Master's Thesis Defense

Comparison of Noncoherent Detectors for SOQPSK and GMSK in Phase Noise Channels

Afzal Syed
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Committee

Dr. Erik Perrins (Chair)

Dr. Glenn Prescott

Dr. Daniel Deavours

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Publications

- Resulting from this work

  A. Syed and E. Perrins, “Comparison of Noncoherent Detectors for SOQPSK and GMSK in Phase Noise Channels”, to appear in *Proceedings of the International Telemetry Conference (ITC)*, Las Vegas, NV, October 22-25, 2007.

- Other

  A. Syed, K. Demarest, D. Deavours, “Effects of Antenna Material on the Performance of UHF RFID Tags”, In *Proceedings of IEEE International Conference on RFID (IEEE-RFID)*, Grapevine, TX, March 26-28, 2007.

Outline

- Motivation for this thesis/Research Objectives
- Introduction
- Coherent Detection
- Reduced Complexity Coherent Detectors
- Noncoherent Detection Algorithm
- Serially Concatenated Systems
- Simulation Results
- Conclusions
- Future work

Motivation for this thesis

- SOQPSK and GMSK – highly bandwidth efficient CPMs.
- Coherent receivers – good performance in AWGN.
- Noncoherent receivers favored – phase noise channels often encountered in practical scenarios.
- No published results on how noncoherent detectors for these schemes compare in phase noise channels for uncoded and coded systems with iterative detection.

Research Objectives

- Develop reduced complexity noncoherent detectors for SOQPSK and GMSK.
- Quantify performance of SOQPSK and GMSK in channels with phase noise for uncoded and coded systems which use these schemes as *inner codes*.
- Determine which is to be preferred for a given requirement.

Outline

- Motivation for this thesis/Research Objectives
- **Introduction**
  - **CPM**
  - **SOQPSK**
  - **GMSK**
- Coherent Detection
- Reduced Complexity Coherent Detectors
- Noncoherent detection algorithm
- Serially Concatenated Systems
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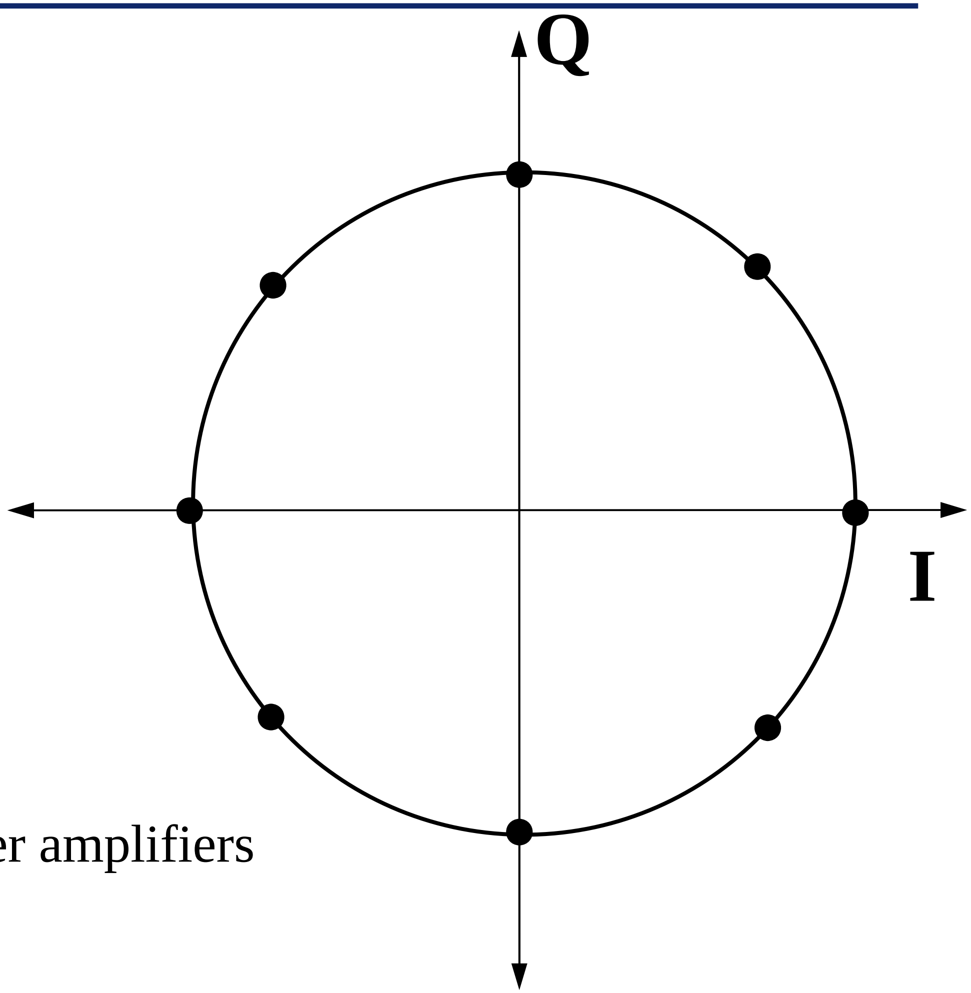
Introduction : CPM

- CPM Characteristics
  - Constant envelope
  - Continuous phase
  - Memory
- Advantages
  - Simple transmitter
  - Power efficient
  - Bandwidth efficient
  - Flexible
  - Suitable for non-linear power amplifiers



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Introduction : CPM

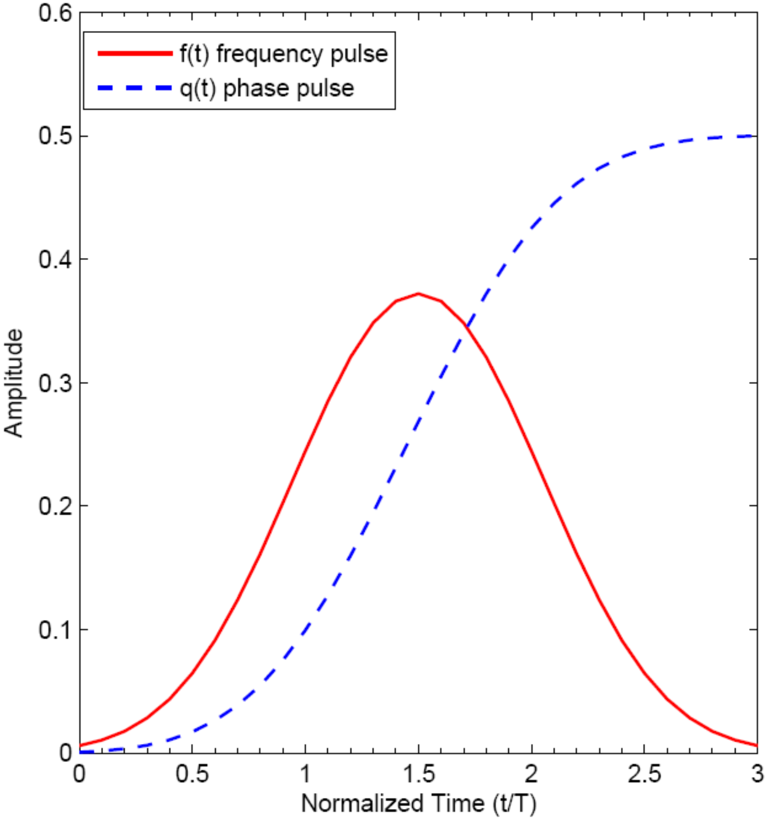
- Signal representation

$$s(t;\boldsymbol{\alpha}) \triangleq \exp\{j\psi(t;\boldsymbol{\alpha})\}$$

$$\psi(t;\boldsymbol{\alpha}) \triangleq 2\pi h \sum_i \alpha_i q(t - iT)$$

$$h = 2k/p$$

- CPM is completely defined by
  - *h :* modulation index
  - *M* : cardinality of the source alphabet α
  - *q(t)* : phase pulse



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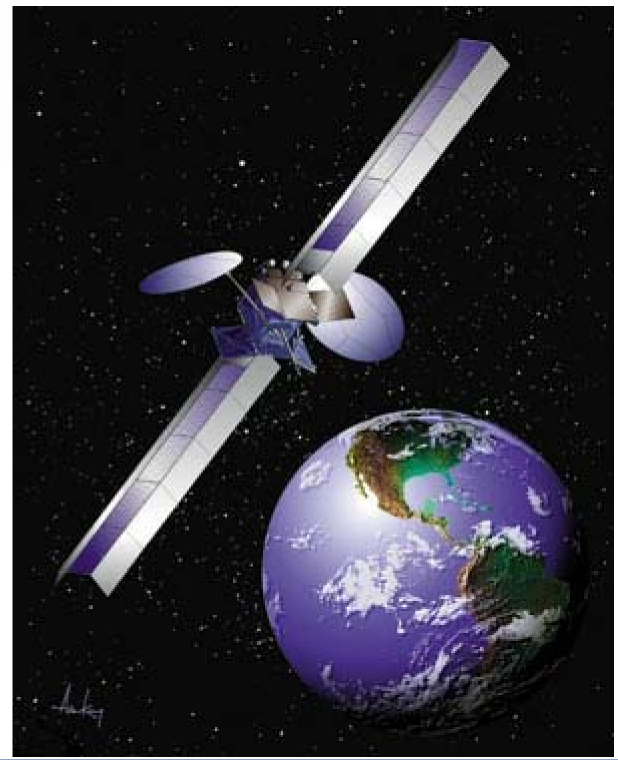
Introduction : CPM

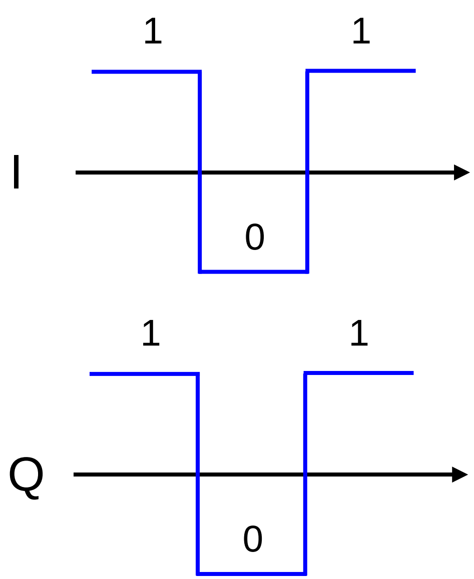
- Applications
  - Aeronautical telemetry
  - Deep-space communication
  - Bluetooth
  - Wireless modems
  - Satellite communication
  - Battery-powered communication

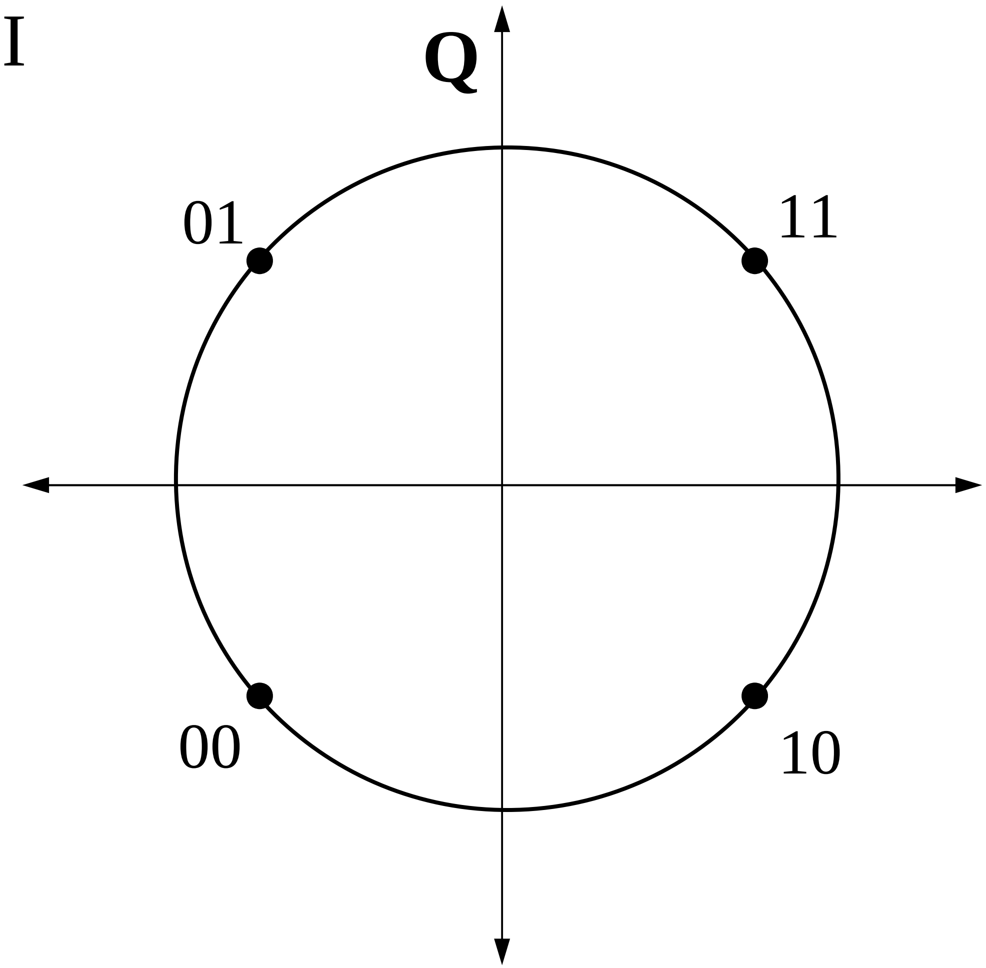
Bluetooth™



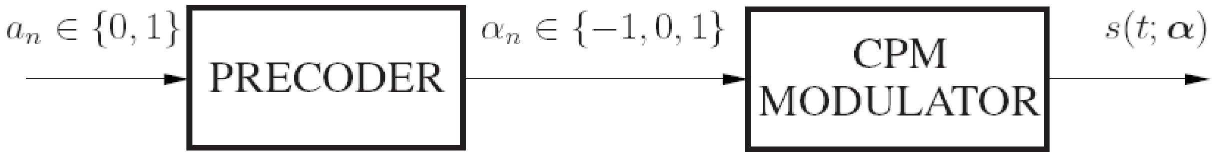
Introduction : SOQPSK

- Similar to OQPSK where I and Q bits are transmitted in offset fashion.

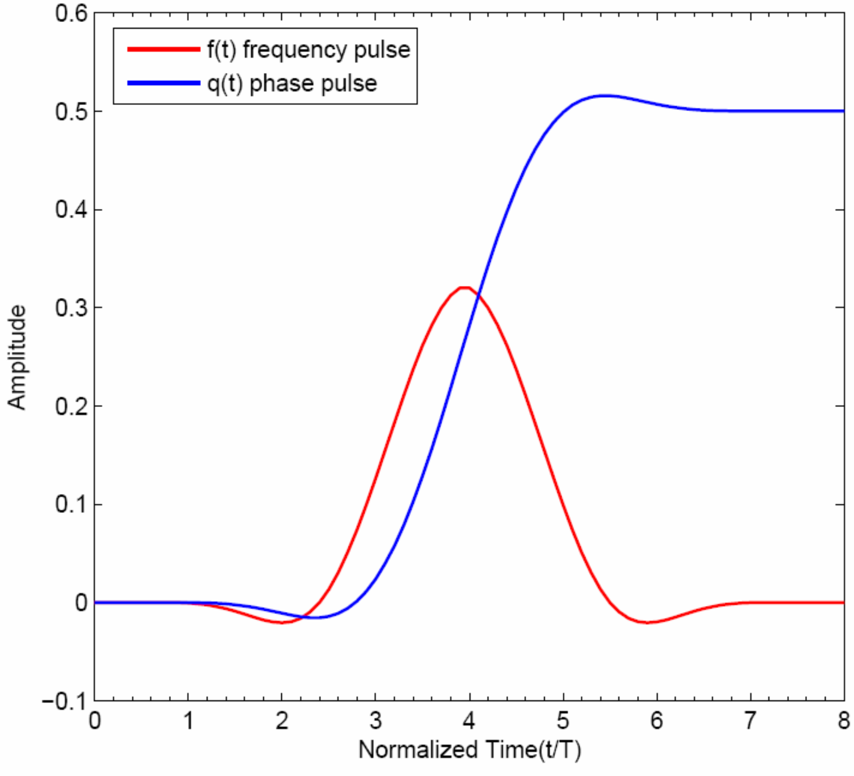




Introduction : SOQPSK



- SOQPSK is a ternary CPM with a precoder.
- 2 standards for SOQPSK
  - SOQPSK-MIL – full-response with rectangular frequency pulse.
  - SOQPSK-TG – partial-response with *L= 8.*



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Introduction : GMSK

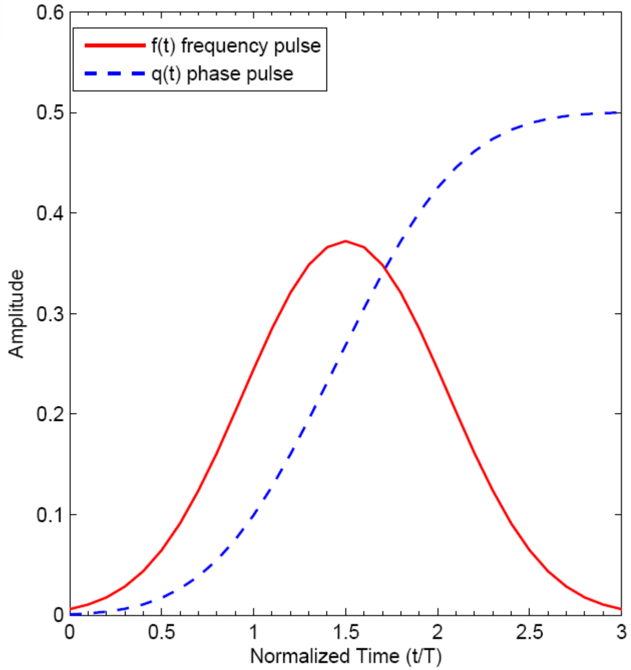
- GMSK is another widely used CPM.
- Can achieve tradeoff between bandwidth efficiency, power efficiency, and detector complexity by appropriately configuring the *BT* product.
- GMSK is binary (M = 2) with $h = ½$.
- We study 2 types of GMSK
  - GMSK with $BT = 0.3$ $(L = 3)$
  - GMSK with $BT = 0.25$ $(L = 4)$
- GMSK with $BT = 0.3$ is used in GSM.

Introduction : GMSK

- GMSK has a Gaussian frequency pulse shape

$$f(t) = \frac{1}{2T}\left\{Q\left[2\pi B\frac{t-T/2}{(\ln 2)^{1/2}}\right] - Q\left[2\pi B\frac{t+T/2}{(\ln 2)^{1/2}}\right]\right\}$$

$$Q(t) = \frac{1}{\sqrt{2\pi}}\int_t^{\infty} e^{-\tau^2/2}\, d\tau.$$



Frequency and phase pulses for GMSK with *BT = 0.3*

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Outline

- Motivation for this thesis/Research Objectives
- Introduction
- **Coherent Detection**
  - **A closer look at the phase of the signal**
  - **Maximum-Likelihood (ML) Decoding**
- Reduced Complexity Coherent Detectors
- Noncoherent detection algorithm
- Serially Concatenated Systems
- Simulation Results
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A closer look at the phase of the signal

- Phase of the signal can be grouped into two terms

$$\psi(t) = 2\pi h \sum_{i=0}^{n} \alpha_i q(t - iT) = \underbrace{\pi h \sum_{i=0}^{n-L} \alpha_i}_{\theta_{n-L}} + \underbrace{2\pi h \sum_{i=n-L+1}^{n} \alpha_i q(t - iT)}_{\theta(t)}$$

- Symbols older than L symbol times indicate the phase of the signal at the beginning of symbol interval (*cumulative phase)*.
- Phase change depends on the most recent L symbols *(correlative state)*. Thus the signal can be described with a finite state machine

$$\sigma_n = \left(\cdots, \alpha_{n-L+1}, \cdots, \alpha_{n-2}, \alpha_{n-1}, \alpha_n\right) \leftrightarrow \sigma_n = \underbrace{\left(\theta_{n-L}, \alpha_{n-L+1,} \cdots, \alpha_{n-2}, \alpha_{n-1}, \alpha_n\right)}_{pM^L branches}$$

Maximum-Likelihood (ML) decoding

- Received signal corrupted by noise $r(t) = s(t;\alpha) + n(t)$
- ML detector matches the received signal with all possible transmitted signals.
- Implemented recursively via the Viterbi algorithm.
- Organization of the trellis
  - Branch vector is the (L+1) tuple $\sigma_n = \left(\theta_{n-L}, \alpha_{n-L+1,} \cdots, \alpha_{n-2}, \alpha_{n-1}, \alpha_n\right)$
  - Each branch has a starting state $S_n = \left(\theta_{n-L}, \alpha_{n-L+1,} \cdots, \alpha_{n-2}, \alpha_{n-1}\right)$
  - And an ending state $E_n = \left(\theta_{n-L+1}, \alpha_{n-L+2,} \cdots \alpha_{n-1}, \alpha_n\right)$
  - Number of phase states is p.

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Maximum-Likelihood (ML) decoding

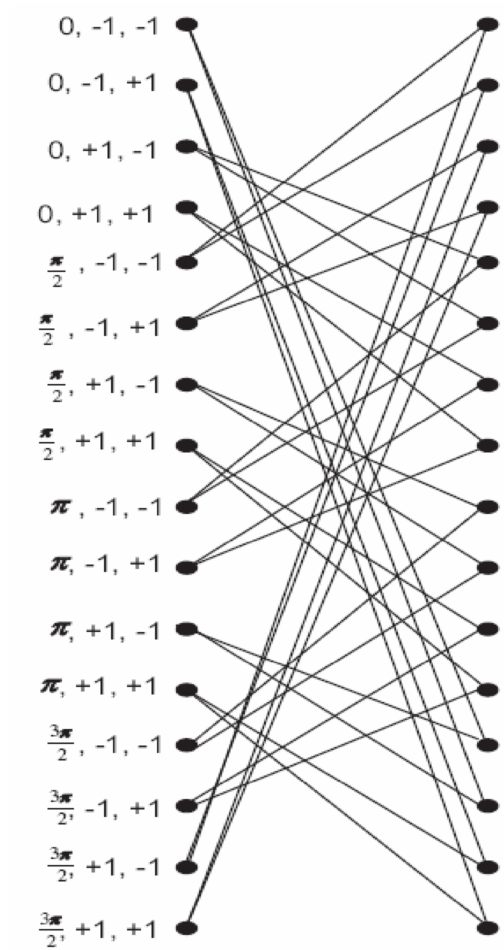
- For a CPM trellis

$$N_S = pM^{L-1}$$

$$N_B = pM^{L}$$

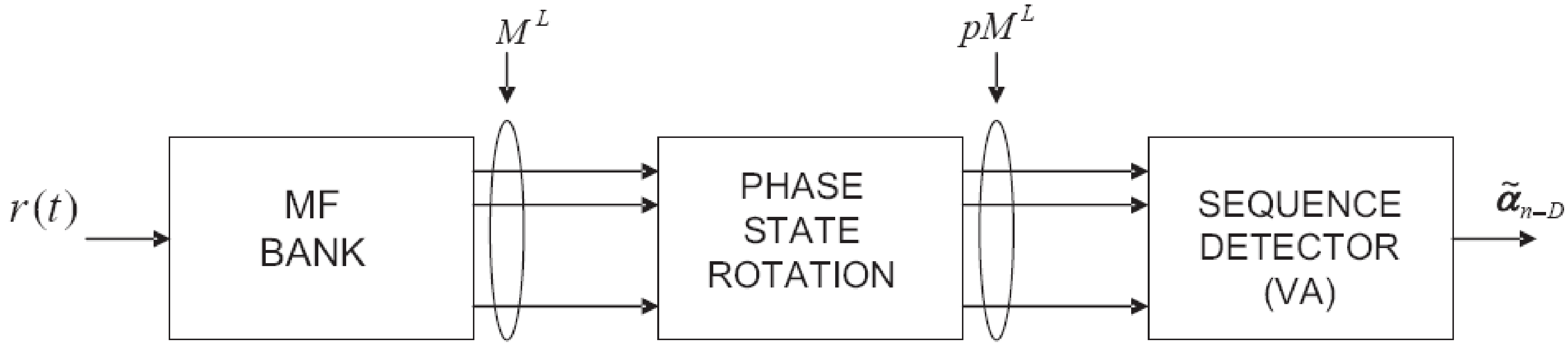
$$N_{MF} = M^{L}$$

- Trellis example, GMSK with *BT = 0.3. (h = ½ , M = 2, L = 3* and *p =4).*
- 16 states, 32 branches and 8 matched filters.



Maximum-Likelihood (ML) decoding

- Optimal coherent ML detector



- Metric update for each state $\lambda_{n+1}(\tilde{E}_n) = \lambda_n(\tilde{S}_n) + \text{Re}\{(e^{-j\theta_{n-L}} z_n(\tilde{\boldsymbol{\alpha}}_n))\}$
- $z_n(\tilde{\boldsymbol{\alpha}}_n)$ is the sampled matched filter output.
- Serves as the benchmark detector for reduced complexity and noncoherent detectors.

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- Coherent Detection
- **Reduced Complexity Coherent Detectors**
  - **Why reduced complexity detectors?**
  - **Reduced complexity approaches**
  - **Frequency Pulse Truncation**
  - **Decision Feedback**
- Noncoherent detection algorithm
- Serially Concatenated Systems
- Simulation Results
- Conclusions
- Future work

Why reduced complexity detectors?

- Longer, smoother pulses – higher bandwidth efficiency.
- Decoding complexity – increases exponentially with pulse length *L*.
- The optimal detector for SOQPSK-TG – 512 trellis states ($L = 8$, $p = 4$, $M = 2$).
- Optimal detector for GMSK with $BT = 0.25$ – 32 trellis states ($L = 4$, $p = 4$, $M = 2$).
- Difficult to implement large trellis structures – reduced complexity approaches.

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Reduced complexity coherent detectors : Approach

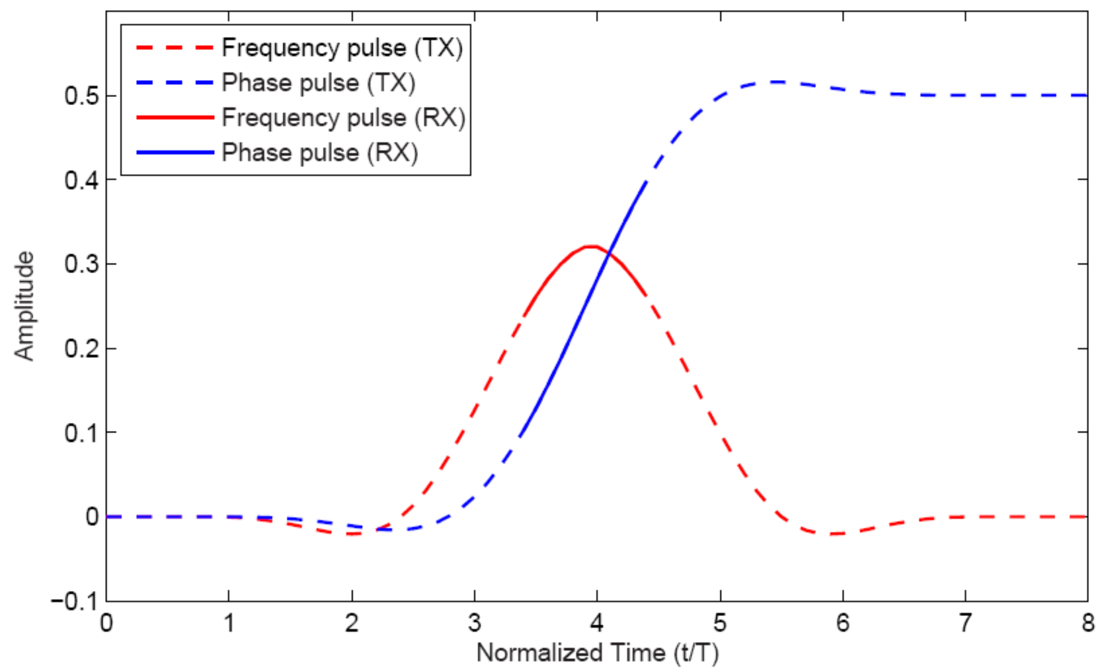
- Each trellis state is defined by

$$S_n = \underbrace{\left(\theta_{n-L}, \alpha_{n-L+1,} \cdots, \alpha_{n-2}, \alpha_{n-1}\right)}_{pM^{L-1} states}$$

- Removing/reducing coordinates from this *L*-tuple is the key to state complexity reduction.
- Number of techniques discussed in literature
  - Frequency pulse truncation (PT) technique
  - Decision feedback
- PT and decision feedback applied to GMSK for the first time in this work.

Frequency Pulse Truncation (PT)

- Use a shorter phase pulse at the receiver: $L_r < L$
- Correlative state reduced
- Number of states and matched filters reduced by a factor $M^{(L-L_r)}$



- Truncated frequency and phase pulse for SOQPSK-TG

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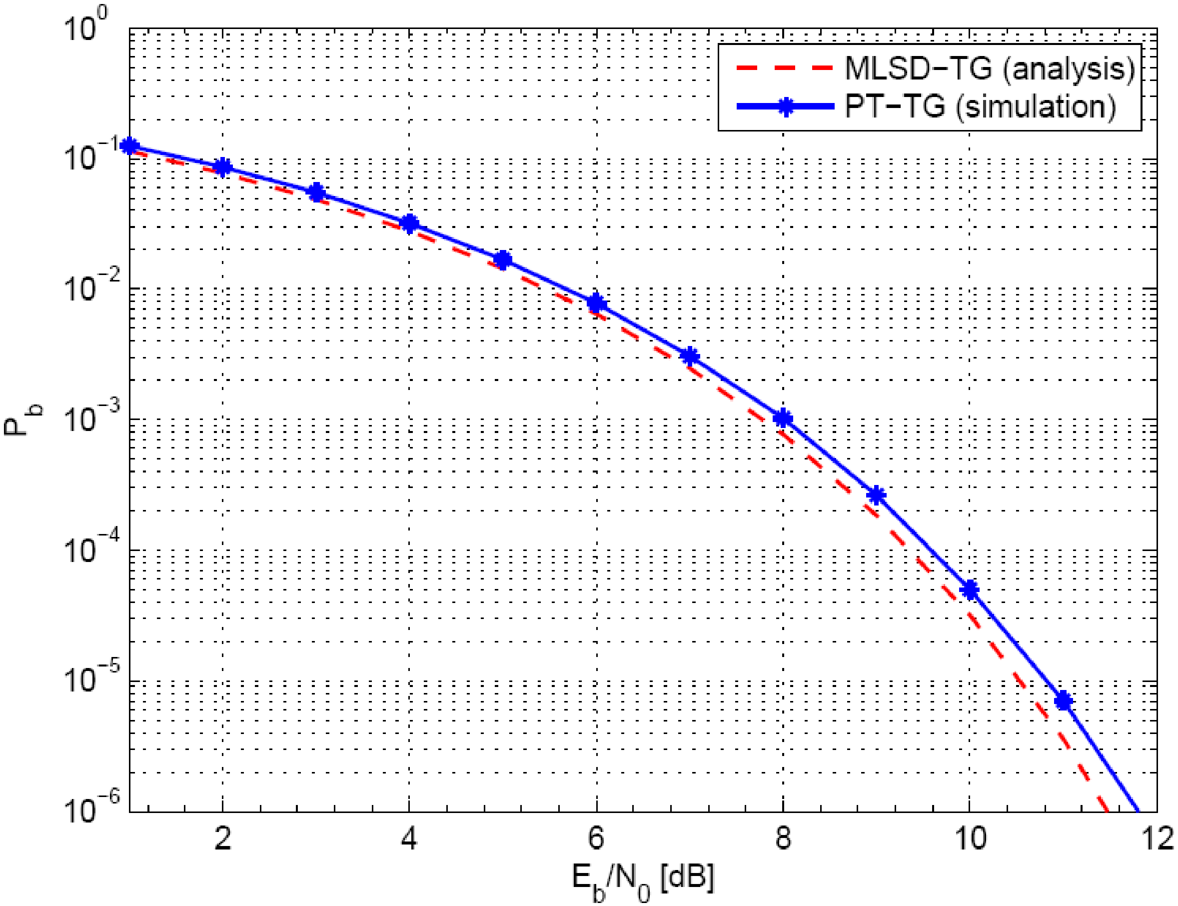
PT performance

- SOQPSK-TG
- Pulse truncated from $L=8$ to $L_r=1$.
- Reduction in trellis states from 512 to 4.
- Loss in performance of 0.2 dB at $P_b = 10^{-5}$



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Decision Feedback

- Phase states chosen at *run time.*
- Since phase state is defined by

$$\theta_{n-L} = h\pi \sum_{i=-\infty}^{n-L} \alpha_i \bmod 2\pi$$

knowing an estimate of the past symbols the phase state for each trellis state can be updated.

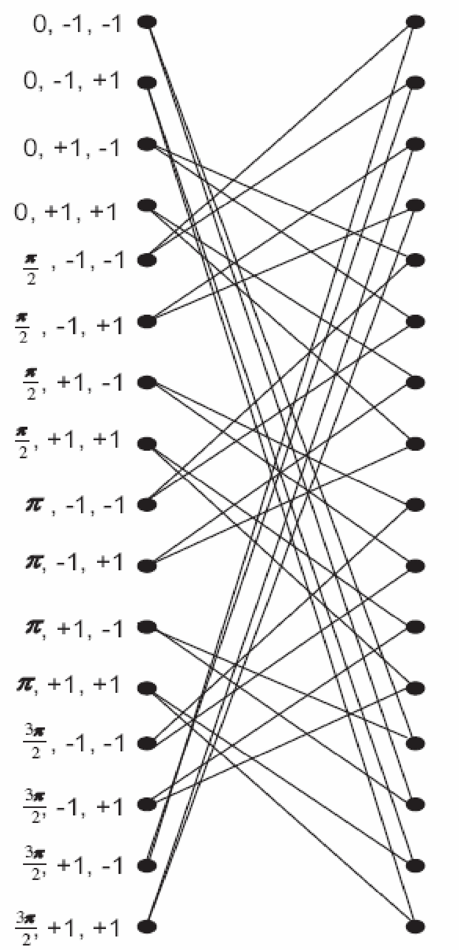
- Using decision feedback to update phase for each trellis state reduces the number of trellis states by a factor *p*.
- The state now is $S_n = \underbrace{\left(\alpha_{n-L+1,} \cdots, \alpha_{n-2}, \alpha_{n-1}\right)}_{M^{L-1} states}$

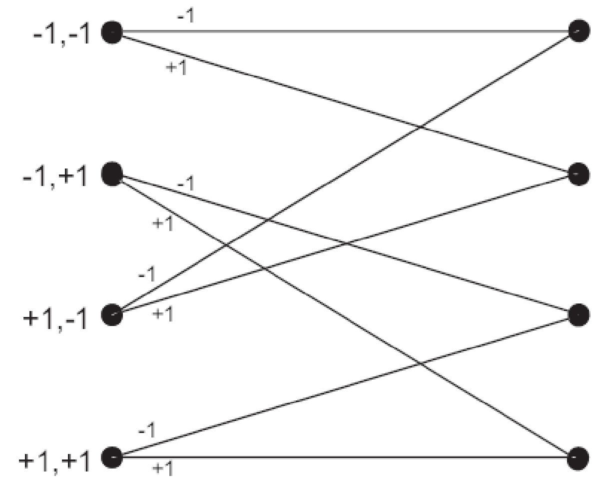
Decision feedback applied to GMSK trellis

Actual trellis

- 16 states

$$S_n = (\theta_{n-3}, \alpha_{n-2}, \alpha_{n-1})$$





Simplified trellis

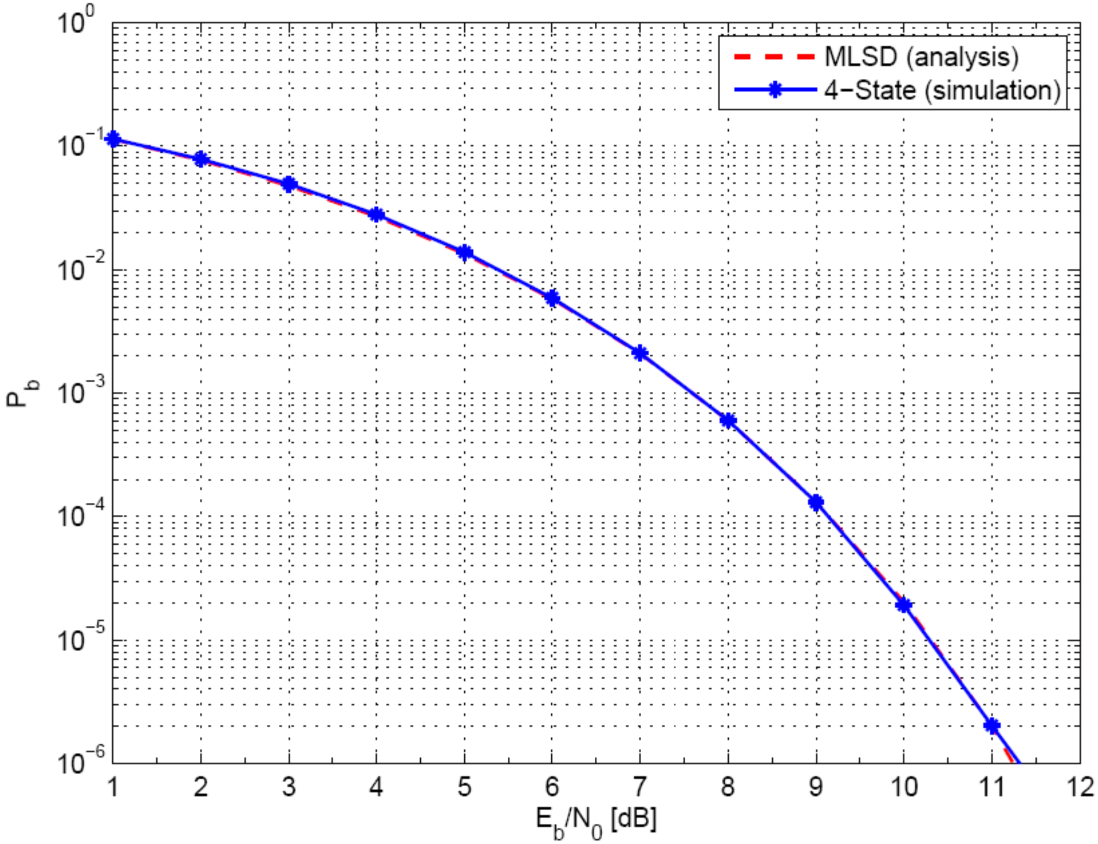
- 4 states

$$S_n = (\alpha_{n-2}, \alpha_{n-1})$$

$$\hat{\theta}_{n-2}(\tilde{E}_n) = \hat{\theta}_{n-3}(\tilde{S}_n) + \pi h \tilde{\alpha}_{n-2}$$

Decision Feedback : Performance

- Performance of GMSK using the simplified 4-state trellis.



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- Introduction
- Coherent Detection
- Reduced Complexity Coherent Detectors
- **Noncoherent detection algorithm**
  - **Why Noncoherent?**
  - **The Algorithm**
  - **Phase Noise Model**
- Serially Concatenated Systems
- Simulation Results
- Conclusions
- Future work

Why Noncoherent?

- Received signal model $r(t) = s(t;\alpha)e^{j\phi(t)} + n(t)$
- Phase noise channels often encountered in practice
- Robust
- Easy to synchronize
- Can recover input bits in the presence of phase noise

Noncoherent detection algorithm

- Phase noise averaged out using exponential window averaging
- Metric increment for noncoherent detection

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

- There is a complex-valued *phase reference* $Q_n(\cdot)$ associated with each trellis stated and is recursively updated using

$$Q_{n+1}(\tilde{E}_n) \triangleq aQ_n(\tilde{S}_n) + (1-a)e^{-j\tilde{\theta}_{n-L}}z_n(\tilde{\boldsymbol{\alpha}}_{\boldsymbol{n}})$$

forgetting factor a is a real number in the range 0 < *a* < *1*.

- Applied to GMSK for the first time in this work.

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Noncoherent detection : Phase noise model

- Motivation for noncoherent detector – carrier phase is not known and is varying.
- Phase noise is given by

$$\phi_n \equiv \phi(nT) = \phi_{n-1} + \nu_n \mod 2\pi$$

where $\{\nu_n\}$ are independent and identically distributed Gaussian random variables with zero mean and variance δ^2.

- Phase noise is modeled as a first order Markov process with Gaussian transition probability distribution.

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- **Serially Concatenated Systems**
  - **Introduction**
  - **System Description**
  - **SISO Algorithm**
  - **Performance**
- Simulation Results
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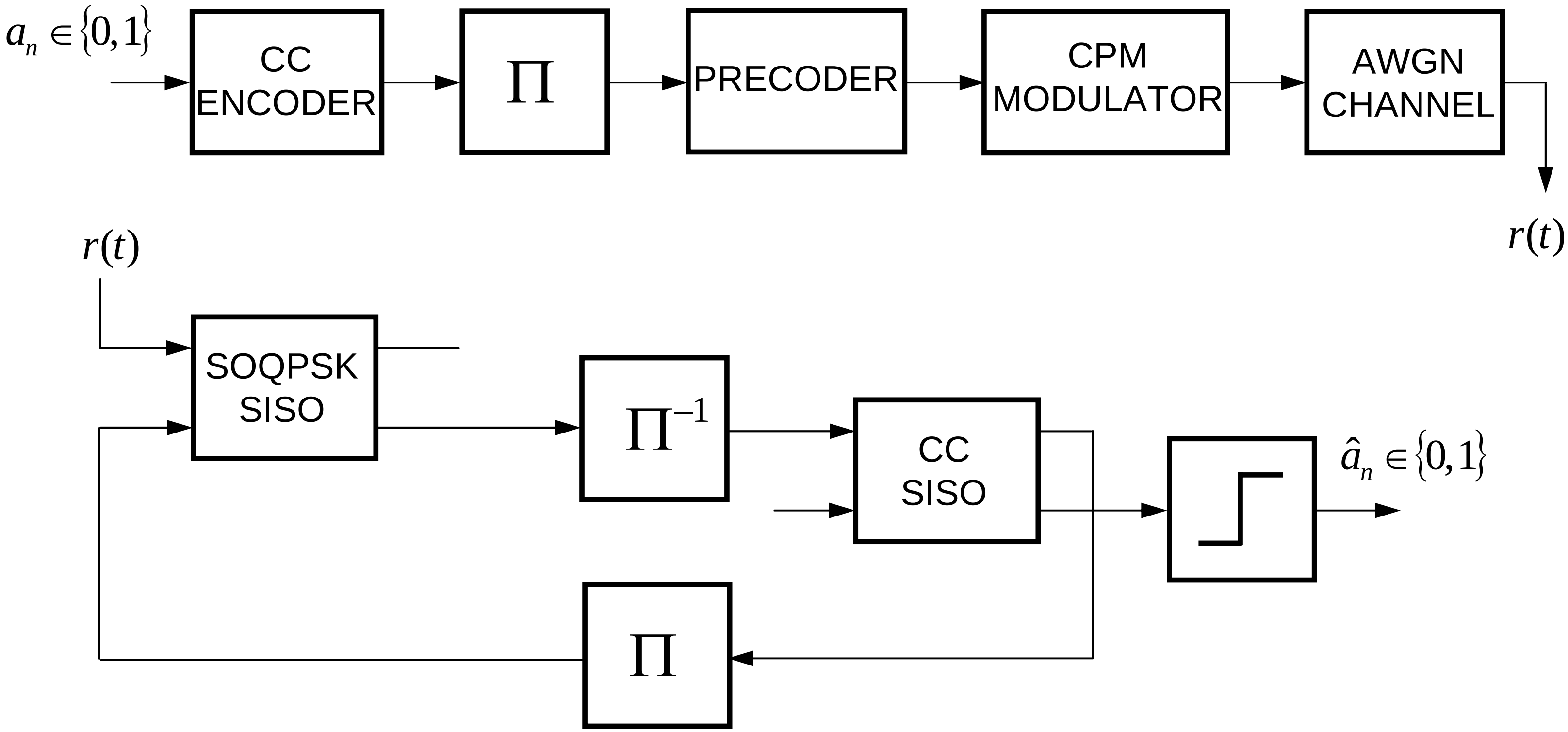
Serially Concatenated Coded Systems: Introduction

- Coded systems – improvement in energy efficiency, large gains.
- Concatenated codes – developed by Forney
- Multistage coding with *inner* and *outer* codes.
- Probability of error decreases exponentially while decoding complexity increases only linearly.
- We discuss SCC systems with CPM (SOQPSK and GMSK) as the *inner* code.
- Reduced complexity GMSK SCC systems studied for the first time.

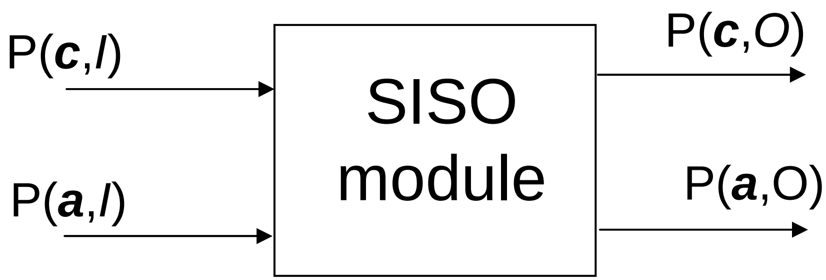
Serially Concatenated Coded Systems : System Description



- Outer code: rate-1/2 convolutional code
- Inner code: SOQPSK and GMSK
- Block length N=2048 and N_i=5

Serially Concatenated Systems :SISO Algorithm

- Outputs *P(**a**,O)* and *P(**c**,O)* based on code constraints.



- Forward and backward recursions to update metrics associated with each trellis state.

$$A_k(\tilde{E}_k) = A_{k-1}(\tilde{S}_{k-1}) + P_k[\tilde{a}_k; I] + P_k[\tilde{c}_k; I]$$

$$B_k(\tilde{S}_k) = B_{k+1}(\tilde{E}_{k+1}) + P_{k+1}[\tilde{a}_{k+1}; I] + P_{k+1}[\tilde{c}_{k+1}; I]$$

- For a CPM SISO $P_k[c_k, I] = \mathrm{Re}\{e^{-j\theta_{n-L}} z_k(\tilde{\boldsymbol{\alpha}}_{\boldsymbol{k}})\}$

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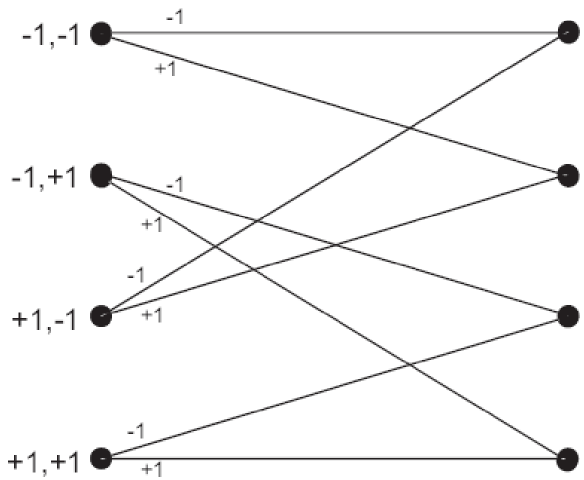
Serially Concatenated Systems :SISO Algorithm

- In case of noncoherent detection

$$P_k[c_k, I] = \mathrm{Re}\{Q_n^*(\tilde{S}_n)e^{-j\theta_{n-L}}z_k(\tilde{\boldsymbol{\alpha}}_{\boldsymbol{k}})\}$$

  where $Q(\cdot)$ is the phase reference associated with each state and is updated only during the forward recursion.

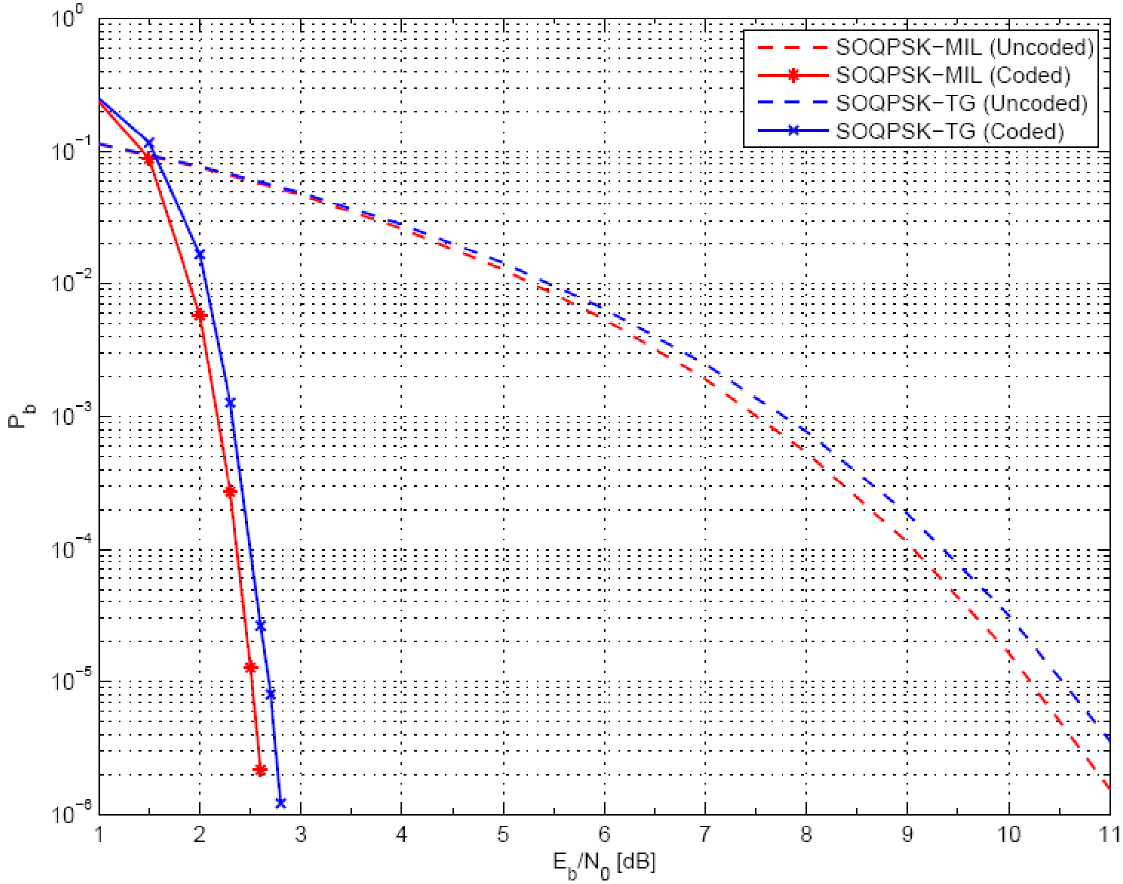


- The output probability distribution for the bit/code word for symbol time *k* is computed as

$$P_k(a_k; O) = A_{k-1}(\tilde{S}_{n-1}) + P_k[a^j; I] + P_k[c^j; I] + B_k(\tilde{E}_n).$$

Performance of Coded SOQPSK Systems

- High coding gain is achieved.



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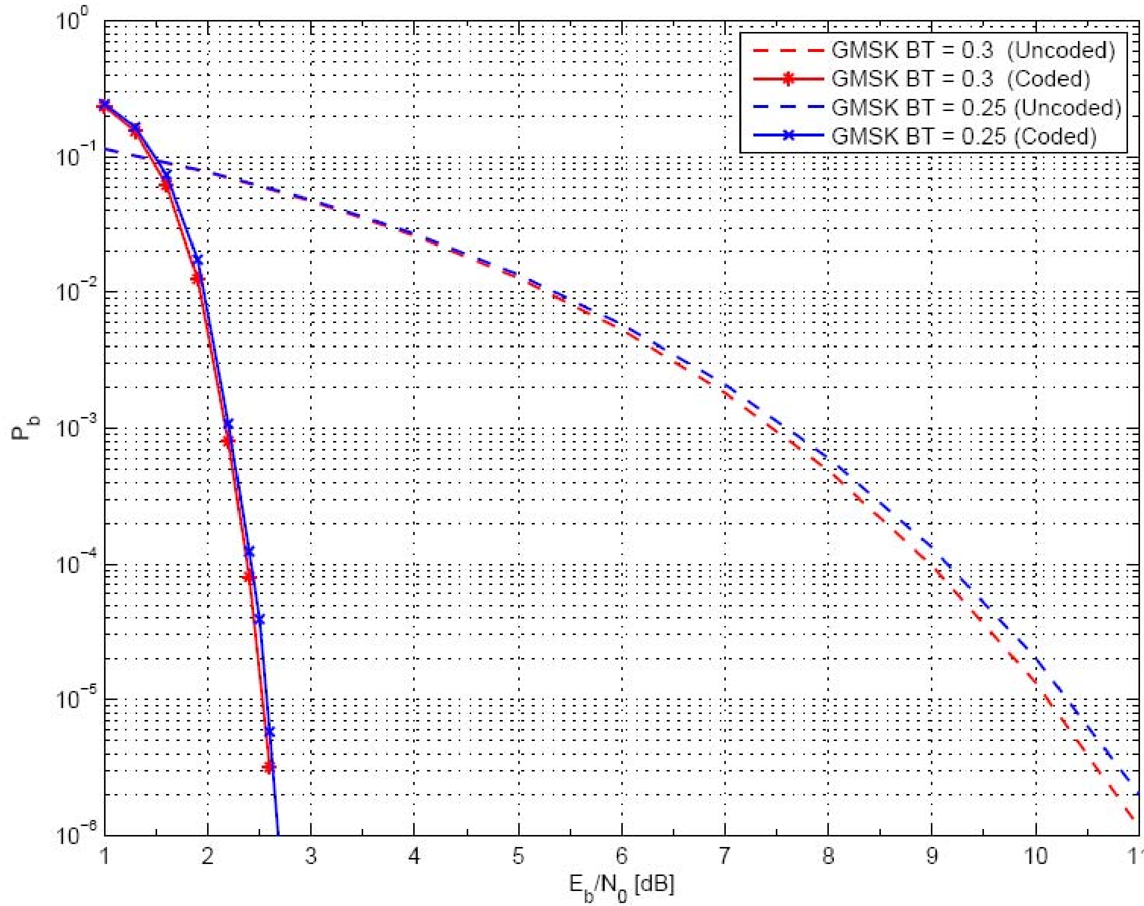
Performance of Coded GMSK Systems

- High coding gain is achieved.



Performance of Coded Systems

- Coding gains for serially concatenated SOQPSK and GMSK

Modulation Scheme	Gain in dB
SOQPSK-MIL	7.35
SOQPSK-TG	7.72
GMSK with $BT = 0.3$	7.46
GMSK with $BT = 0.25$	7.53

- More bandwidth efficient schemes have higher coding gains.

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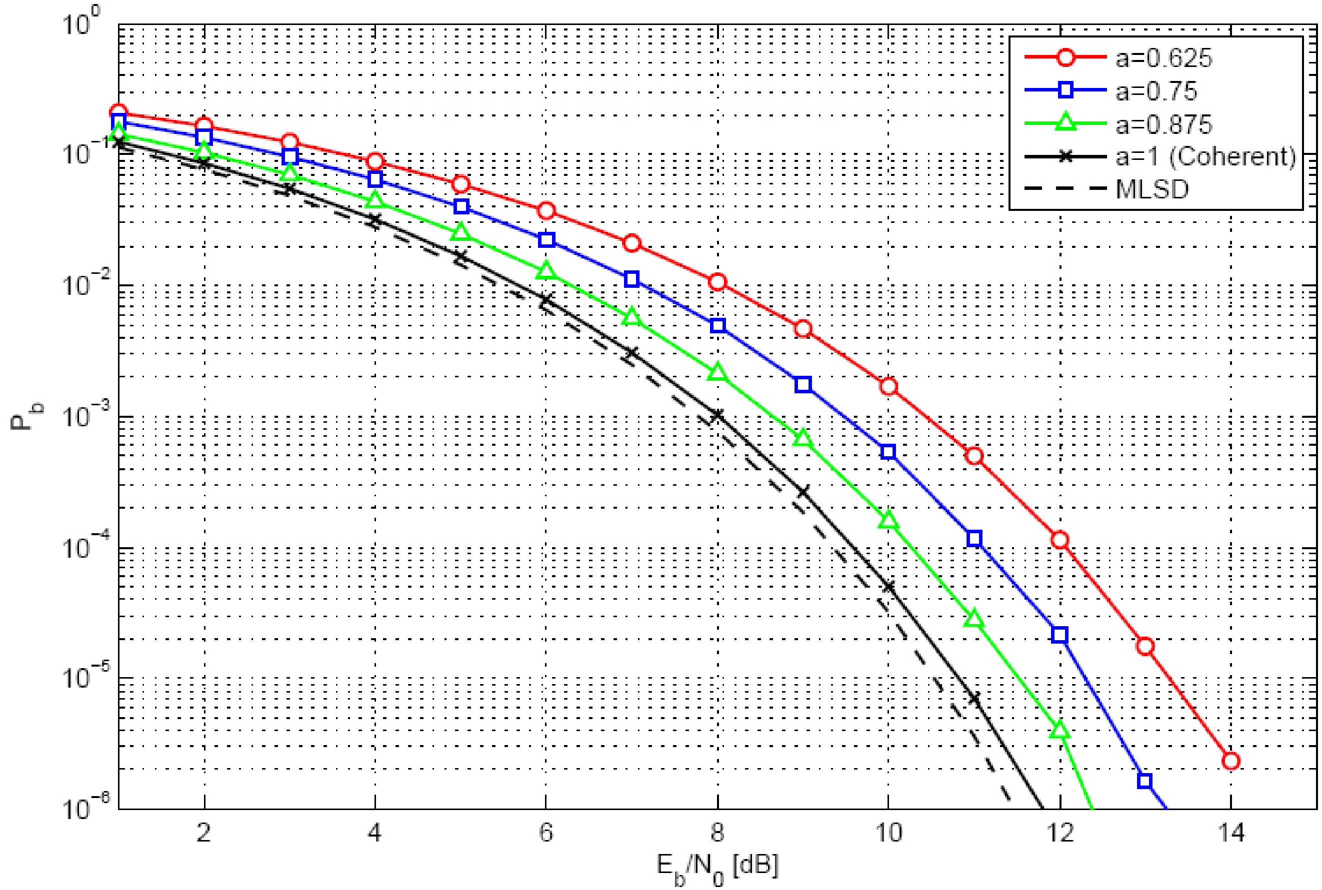
- **Simulation Results**
  - **Performance of Noncoherent detectors**
  - **Performance of Noncoherent (Coded) systems**
- Conclusions
- Future work

Performance of Noncoherent SOQPSK detectors

- Noncoherent detection of SOQPSK-TG with no phase noise.
- Loss of 0.75 dB when *a = 0.875*



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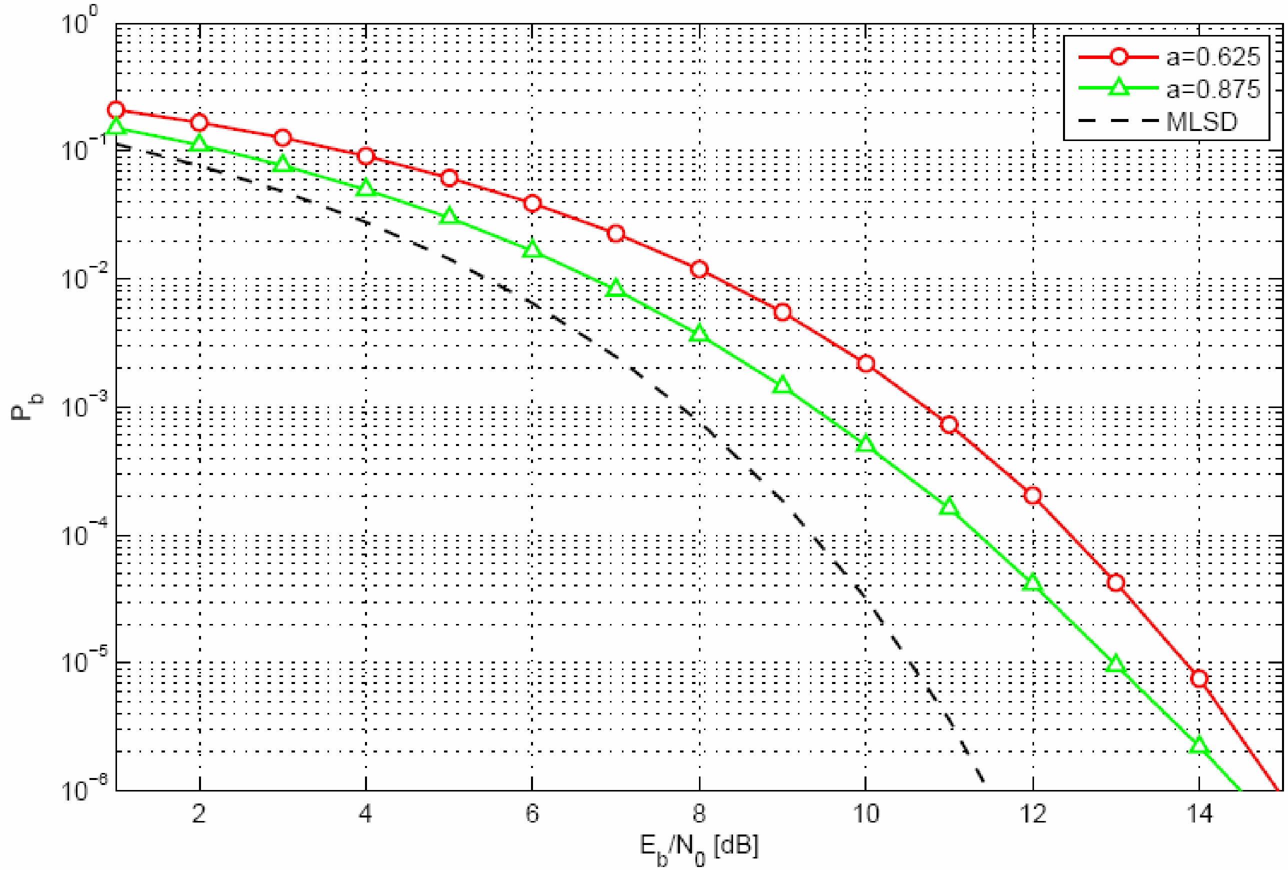
Performance of Noncoherent SOQPSK detectors

- Noncoherent detection of SOQPSK-TG with phase noise of

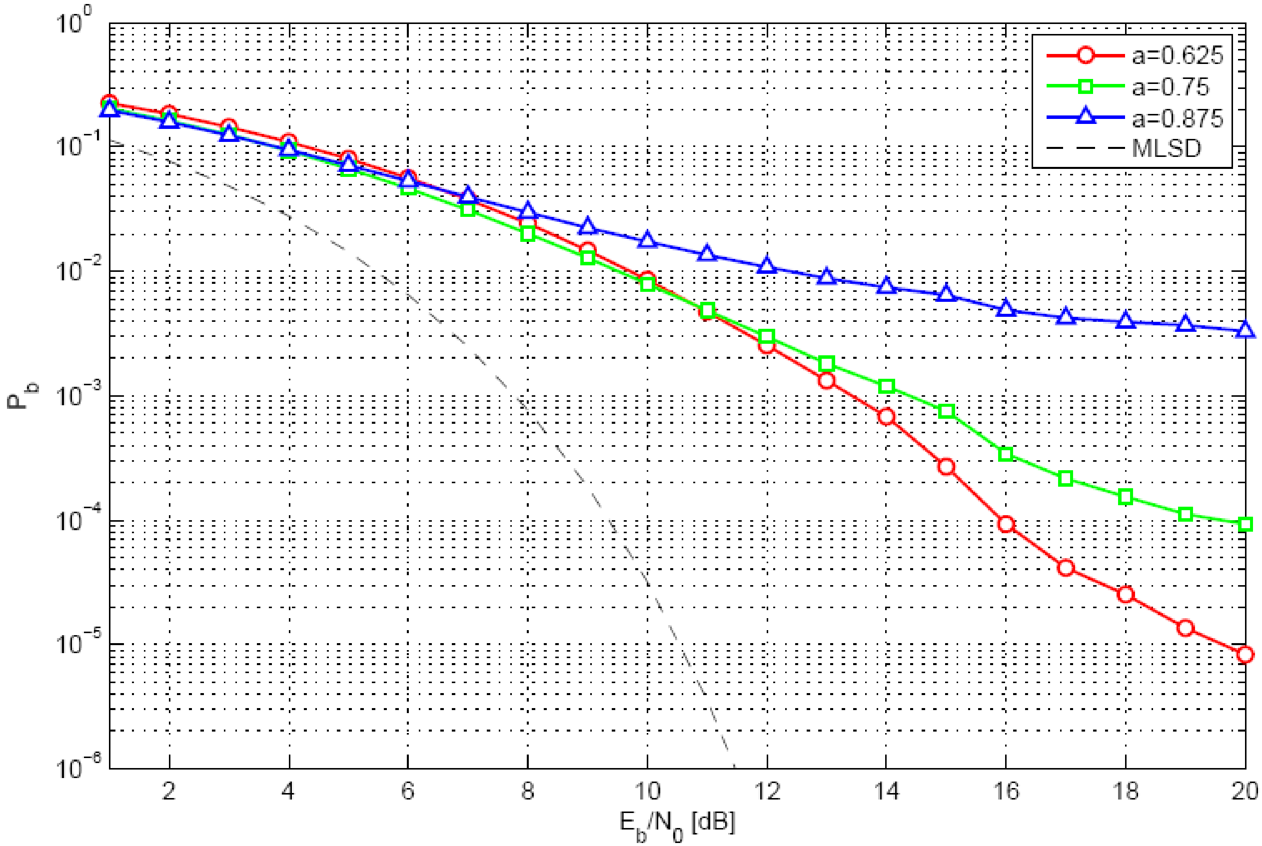
  $\delta = 2° / \text{sym.}$

- Loss of 3.1 dB when a = 0.875



Performance of Noncoherent SOQPSK detectors

- Noncoherent detection of SOQPSK-TG with phase noise of $\delta = 5° /$ sym.
- Loss of 9.8 dB when a = 0.625
- Lower value of a betters tracks faster phase changes.



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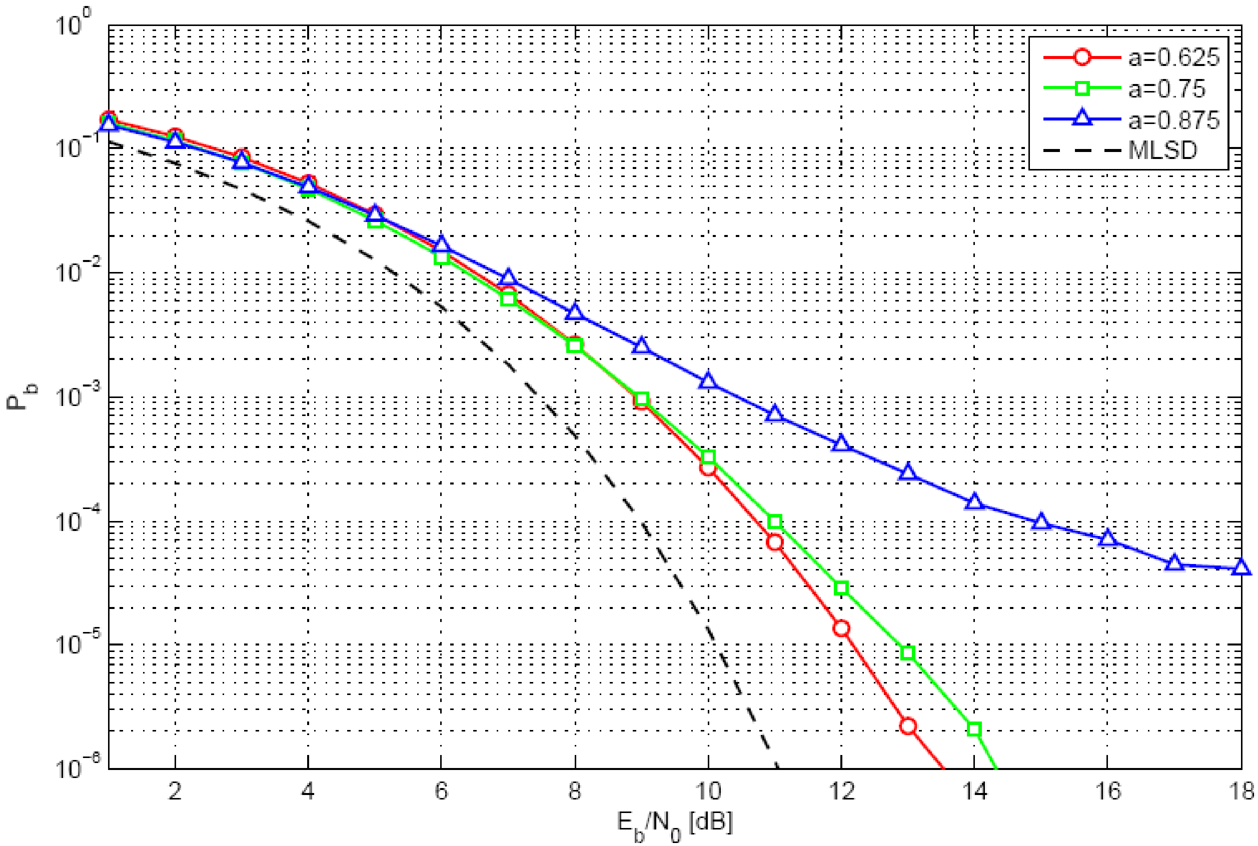
Performance of Noncoherent GMSK detectors

- Noncoherent detection of GMSK (*BT = 0.3)* with phase noise

  $\delta = 5° /$ sym.
- Loss of 2.0 dB when a = 0.625



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Performance of Noncoherent detectors

- Loss in dB for noncoherent systems with phase noise of

$\delta = 2° /$ sym. at $P_b = 10^{-5}$

Modulation Scheme	$a = 0.875$	$a = 0.75$	$a = 0.625$
SOQPSK-MIL	1.15	1.45	1.9
SOQPSK-TG	2.3	2.4	3.1
GMSK with $BT = 0.3$	0.90	0.95	1.15
GMSK with $BT = 0.25$	1.2	1.25	1.6

- GMSK *(BT = 0.3)* has the best performance.
- SOQPSK – MIL and GMSK *(BT = 0.25)* are comparable.

Performance of Noncoherent detectors

- Loss in dB for noncoherent systems with phase noise of

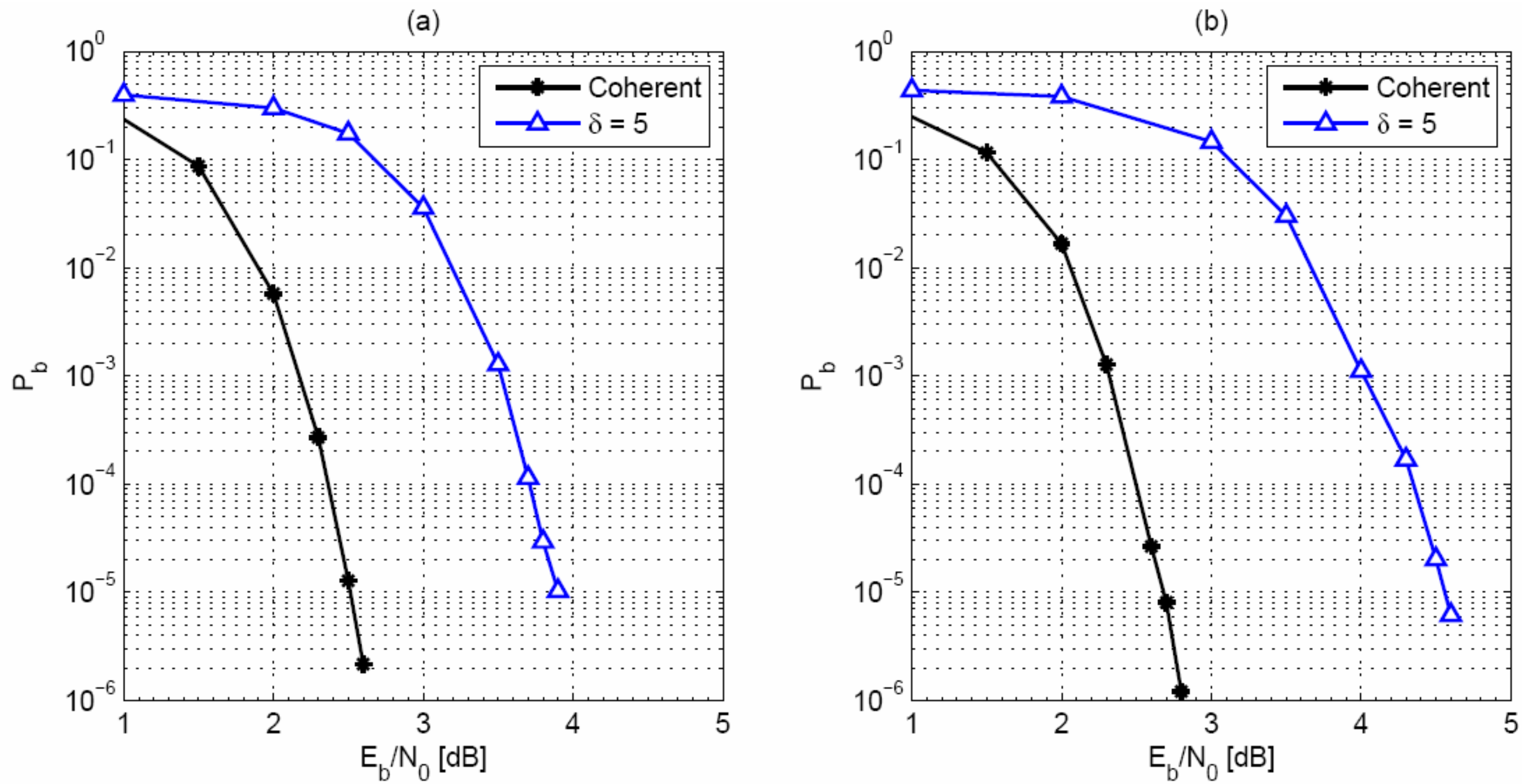
$\delta = 5° /$ sym. at $P_b = 10^{-5}$

Modulation Scheme	$a = 0.875$	$a = 0.75$	$a = 0.625$
SOQPSK-MIL	∞	6.2	4.1
SOQPSK-TG	∞	∞	9.8
GMSK with $BT = 0.3$	∞	3.05	2.0
GMSK with $BT = 0.25$	∞	3.1	2.85

- GMSK *(BT = 0.3)* has the best performance.
- SOQPSK – TG performs significantly worse.
- Lower values of *a* enable faster carrier phase tracking.

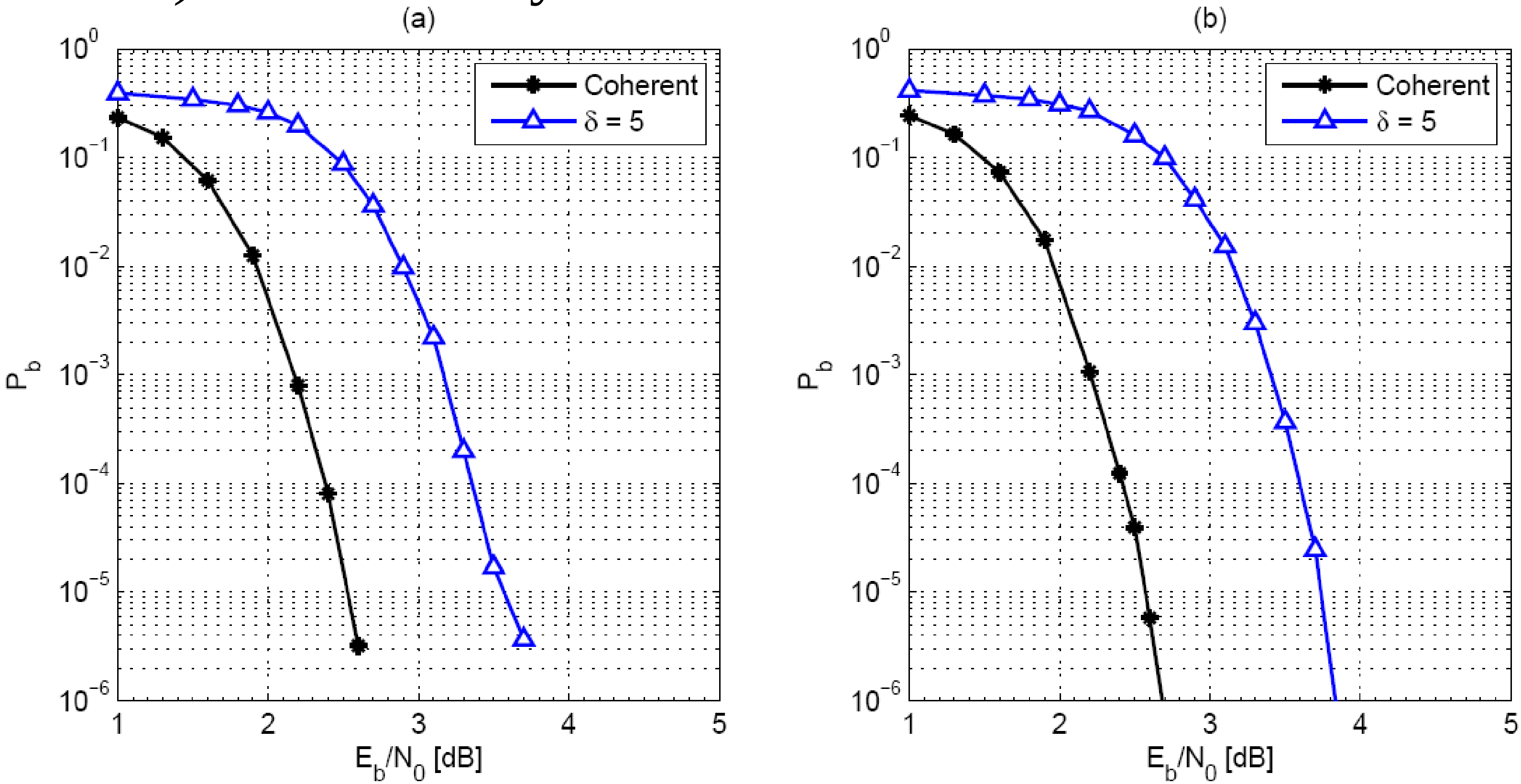
Performance of Noncoherent Coded Systems

- Noncoherent detection of coded a) SOQPSK–MIL and b) SOQPSK–TG with $\delta = 5°/$ sym.



Performance of Noncoherent Coded Systems

- Noncoherent detection of coded a) GMSK *(BT = 0.3)* and b) GMSK *(BT = 0.25)* with $\delta = 5° /$ sym.



Performance of Noncoherent Coded Systems

- Loss in dB for noncoherent (coded) systems at $P_b = 10^{-5}$

Modulation Scheme	$\delta = 0°/\text{sym.}$	$\delta = 2°/\text{sym.}$	$\delta = 5°/\text{sym.}$
SOQPSK-MIL	0.68	0.54	1.40
SOQPSK-TG	0.79	0.71	1.88
GMSK with $BT = 0.3$	0.50	0.55	1.03
GMSK with $BT = 0.25$	0.61	0.71	1.17

- a chosen to be 0.875 for all cases as E_b/N_0 is low.
- SOQPSK and GMSK have comparable performance when $\delta = 2°$/sym.
- GMSK is marginally better than SOQPSK for the severe phase noise case i.e. $\delta = 5°$/sym.

Outline

- Motivation for this thesis/Research Objectives
- Introduction
- Coherent Detection
- Reduced Complexity Coherent Detectors
- Noncoherent Detection Algorithm
- Serially Concatenated Systems
- Simulation Results
- **Conclusions**
  - **Key contributions**
- Future work

Conclusions

- Noncoherent (uncoded) detectors for GMSK and SOQPSK have comparable performance for low to moderate phase noise, for severe phase noise GMSK performs significantly better.
- For coded systems noncoherent GMSK detectors have marginally better performance than SOQPSK.
- SOQPSK – TG has the highest coding gain (it is also the most bandwidth efficient).

Conclusions : Key contributions

- Developed reduced complexity coherent detectors for GMSK for the first time.
- Noncoherent detection algorithm which can be used for uncoded and coded systems was applied to GMSK for the first time.
- A comprehensive set of numerical performance results for SOQPSK and GMSK noncoherent detectors in phase noise channels were provided.

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Future Work

- Noncoherent coded SOQPSK and GMSK performance with other convolutional codes as *outer codes*.
- Investigation of GMSK with lower *BT* values (more bandwidth efficient).
- Other complexity reduction techniques such as the PAM decomposition for GMSK.

References

- J. B. Anderson, T. Aulin, and C.-E. Sundberg. *Digital Phase Modulation*. Plenum Press, New York, 1986.
- S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara. A soft-input soft-output APP module for iterative decoding of concatenated codes. *IEEE Communication Letters*, Jan. 1997.
- G. Colavolpe, G. Ferrari, and R. Raheli. Noncoherent iterative (turbo) decoding. *IEEE Transactions on Communication*, Sept. 2000.
- M. K. Howlader and X. Luo. Noncoherent iterative demodulation and decoding of serially concatenated coded MSK. In *Proc. IEEE Global Telecommunications Confernce*, Nov./Dec. 2004.
- L. Li and M. Simon. Performance of coded OQPSK and MIL-STD SOQPSK with iterative decoding. *IEEE Transactions on Communication*, Nov. 2004.
- P. Moqvist and T. Aulin. Serially concatenated continuous phase modulation with iterative decoding. *IEEE Transactions on Communication*, Nov. 2001.
- A. Svensson, C.-E. Sundberg, and T. Aulin. A class of reduced-complexity Viterbi
- detectors for partial response continuous phase modulation. *IEEE Transactions on Communication*, Oct. 1984.
- J.Wu and G. Saulnier. A two-stage MSK-type detector for Low-BT GMSK signals. *IEEE Transactions on Vehicular Technology*, July 2003.

Questions/Thanks

- The End
- Thank you for listening!