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 Continuous Phase Modulations

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- 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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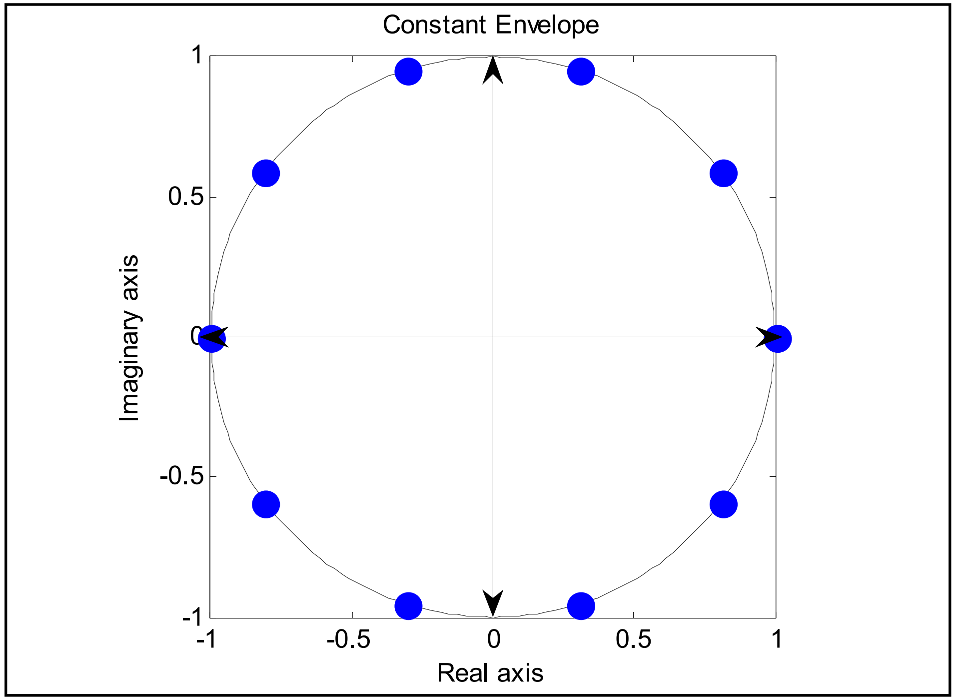
Introduction: Background

- 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



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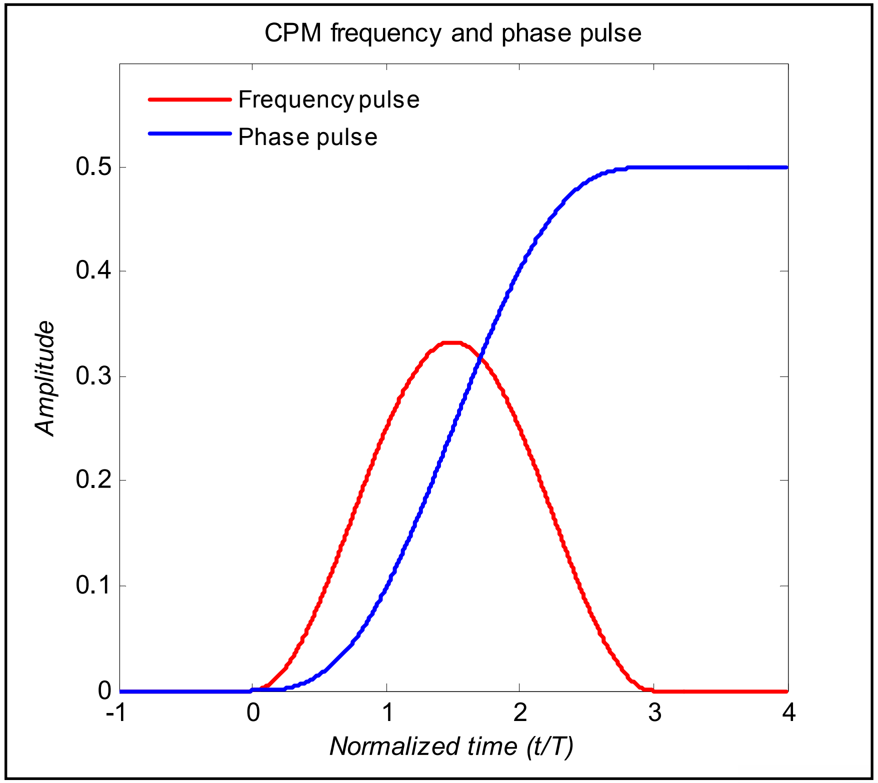
Introduction: Background

- 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 $q(t)$

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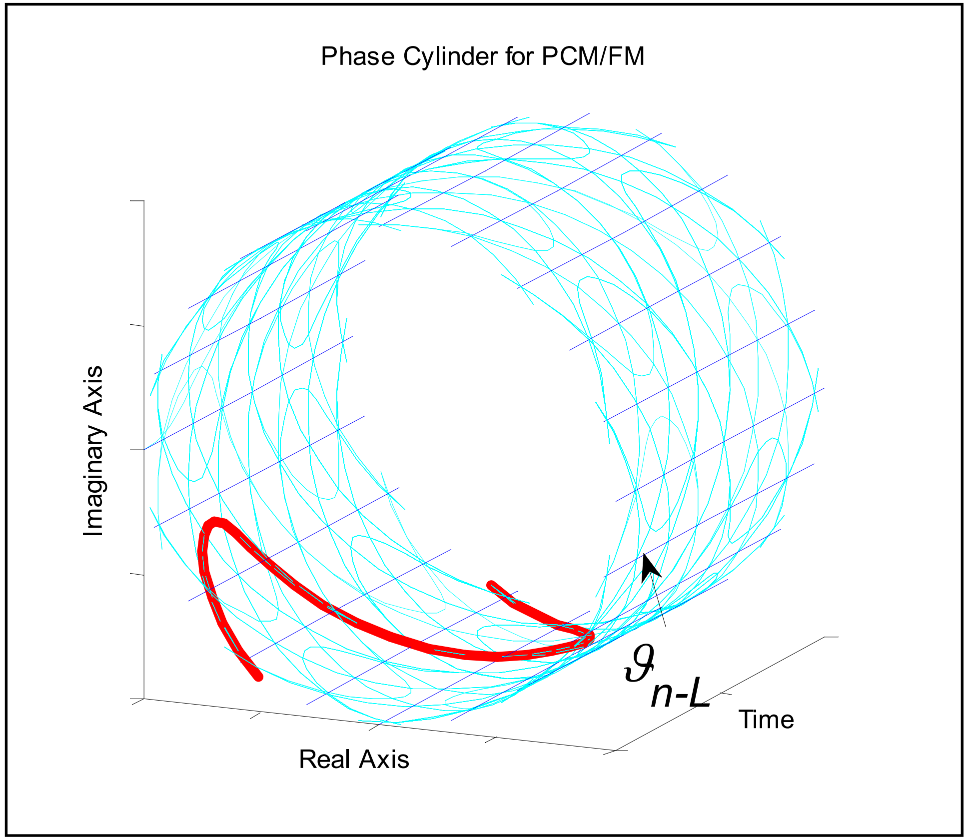
Complexity of a CPM

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

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

- 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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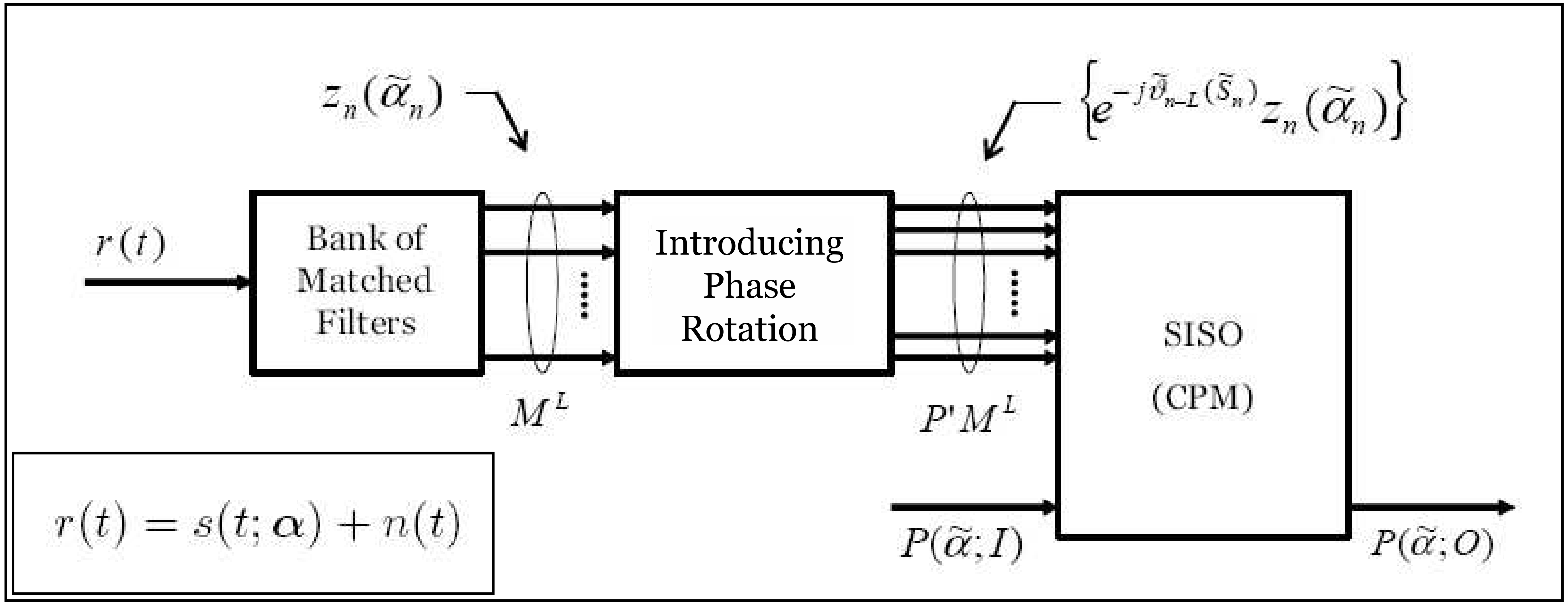
ML decoding: Branch metric computation

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

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

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



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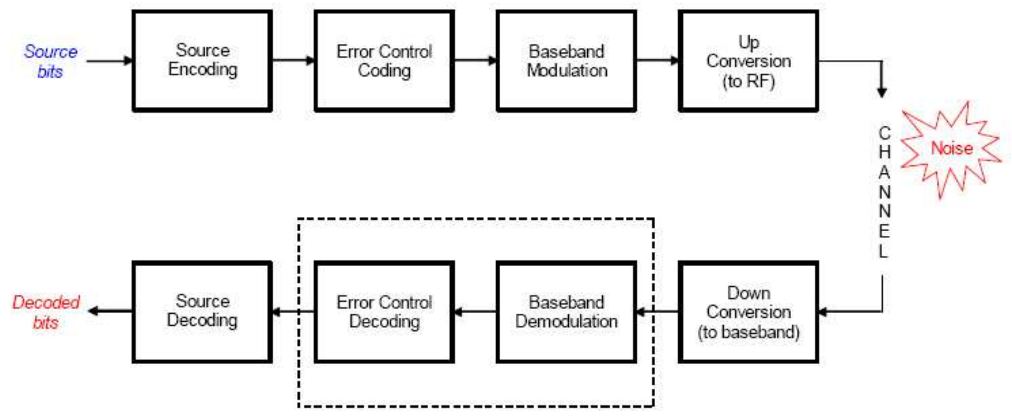
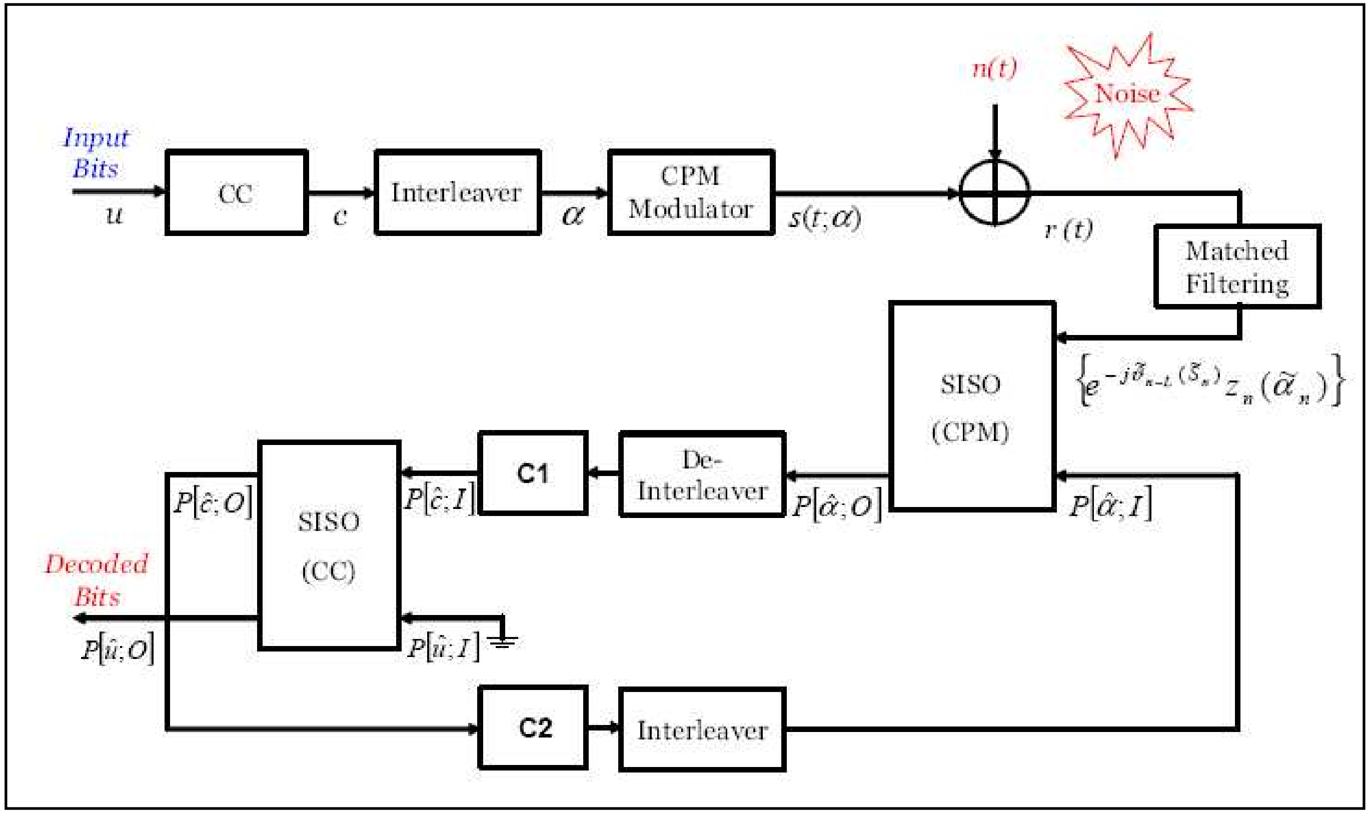
Serial Concatenation of CPM with Convolutional Codes (CC)

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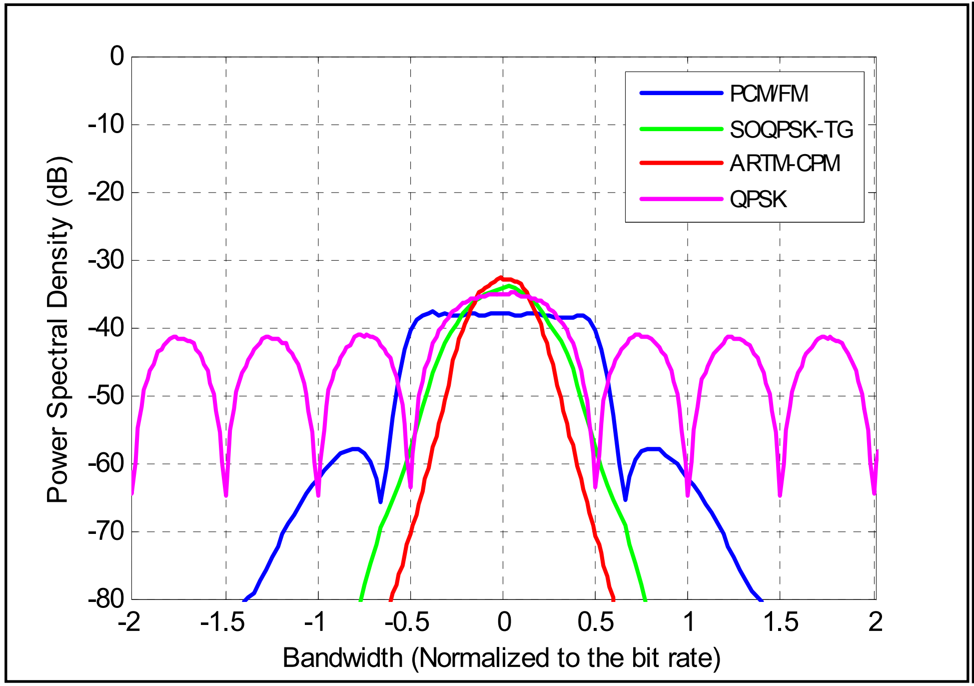
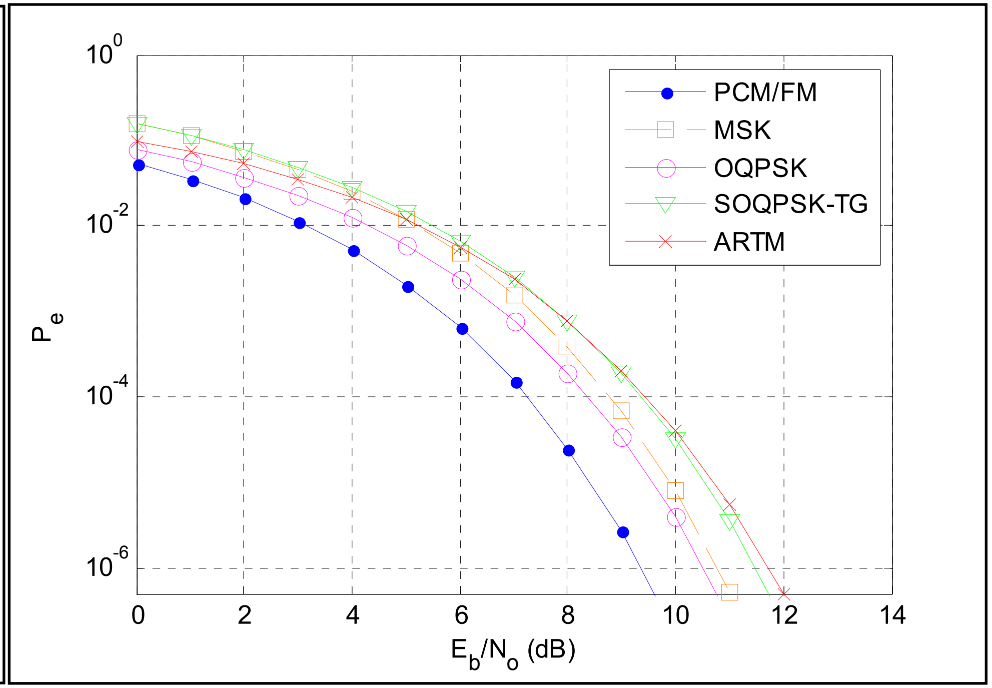
Motivation for the Thesis: *IRIG-106-04* CPMs





IRIG - 106-04 Aeronautical telemetry:

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

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*

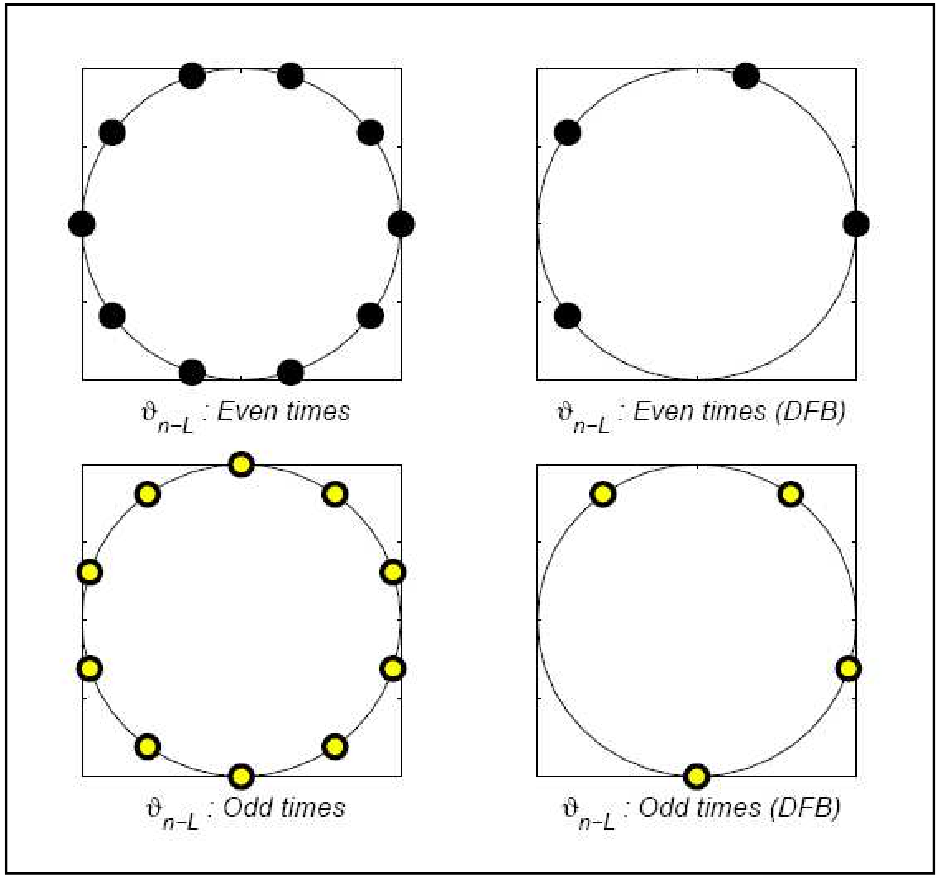
- Fewer phase states: $P_r < P \,, P = P'/2$
  complexity reduction by P/P_r

- 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



Decision Feedback – Efficient Implementation

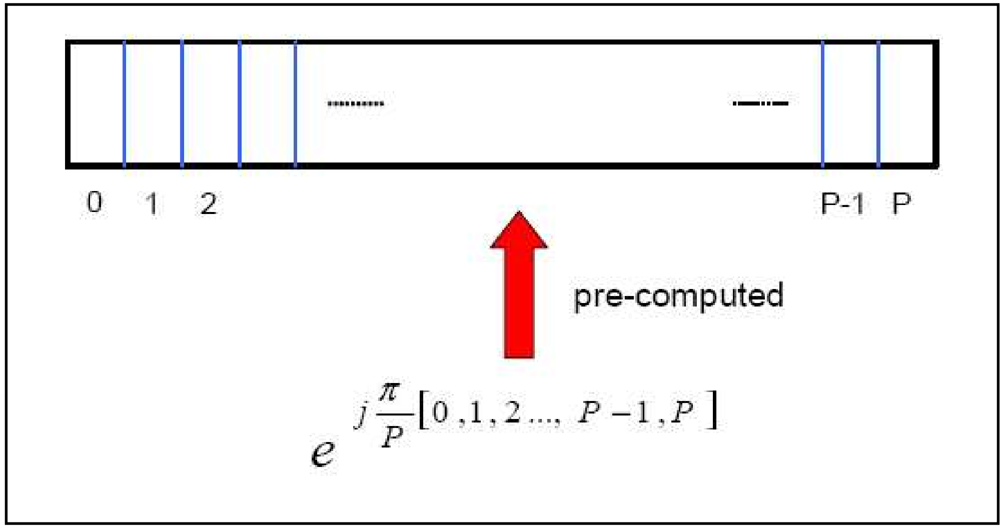
$$\hat{\theta}_{n-L+1}(\widetilde{E}_n^f) = \hat{\theta}_{n-L}(\widetilde{S}_n^f) + \pi h_{\underline{n-L+1}} \hat{u}_{n-L+1}$$

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

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

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

Phase state table



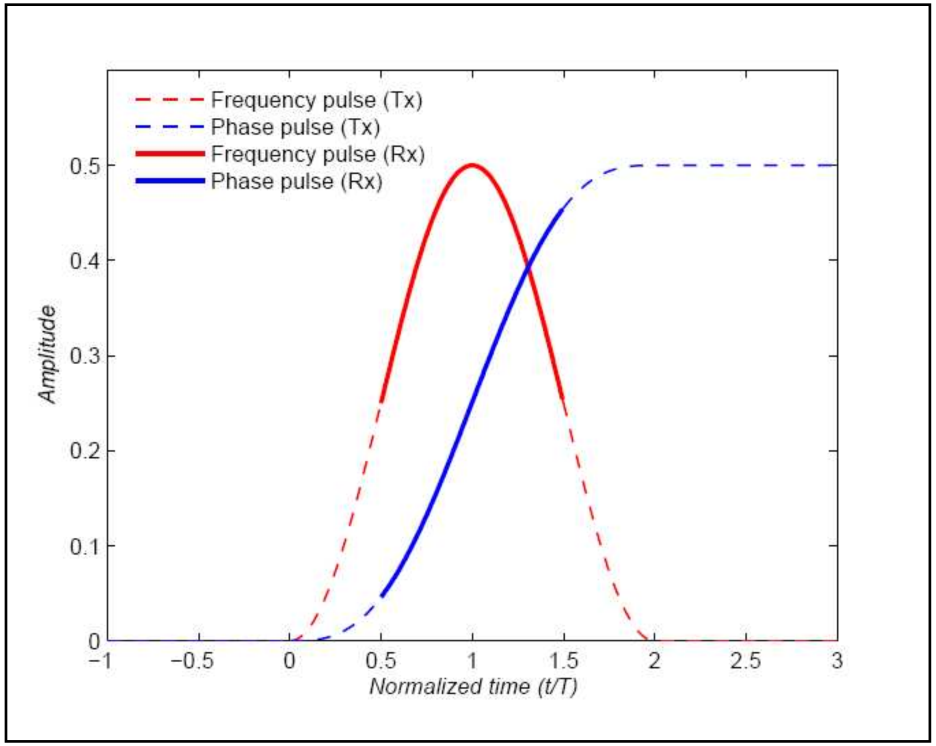
- ❑ Complex phase state computations need floating point arithmetic
- ❑ Exploit the *modulo*-2π property of complex phase, so finite number of phase states can be represented by finite number of integer indices
- ❑ Access phase states by look-up index

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

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



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

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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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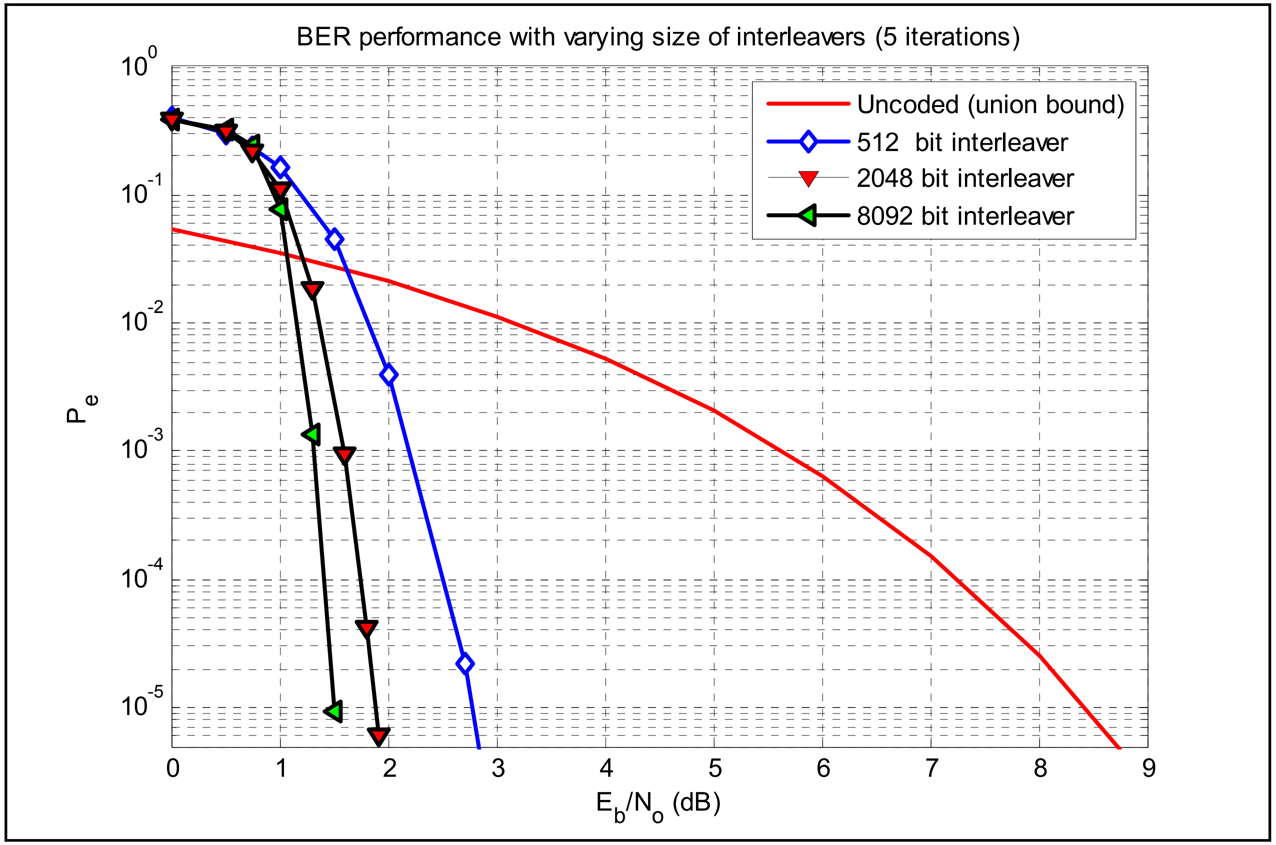
Results: SCC PCM/FM

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



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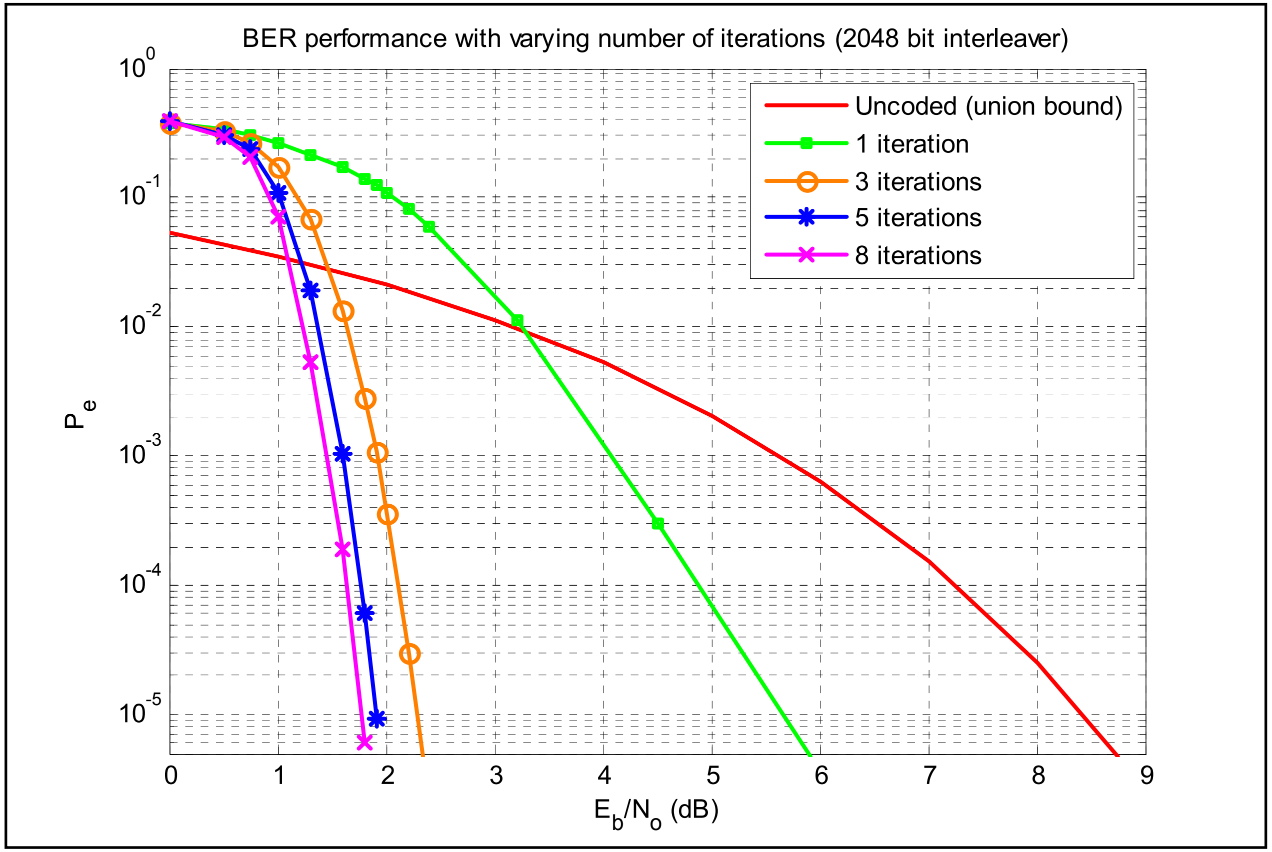

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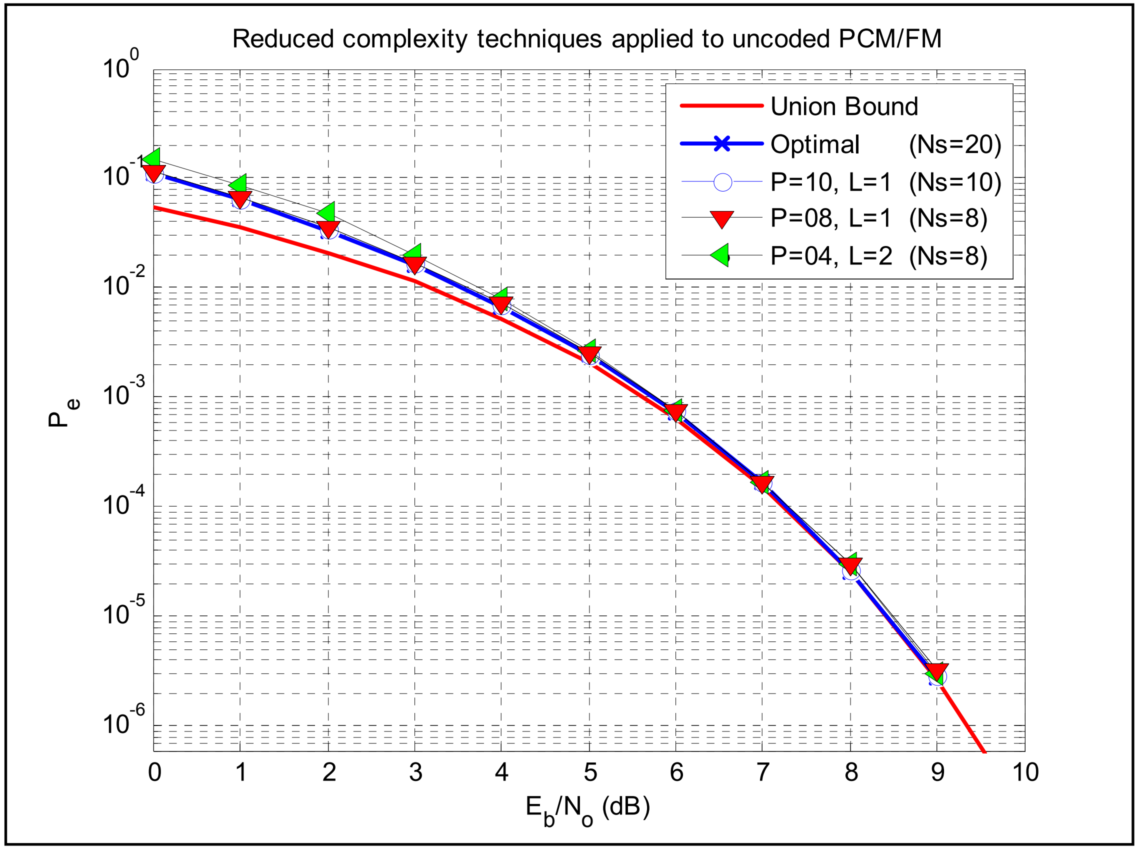
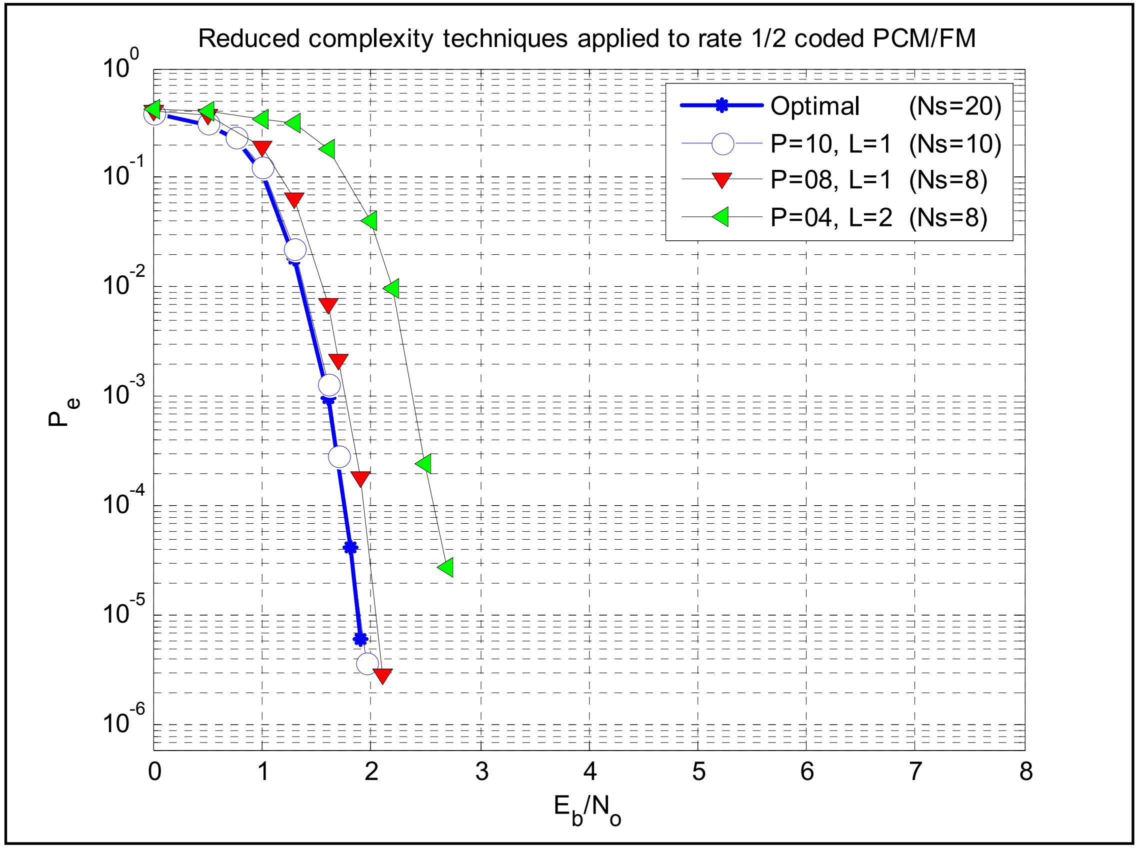
Results : Reduced Complexity PCM/FM

- 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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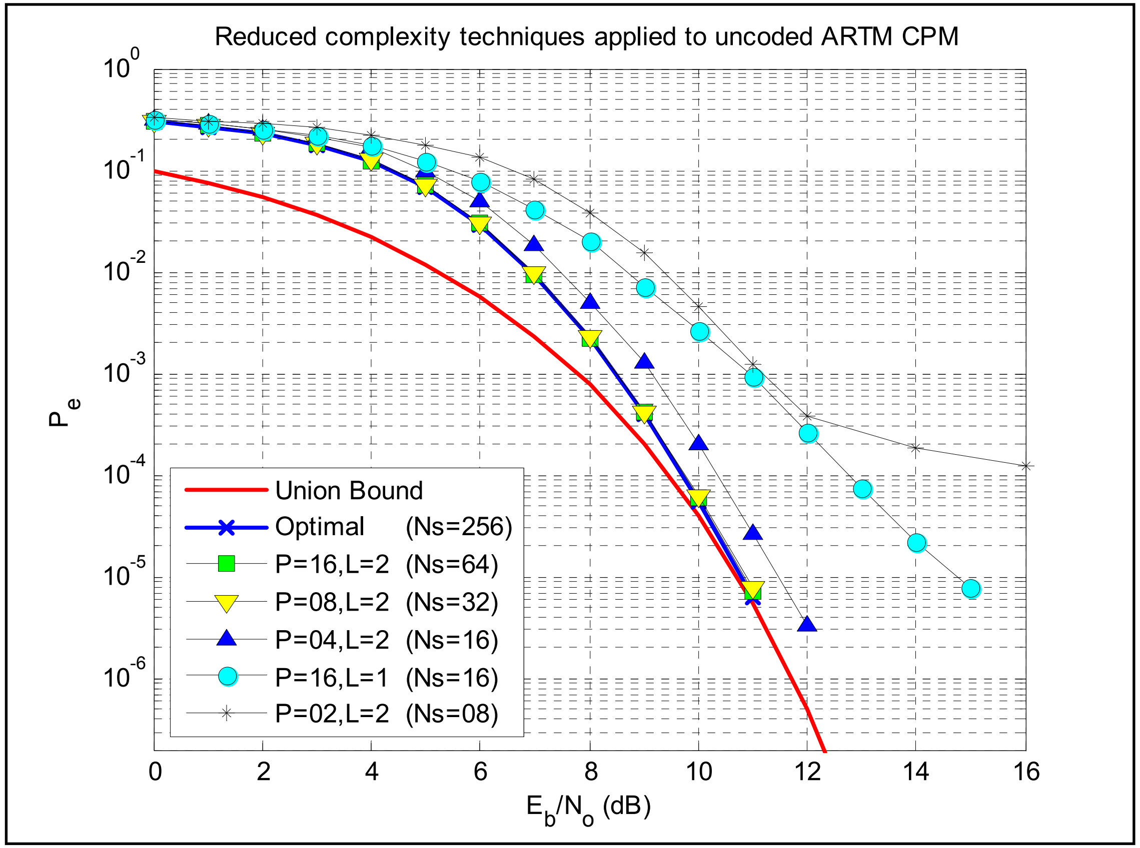
Results : Reduced Complexity ARTM CPM

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



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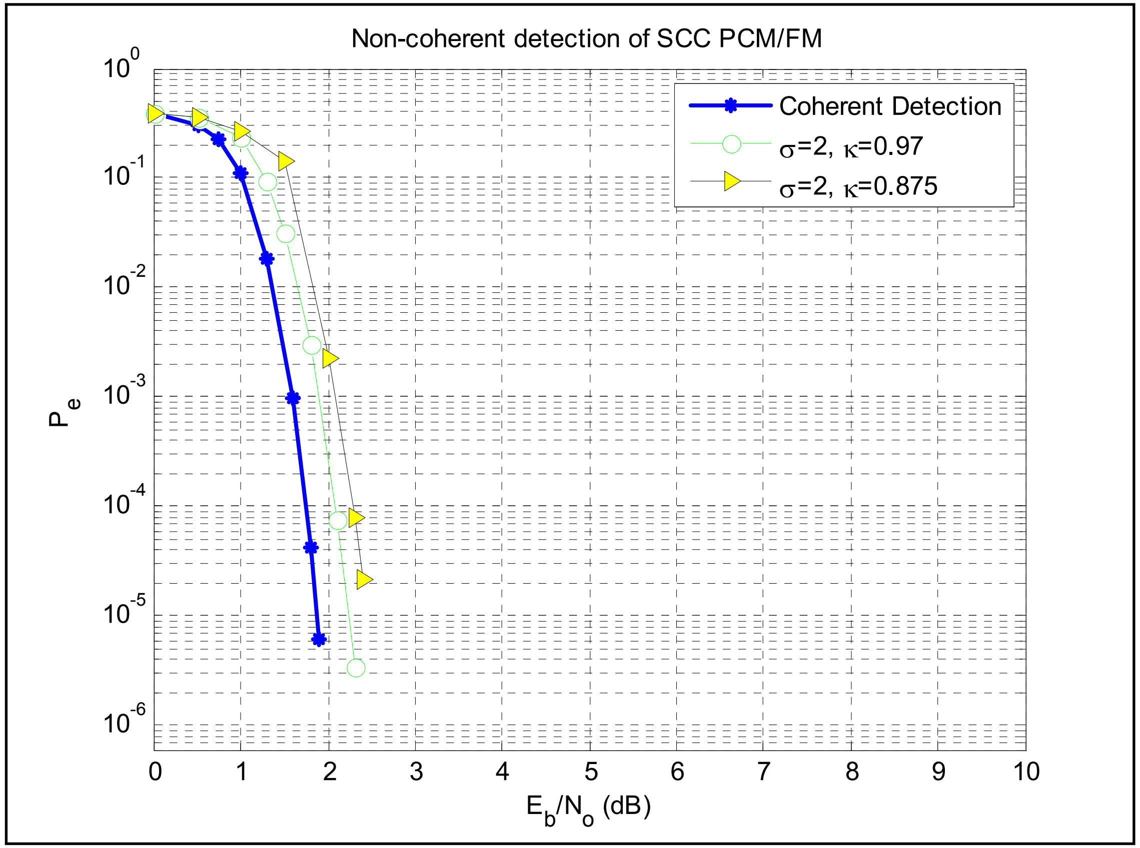
Results : Non-coherent PCM/FM

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



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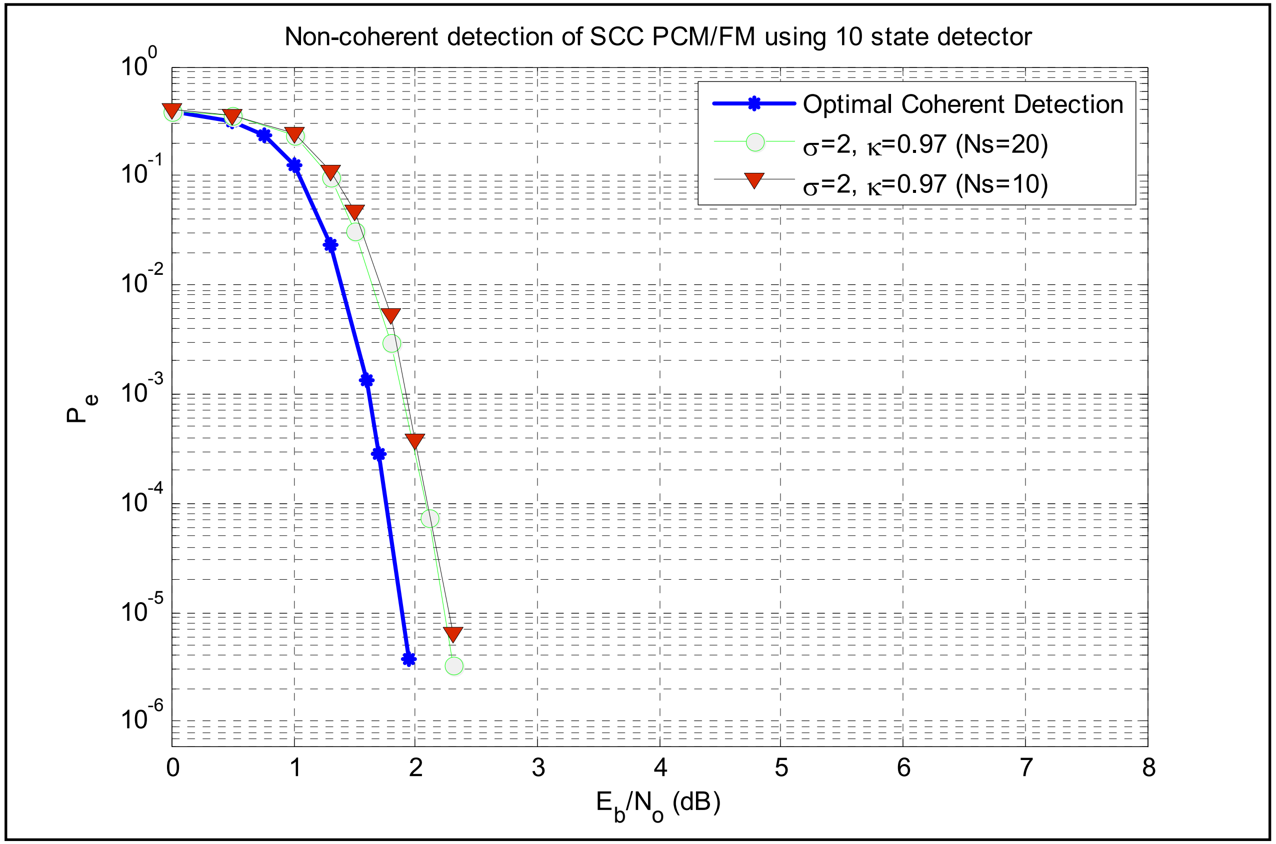
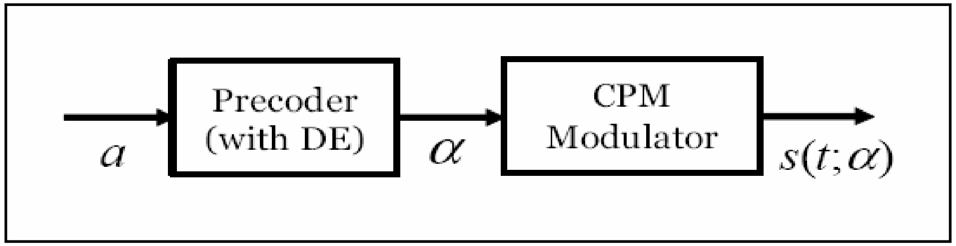
Results : Non-coherent PCM/FM

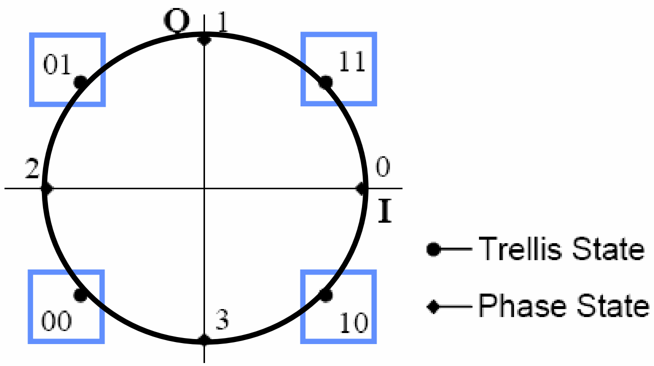
- Loss in 10 state non-coherent detector for SCC PCM/FM: 0.39 dB

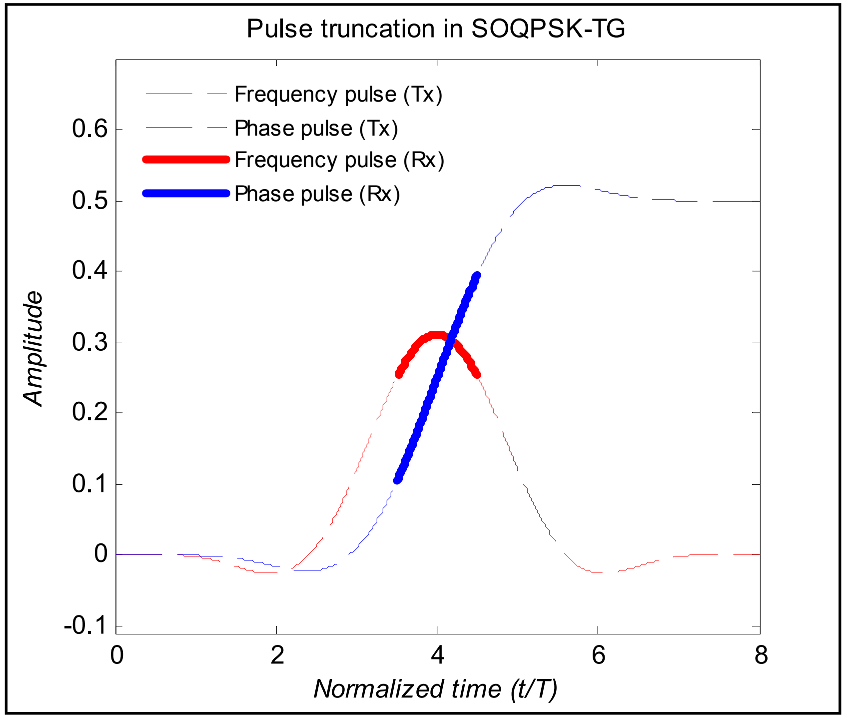


A digression: SOQPSK



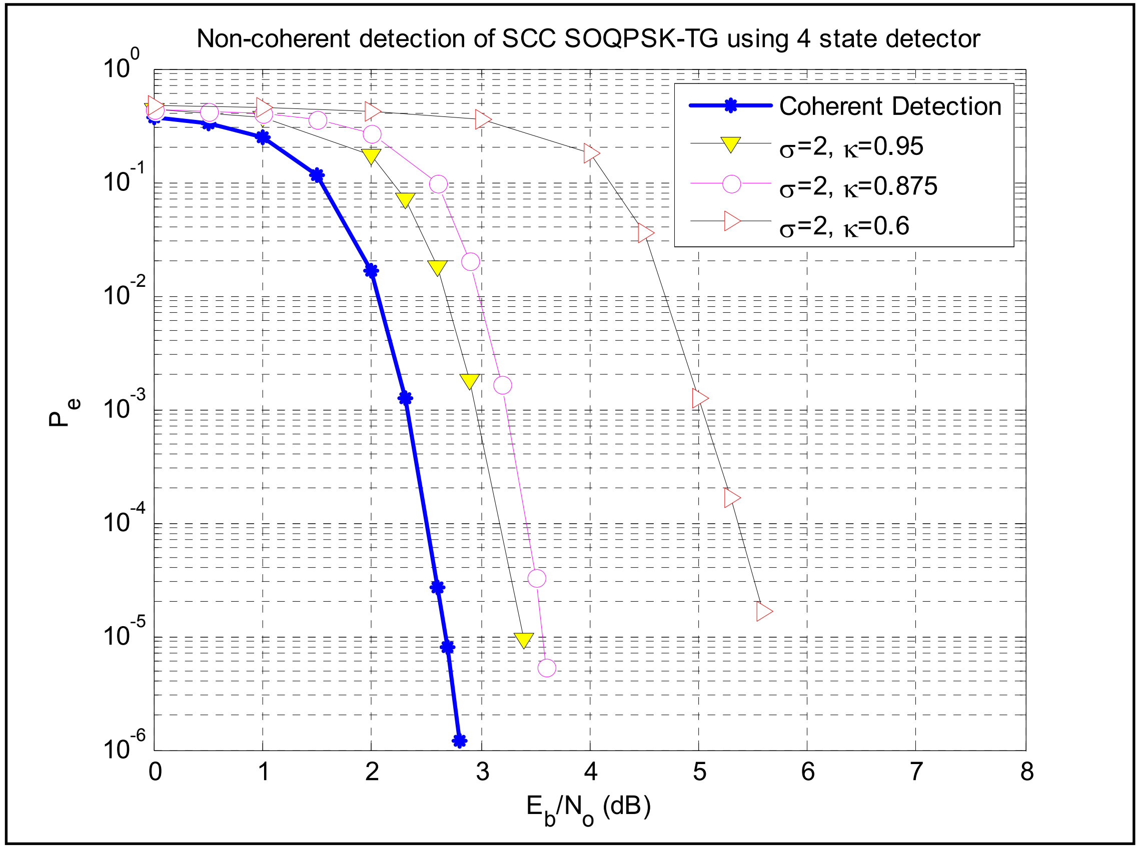
State	P_l
00	3
01	2
10	0
11	1





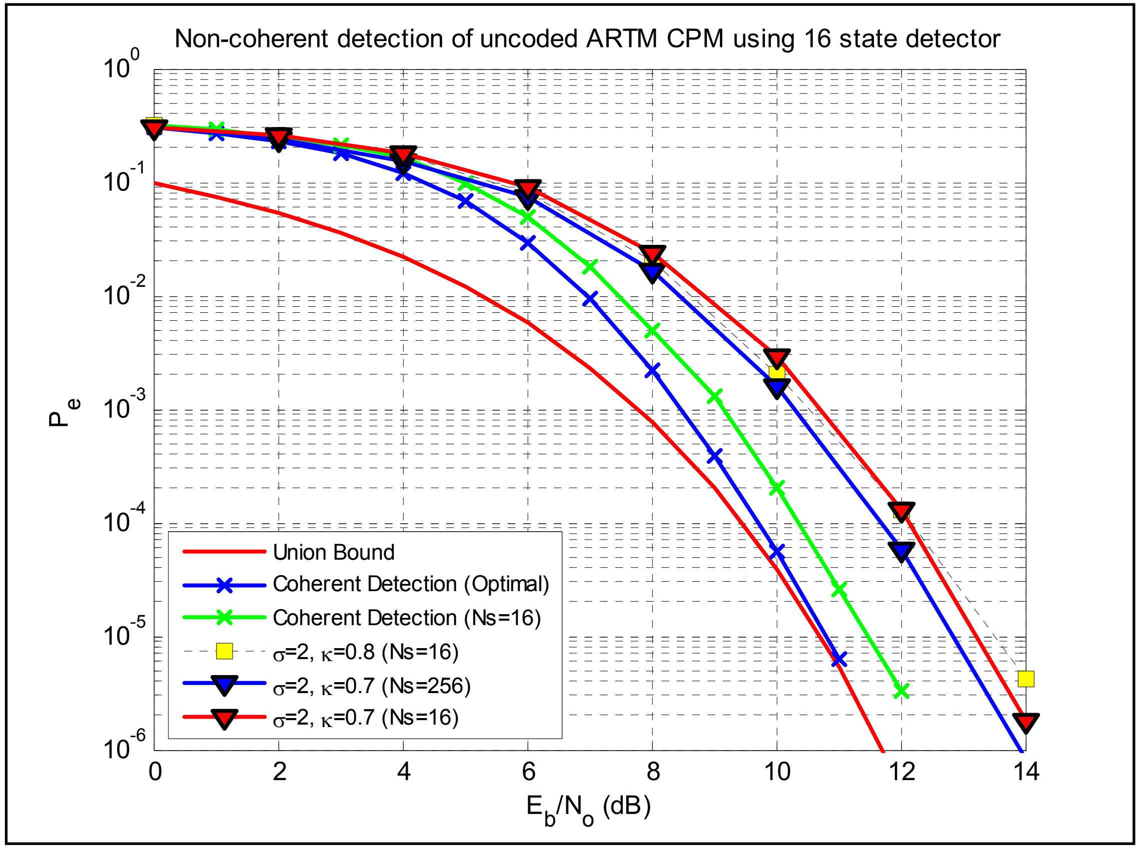
Results : Non-coherent SOQPSK-TG

- 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 ARTM CPM

References

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Acknowledgements

- Dr. Erik Perrins
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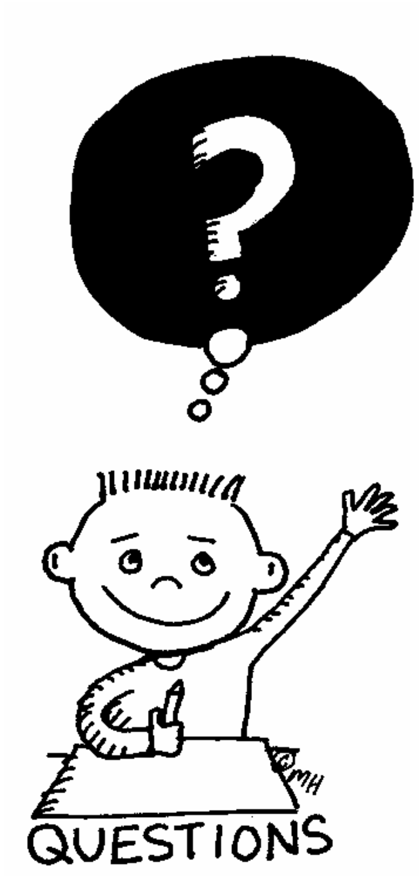
Questions



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SISO algorithm - forward and reverse recursions

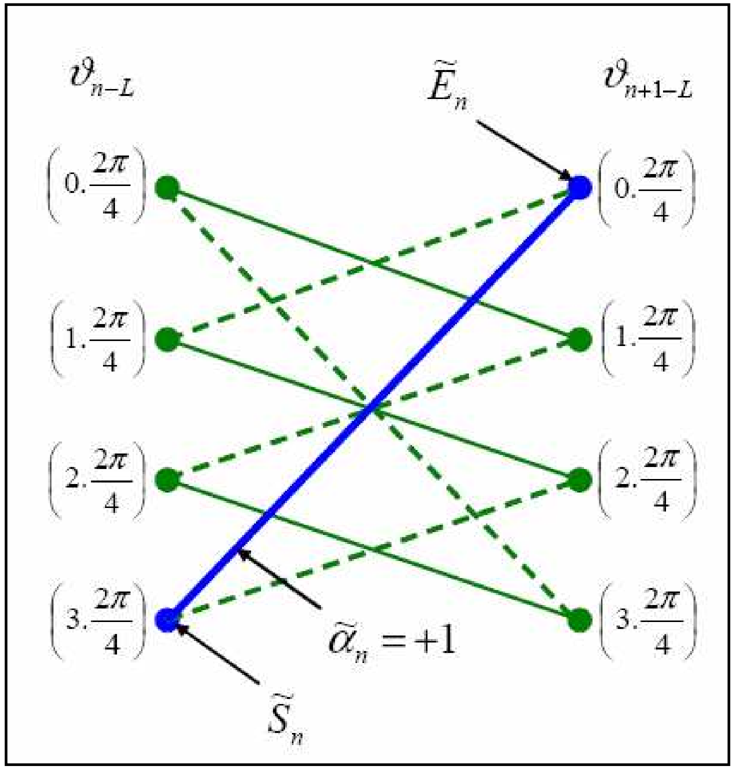
$$F_n(\widetilde{S}_n, \widetilde{E}_n) = \text{Re}\left\{e^{-j\widetilde{\vartheta}_{n-L}(\widetilde{S}_n)} z_n(\widetilde{\boldsymbol{\alpha}}_n)\right\}$$

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

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

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

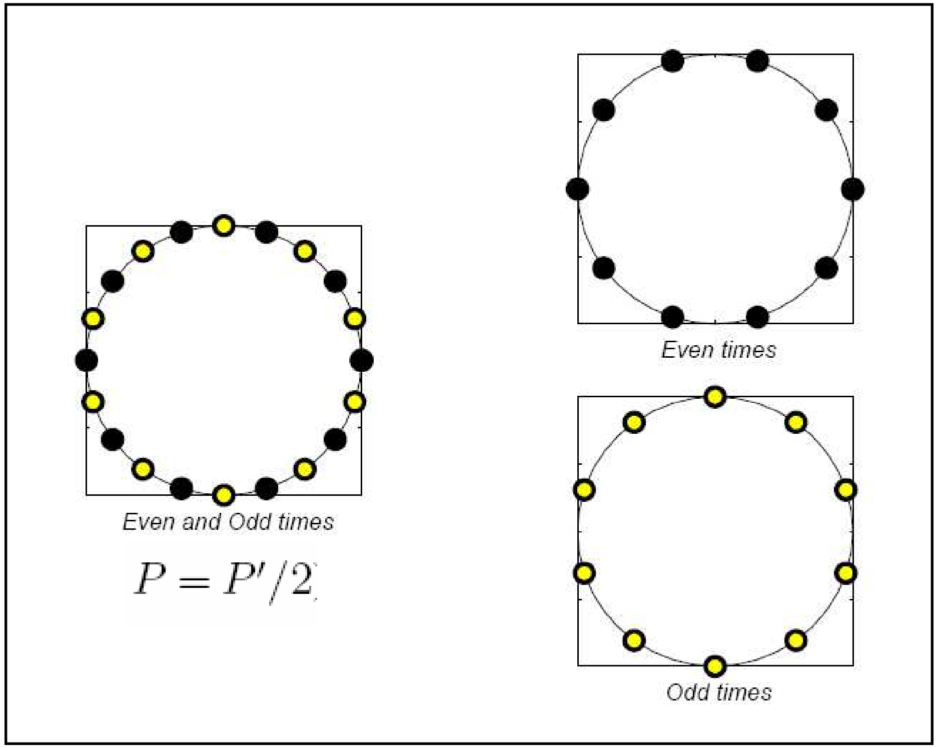
$$P_n(\hat{\boldsymbol{\alpha}}; O) = P_n(\widetilde{\boldsymbol{\alpha}}; O) - P_n(\widetilde{\boldsymbol{\alpha}}; I)$$



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

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

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

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

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