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
Introduction: Background

- Signal representation for a CPM
  - Phase of a CPM – linear filtering
    \[ s(t; \alpha) = e^{j\phi(t; \alpha)} \]
    \[ \phi(t; \alpha) = 2\pi \sum_{i=-\infty}^{\infty} h_i \alpha_i q(t - iT_s) \]
    \[ h_i = \frac{2K_i}{P} \]

- 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

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

\[ \sigma_S = \left( \vartheta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1} \right) \]

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

\[
h_i = \frac{2K_i}{P'}
\]

\[
P'
\]

\[
M^L
\]

\[
N_{MF} = M^L
\]

\[
P'M^L
\]

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

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

\[
N_{\text{MF}} = M^L \\
N_S = P'M^{L-1} \\
N_B = P'M^L
\]

\[r(t) = s(t; \alpha) + n(t)\]
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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

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

![Graphs showing Power Spectral Density and Error Rate vs. Signal-to-Noise Ratio for different modulation schemes.](image)

*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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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

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

\[
\sigma_{\text{DFB}} = \left( \hat{\theta}_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1} \right)_{P'M^{L-1} \text{ states}}
\]
Decision Feedback – Efficient Implementation

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

\[
h_2 = \frac{K_i}{P}
\]

\[
\theta_{n-L} = \frac{\pi}{P} \hat{I}_{n-L} = \frac{\pi}{P} \sum_{i=0}^{n-L} 2K_i u_i
\]

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

- 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
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

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

\[
\tilde{z}_n(\tilde{\alpha}_n^t) = \int_{nT_c}^{(n+1)T_s} r(t - DT_s) e^{-j2\pi h \tilde{\alpha}_n^t} q_{PT}(t-nT_s) dt
\]
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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:

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

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

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

- Phase noise averaged out, exponential window averaging

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

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

1. Inexpensive
2. Compact
3. Robust
4. Low Complexity
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Results: SCC PCM/FM

- 6.55 dB coding gain with 2048 bit interleaver and 5 iterations
Results: SCC PCM/FM

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

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

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

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

$P_n(\tilde{\alpha}; O) = P_n(\tilde{\alpha}; O) - P_n(\tilde{\alpha}; I)$
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
Rimoldi’s Approach

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

\[ \vartheta_{n-L} = \vartheta_{n-L} + \nu_{n-L} \]

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

\[ \sigma_{\text{Rimoldi}} = (\vartheta_{n-L}, \alpha_{n-L+1}, \alpha_{n-L+2}, \ldots, \alpha_{n-1}) \quad PM^{L-1} \text{ states} \]