ENERGY SEPARATION AND DEMODULATION OF CPM SIGNALS

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Motivation

- CPM has power/bandwidth efficiency and used in the wireless system infrastructure.
- Maximum likelihood demodulation has significant complexity.
- Sub-optimal schemes : trade-off complexity for optimality, e.g., polynomial phase modeling.
- Traditional applications: speech analysis/synthesis, image texture analysis, FM-voice separation.

Teager-Kaiser Energy Operator

- Continuous time:

$$\Psi(x(t)) = [\dot{x}(t)]^2 - x(t)\,\ddot{x}(t)$$

- Discrete time:

$$\Psi(x[n]) = x^2[n] - x[n-1]x[n+1]$$

Energy Separation Algorithm (ESA)

- Monocomponent AM—FM Signals:

$$x(t) = a(t)\cos\left(\int_{-\infty}^{t} \omega_i(\tau)\,d\tau\right)$$

- ESA IF/IA Estimates:

$$\omega_i(t) \approx \sqrt{\frac{\Psi(\dot{x})}{\Psi(x)}} \qquad a(t) \approx \frac{\Psi(x)}{\sqrt{\Psi(\dot{x})}}$$

Higher-order Energy Operators

Continuous Signals:

$$Y_k(x) = \overset{o}{x} x^{(k-1)} - x x^{(k)}$$

Discrete Signals:

$$Y_k(x) = x[n]x[n+k-2] - x[n-1]x[n+k-1]$$

Features of Energy Operators

- Output of energy operator for sinusoidal inputs is the normalized signal energy.
- For time-varying sources, energy operator output tracks the energy of source.
- k=2: energy, k=3: energy-velocity, k=4: energy-acceleration.
- Possess simplicity, efficiency, and excellent time resolution.

Traditional Energy Applications

- Speech processing: AM/FM analysis/synthesis, formant frequency/bandwidth tracking, AM/FM vocoder.
- Image processing: Multidimensional AM/FM models, image texture analysis, segmentation.
- Biomedical applications: MEG spike detection, vocal tract pathology diagnosis, ECG analysis.
- Communications: cochannel FM-voice separation and demodulation.

CPM Signal Model

$$x_{cpm}(t) = \sqrt{\frac{2\varepsilon}{T_b}} \cos(\omega_c t + \phi(t;a) + \phi_0)$$

$$\phi(t;a) = 2\pi h \sum_{k=-\infty}^{\infty} a[k] q(t - kT_b) \qquad q(t) = \int_{-\infty}^{t} p(\tau) d\tau$$

$$\omega_i(t) = \omega_c + 2\pi h \sum_{k=-\infty}^{\infty} a[k] p(t - kT_b)$$

$$a[k] \in \{\pm 1, \pm 3, \pm 5, \ldots\ldots, \pm(M-1)\}$$

CPM Signal Model

- IF discontinuous but has continuous phase (CP).
- Smaller spectral side lobes due to CP property.
- p(t) rectangular: REC-CPM, raised cosine: RAC-CPM, LPF Gaussian: GMSK, 1-REC-CPM (CPFSK).
- Full response p(t): $L = 1$ (memoryless), partial response: $L > 1$ (memory).
- Constant modulus with FM modulation index : h

Energy-based CPM Demodulation

- Apply multiband filtering and energy detection to suppress noise.
- Apply energy demodulation algorithm: ESA/EDM/PASED to estimate IF.
- Median filter IF estimates to remove spikes and subtract carrier bias.
- Apply matched filtering with sign detection on carrier unbiased IF estimate.

Performance Metrics

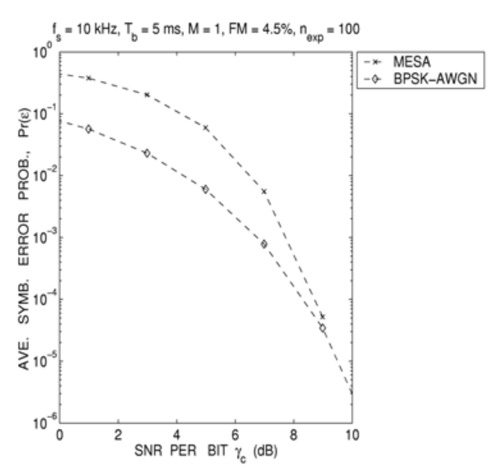
Binary CPM: BPSK-AWGN

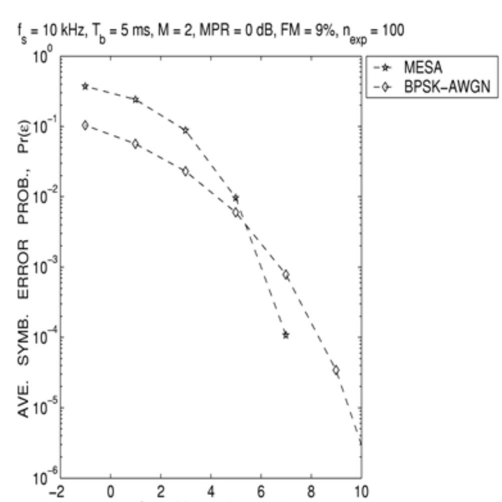
$$P_1(\varepsilon) = Q\left(\sqrt{2\gamma_b}\right), \gamma_b = \sqrt{\frac{2E_b}{N_o}}$$

M-ARY CPM: M-ARY PAM

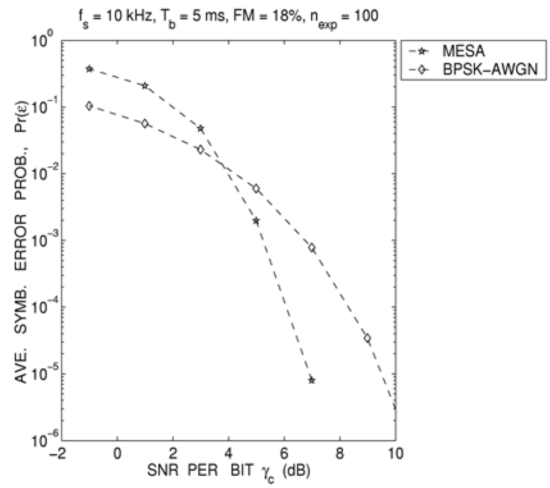
$$P_2(\varepsilon) = \frac{2(\mathrm{M}-1)}{\mathrm{M}} Q\left(\sqrt{\frac{6\log_2 M E_{av}}{(M^2-1)N_o}}\right)$$

1-REC-CPM: Effect of h



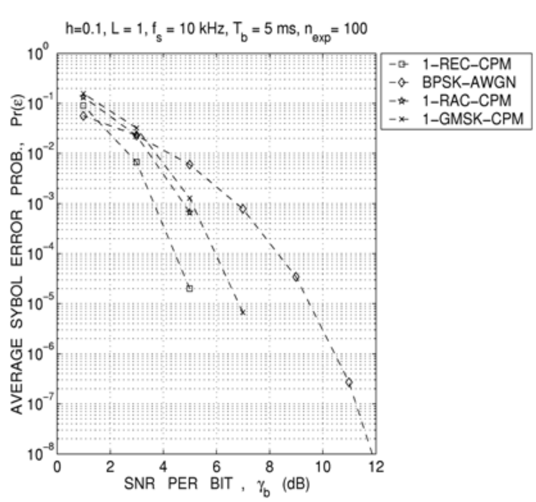


1-REC-CPM: Effect of h



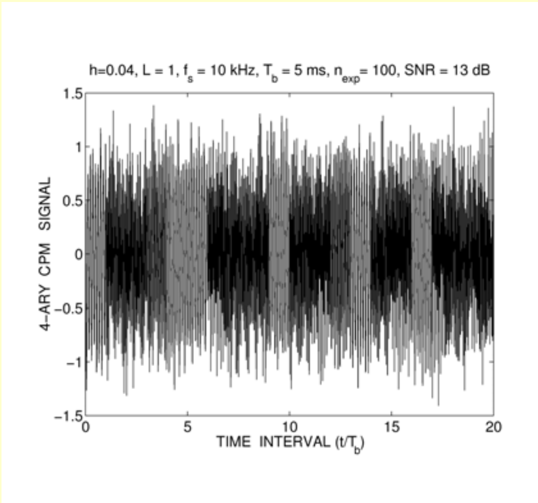
- Small h: weak modulations
- Increasing h increases strength of signal modulations
- MESA zero-error threshold decreases as h increases.
- Large h: ESA narrowband approximation fails.

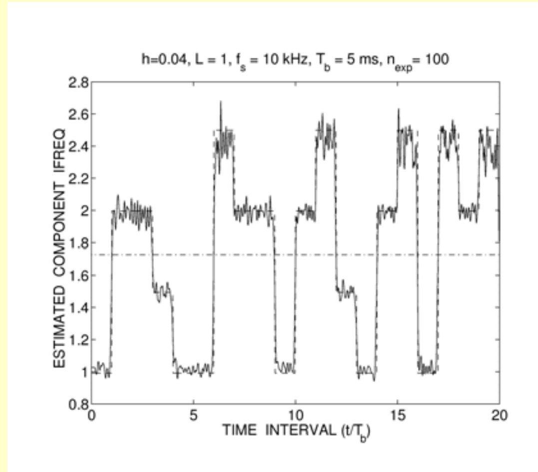
L=1 CPM: Effect of p(t)



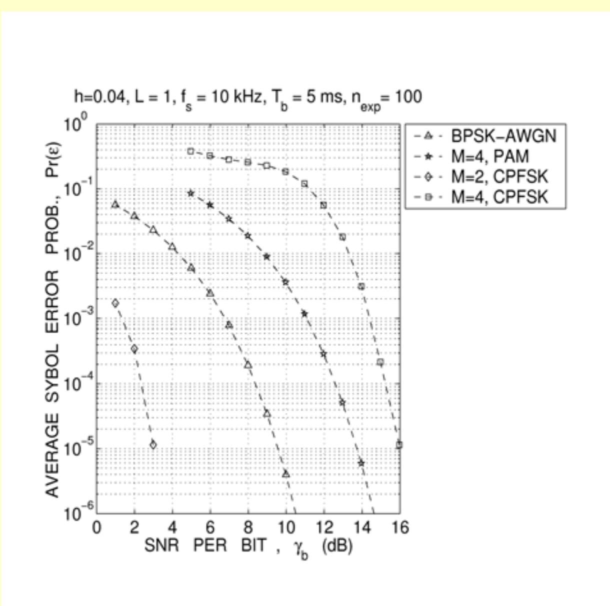
- Smoothness of phase trajectories related to continuity of p(t).
- Smoothness of phase results in smaller spectral sidelobes.
- 1-REC-CPM has narrower mainlobe but larger sidelobes.
- GMSK: trade-off ISI for spectral compactness.

M=4, 1-REC-CPM





M=4, 1-REC-CPM



- As M increases, bandwidth of signal increases.
- Larger bandwidth: causes ESA to incur more error.
- MESA filters: larger noise bandwidth.
- Narrowband approximation fails after a certain stage.

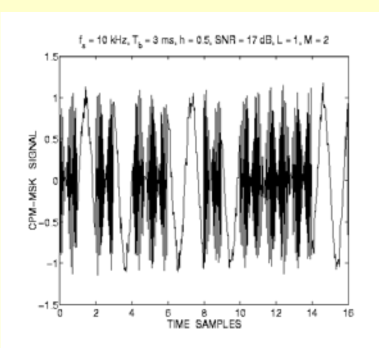
Minimum Shift Keying (MSK)

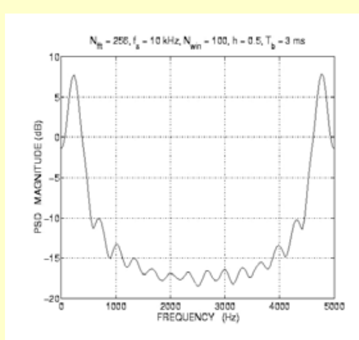
- Special case of 1-REC-CPM (CPFSK) with h=0.5.
- Orthogonal signaling scheme with frequencies:

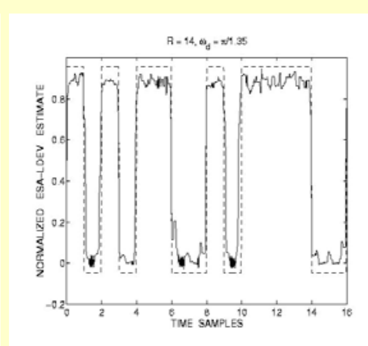
$$f_1 = f_c - \frac{1}{4T_b}, \quad f_2 = f_c + \frac{1}{4T_b}$$

- Minimum frequency deviation to maintain an orthogonal signal constellation.
- Phase transitions are either $+\pi h$ and $-\pi h$

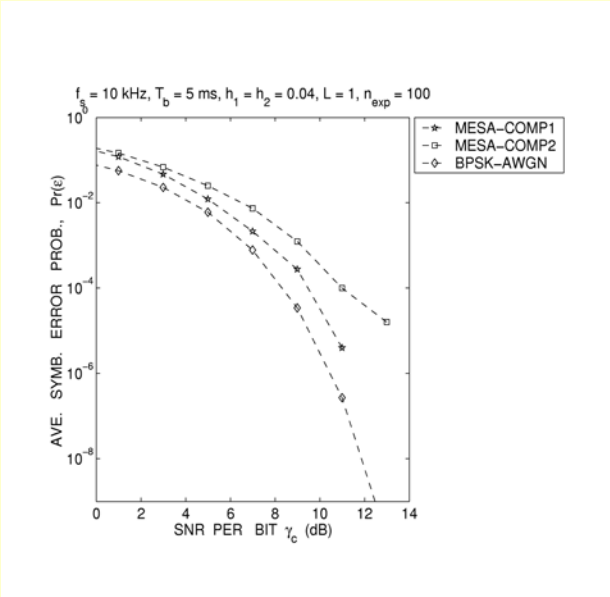
Minimum Shift Keying (MSK)





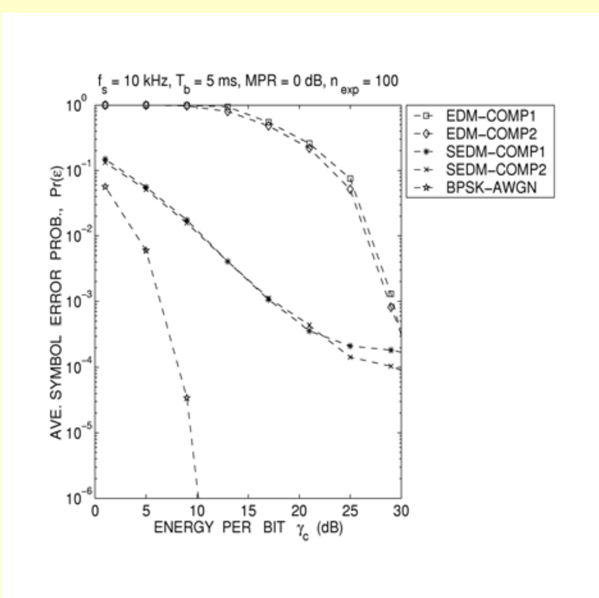


Two-component CPM



- Distinct components: filtering adequate for separation.
- MESA: multiband filtering and energy detection.
- Small spectral separations: significant component interaction.
- For cochannel conditions, filtering inadequate for component separation.

Two-component CPM: EDM



- Multiband version (MEDM) helps to an extent with noise.
- For small spectral separations, EDM energy equations become singular.
- Filter design: trade-off noise suppression and signal distortion.
- Doppler shift manifests as carrier drift in the IF estimate and can be subtracted off.

Conclusions

- CPM -- related forms: CPFSK,MSK,GMSK formulated in the AM—FM framework of energy approaches.
- Energy operator based CPM demodulation computationally simpler alternative.
- Energy demodulation based framework can accommodate a Doppler shift in data.
- Particularly suited for binary modulation (M=2).