Master's Thesis Defense

Simplified Detection Techniques for Serially Concatenated Coded Continuous Phase Modulations

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Committee

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Relevance of this research

- Resources – power, bandwidth, and complexity
- Previous research on theoretical communication
- Intersection of theoretical research with reality: hardware implementation
- Objective
  - High gain (low power)
  - Low complexity

Simplified Detection Techniques for
Serially Concatenated Coded
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Presentation Outline

- Introduction
  - Background
  - Applications
  - Decoding algorithm
- Serially Concatenated Systems
  - Detection problems – decoding complexity, phase synchronization
  - Previous works on detection problems
- Motivation for the thesis
- Reduced complexity approaches
- Non-coherent detection algorithm
- Results
- Conclusions
- Future work

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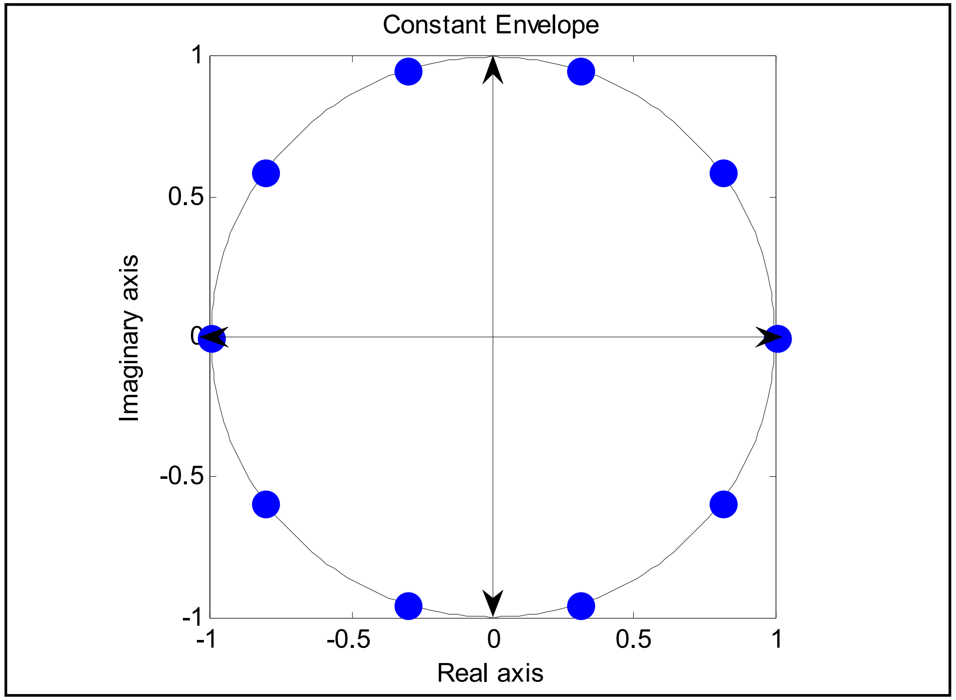
Introduction: Background

- Continuous Phase Modulation (CPM)
  - Constant envelope of phase
  - Memory
- Advantages
  - Simple and inexpensive transmitter
  - Power efficiency
  - High detection efficiency (BER)
  - Spectral efficiency
  - Suitable for non-linear power amplifiers
- Applications
  - Aeronautical telemetry
  - Deep space applications
  - Satellite communication
  - Bluetooth
  - Wireless modems



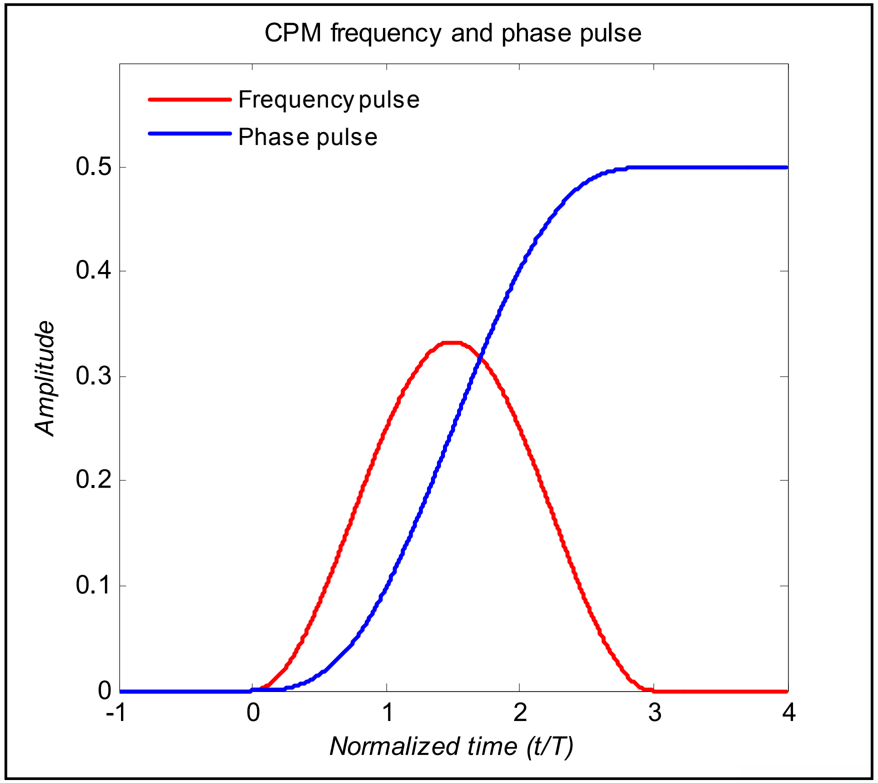
Introduction: Background

- Signal representation for a CPM
  - Phase of a CPM – linear filtering

$$s(t;\boldsymbol{\alpha}) = e^{j\phi(t,\boldsymbol{\alpha})}$$

$$\phi(t;\boldsymbol{\alpha}) = 2\pi \sum_{i=-\infty}^{\infty} h_{\underline{i}}\alpha_i q(t - iT_s)$$

$$h_{\underline{i}} = \frac{2K_{\underline{i}}}{P'}$$



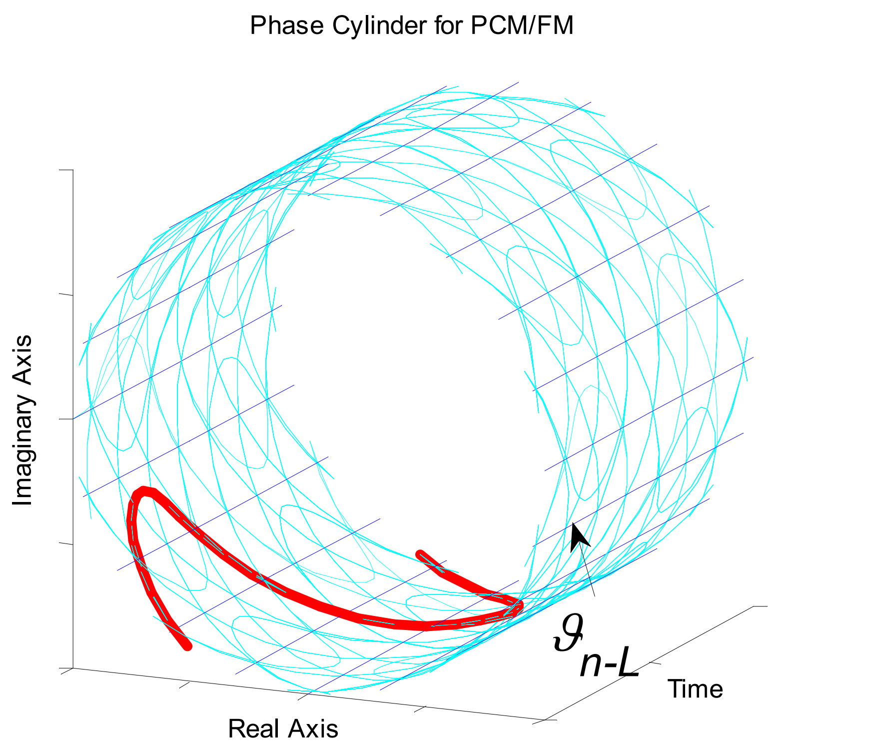
- Parameters defining a CPM
  - $h_{\underline{i}}$: modulation index
  - M : cardinality of source alphabet α
  - $q(t)$: phase pulse
  - L : length *(memory)* of $q(t)$

Complexity of a CPM

$$\phi(t;\boldsymbol{\alpha}) = \underbrace{\pi \sum_{i=0}^{n-L} h_{\underline{i}} \alpha_i}_{\vartheta_{n-L}} + \underbrace{2\pi \sum_{i=n-L+1}^{n} h_{\underline{i}} \alpha_i q(t - iT_s)}_{\theta(t)}$$

$$\sigma_S = \underbrace{\left(\vartheta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{P'M^{L-1} \text{ states}}$$

- Phase change depends on most recent L symbols *(phase trajectory)*
- Symbols older than L symbol times only indicate the phase of CPM at beginning of symbol interval *(cumulative phase)*



Maximum-Likelihood (ML) Decoding

- Recovery of information from *noisy* received signal
  - Matching received signal with all possible transmitted signals
  - Bank of matched filters *(correlators)*
  - Evaluated recursively by a *Soft Input Soft Output (SISO)* algorithm
  - Metrics given by matched filtered output combined with cumulative phase states

$$h_{\underline{i}} = \frac{2K_{\underline{i}}}{P'}$$

P' *cumulative phase states*

M^L *modulating symbols*

$N_{\mathrm{MF}} = M^L$ matched filters

$\boxed{P'M^L}$ *possible received signals*

$$\sigma_B = \underbrace{\left(\vartheta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}, \alpha_n\right)}_{P'M^L \text{ branches}}$$

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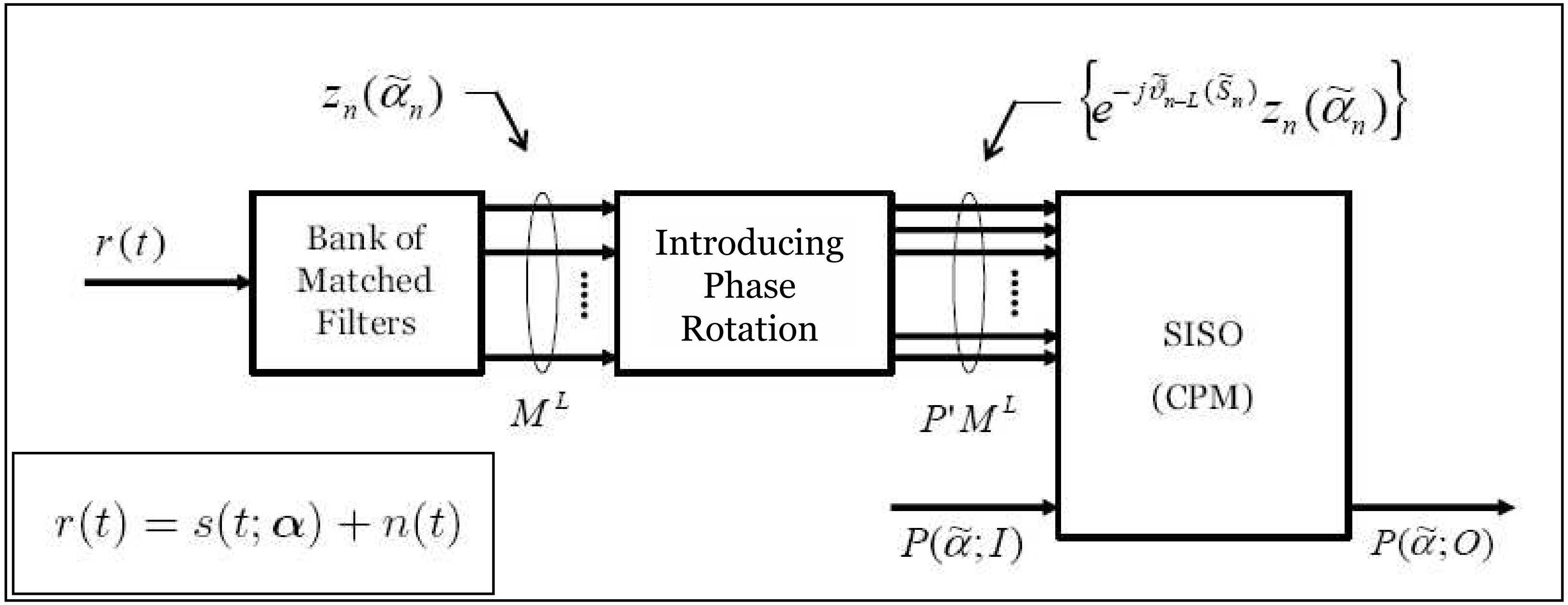
ML decoding: Branch metric computation

$$N_{\mathrm{MF}} = M^{L}$$

$$N_{\mathrm{S}} = P' M^{L-1}$$

$$N_{\mathrm{B}} = P' M^{L}$$



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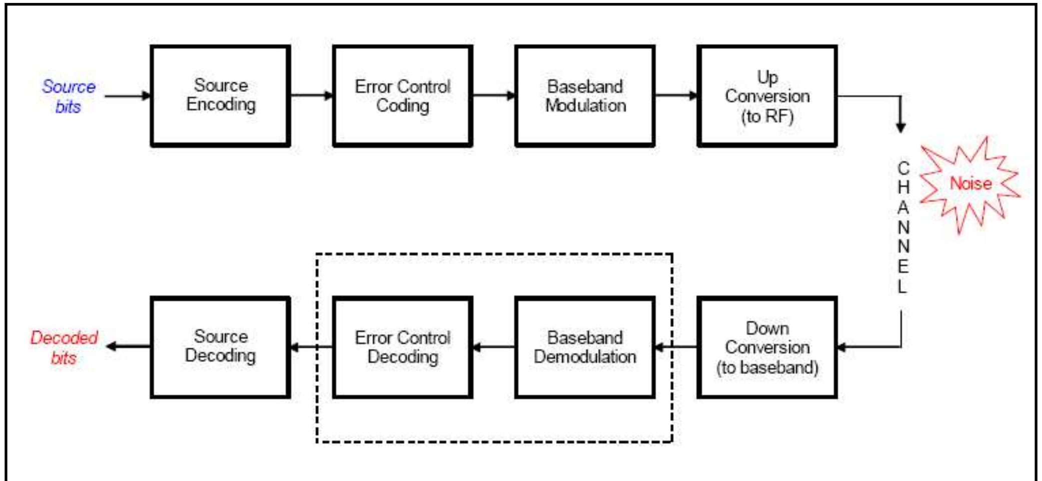
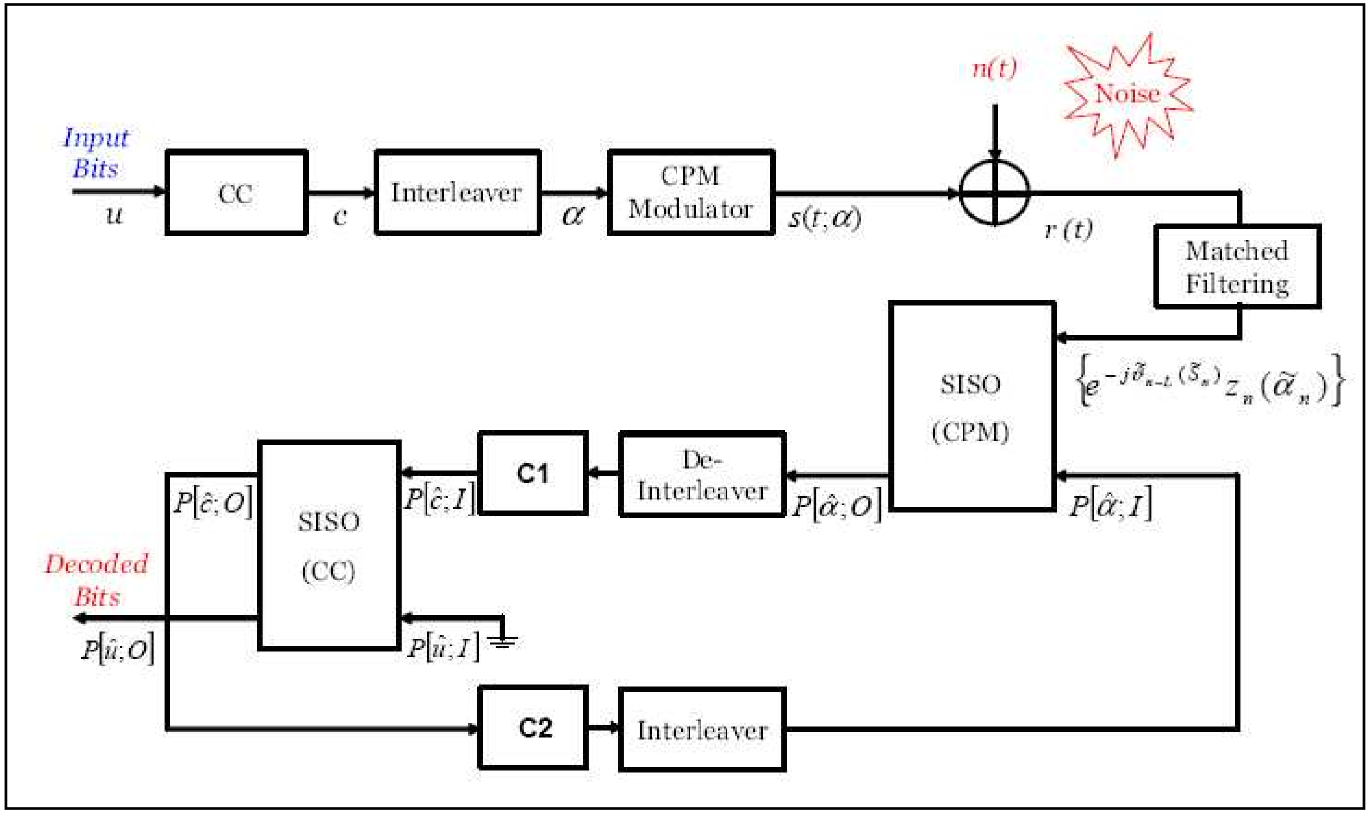
Serial Concatenation of CPM with Convolutional Codes (CC)

- Idea derived from the working principle of Turbo codes *(parallel concatenated codes)*
- Best gain if demodulation and decoding are done together *(ML decoding)*
- SCC system vs. *ML* decoding
- Benefits
  - Very high coding gains
  - Less complex than *ML* decoding of the system



A Simple Digital Communication System

Serial Concatenation of CPM with CC



$$P_e = k_1.Q\left(\sqrt{\frac{d_1 E_b}{N_0}}\right) + k_2.Q\left(\sqrt{\frac{d_2 E_b}{N_0}}\right) + ... + k_l.Q\left(\sqrt{\frac{d_l E_b}{N_0}}\right)$$

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Detection Problems

- High decoding complexity (*latency* and *computational* power)
  - Interleaver size
  - Number of iterations
  - Complexity vs. bandwidth efficiency
- Carrier phase synchronization
  - *Assumption* of perfect synchronization to carrier phase is *not often true*
  - PLL problems at low SNR: false locks, phase slips, loss of lock (Doppler shift), frequency jitters
  - Synchronization vs. with bandwidth efficiency
- Phase noise in addition to white noise
  - Channel affecting phase of CPM, which contains information

Previous Works (*on detection problems*)

SCC system, complexity reduction

- Pulse Truncation: Svensson, Sundberg, Aulin
- Decomposition approach to CPM: Rimoldi
- State space partitioning: Larsson, Aulin
- SCC CPM – Moqvist, Aulin (using SISO algorithm by Benedetto & others)
- SCC SOQPSK: Perrins (with *max-log* SISO and pulse truncation)

Non-coherent detection

- Non-coherent sequence estimation: Colavolpe, Raheli
- Reduced state BCJR type algorithm: Colavolpe, Ferrari, Raheli
- Non-coherent SCC MSK: Howlader
- Metric for non-coherent sequence estimation: Schober, Gerstacker

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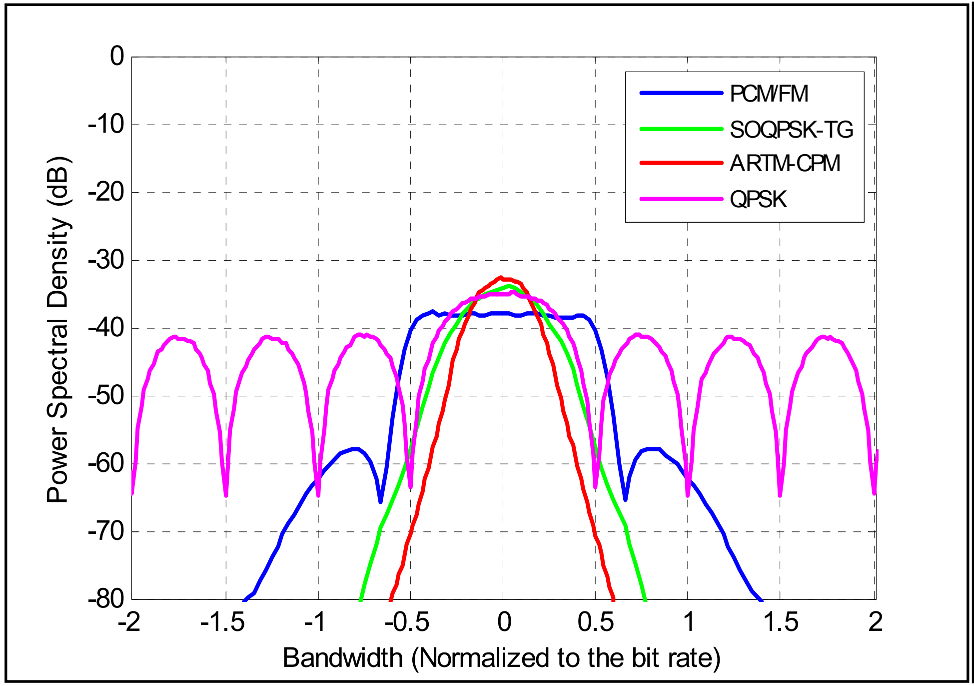
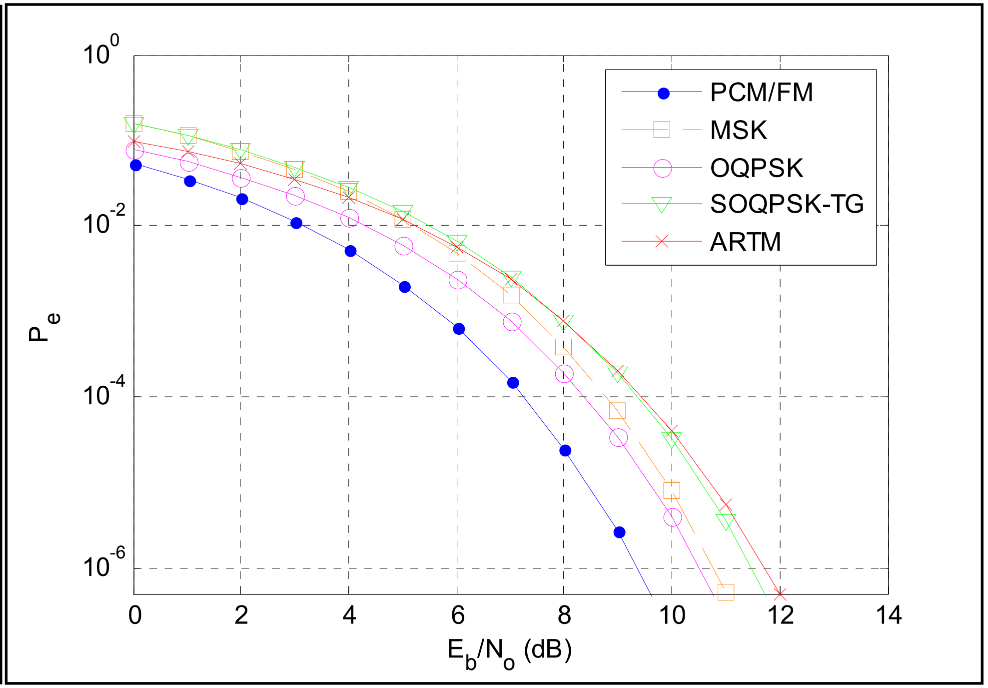
Motivation for the Thesis: *IRIG-106-04* CPMs





IRIG - 106-04 Aeronautical telemetry:

- PCM/FM (Tier-0)
- SOQPSK-TG (Tier-1)
- ARTM CPM (Tier-2)

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Motivation for the Thesis

Modulation	h	M	L	Pulse Type	State Complexity	Detection Efficiency	Spectral Efficiency	Decoding Complexity
PCM/FM	7/10	2	2	RC	**40**	1	3	1
SOQPSK-TG	1/2	2	8	TG	**512**	2	2	2
ARTM CPM	4/16, 5/16	4	3	RC	**512**	3	1	3

- *Complexity reduction* techniques for near optimal detection efficiency
- *Non-coherent detection* to recover information in presence of phase noise

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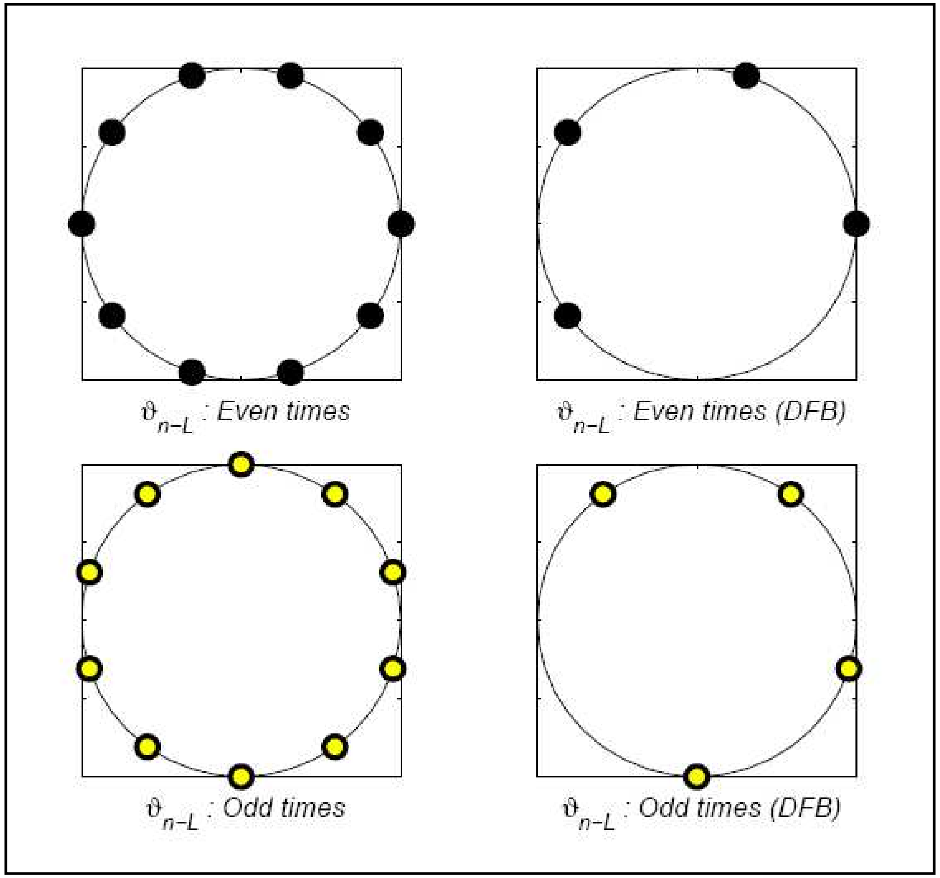
Decision Feedback

- Phase states chosen at *run time*
- Fewer phase states: $P_r < P \,, P = P'/2$
  complexity reduction by P/P_r
- Initial condition assumptions for cumulative phase states

$$\sigma_{\text{Earlier}} = \underbrace{\left(\upsilon_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{P'M^{L-1} \text{ states}}$$

$$\boxed{\sigma_{\text{DFB}} = \underbrace{\left(\hat{\theta}_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{P_r M^{L-1} \text{ states}}}$$

Phase state reduction



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Decision Feedback – Efficient Implementation

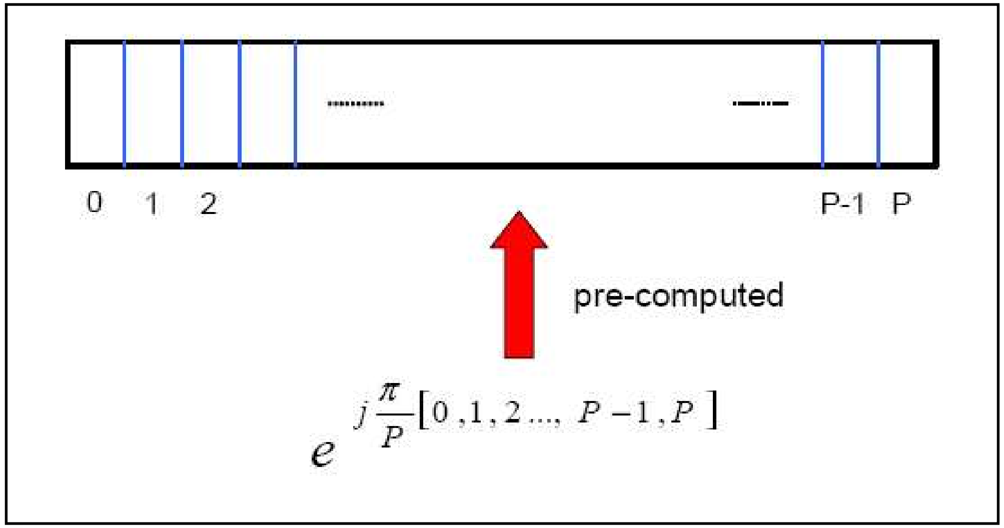
$$\hat{\theta}_{n-L+1}(\widetilde{E}_n^f) = \hat{\theta}_{n-L}(\widetilde{S}_n^f) + \pi h_{\underline{n-L+1}}\hat{u}_{n-L+1}$$

$$h_{\underline{i}} = \frac{K_{\underline{i}}}{P}$$

$$\theta_{n-L} = \frac{\pi}{P}.I_{n-L} = \frac{\pi}{P}.\underbrace{\sum_{i=0}^{n-L} 2K_{\underline{i}}u_i}_{integer}$$

$$\hat{I}_{n-L+1}(\widetilde{E}_n^f) = \left[\hat{I}_{n-L}(\widetilde{S}_n^f) + K_{\underline{n-L+1}}\hat{u}_{n-L+1}\right]_{\mathrm{mod}\ P}$$

Phase state table



- Complex phase state computations need floating point arithmetic
- Exploit the *modulo*-2π property of complex phase, so finite number of phase states can be represented by finite number of integer indices
- Access phase states by look-up index

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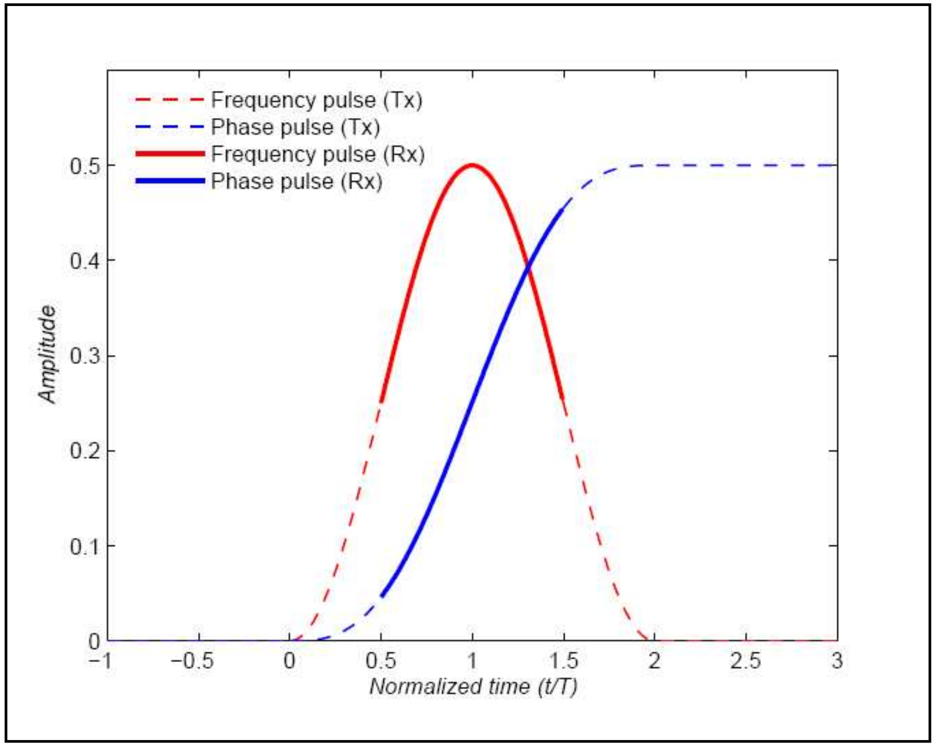
Pulse Truncation

- Truncated phase pulse: $L_r < L$
- Correlative state reduction
- Number of matched filters is reduced by a factor $< M^{(L-Lr)}$
- Time and Phase correction

ignored

$$\boxed{\sigma_{\mathrm{PT}} = \underbrace{\left(\theta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{PM^{L_r-1}\ \text{states}}}$$



$$z_n(\tilde{\alpha}_n^t) = \int_{nT_s}^{(n+1)T_s} r(t - DT_s)\, e^{-j2\pi \boldsymbol{h}_{\underline{n}}^t \tilde{\boldsymbol{\alpha}}_n^t q_{PT}(t-nT_s)} dt$$

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Non-coherent detection

- Received signal: $r(t) = e^{j\psi(t)} s(t; \boldsymbol{\alpha}) + n(t)$

- Previous works - branch metric computations:

$$\gamma_k^{\alpha}(e_k) = I_0\left(\frac{2}{N_0}\left|r_k x_k^* + q_{ref}(k-1)\right|^2\right)$$

$$\psi_k^{\alpha}(e_{k-1}, e_k) = \frac{I_0\left(\frac{2}{N_0}\left|r_k x_k^* + r_{k-1} x_{k-1}^* + q_{ref}(k-2)\right|^2\right)}{\gamma_k^{\alpha}(e_k)}$$

$$\phi_{k+1}^{\alpha}(e_k, e_{k+1}) = \frac{I_0\left(\frac{2}{N_0}\left|r_{k+1} x_{k+1}^* + r_k x_k^* + q_{ref}(k-1)\right|^2\right)}{\gamma_k^{\alpha}(e_k)}$$

Non-coherent detection: Proposed algorithm

- Phase noise averaged out, exponential window averaging

- Coherent detection: $\mathrm{Re}\left\{ e^{-j\nu_{n-L}} e^{-j\,\tilde{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\}$

- Non-coherent detection: $\mathrm{Re}\left\{ Q_n^*(\tilde{S}_n)\; e^{-j\nu_{n-L}} e^{-j\,\tilde{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\}$

1. Inexpensive
2. Compact
3. Robust
4. Low Complexity

$$Q_n(\tilde{E}_n) = \kappa Q_{n-1}(\tilde{S}_n) + (1-\kappa)\left\{ e^{-j\nu_{n-L}} e^{-j\,\tilde{\theta}_{n-L}(\tilde{S}_n)} \right\}$$

$$\lambda_n(\tilde{E}_n) = \lambda_{n-1}(\tilde{S}_n) + \mathrm{Re}\left\{ Q_n^*(\tilde{S}_n)\; e^{-j\nu_{n-L}} e^{-j\,\tilde{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\}$$

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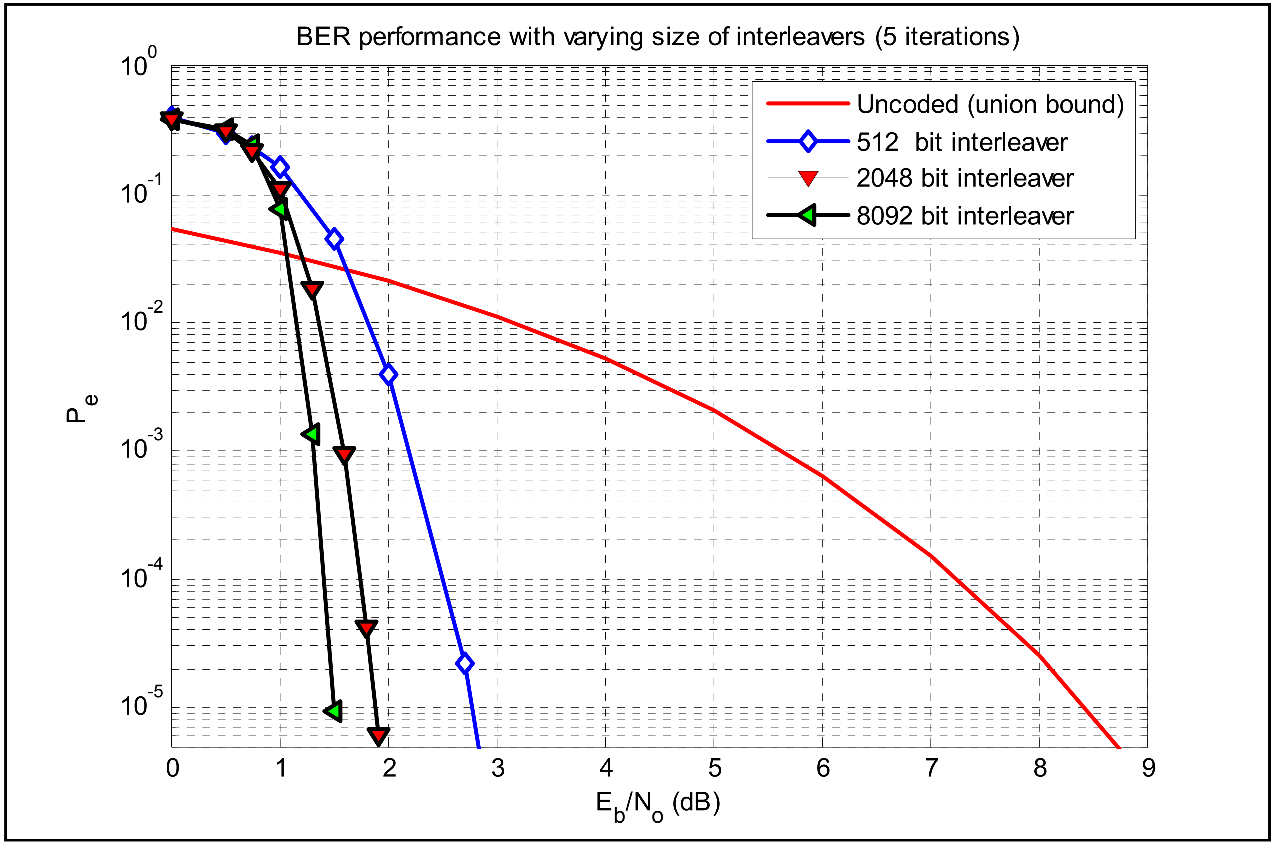
Results: SCC PCM/FM

- 6.55 dB coding gain with 2048 bit interleaver and 5 iterations



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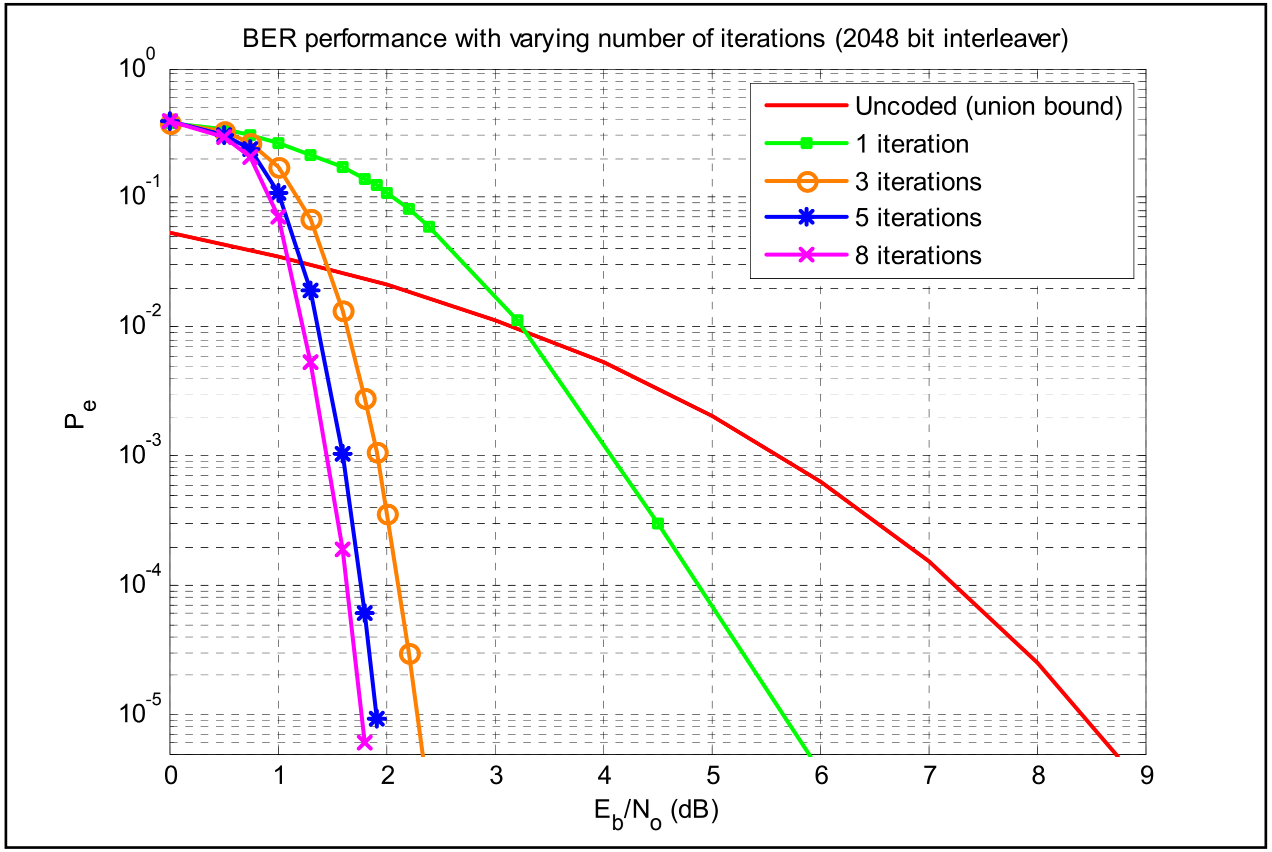

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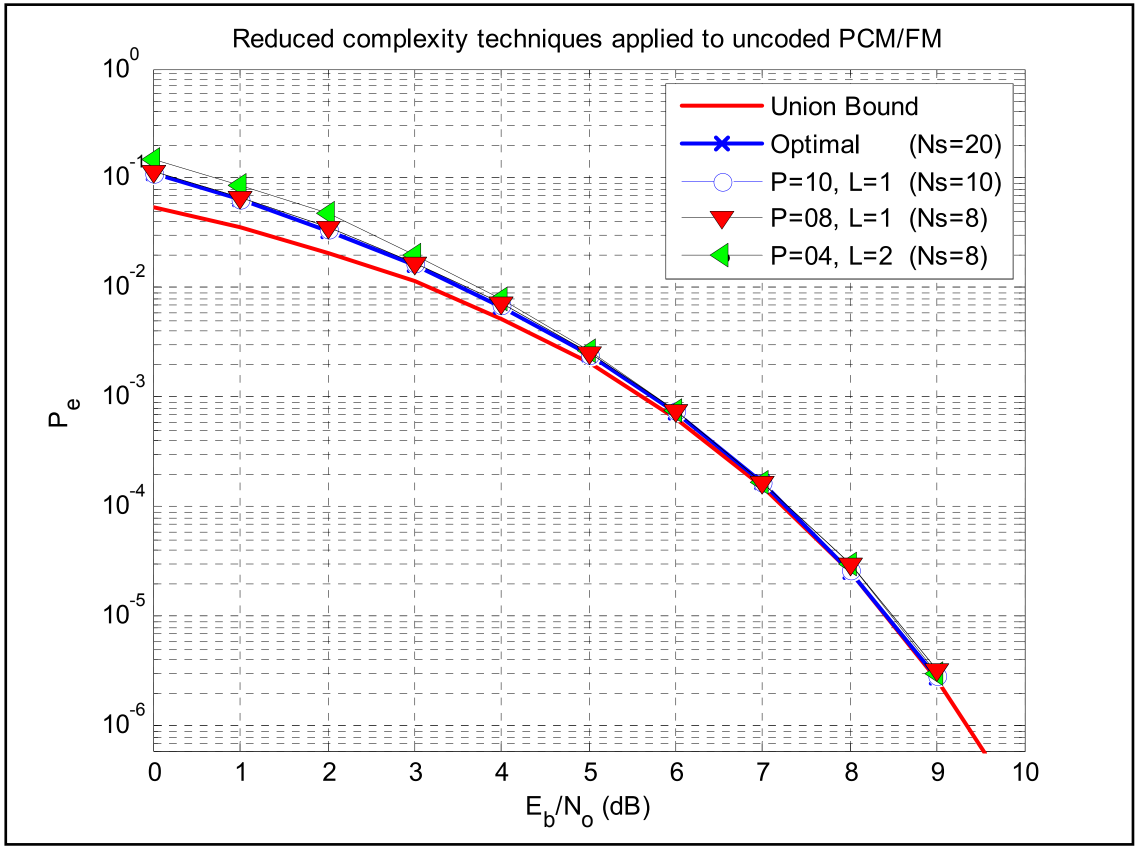
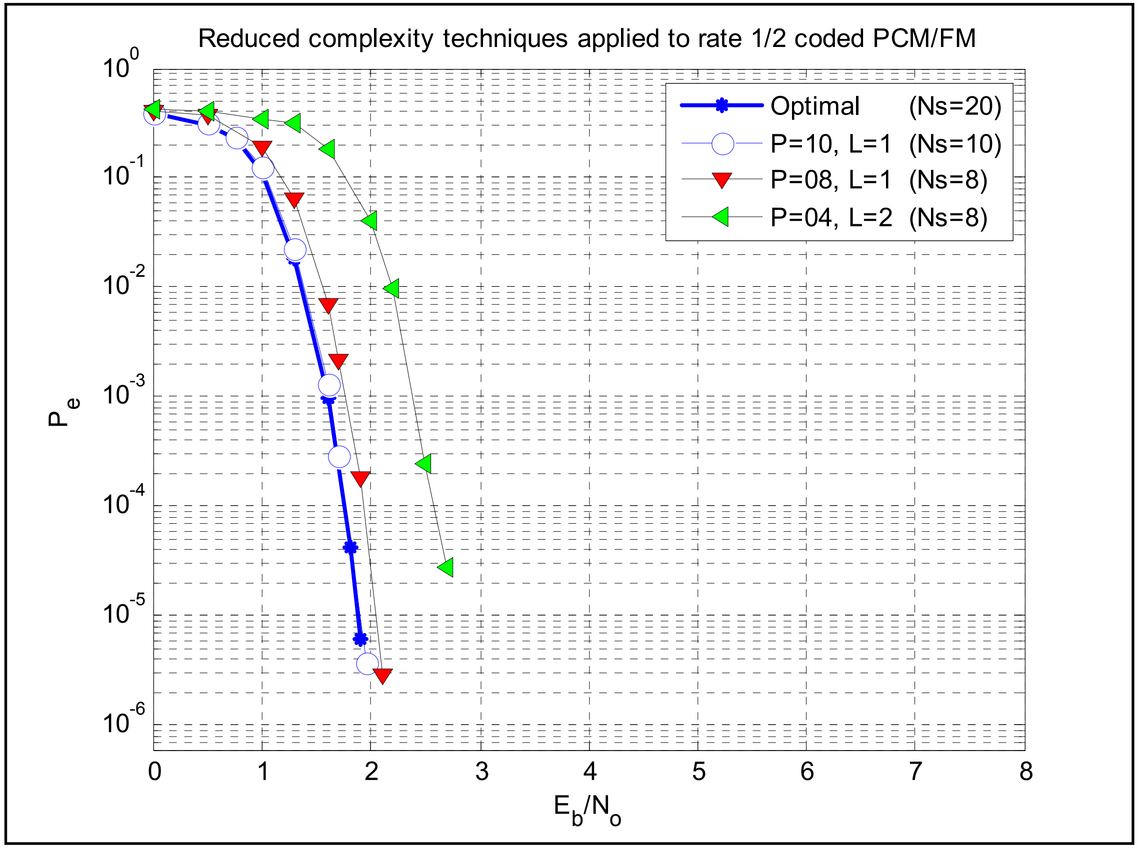
Results : Reduced Complexity PCM/FM

- Approximation at low E_b/N_0 is the key for the technique to be used in coded systems



Results : Reduced Complexity PCM/FM

- Loss in 10 state detector: 0.02 dB (reduction in complexity by a factor of 2)



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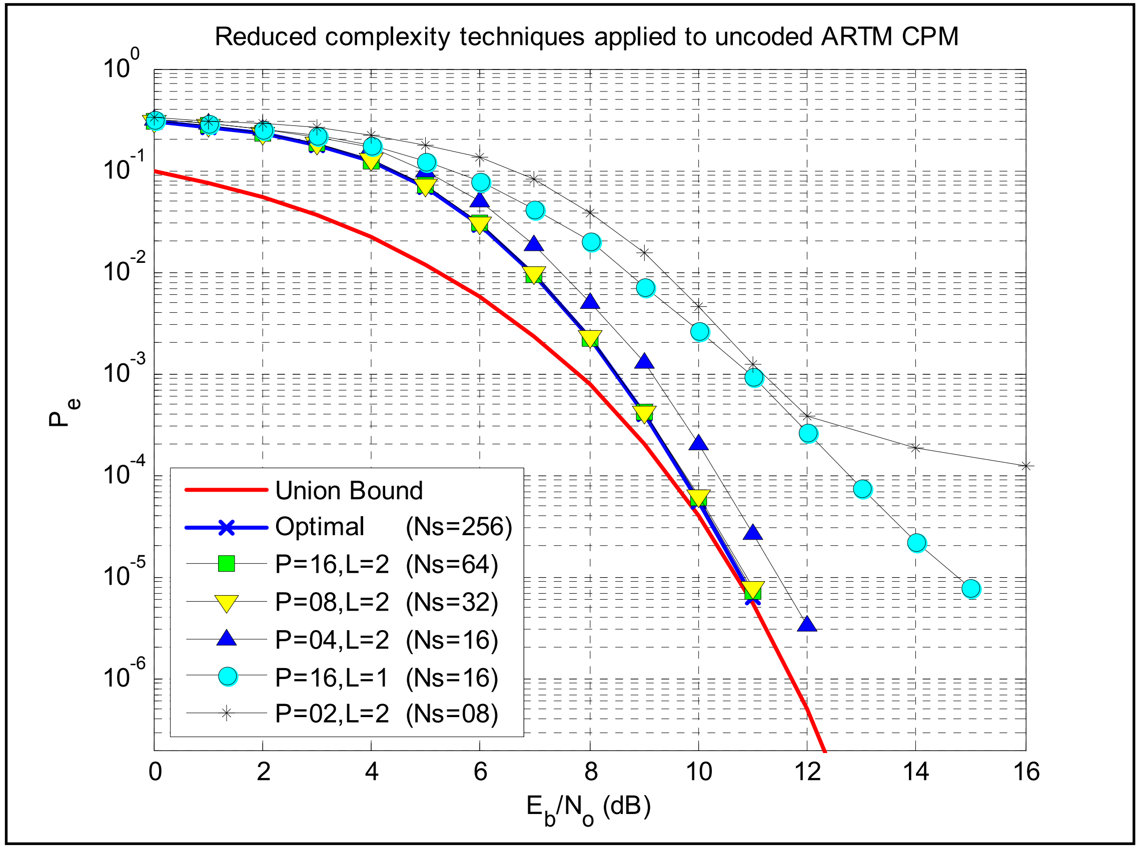
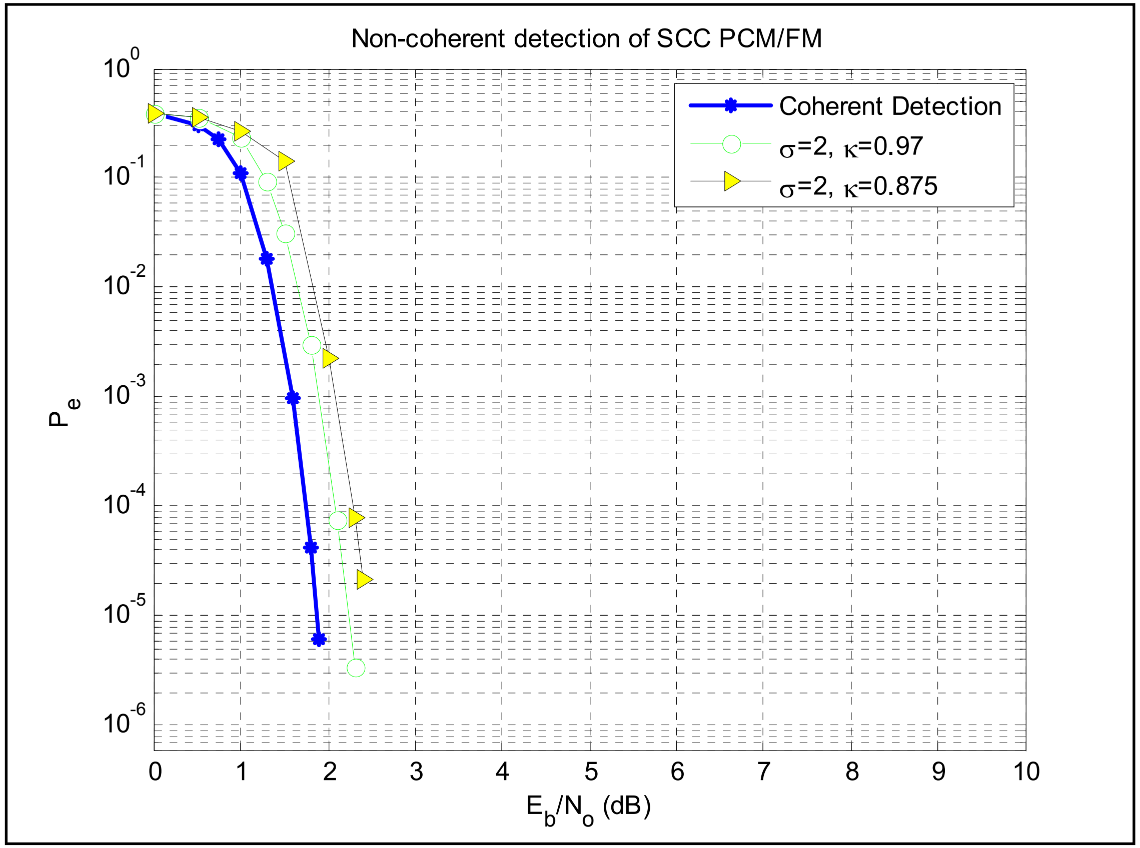
Results : Reduced Complexity ARTM CPM

- Loss in 32 state detector: 0.1 dB (reduction in complexity by a factor of 8)



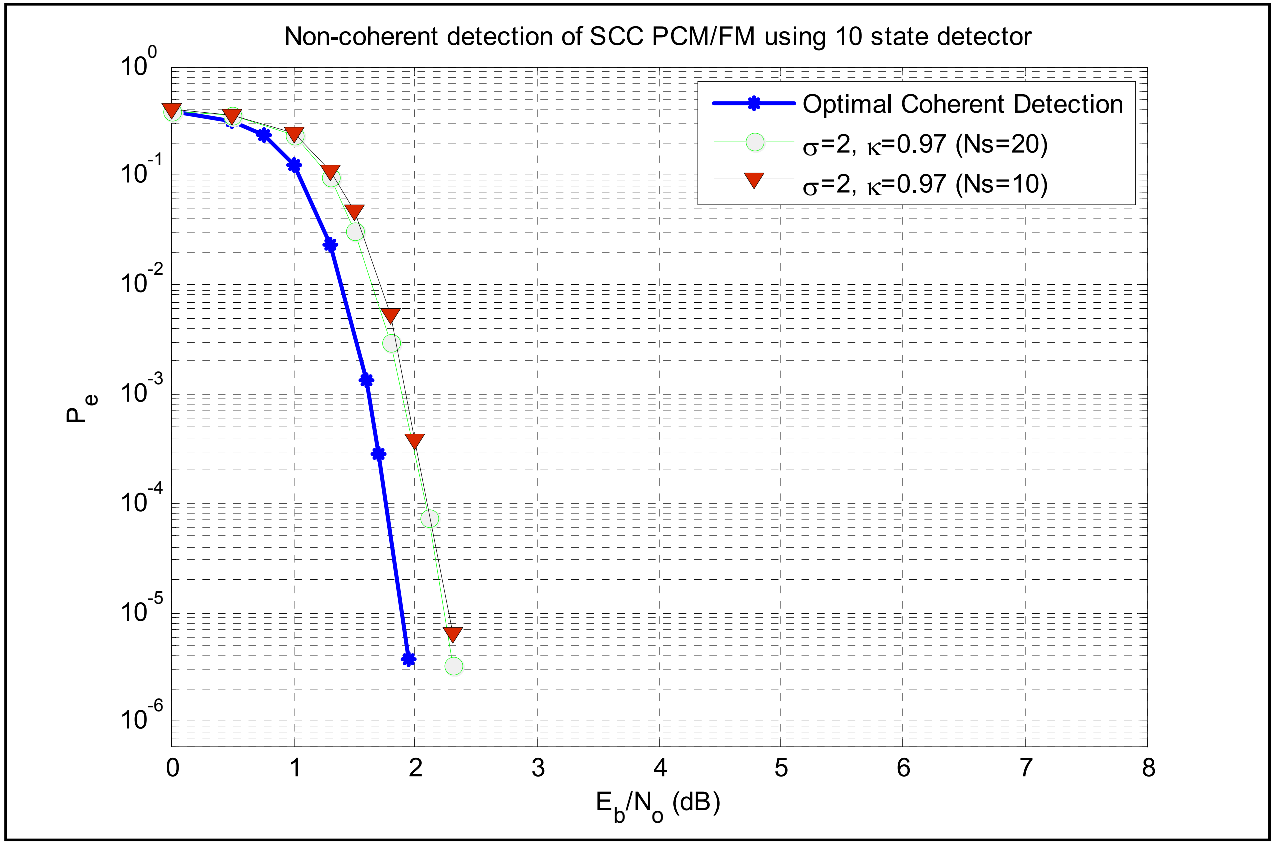
Results : Non-coherent PCM/FM

- Loss in 20 state non-coherent detector : 0.35 dB

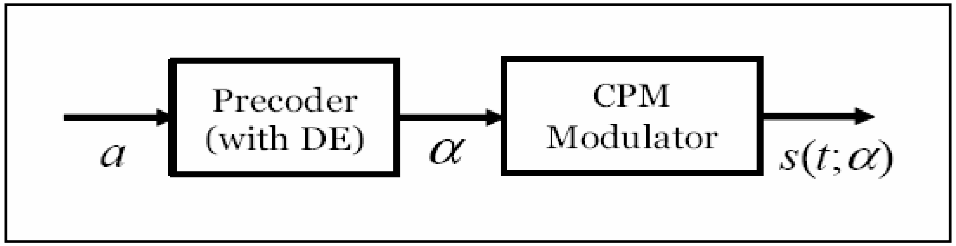


Results : Non-coherent PCM/FM

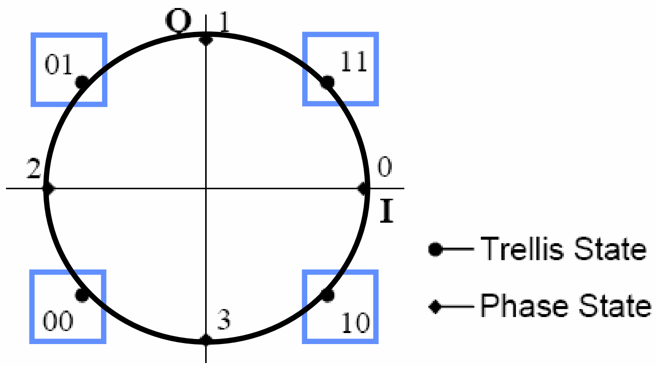
- Loss in 10 state non-coherent detector for SCC PCM/FM: 0.39 dB

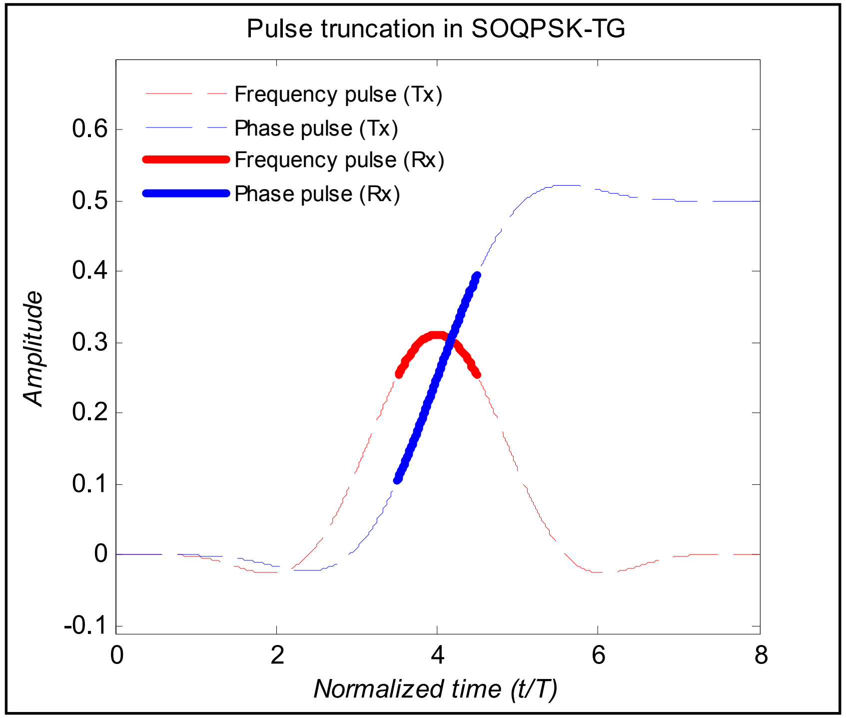


A digression: SOQPSK



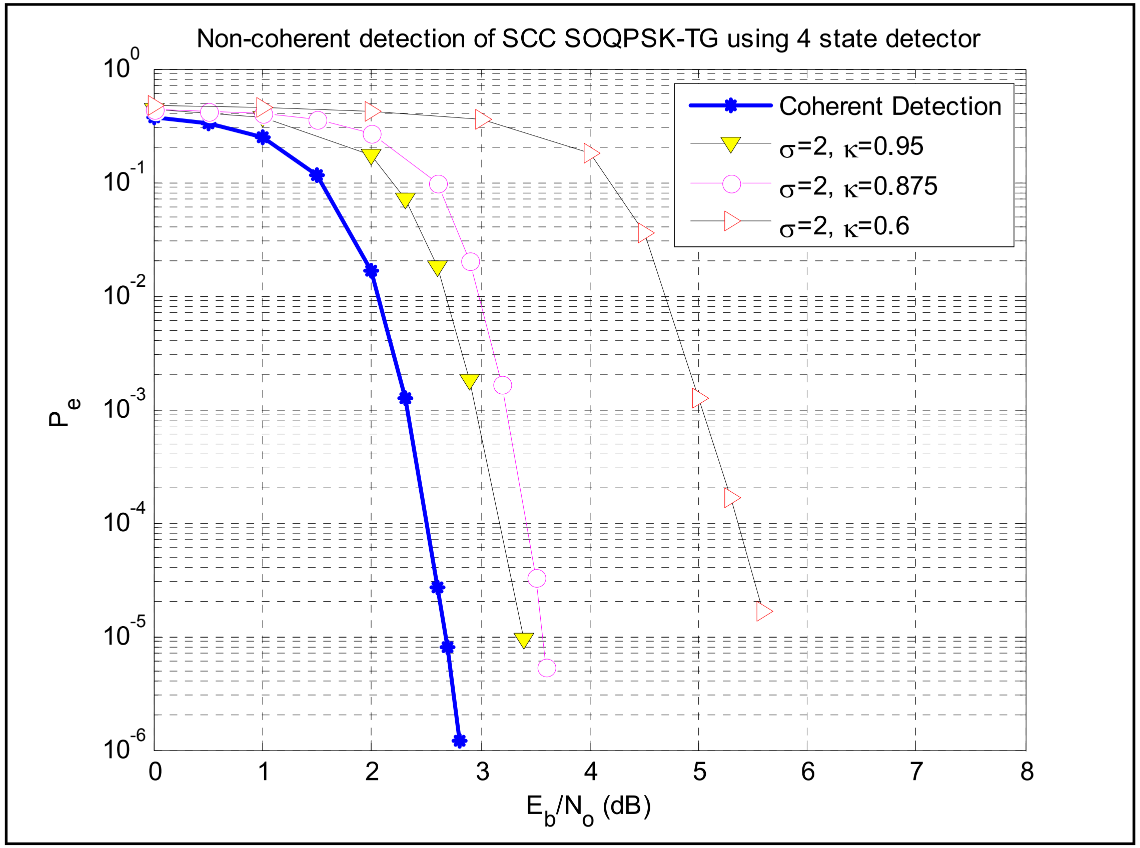
State	P_l
00	3
01	2
10	0
11	1





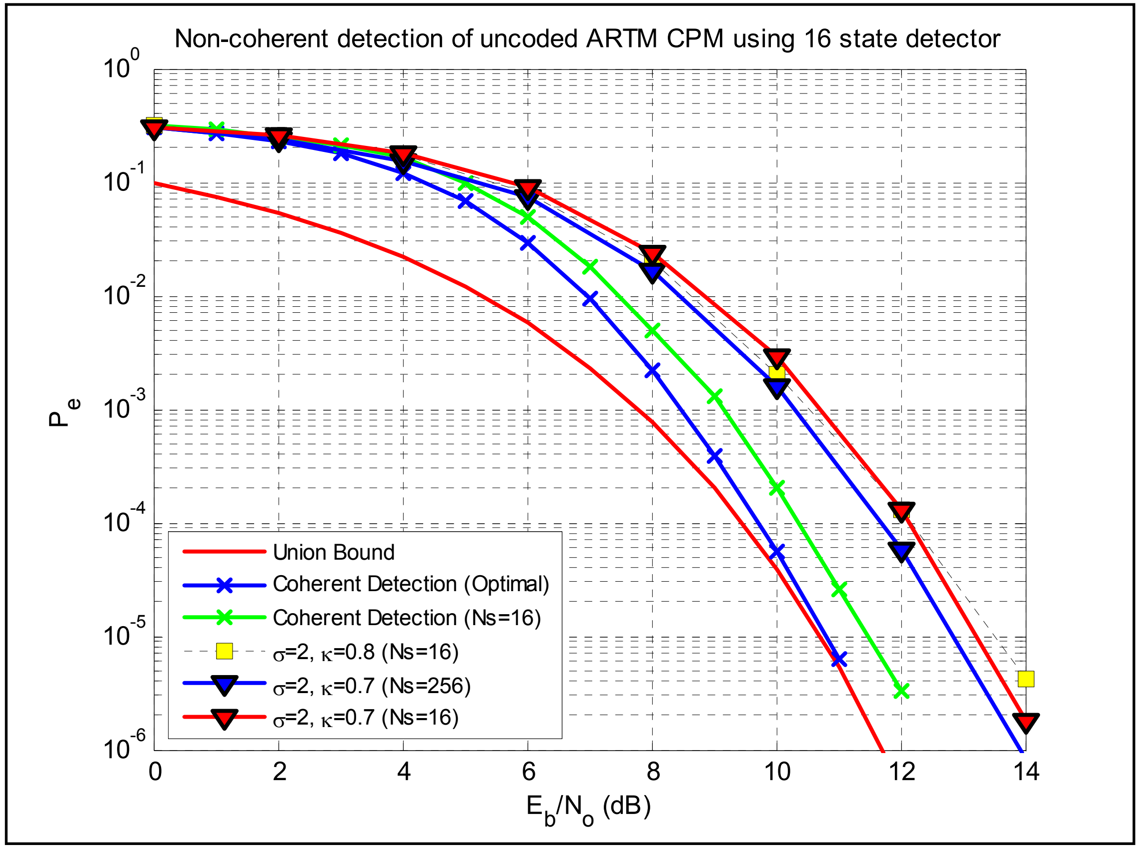
Results : Non-coherent SOQPSK-TG

- Loss in 4 state non-coherent detector for SCC SOQPSK: 0.71 dB



Results : Non-coherent ARTM

- Loss in 16 state non-coherent detector for uncoded ARTM CPM: 2.4 dB



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Conclusions: Key Contributions

- Reduced complexity detectors for coded PCM/FM
- Non-coherent detectors for uncoded PCM/FM, SOQPSK-TG, ARTM CPM
- Non-coherent detectors for reduced complexity SCC PCM/FM and SCC SOQPSK-TG
- Non-coherent detector for reduced complexity uncoded ARTM CPM

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Future work

- SCC ARTM CPM on the lines of SCC PCM/FM and SCC SOQPSK-TG

- The 32 and 16 state detectors could be used in the SCC ARTM CPM

- Non-coherent detector for 32/16 state SCC ARTM CPM

Paper publication

- Dileep Kumaraswamy and Erik Perrins, ”On Reduced Complexity Techniques For Bandwidth Efficient Continuous Phase Modulations in Serially Concatenated Coded Systems”, to appear in Proceedings of the International Telemetering Conference (ITC), Las Vegas, NV, October 22-25, 2007

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Acknowledgements

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- Dr. Alexander Wyglinski
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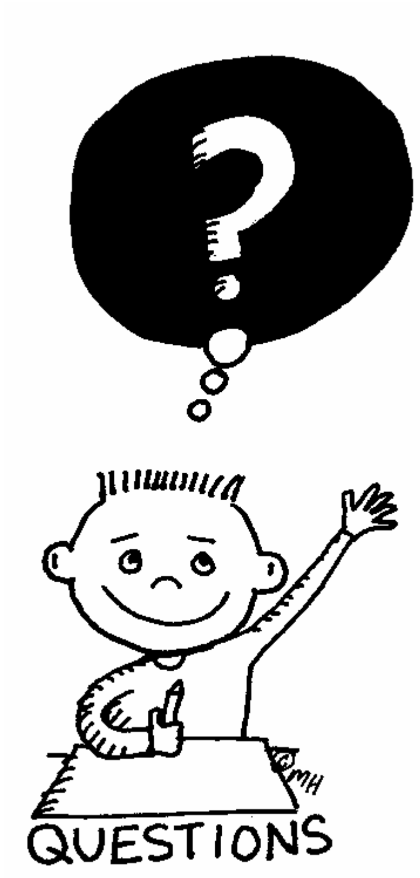
Questions



SISO algorithm - forward and reverse recursions

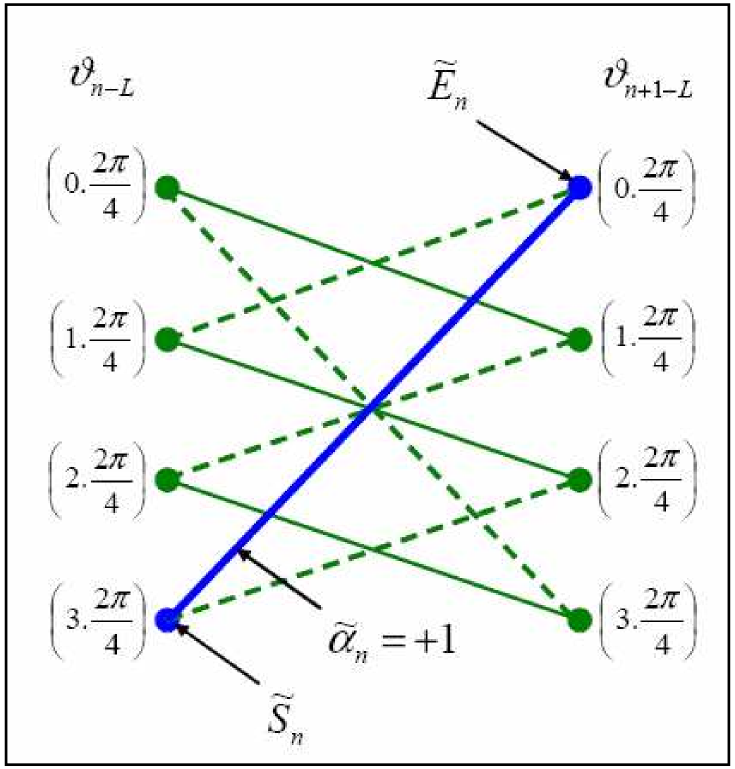
$$F_n(\widetilde{S}_n, \widetilde{E}_n) = \mathrm{Re}\left\{e^{-j\widetilde{\vartheta}_{n-L}(\widetilde{S}_n)} z_n(\widetilde{\boldsymbol{\alpha}}_n)\right\}$$

$$A_n(\widetilde{E}_n) = \left[A_{n-1}(\widetilde{S}_{n-1}) + P_n\left[\widetilde{\alpha}_n; I\right] + F_n(\widetilde{S}_n, \widetilde{E}_n)\right]$$

$$B_n(\widetilde{S}_n) = \left[B_{n+1}(\widetilde{E}_{n+1}) + P_{n+1}\left[\widetilde{\alpha}_{n+1}; I\right] + F_{n+1}(\widetilde{S}_{n+1}, \widetilde{E}_{n+1})\right]$$

$$P_n\left[\hat{\alpha}_n; O\right] = \left[A_{n-1}(\widetilde{S}_{n-1}) + P_n\left[\widetilde{\alpha}_n; I\right] + F_n(\widetilde{S}_n, \widetilde{E}_n) + B_{n+1}(\widetilde{E}_n)\right]$$

$$P_n(\hat{\boldsymbol{\alpha}}; O) = P_n(\widetilde{\boldsymbol{\alpha}}; O) - P_n(\widetilde{\boldsymbol{\alpha}}; I)$$



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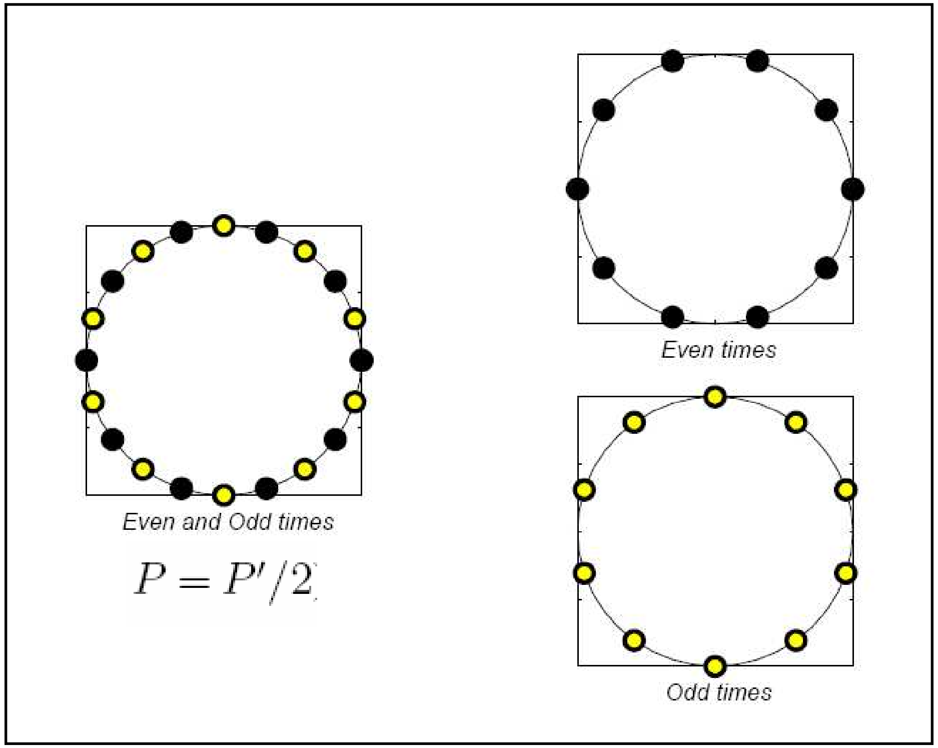
Rimoldi's Approach

- Odd and Even phase states
- Constant data independent (deterministic) phase change to switch from the phase states
- Complexity reduction by *half*
- *Optimal* decoding
- Not applicable to SOQPSK-TG

Decomposition of complex phase states



Rimoldi's Approach

$$\phi(t;\boldsymbol{\alpha}) = \underbrace{\pi \sum_{i=0}^{n-L} h_{\underline{i}}\alpha_i}_{\vartheta_{n-L}} + \underbrace{2\pi \sum_{i=n-L+1}^{n} h_{\underline{i}}\alpha_i q(t-iT_s)}_{\theta(t)}$$

$$\vartheta_{n-L} = \theta_{n-L} + \nu_{n-L}$$

$$\sigma_{\text{Earlier}} = \underbrace{\left(\upsilon_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{P'M^{L-1} \text{ states}}$$

$$\boxed{\sigma_{\text{Rimoldi}} = \underbrace{\left(\theta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}\right)}_{PM^{L-1} \text{ states}}}$$