Master’s Thesis Defense

Simplified Detection Techniques for Serially Concatenated Coded Continuous Phase Modulations

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

\[ s(t; \alpha) = e^{j\phi(t; \alpha)} \]

\[ \phi(t; \alpha) = 2\pi \sum_{i=-\infty}^{\infty} h_i \alpha_i q(t - iT_s) \]

\[ h_i = \frac{2K_i}{P_i} \]

Parameters defining a CPM
- \( h_i \) : modulation index
- \( M \) : cardinality of source alphabet \( \alpha \)
- \( q(t) \): phase pulse
- \( L \) : length (memory) of \( q(t) \)
Complexity of a CPM

\[ \phi(t; \alpha) = \pi \sum_{i=0}^{n-L} h_i \alpha_i + 2\pi \sum_{i=n-L+1}^{n} h_i \alpha_i q(t - iT_s) \]

\[ \sigma_{S} = \left( \theta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1} \right) \]

- 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

\[
\sigma_B = \left\{ g_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}, \alpha_n \right\}
\]

\[ h_i = \frac{2K_i}{P_i} \]

\[ P' \quad \text{cumulative phase states} \]

\[ M^L \quad \text{modulating symbols} \]

\[ N_{MF} = M^L \quad \text{matched filters} \]

\[ P'M^L \quad \text{possible received signals} \]

\[ P'M^L \text{ branches} \]
ML decoding: Branch metric computation

\[
\begin{align*}
N_{MF} &= M^L \\
N_S &= P'M^{L-1} \\
N_B &= P'M^L
\end{align*}
\]
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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

\[ P_e = k_1 \cdot Q \left( \sqrt{\frac{d_1 E_b}{N_0}} \right) + k_2 \cdot Q \left( \sqrt{\frac{d_2 E_b}{N_0}} \right) + \ldots + k_i \cdot Q \left( \sqrt{\frac{d_i E_b}{N_0}} \right) \]
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

<table>
<thead>
<tr>
<th>Modulation</th>
<th>$h$</th>
<th>$M$</th>
<th>$L$</th>
<th>Pulse Type</th>
<th>State Complexity</th>
<th>Detection Efficiency</th>
<th>Spectral Efficiency</th>
<th>Decoding Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM/FM</td>
<td>7/10</td>
<td>2</td>
<td>2</td>
<td>RC</td>
<td>40</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>SOQPSK-TG</td>
<td>1/2</td>
<td>2</td>
<td>8</td>
<td>TG</td>
<td>512</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ARTM CPM</td>
<td>4/16, 5/16</td>
<td>4</td>
<td>3</td>
<td>RC</td>
<td>512</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

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

**IRIG-106-04** Aeronautical telemetry:
- PCM/FM (Tier-0)
- SOQPSK-TG (Tier-1)
- ARTM CPM (Tier-2)
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  - Applications
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Serially Concatenated Systems
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Motivation for the thesis

Reduced complexity approaches

Non-coherent detection algorithm

Results

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Future work
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

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

\[
\sigma_{\text{DFB}} = \left( \hat{\nu}_{n-L}, \hat{\alpha}_{n-L+1}, \hat{\alpha}_{n-L+2}, \ldots, \hat{\alpha}_{n-1} \right)_{P_rM^{L-1}} \text{ states}
\]
Decision Feedback – Efficient Implementation

\[
\hat{\theta}_{n-L+1}(\hat{E}_n^f) = \hat{\theta}_{n-L}(\hat{S}_n^f) + \pi \hat{h}_{n-L+1} \hat{u}_{n-L+1} \\
\hat{h}_i = \frac{K_i}{P} \\
\theta_{n-L} = \frac{\pi}{P} \cdot \hat{I}_{n-L} = \frac{\pi}{P} \cdot \sum_{i=0}^{n-L} 2K_i \hat{u}_i \\
\hat{I}_{n-L+1}(\hat{E}_n^f) = \left[ \hat{I}_{n-L}(\hat{S}_n^f) + K_{n-L+1} \hat{u}_{n-L+1} \right] \mod P
\]

- Complex phase state computations need floating point arithmetic
- Exploit the modulo-2\(\pi\) 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

Phase state table

pre-computed

\(j \frac{\pi}{P} \left[ 0, 1, 2, \ldots, P-1, P \right] \)
Pulse Truncation

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

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

$$\tilde{z}_n(\tilde{\alpha}_n^t) = \int_{nT_c}^{(n+1)T_s} r(t - DT_s) e^{-j2\pi h_2 \tilde{\alpha}_n^t} q_{PT}(t - nT_s) dt$$
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Non-coherent detection

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

- Previous works - branch metric computations:

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

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

  \[
  \phi_k^{\alpha+1}(e_k, e_{k+1}) = \frac{I_0 \left( \frac{2}{N_0} |r_{k+1} x_{k+1}^* + r_k x_k^* + q_{ref}(k - 1)|^2 \right)}{\gamma_k^\alpha(e_k)}
  \]
Non-coherent detection: Proposed algorithm

- Phase noise averaged out, exponential window averaging

- Coherent detection:
  \[ \text{Re} \left\{ e^{-j\nu_{n-L}} e^{-j\hat{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\} \]

- Non-coherent detection:
  \[ \text{Re} \left\{ Q_n^*(\tilde{S}_n) e^{-j\nu_{n-L}} e^{-j\hat{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\} \]

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

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

\[ \lambda_n(\tilde{E}_n) = \lambda_{n-1}(\tilde{S}_n) + \text{Re} \left\{ Q_n^*(\tilde{S}_n) e^{-j\nu_{n-L}} e^{-j\hat{\theta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n) \right\} \]
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Results: SCC PCM/FM

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

![Graph showing BER performance with varying size of interleavers (5 iterations)]
6.55 dB coding gain with 2048 bit interleaver and 5 iterations
Approximation at low $E_b/N_0$ is the key for the technique to be used in coded systems.

Reduced complexity techniques applied to uncoded PCM/FM

- Union Bound
- Optimal ($N_s=20$)
- $P=10$, $L=1$ ($N_s=10$)
- $P=08$, $L=1$ ($N_s=8$)
- $P=04$, $L=2$ ($N_s=8$)
Results: Reduced Complexity PCM/FM

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

Precoder (with DE) → CPM Modulator → \( s(t; \alpha) \)

<table>
<thead>
<tr>
<th>State</th>
<th>( P_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>3</td>
</tr>
<tr>
<td>01</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

Pulse truncation in SOQPSK-TG

- Frequency pulse (Tx)
- Phase pulse (Tx)
- Frequency pulse (Rx)
- Phase pulse (Rx)

Normalized time (t/T) vs. Amplitude
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
References


Acknowledgements

- Dr. Erik Perrins
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- Dr. Alexander Wyglinski
- Kanagaraj
Questions
\[ F_n(\tilde{S}_n, \tilde{E}_n) = \text{Re}\left\{e^{-j\tilde{\delta}_{n-L}(\tilde{S}_n)} z_n(\tilde{\alpha}_n)\right\} \]

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

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

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

\[ P_n(\tilde{\alpha}; O) = P_n(\tilde{\alpha}; O) - P_n(\tilde{\alpha}; I) \]
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

\[ P = \frac{P'}{2} \]
Rimoldi’s Approach

$$\phi(t; \alpha) = \pi \sum_{i=0}^{n-L} h_i \alpha_i + 2\pi \sum_{i=n-L+1}^{n} h_i \alpha_i q(t - iT_s)$$

$$\vartheta_{n-L} = \vartheta_{n-L} \pm \omega_{n-L}$$

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

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