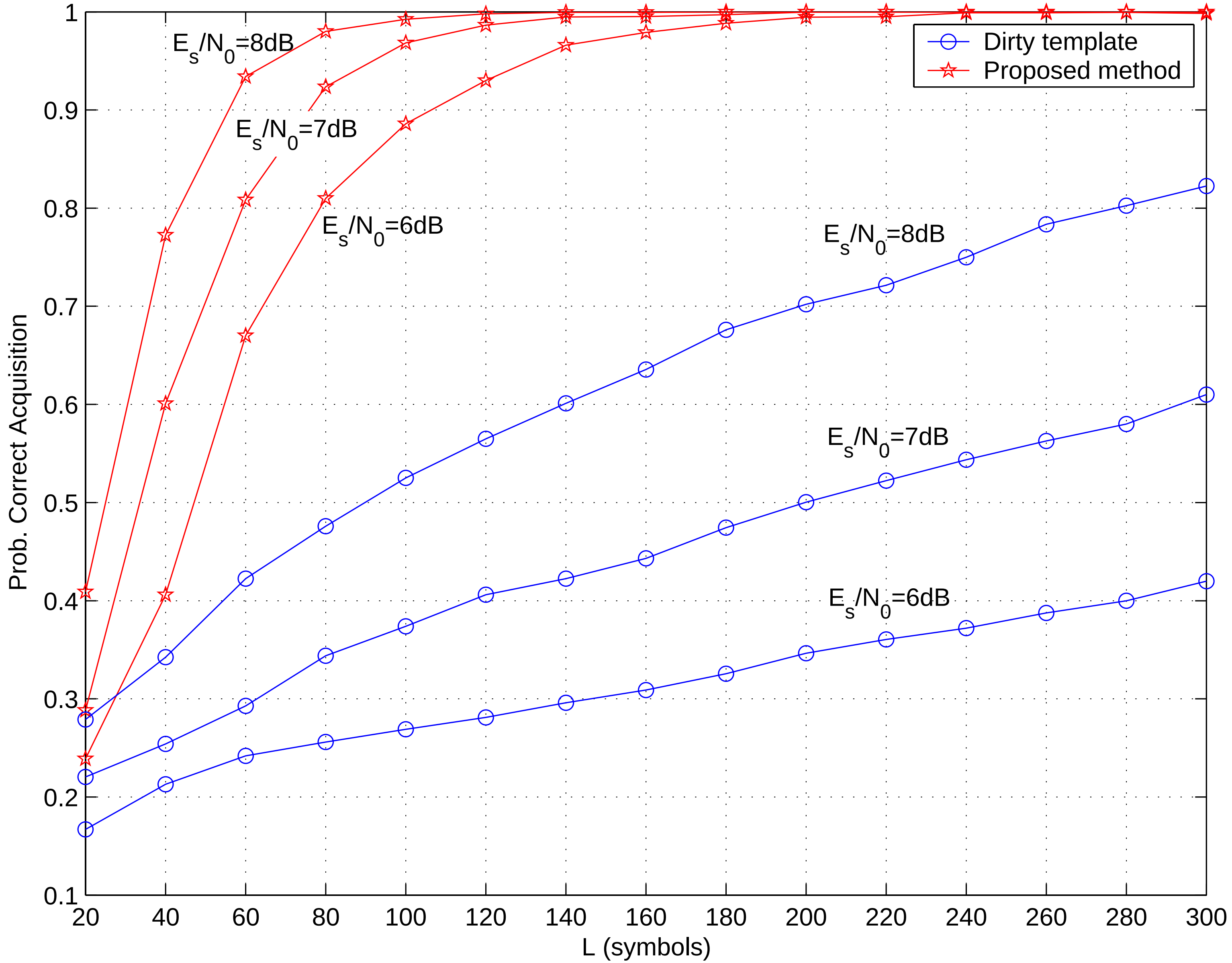
$s_{n-1} = +1$
$s_n = -1$
$s_{n+1} = +1$
Transmitted signal
t
N_{sf}
Received signal
(frame-timing error $N_\epsilon = 1$)
t
$\mathbf{r}_{n-1}$
$\mathbf{r}_n$
$\mathbf{r}_{n+1}$
$\mathbf{b}_{n-1}$
$\mathbf{a}_n$



Matrix $\mathbf{R}_2$ when no timing error is present

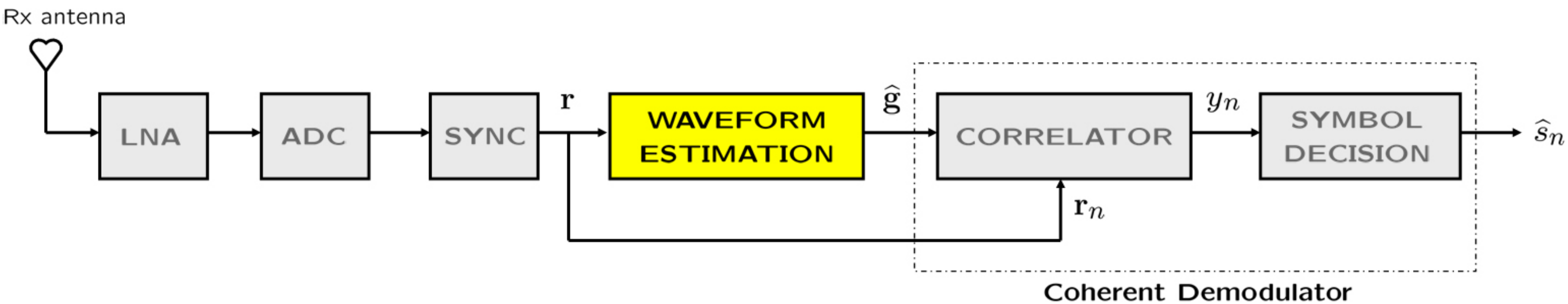


Matrix $\mathbf{R}_2$ when a timing error $\tau = N_\epsilon N_{sf} + \epsilon$ is present



Prob. Correct Acquisition
L (symbols)
Dirty template
Proposed method
E_s/N_0=8dB
E_s/N_0=7dB
E_s/N_0=6dB
E_s/N_0=8dB
E_s/N_0=7dB
E_s/N_0=6dB
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300

WAVEFORM ESTIMATION FOR COHERENT DETECTION OF UWB SIGNALS



$$L(\mathbf{r}/\mathbf{g}) = Tr\left(\mathbf{M}_{\mathbf{g}}\left[\hat{\mathbf{R}}_n - \sigma_w^2 \mathbf{I}\right]\right) + \frac{1}{2}\left\|\mathbf{M}_{\mathbf{g}}\right\|_F^2$$

Thanks!