Coherent and Non-Coherent UWB Communications

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Ph.D. Dissertation

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INTRODUCTION AND MOTIVATION

Fundamentals of UWB Technology

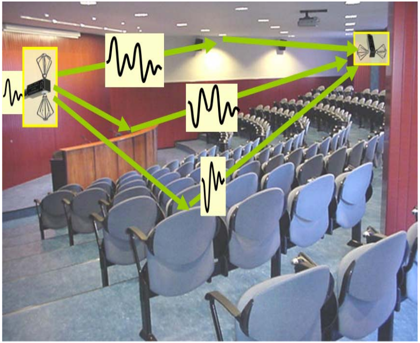
Basic features

- It is the oldest but least explored form of radio communication
- Main characteristics:
  - Impulsive transmission (i.e. no continuous wave)
  - Very large spectral occupancy
- Advantages:
  - Low-complexity due to baseband transmission (i.e. no RF)
  - Extremely-short pulses $\Rightarrow$ high data-rates
    $\Rightarrow$ multipath immunity
    $\Rightarrow$ precise positioning
  - Low power pulses $\Rightarrow$ low probability of interception
  - High penetration capability

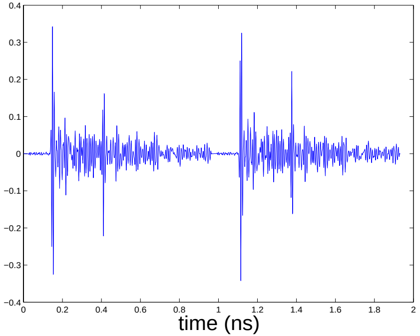
Fundamentals of UWB Technology

Temporal characteristics

Frequency-Selective and Direction-Dependent Propagation



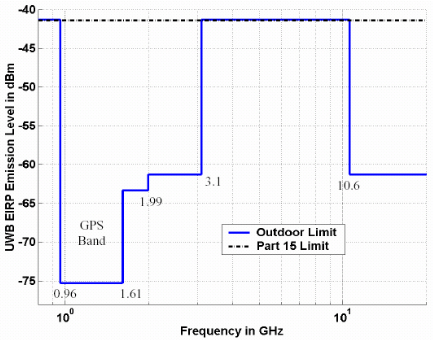
Typical UWB Received Waveforms (Unknown Aggregated Response)



Fundamentals of UWB Technology

Spectral characteristics

FCC Spectral Mask (outdoors)



Industry standardization approaches

- UWB Forum
  - Baseband approach (impulse radio)
  - DS-UWB
- WiMedia Alliance
  - Carrier-based approach
  - MB-OFDM

Motivation and Objectives of this Dissertation

- Motivation of this dissertation:
  - Evaluate the impact of pulse distortion in UWB communications
  - Design robust signal processing techniques for UWB receivers

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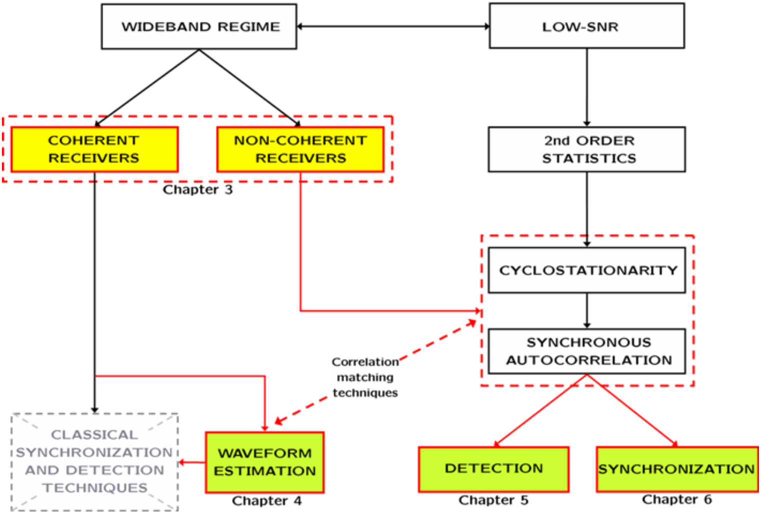
- Evaluate the performance loss with unknown received waveforms
- Design optimal detectors to cope with the absence of CSI
- Design optimal non-coherent and non-assisted timing synchronizers
- Design waveform estimation techniques for low-SNR scenarios

Roadmap


WIDEBAND REGIME
LOW-SNR
COHERENT RECEIVERS
NON-COHERENT RECEIVERS
Chapter 3
2nd ORDER STATISTICS
CYCLOSTATIONARITY
SYNCHRONOUS AUTOCORRELATION
Correlation matching techniques
CLASSICAL SYNCHRONIZATION AND DETECTION TECHNIQUES
WAVEFORM ESTIMATION
Chapter 4
DETECTION
Chapter 5
SYNCHRONIZATION
Chapter 6

PERFORMANCE LIMITS FOR COHERENT & NON-COHERENT UWB

- **J. A. López-Salcedo**, G. Vázquez, "*Closed-Form Upper Bounds for the Constellation-Constrained Capacity of UWB Communications*", Proc. IEEE ICASSP'2007, Hawaii (USA), **April 2007**.

Capacity in the Wideband Regime

Impact of Channel State Information

- Controversial result by Kennedy (1969) and Telatar (2000):

$$\mathsf{C}_{W\to\infty}^{\mathsf{AWGN}} = \mathsf{C}_{W\to\infty}^{\mathsf{no\ CSI}} = \frac{P_S}{N_0}\log_2 e$$

- But, **does UWB capacity -really- depend on CSI?**

  YES when taking into consideration:
  - the actual effect of finite bandwidth
  - peakiness constraints

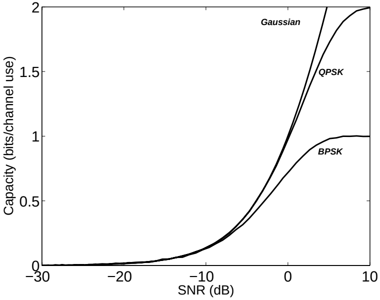
- **How to analyze capacity in the wideband regime?**

  Introducing the spectral efficiency ratio $\left(\frac{R}{W}\right) \Rightarrow \frac{\mathsf{SNR}}{\frac{R}{W}} = \frac{\mathbf{E_b}}{\mathbf{N_0}}$

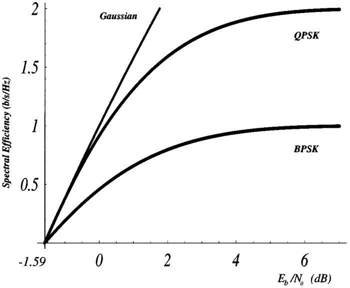
Capacity in the Wideband Regime

The same magnitude, two different perspectives

Capacity vs. SNR



Capacity vs. E_b/N_0



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SPECTRAL EFFICIENCY

Capacity in the Wideband Regime

Analysis of Spectral Efficiency

- Key parameters for analyzing spectral efficiency [Verdu(2002)]:
  - **Local analysis** of capacity around $\mathsf{SNR} = 0$

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

  - **Minimum required bit energy** for reliable communication:

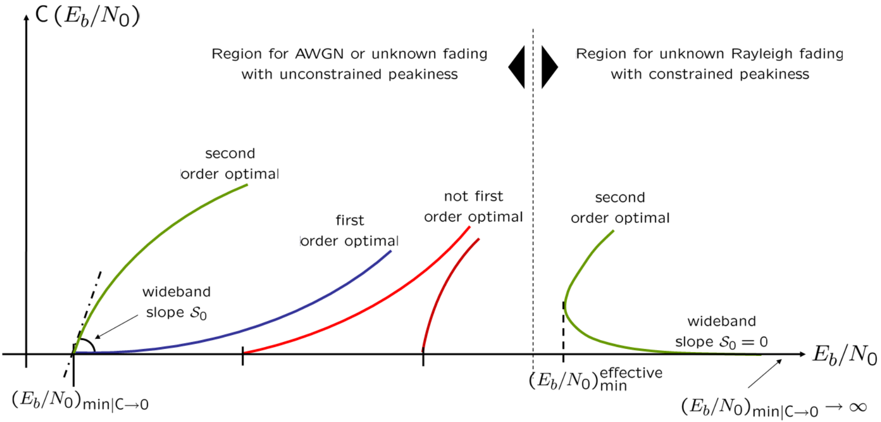
$$\left(\frac{E_b}{N_0}\right)_{\mathsf{min}} = \frac{1}{\mathsf{C}'\left(\mathsf{SNR}=0\right)}$$

  - **Wideband slope** or capacity increase per 3 dB of $\mathsf{E_b}/\mathsf{N_0}$,

$$\mathcal{S}_0 = -2\frac{\left[\mathsf{C}'\left(\mathsf{SNR}=0\right)\right]^2}{\mathsf{C}''\left(\mathsf{SNR}=0\right)} \qquad (\mathsf{bits/s/Hz/3dB})$$

Capacity in the Wideband Regime

Wideband Optimality



Capacity in the Wideband Regime

Wideband Optimality

- Results for AWGN and unknown Rayleigh fading channels

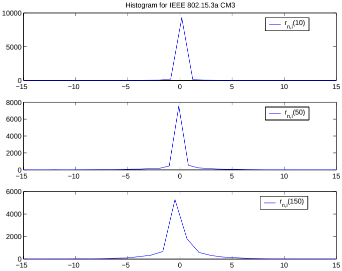
		$(E_b/N_0)_{\min}$	$\mathcal{S}_0$
Unconstrained peakiness	AWGN	$\log 2$	2
	Unknown Rayleigh fading	$\log 2$	0
Constrained peakiness	AWGN	$\log 2$	2
	Unknown Rayleigh fading	∞	0

- Concept of **wideband optimality**
  - **1st Order optimal :** $\left(\frac{E_b}{N_0}\right)_{\text{min}} = \left(\frac{E_b}{N_0}\right)_{\text{min}}^{\text{AWGN}}$
  - **2nd Order optimal :** if 1st order optimal **and** $\mathcal{S}_0$ is achieved

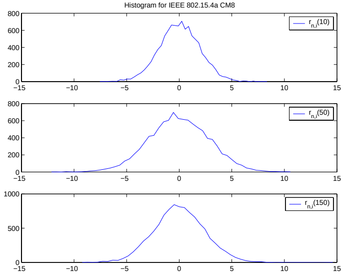
Capacity Upper Bounds for UWB Communications
Channel Model

- UWB channel modeling is rather controversial.
- However, for some working conditions:

Gaussian assumption holds $\Rightarrow$ easy statistical formulation



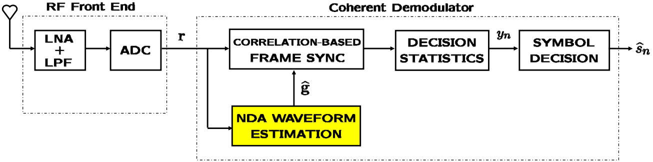
IEEE 802.15.3a CM3 (NLOS)



IEEE 802.15.4a CM8 (industrial)

Capacity Upper Bounds for UWB Communications

Coherent receivers - Available CSI

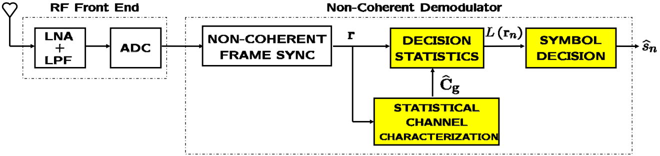


- Statistics for coherent PPM: $f\left(\mathbf{y}|\mathbf{x}_i, \mathbf{g}\right) \sim \mathcal{N}\left(\mathbf{h}_i, \mathbf{C}_w\right)$
- Closed-form upper bound for the constellation-constrained capacity:

$$\mathsf{C}_{\mathsf{c}\,|\,\mathrm{coh}} \leq \log_2 P - \log_2\left(1 + (P-1)\exp\left(-\frac{\rho}{2}\right)\right)$$

Capacity Upper Bounds for UWB Communications

Non-coherent receivers - Not available CSI



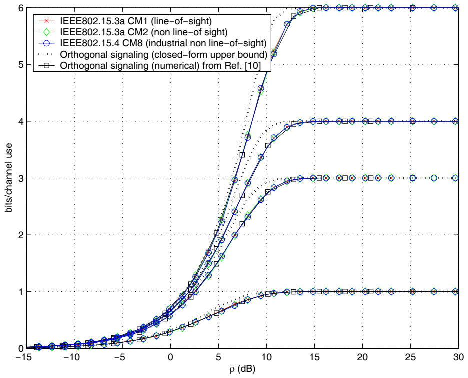
- Statistics for non-coherent PPM: $f\left(\mathbf{y}|\mathbf{x}_i\right) \sim \mathcal{N}\left(0, \mathbf{C}_w + \mathbf{C}_{\mathbf{h}_i}\right)$
- Closed-form upper bound for the constellation-constrained capacity:

$$C_{c\,|\,\text{no-coh}}^{\text{US}} \leq \log_2 P - \frac{1}{P}\sum_{i=0}^{P-1}\log_2\sum_{j=0}^{P-1}\exp\left(-\frac{1}{2}\sum_{k=0}^{N_{ss}-1}\frac{\gamma_i(k)-\gamma_j(k)}{\sigma_w^2+\gamma_j(k)}\right)$$

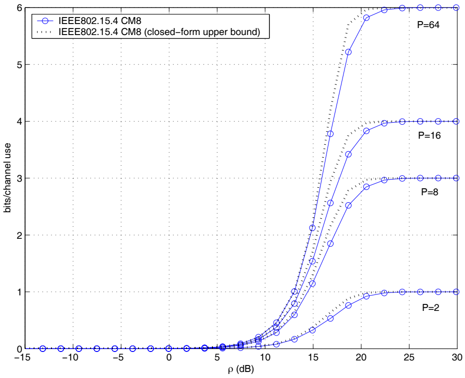
Capacity Upper Bounds for UWB Communications

Coherent vs. Non-coherent receivers

Coherent receivers



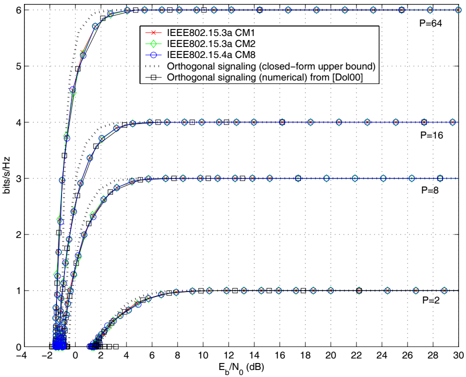
Non-coherent receivers (US)



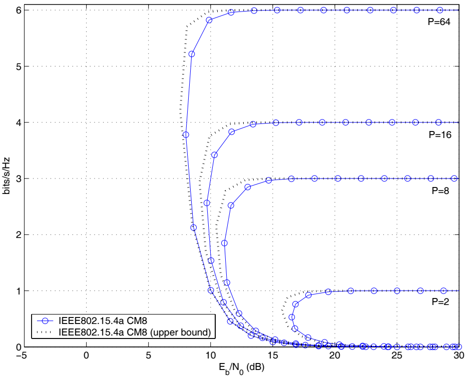
Capacity Upper Bounds for UWB Communications

Coherent vs. Non-coherent receivers

Coherent receivers



Non-coherent receivers (US)



$$\left(\frac{E_b}{N_0}\right)_{|\min} = \frac{\rho}{2C(\rho)}$$

Capacity Upper Bounds for UWB Communications

Some Conclusions...

- Then, which is the most convenient approach? Coherent? Non-coherent?

Channel time variation	Available CSI	Detection approach	Observations
slow	yes	coherent	-Excellent performance but, how to obtain perfect CSI?
moderate/rapid	no	non-coherent	-Low-complexity but, penalty for no CSI -Efficiency problem when $P \upuparrows$

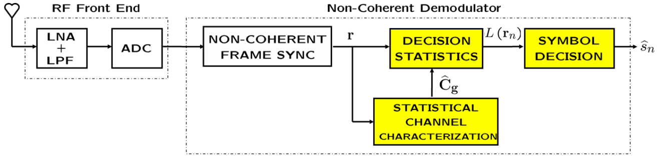
NON-COHERENT DETECTION OF UWB RANDOM SIGNALS

- **J. A. López-Salcedo**, G. Vázquez, "*Detection of UWB Random Signals*", Under second review in **IEEE Trans. on Signal Processing**, **May 2006**.

Motivation

- How to detect information symbols from UWB signals?

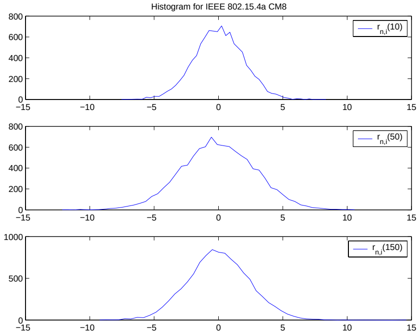
Channel time variation	Available CSI	Detection approach	Receiver implementation
slow	yes	coherent	correlator-based
moderate	no	non-coherent	transmitted-reference (TR)
rapid	**no**	**non-coherent**	**statistics-based (?)**



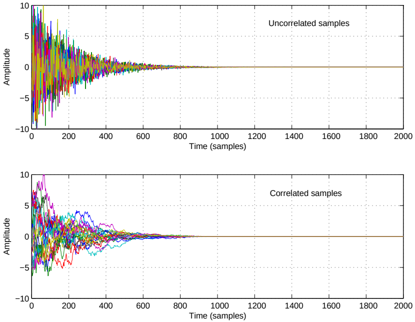
Waveform Signal Model

- Received waveforms $\sim$ Gaussian distributed with exponential PDP

- [Kar04], [Sch05b] -



IEEE 802.15.4a CM8 (industrial)



Uncorrelated and Correlated Scattering

Optimal Decision Statistics

- Decision based on the Generalized Likelihood Ratio Test (GLRT)

$$L(\mathbf{r}_n|\mathbf{C_g}) \doteq \log \frac{f\left(\mathbf{r}_n|\mathcal{H}_+;\mathbf{C_g}\right)}{f\left(\mathbf{r}_n|\mathcal{H}_-;\mathbf{C_g}\right)} \quad \Rightarrow \quad \widehat{s}_n = \mathsf{sign}\left(L(\mathbf{r}_n|\mathbf{C_g})\right)$$

- **Low-SNR** optimal decision statistics (GLRT):

$$L'(\mathbf{r}_n|\mathbf{C_g}) = Tr\Big(\underbrace{\left[\mathbf{C}_+ - \mathbf{C}_-\right]}_{\text{2nd order correlation template}} \widehat{\mathbf{R}}_n\Big)$$

  - Consistent with traditional but *ad-hoc* energy detection schemes
  - Extends deterministic correlation receivers to second order statistics
  - Insensitive to narrowband interferences

Optimal Decision Statistics

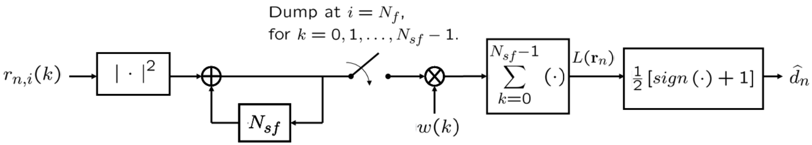
Uncorrelated Scattering Assumption

- **Low-SNR US** optimal decision statistics:

$$L'(\mathbf{r}_n) = \sum_{k=0}^{N_{sf}-1} w(k) \sum_{i=0}^{N_f-1} r_{n,i}^2(k)$$

  - Optimal statistics become a pure energy detector, **but...**
  - incoming samples are weighted according to their SNR

- Allows a simple receiver implementation:



Optimal Decision Statistics

Correlated Scattering Assumption

- **Low-SNR CS** optimal decision statistics:

$$L'(\mathbf{r}_n|\mathbf{C}_\mathbf{g}) = Tr\Big(\underbrace{\left[\mathbf{C}_+ - \mathbf{C}_-\right]}_{\textbf{unknown!!}}\widehat{\mathbf{R}}_n\Big)$$

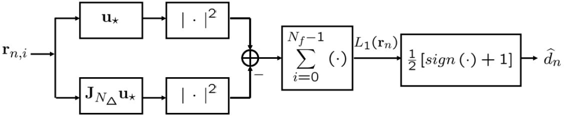
- Proposed **Conditional log-GLRT**
  1. Estimate $\mathbf{C}_+$ from incoming data: $vec\left(\widehat{\mathbf{C}}_+\right) = \mathbf{A}_\mathrm{S}^{-1} vec\left(\widehat{\mathbf{R}} - \mathbf{C}_\mathrm{N}\right)$
  2. Create the correlation template: $vec\left(\widehat{\mathbf{C}}_+ - \widehat{\mathbf{C}}_-\right) = \mathbf{A}_\mathrm{D}^T vec\left(\widehat{\mathbf{C}}_+\right)$
  3. **Compress** the estimated template into the low-SNR GLRT:

$$L'\left(\mathbf{r}_n\right) = \underbrace{vec^T\left(\widehat{\mathbf{R}} - \mathbf{C}_\mathrm{N}\right)\left(\mathbf{A}_\mathrm{S}^T\right)^{-1}\mathbf{A}_\mathrm{D}^T}_{\text{hypothesis testing template}} vec\,\widehat{\mathbf{R}}_n.$$

Optimal Decision Statistics

Rank-1 Receiver via Jeffrey's Divergence Maximization

- Rank-1 receiver:



- Rank-1 filter design criterion:

$$\mathbf{u}_\star \quad = \quad \arg\max_{\mathbf{u}_m} J(\mathcal{H}_+\|\mathcal{H}_-)\Big|_{\mathbf{C}_+=\mathbf{u}_m\mathbf{u}_m^T}$$

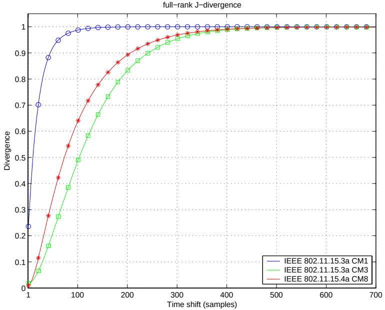
- **Jeffrey's divergence**:

$$J\left(\mathcal{H}_+\|\mathcal{H}_-\right) \doteq \mathsf{E}_{\mathbf{r}_n|\mathcal{H}_+}\left[L(\mathbf{r}_n)\right] - \mathsf{E}_{\mathbf{r}_n|\mathcal{H}_-}\left[L(\mathbf{r}_n)\right]$$

Optimal Decision Statistics

Rank-1 Receiver via Jeffrey's Divergence Maximization

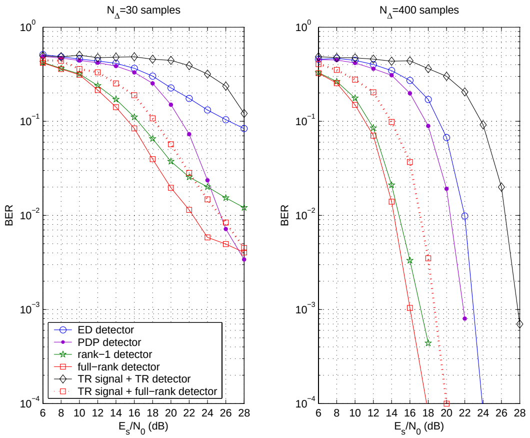
- For the problem at hand: $J(\mathcal{H}_+\|\mathcal{H}_-)=\|\mathbf{C}_+-\mathbf{C}_-\|_F^2$



- Rank-1 Jeffrey's divergence:

$$J(\mathcal{H}_+\|\mathcal{H}_-)\Big|_{\mathbf{C}_+=\mathbf{u}_m\mathbf{u}_m^T}=\frac{2}{N_f}\cdot\underbrace{\lambda_m^2}_{\text{eigenmode energy}}\cdot\left[1-\underbrace{\left(\mathbf{u}_m^T\mathbf{J}_{N_\Delta}\mathbf{u}_m\right)^2}_{\text{false detection constraint}}\right]$$

Simulation Results



Simulation parameters:

- 2-PPM in CS scenario
- Gaussian random waveforms
- Exp-Ds=100 samples, Exp-Cs=200 samples
- $N_f = 20$, $N_{sf} = 2000$, $L = 500$
- Channel changes every two frames

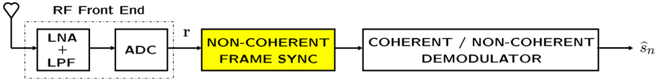
Conclusions:

- ED and PDP significantly degrade
- Rank-1 near-optimal performance when increasing N_Δ

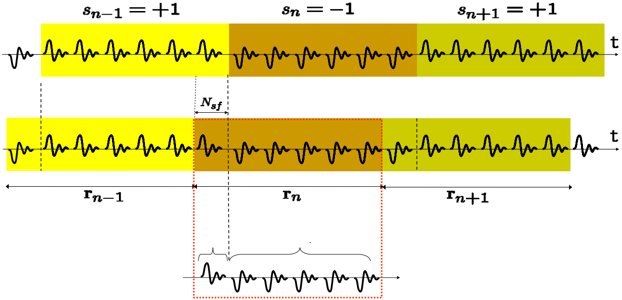
NON-COHERENT TIMING SYNCHRONIZATION

- **J. A. López-Salcedo**, G. Vázquez, "*Waveform Independent Frame-Timing Acquisition for UWB Signals*", **IEEE Trans. on Signal Processing**, Vol. 55, No. 1, **January 2007**.
- **J. A. López-Salcedo**, G. Vázquez, "*Frame-Timing Acquisition for UWB Signals via the Multifamily Likelihood Ratio Test*", IEEE SPAWC, Cannes (France), **June 2006**.

Motivation



- How to synchronize when the received waveform is unknown?



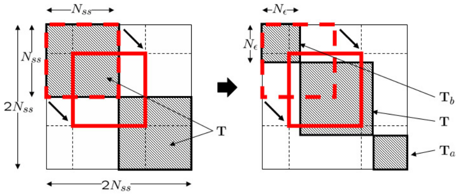
Proposed Frame-Timing Acquisition Technique (I)

Direct UML Approach

- Low-SNR Unconditional Maximum Likelihood (UML) criterion:

$$\widehat{N}_{\epsilon}^{\mathsf{UML}} = \arg \max_{0 \le m \le (N_f - 1)} \|\mathbf{\Pi}^T(m)\mathbf{R}_2(0)\mathbf{\Pi}(m)\|_F^2$$

- Interpretation as an **energy detection** technique

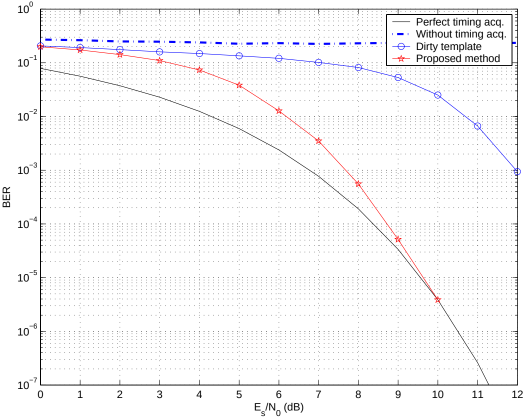


Matrix $\mathbf{R}_2$ when no timing error is present

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

Simulation Results

Direct UML Approach



Simulation parameters:

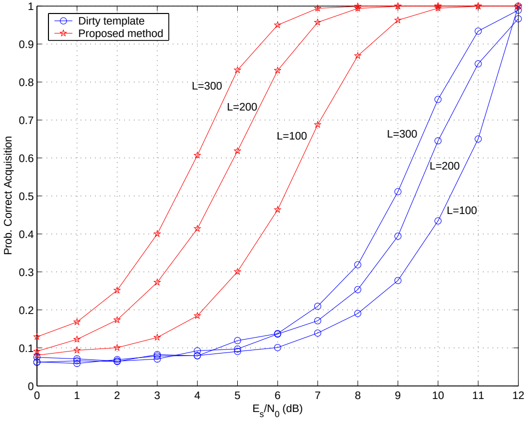
- 2-PAM
- IEEE 802.15.3a CM1
- $T_f = 86$ ns, $N_f = 16$, $L = 200$
- Uniformly distributed timing error

Conclusion:

- Much more robust performance compared to existing techniques (DT)

Simulation Results

Direct UML Approach



Simulation parameters:

- 2-PAM
- IEEE 802.15.3a CM1
- $T_f = 86$ ns, $N_f = 16$, $L = 200$
- Uniformly distributed timing error

Conclusion:

- Probability of correct acquisition can be improved up to a factor of 8 compared to DT

Proposed Frame-Timing Acquisition Technique (II)

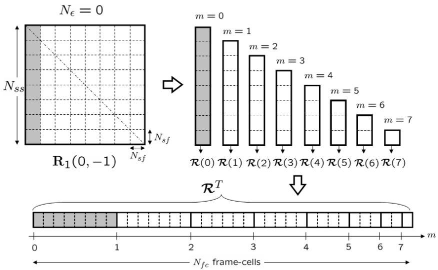
Multifamily Likelihood Ratio Test Approach

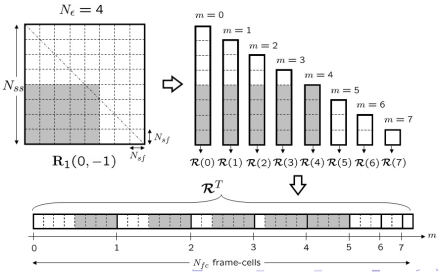
- Complexity can be reduced by reformulating the UML criterion as

$$\widehat{N}_{\epsilon}^{\mathrm{UML}} = \arg \max_{0 \le m \le N_f - 1} \|\mathbf{R}_1(0,-1)\|_F^2$$

$$\mathbf{R}_k(m,l) \doteq E\left[\mathbf{r}_n(m)\,\mathbf{r}_{n+k}^T(m+l)\right]$$

- Timing acquisition becomes a **model order detection** problem





Proposed Frame-Timing Acquisition Technique (II)

Multifamily Likelihood Ratio Test Approach

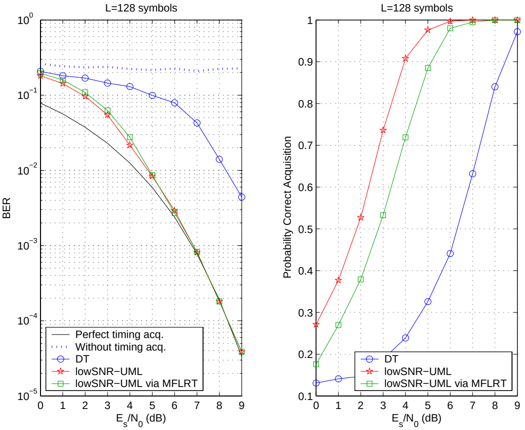
- How to determine the length of an unknown signal?
  - Multifamily Likelihood Ratio Test (MFLRT) [Kay05]
  - Reformulation of the UML cost function:

$$\widehat{N}_{\epsilon}^{\mathsf{MFLRT}} = \arg \max_{0 \leq m \leq (N_f - 1)} T_m(\boldsymbol{\mathcal{R}})$$

$$T_m(\boldsymbol{\mathcal{R}}) = \left[\underbrace{L_m(\boldsymbol{\mathcal{R}})}_{\text{log-Likelihood}} - \underbrace{N_u(m)\left(\ln\left(\frac{L_m(\boldsymbol{\mathcal{R}})}{N_u(m)}\right) + 1\right)}_{\text{model order penalty}} \right] u\left(\frac{L_m(\boldsymbol{\mathcal{R}})}{N_u(m)} - 1\right)$$

Simulation Results

Multifamily Likelihood Ratio Test Approach



Simulation parameters:

- 2-PAM
- IEEE 802.15.3a CM1
- $T_f = 46$ ns, $N_f = 8$, $L = 128$
- Uniformly distributed timing error

Conclusion:

- No performance degradation in terms of BER

WAVEFORM ESTIMATION FOR COHERENT RECEIVERS

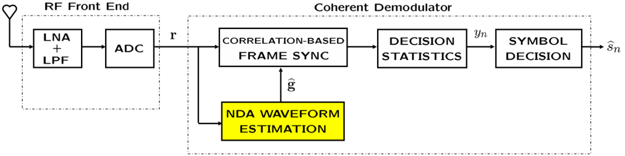
- **J. A. López-Salcedo**, G. Vázquez, "*NDA Waveform Estimation in the Low-SNR Regime*", **IEEE Trans. on Signal Processing**, accepted for publication.
- **J. A. López-Salcedo**, G. Vázquez, "*NDA Maximum-Likelihood Waveform Identification by Model Order Selection in Digital Modulations*", IEEE SPAWC, New York (USA), **June 2005**.

Motivation

- How to obtain (perfect) channel state information?
- **Problems:**
  - Traditional channel estimation techniques require high SNR...

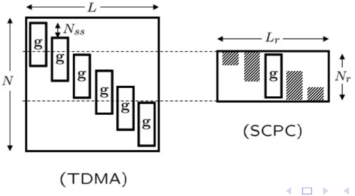
    but UWB operates in the low-SNR regime
  - Estimating the channel response may imply hundreds of delays and amplitudes to be estimated
- **Proposed approach:**
  - Unstructured approach for estimating the **whole** waveform
  - The **low-SNR** Maximum Likelihood criterion is adopted
  - **Nondata-aided** approach to avoid pilot symbols

Signal Model



- General signal model for PAM, PPM and APPM modulations:

$$\mathbf{r} = \sum_{p=0}^{P-1} \mathbf{A}_p(\mathbf{g})\mathbf{x}_p + \mathbf{w} \quad \Rightarrow \quad \mathbf{r} = \sum_{p=0}^{P-1} \sum_{n=-K}^{K} x_{n,p}\mathbf{K}_{n,p}\mathbf{g} + \mathbf{w}$$



Maximum Likelihood Estimation

Low-SNR Approximation

- Optimal ML waveform estimate:

$$\widehat{\mathbf{g}}_{\mathrm{ML}} = \arg\max_{\mathbf{g}} \Lambda\left(\mathbf{r}|\mathbf{g};\mathbf{x}\right)$$

- The **low-SNR** approximation leads to a compact log-Likelihood cost function

$$L'\left(\mathbf{r}|\mathbf{g}\right) = \underbrace{Tr\left(\breve{\mathbf{M}}\left[\mathbf{R} - \sigma_w^2 \mathbf{I}_{N_r}\right]\right)}_{\text{Correlation Matching}} + \underbrace{\frac{1}{2}\|\breve{\mathbf{M}}\|_F^2}_{\text{2nd Order Constraint}}$$

$$\breve{\mathbf{M}} \doteq \sum_{p=0}^{L_p-1} \sum_{n=-K_r}^{K_r} \breve{\mathbf{K}}_{n,p}\mathbf{g}\mathbf{g}^H \breve{\mathbf{K}}_{n,p}^H$$

Maximum Likelihood Estimation

Subspace Compressed Approach

- Efficient formulation by using the projection coordinates onto the signal subspace rather than the waveform samples themselves,

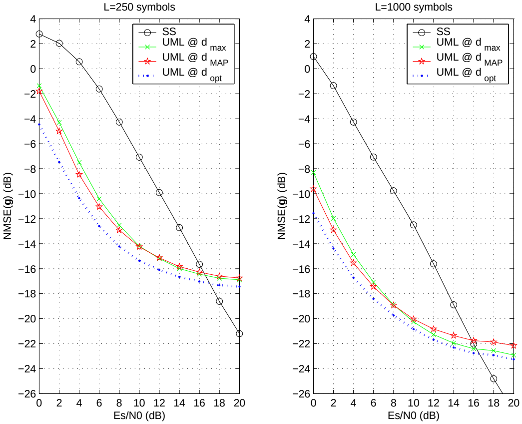
$$\mathbf{g} = \mathrm{U}_{\mathrm{s}}\boldsymbol{\alpha} \;\Rightarrow\; \frac{\text{length}\,\{\boldsymbol{\alpha}\}}{\text{length}\,\{\mathbf{g}\}} < 1 \;\Rightarrow\; \text{SNR gain}$$

- The log-Likelihood can indeed be formulated as a **least-squares** problem by using the $vec(\cdot)$ operator,

$$\max_{\boldsymbol{\alpha}_{\mathrm{v}}} L'\left(\mathbf{r}|\mathbf{g}\right) = \max_{\boldsymbol{\alpha}_{\mathrm{v}}} \left\{ \underbrace{\boldsymbol{\alpha}_{\mathrm{v}}^{H}\mathbf{Q}^{H}\mathring{\mathbf{r}}_{\mathrm{v}}}_{\text{CM}} + \underbrace{\frac{1}{2}\boldsymbol{\alpha}_{\mathrm{v}}^{H}\mathbf{Q}^{H}\mathbf{Q}\boldsymbol{\alpha}_{\mathrm{v}}}_{\text{2nd OC}} \right\} = \min_{\boldsymbol{\alpha}_{\mathrm{v}}} \left\| \mathring{\mathbf{r}}_{\mathrm{v}} - \mathbf{Q}\boldsymbol{\alpha}_{\mathrm{v}} \right\|^{2}$$

Simulation Results

MSE Performance



Simulation parameters:

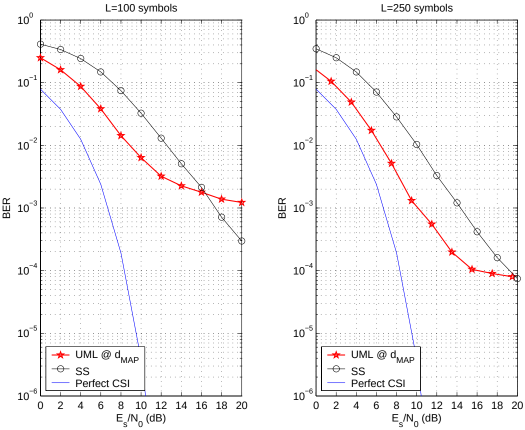
- 16-QAM modulation
- Complex-valued Gaussian waveform with $N_g = 8$
- Oversampling $N_{ss} = 2$

Conclusions:

- Significant gain in low-SNR regime
- Same slope as SS $\Rightarrow$ optimal performance in low-SNR regime
- Floor effect at high-SNR

Simulation Results

BER Performance



Simulation parameters:

- 16-QAM modulation
- Complex-valued random waveform with $N_g = 8$
- Oversampling $N_{ss} = 2$

Conclusions:

- No significant degradation is observed due to ill-conditioning
- BER can be reduced up to one order of magnitude

CONCLUSIONS

Conclusions

- Performance limits for coherent and non-coherent receivers
  - Closed-form approximations of capacity are derived
  - Tradeoff between using coherent or non-coherent receivers
- Non-coherent detection of UWB signals
  - Optimal schemes are proposed for rapid time-varying channels
  - Low-complexity implementations are proposed via rank-reduction
- Non-coherent timing synchronization
  - Optimal acquisition techniques are proposed based on low-SNR UML
  - Proposed techniques outperform existing frame-timing synchronizers
- Waveform estimation for coherent receivers
  - Optimal operation under the low-SNR regime is possible
  - The link with correlation matching techniques is established

Future Work

- Capacity analysis for UWB signals
  - Link between waveform distributions and capacity maximization
  - Further insights into the capacity convergence rate of coherent and non-coherent receivers
- Challenges in specific applications
  - Cognitive radio
  - Self-synchronized ad-hoc networking
  - High-sensibility positioning techniques

Thank you for your attention!