Joint Turbo Decoding and Synchronisation

ESA Contract 18261/04/NL/AR

ABSM Workshop

ESTEC, 30 March 2006

ADVANTECH SATELLITE NETWORKS

Turbo Concept

EURECOM
Sophia Antipolis

Overview

- Project Overview
- Objectives
  - Market Justifications
- System Overview
  - Problem Statement
- Joint Synchronisation and Decoding
  - Algorithm Selections
- Hardware Implementation

Project Overview

Team Members and their Contributions:

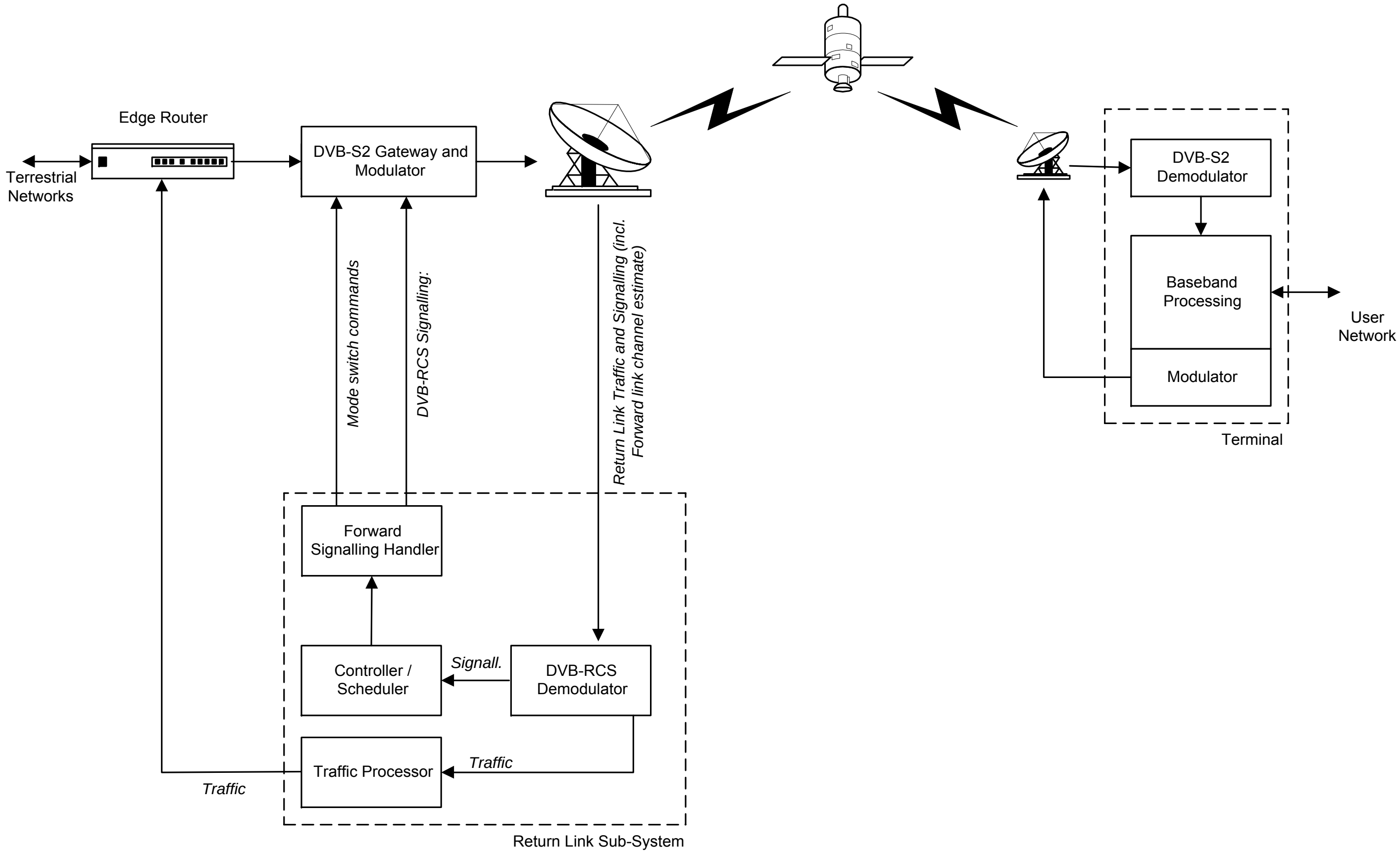
- **Advantech Satellite Networks (Former EMS)**
  - Thorough knowledge of DVB-RCS and commercial needs
  - Existing demodulator designs and implementation
  - Previous work on joint techniques
- **Turbo Concept:**
  - Industry-standard IP core products for turbo code and turbo like decoders
  - Thorough knowledge of implementation of iterative algorithms
  - Previous work on joint techniques
- **Eurecom:**
  - State-of-the-art advanced techniques

Project Overview: Incentives

- **Advantech Satellite Networks:**
  - To enhance the performance of the DVB-RCS demodulator product, in particular rain fade counter measure
  - In response to identified customer needs
- **Turbo Concept:**
  - To improve the DVB-RCS and DVB-S2 decoder products, by allowing them to operate with synchronisation algorithms in an integral fashion
- **Eurecom:**
  - To advance the state of the art of joint techniques, with special emphasis on short-burst applications
  - Build upon experiences gained in a previous ESA Contract: “Carrier phase estimation with iterative decoding” (Contract No. 17337/03/NL/LvH).

System Baseline

- **Return Link**: DVB-RCS: Potential extension to 8PSK modulation and more flexible burst structure
- **Forward Link**: DVB-S2
- The main emphasis on the performance improvement of the return link.



Objectives

- Robust synchronisation for power efficient transmission schemes
  - Reduce transmitted power requirement.
  - Improvement in carrier synchronisation
- Performance improvement of DVB-RCS return link channel
  - Low turbo coding rates
  - Short bursts (carrying one or two ATM bursts, overhead bursts)
- Robust synchronisation in the presence of phase noise at low symbol rate

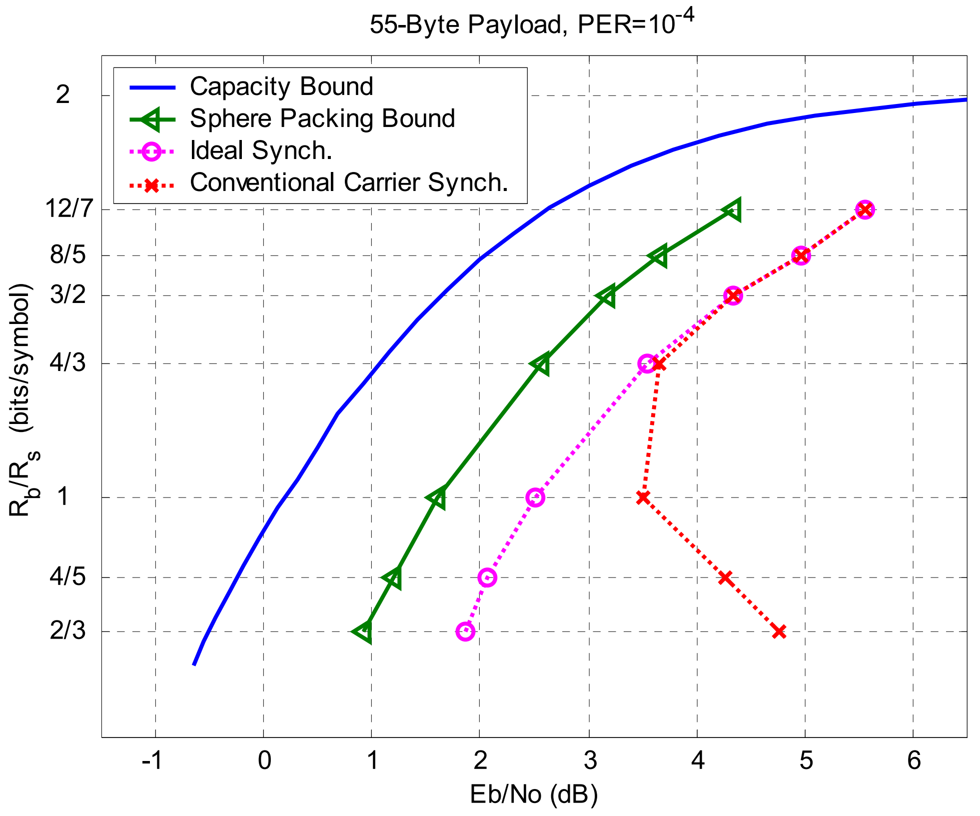
EURECOM
Sophia Antipolis

Turbo Concept

ADVANTECH
SATELLITE NETWORKS

Problem Statement

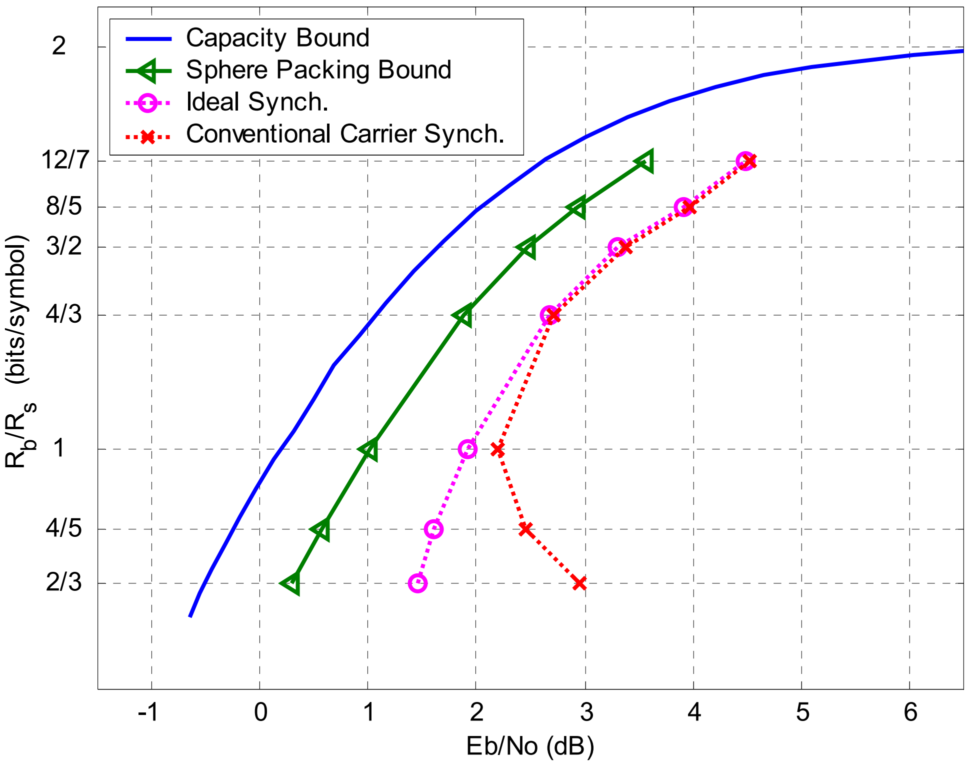
- 55-byte payload, PER=1e-4
- Performance degradation at coding rates below r=2/3.
- Similar trend at lower PER targets.



Problem Statement

- 188-byte payload (One MPEG Unit), PER=1e-4

188-Byte Payload, PER=10^{-4}



Algorithm Selection

- A short list containing two sets of algorithms were identified:
- Group1: Evolutionary algorithms
  - Enhanced carrier frequency offset estimator
  - Decoder–assisted frequency offset selection
  - Soft-decision aided phase tracking
- Group 2:State-of-the-art algorithms
  - Bayesian algorithms for carrier synchronisation and decoding
  - Factor Graph and Product sum approach.
  - C.B.C. Algorithm

Evolutionary Algorithms

Conventional Carrier Synchronisation

- Coherent demodulation of DVB-RCS signal:
  - Carrier Frequency Estimation (NDA or DA)
  - Carrier Phase Estimation and Tracking (DA, NDA, DD)
- **Carrier frequency estimation**, main cause of carrier synchronisation error at low SNR in DVB-RCS return channel for short bursts.
  - Data-Aided Approach: Inaccurate estimate based on short preamble
  - Non-Data-Aided Approach: “Threshold Effect” at low SNR.
- **Phase noise**: the main cause of performance degradation for longer bursts operating at low symbol rate and low coding rate

Carrier Frequency Estimator

- Threshold Effect:
  - Increased Probability of large errors (“outliers”)
  - Deviation from expected performance predicted by Cramér-Rao Bound
- Important to identify whether the threshold effect is fundamental
- Investigate theoretical bounds on performance

Performance Bounds: Cramér-Rao Bounds

- **Cramér-Rao Bound on the estimate variance**
  - **Frequency Estimate of QPSK Signals**

- **CRB does not identify the threshold effect.**

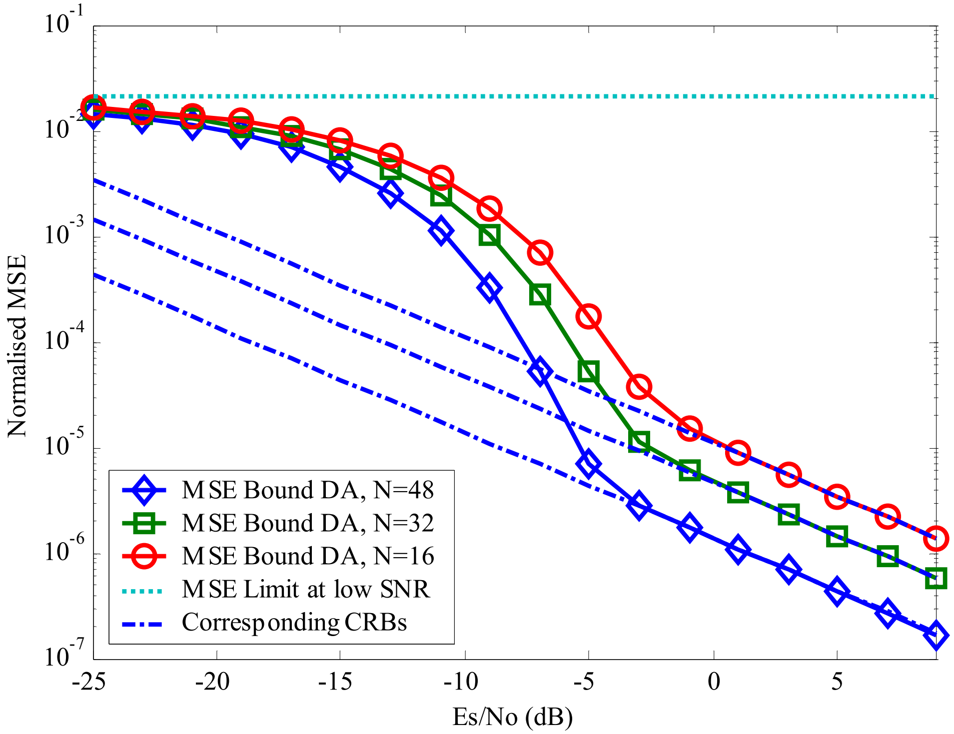
$$\mathrm{CRB}\left(f_e\right)=\frac{6}{\left(2\pi\right)^2 N\left(N^2-1\right)\frac{E_s}{N_0}F\left(\frac{E_s}{N_0}\right)}$$

  - ***N*** : Number of channel Observations
  - ***F(.):*** *Non-linear function, dependent on Es/No and Modulation*

- **Other Mean Square Error (MSE) lower bounds provide tighter lower bounds at different SNR regions**
  - Ziv-Zakai Bound, Chazan-Zakai-Ziv Bound, Bellini-Tartara Bound

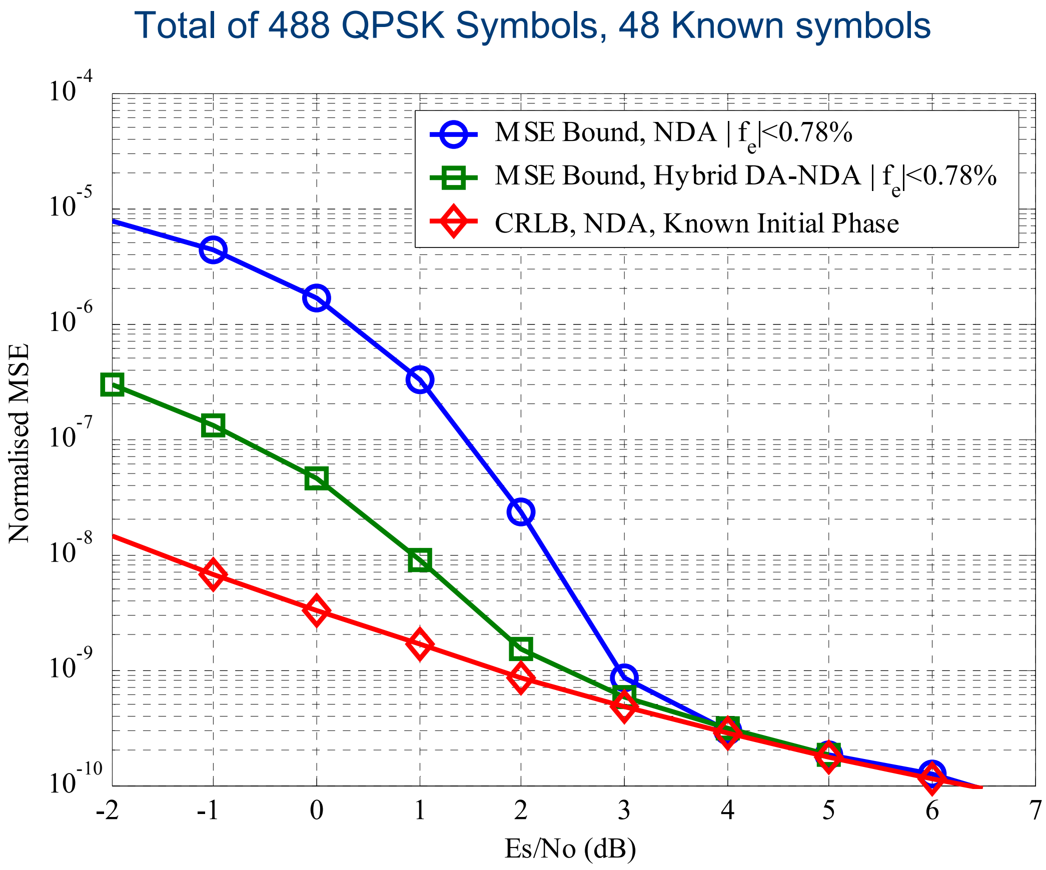
MSE Bounds for DA Frequency Estimate

- Performance bounds computed for data Estimators
- MSE bounds and CRBs are similar at high SNR
- Consistent with previously reported results



MSE Bounds for Frequency Estimate of QPSK Signals

- MSE bounds under two different Assumptions:
  - All QPSK symbols are unknown
  - QPSK symbols are partially known (e.g. preamble)
- Performance bounds are different at low SNR


Total of 488 QPSK Symbols, 48 Known symbols

Observations based on MSE Bounds

- Threshold effect of the frequency estimator is fundamental
- The SNR at threshold depends on:
  - Observation length
  - Modulation type
  - Parameter range and its distribution
- Combination of data aided and non-data aided information reduces the threshold level.
- At a given SNR, hybrid DA-NDA estimator has lower probability of outliers than an NDA estimator.
- **Solution: Hybrid DA-NDA Frequency Estimator**

Hybrid DA-NDA Frequency Estimator

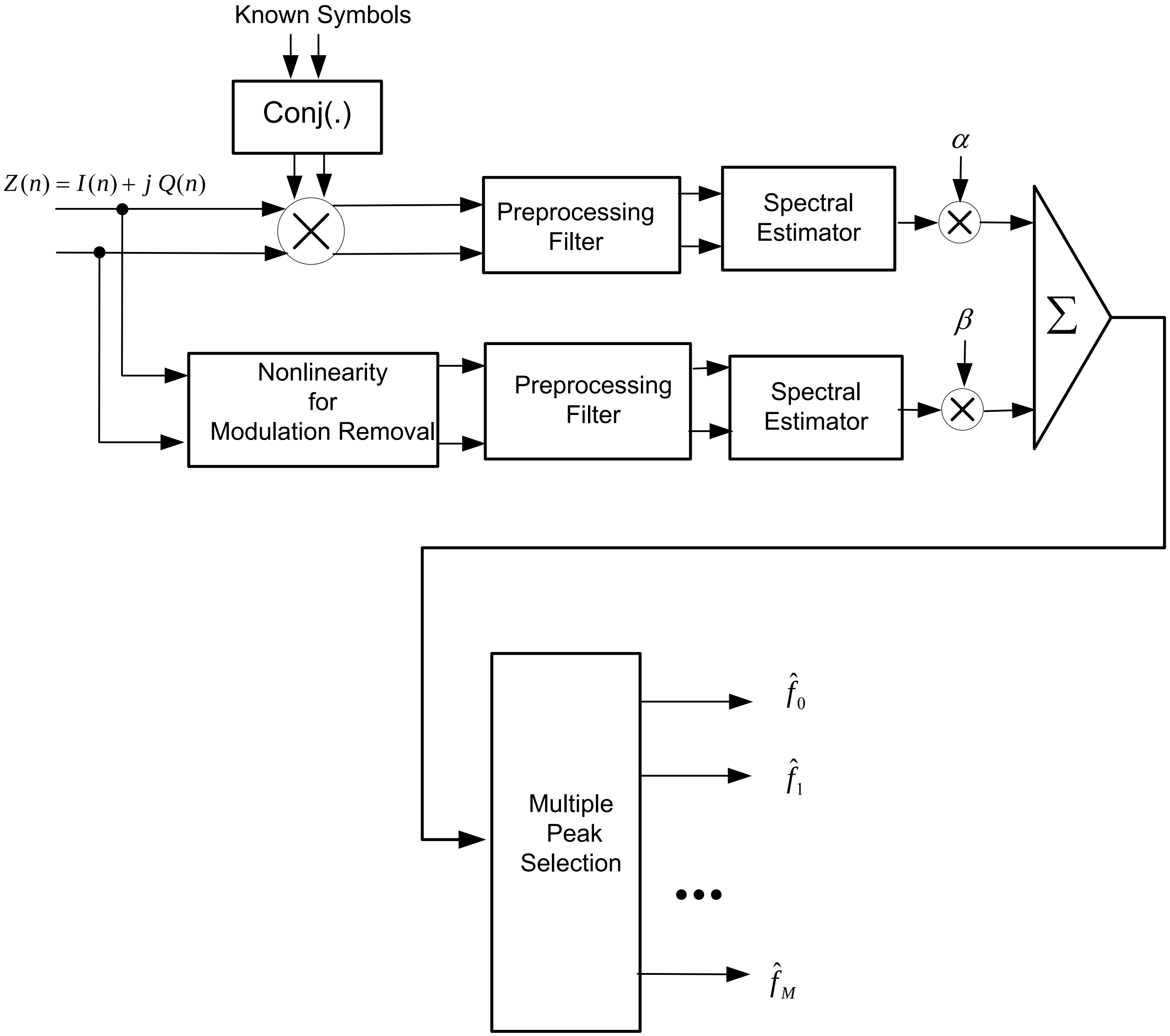
- According to MSE bounds, a significant improvement in probability of outliers by combining DA and NDA estimation.

- Maximum Likelihood Frequency estimation confirms the theoretical results.

- An approximation of ML estimator with feasible implementation was proposed.
- Hybrid DA-NDA estimator reduces the probability of outliers.

- Hybrid frequency estimator provides the flexibility of DA, NDA or Hybrid frequency estimation

Hybrid Frequency Estimator



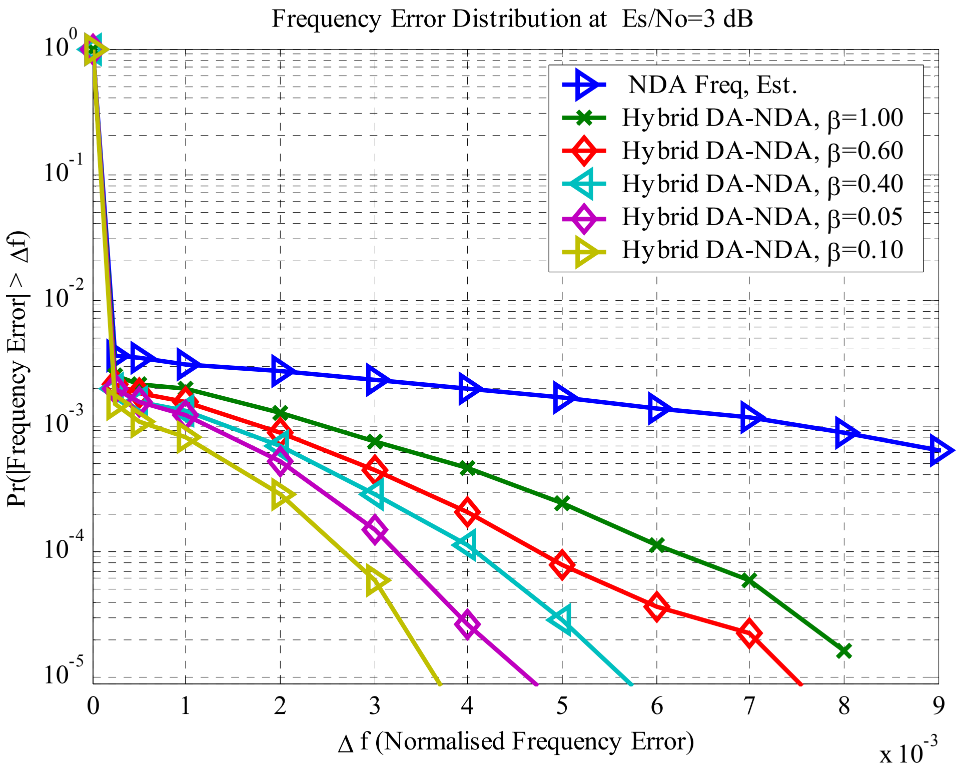
Hybrid DA-NDA Carrier Frequency Estimator

Main Features:

- **Unbiased Estimate, Minimum MSE.**
- **Scaling Factors can be adjusted for pure DA or NDA frequency estimation.**
- **Optimal combination to minimise the probability of outliers.**
- **Flexibility in pilot symbol distribution**
- **A priori knowledge of frequency range can be incorporated.**

Simulation Result Examples

- **Error Distribution for Hybrid and NDA Frequency Estimators**
  - Total of 488 QPSK Symbols, first 48 symbols are known.
  - Es/No=3 dB
- **Optimisation of Combination Method**

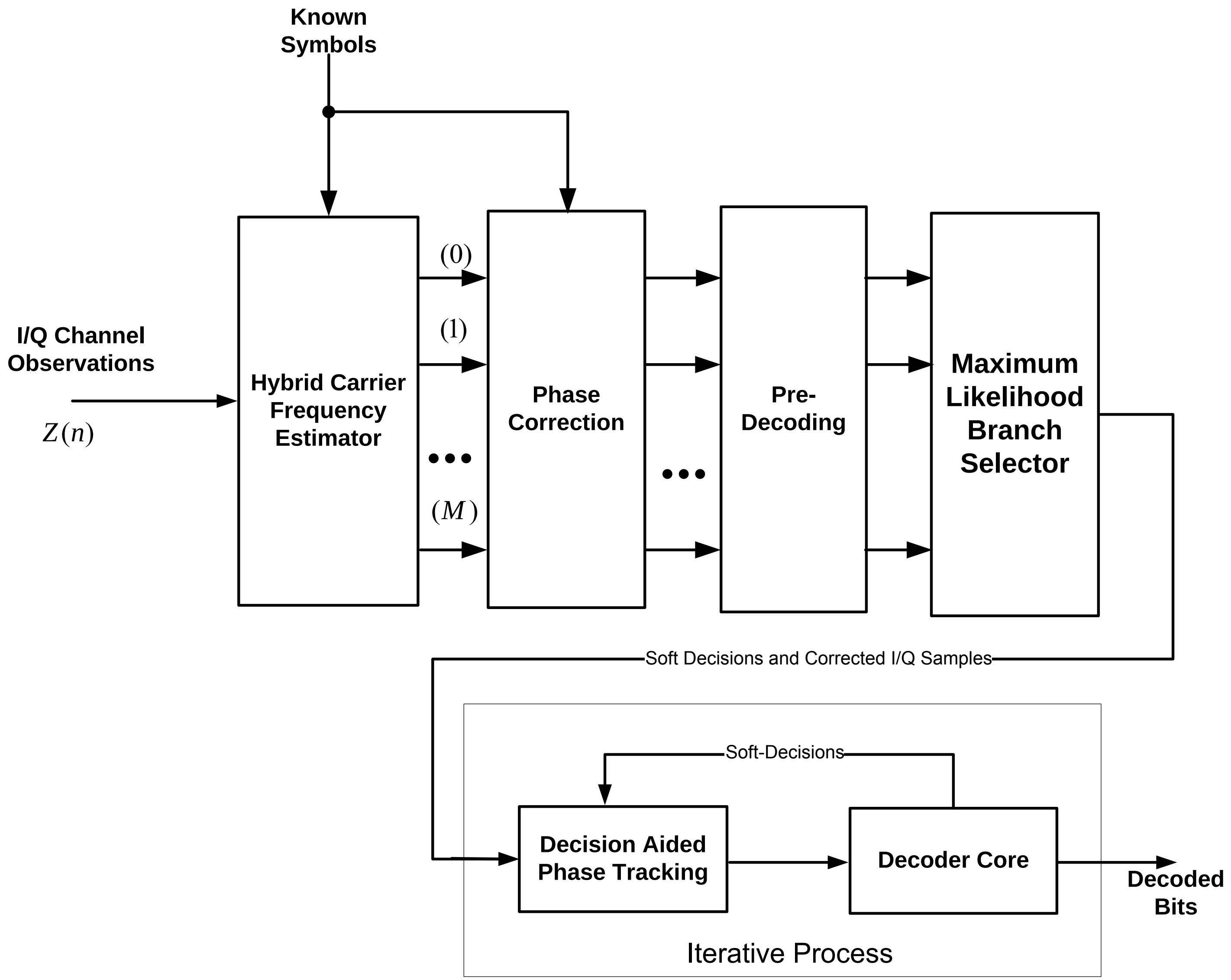


Joint Synchronisation and Decoding Algorithms

- Main Constituents:
  - Hybrid Frequency Estimator
  - Phase estimation and correction
  - Decoder Assisted Frequency Estimation:
    - Use maximum Likelihood Branch selection to choose most likely value of the frequency estimate.
  - Soft-Decision Aided Phase Tracking

- Pending Patent Applications:
  - "Hybrid Frequency Estimator",
    - U.S. 2005/0058229 A1,
    - PCT WO 2005/027353 A2
  - "Joint Synchronisation and Decoding",
    - U.S. 2005/0058224 A1,
    - PCT WO 2005/027451 A1

Joint Synchronisation and Decoding Algorithms



Known Symbols

I/Q Channel Observations

$Z(n)$

Hybrid Carrier Frequency Estimator

(0)

(1)

(M)

Phase Correction

Pre-Decoding

Maximum Likelihood Branch Selector

Soft Decisions and Corrected I/Q Samples

Soft-Decisions

Decision Aided Phase Tracking

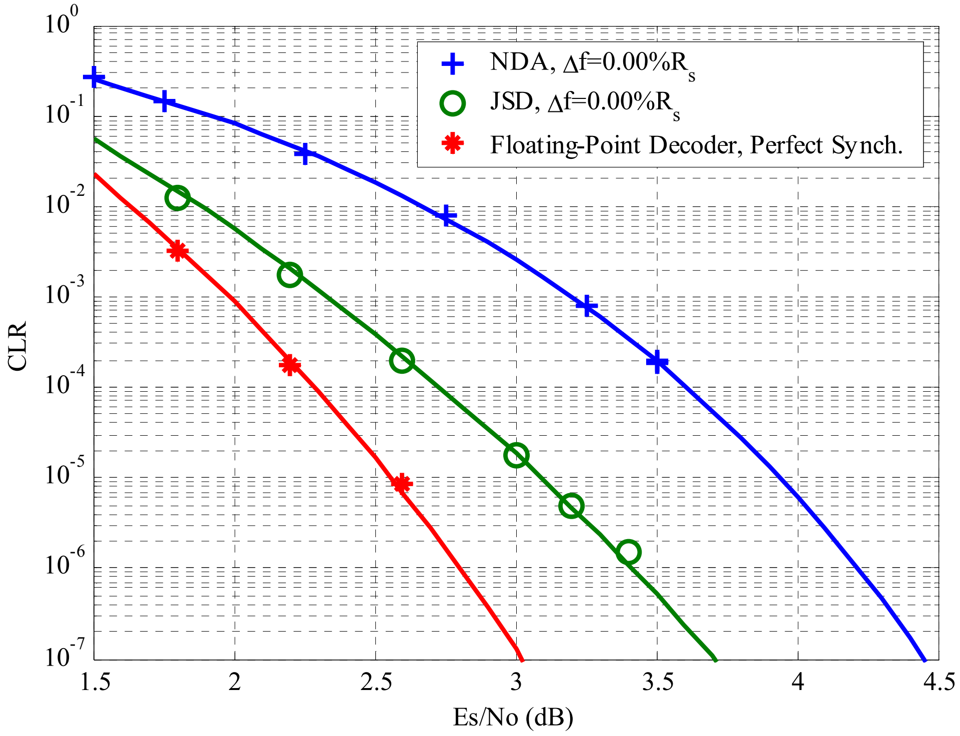
Decoder Core

Decoded Bits

Iterative Process

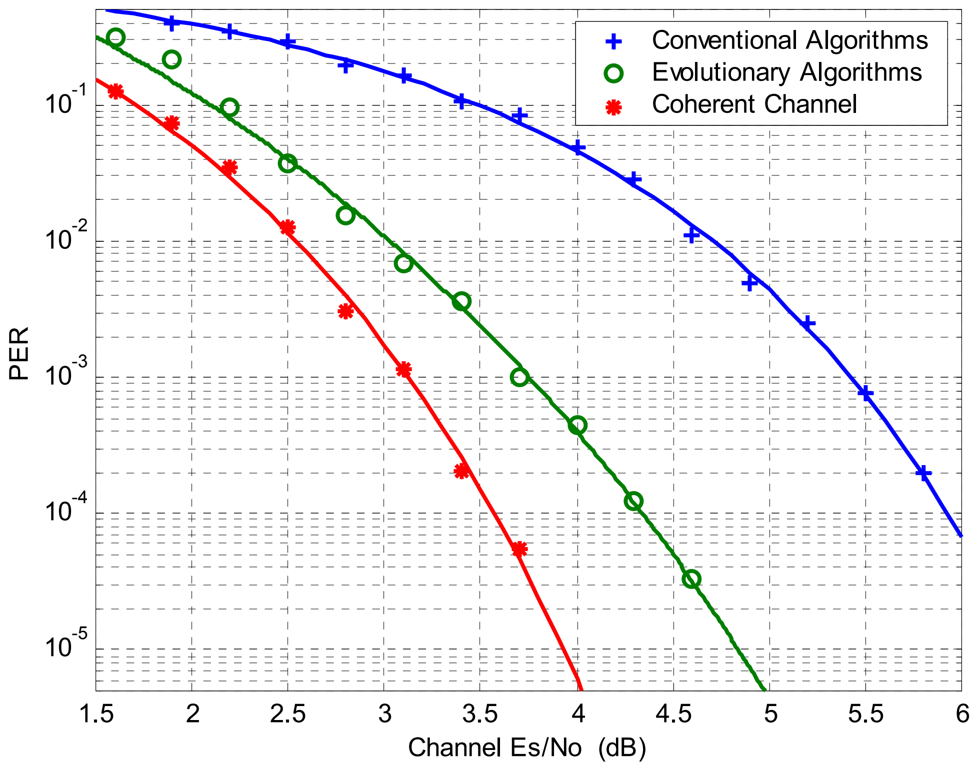
Carrier Synchronization- Frequency Estimation

- Payload Size: 55 Bytes, Coding Rate:1/2
- Preamble Size: 48 Symbols
- Ideal Symbol Timing Synchronization



Carrier Synchronization- Frequency Estimation

- Payload Size: 12 Bytes, Coding Rate:1/2
- Preamble Size: 48 Symbols
- Ideal Symbol Timing Synchronization



Summary of Performance Results

- Performance improvements compared to the conventional methods:
  - TRF bursts carrying one ATM cell, coding rate 1/2:
    - More than 1.0 dB performance improvement in the presence of carrier frequency offset and phase noise.
    - Less than 0.3 dB degradation compared to Ideal synchronisation.
  - Similar improvement for bursts carrying 2 ATM cells
  - Overhead bursts (12 byte payload), coding rate 1/2:
    - More than 1.5 dB performance improvement
- For long bursts and low symbol rate, the preamble symbols alone are not sufficient to mitigate the impact of the phase noise.
- For short overhead bursts, increase in preamble size improves the PER performance (ignoring the Eb/N0 penalty due to longer preamble size).

Test Bed

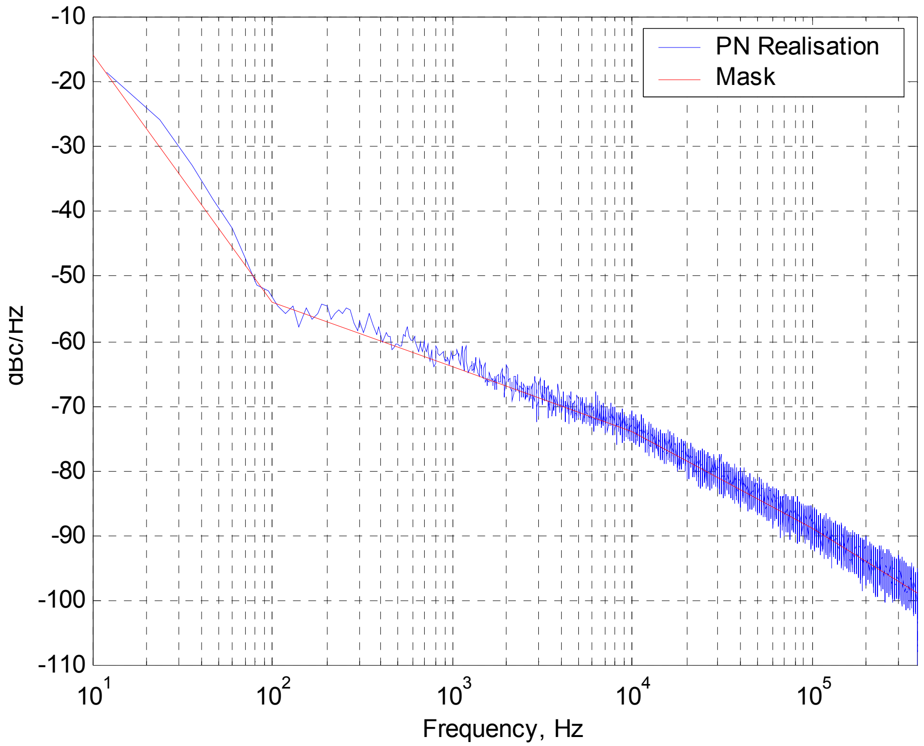
- Using our existing test bed for demodulator hardware validation.
  - Signal Generation Software
  - STE Hardware
  - Demodulator Hardware
  - Control and Monitoring Functions
- Real-time generation of
  - AWGN
  - Phase noise according a given mask
- Performance tests
  - Error counting done on processor board
  - Missed detection, false alarm
  - Burst/cell error ratio
  - Residual bit error ratio

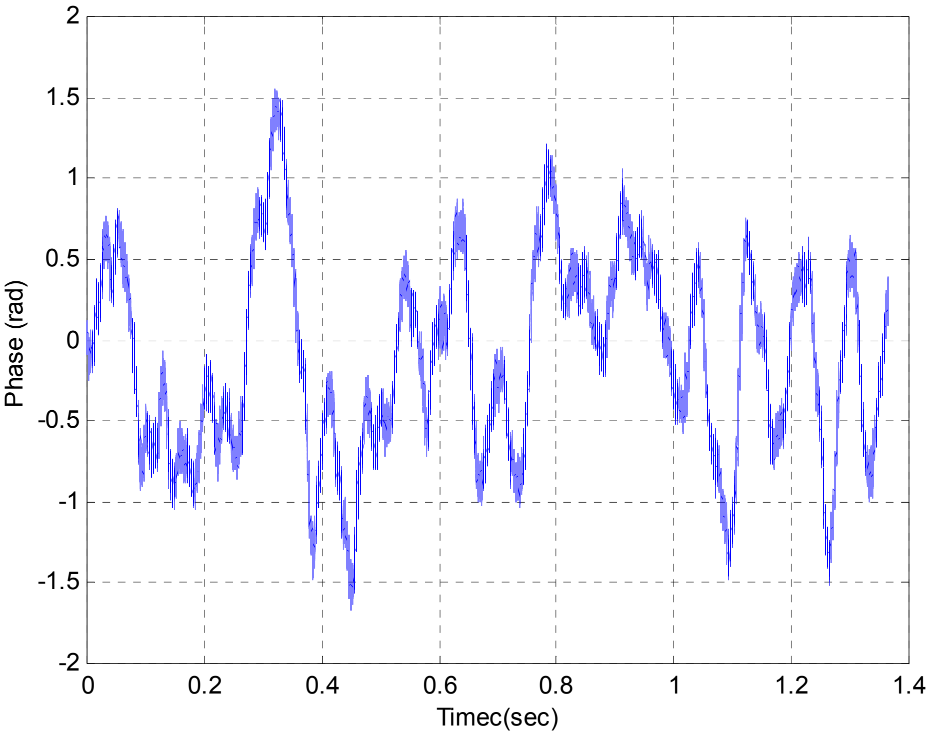
Real-Time Phase Noise Generator

- Sub-Band Frequency Domain Filtering
  - To handle total bandwidth as well as detail at low frequencies
- Spectral Shaping according to arbitrary phase noise mask
- Sub-band Filtering for enhanced resolution at low frequencies
- Direct Block Processing in Frequency Domain
  - Reduced complexity
- Programmable Phase Noise Mask
  - Mask to be adjusted according to the sampling rate
- Large Dynamic Range (more than 80 dB)
- Successfully tested in the lab

Example of Phase Noise samples

- DVB-RCS Mask
  - Sampling rate: 768 kHz





Hardware Implementation Status

- Bit Exact fixed-point development completed
- Bit-true VHDL model developed
- RTL Simulations were carried out.
  - Different burst sizes
  - Carrier frequency offset
  - AWGN
  - Initial Phase Offset
  - Different Signal Power levels
- All FPGA’s were synthesized
  - Proper pin-out
  - Design meets timing constraints
- Work in progress to validate the hardware implementation and carry out performance tests.

Joint Turbo Decoding and Synchronisation: CBC Algorithm Investigations

ESA Contract 18261/04/NL/AR
ABSM Workshop
ESTEC, 30 March 2006

ADVANTECH SATELLITE NETWORKS
Turbo Concept
EURECOM Sophia Antipolis

Overview

- CBC Algorithm: Background and Principles
- Application to DVB-RCS
- Application to DVB-S2

Problem Statement

- Goal : solve the optimal decision rule on information bits b_i, given the channel observation :

$$\hat{b}_i = \arg \max_{b \in \{0;1\}} P_i(b|\mathbf{y})$$

- Channel model :

$$y_k = x_k e^{j\theta_k} + w_k, \qquad k = 0,\ldots,N-1$$

- $P_i(b|\mathbf{y})$ can be obtained using $P(\mathbf{b},\theta \mid \mathbf{y})$, which can be factored into :

$$P(\mathbf{b},\theta|\mathbf{y}) \propto \chi[\mathbf{x} = \mu_C(\mathbf{b})]\, p(\theta_0) \prod_{k=1}^{N-1} p_\Delta(\theta_k - \theta_{k-1}) \prod_{k=0}^{N-1} f_k(x_k,\theta_k) .$$

code indicator function

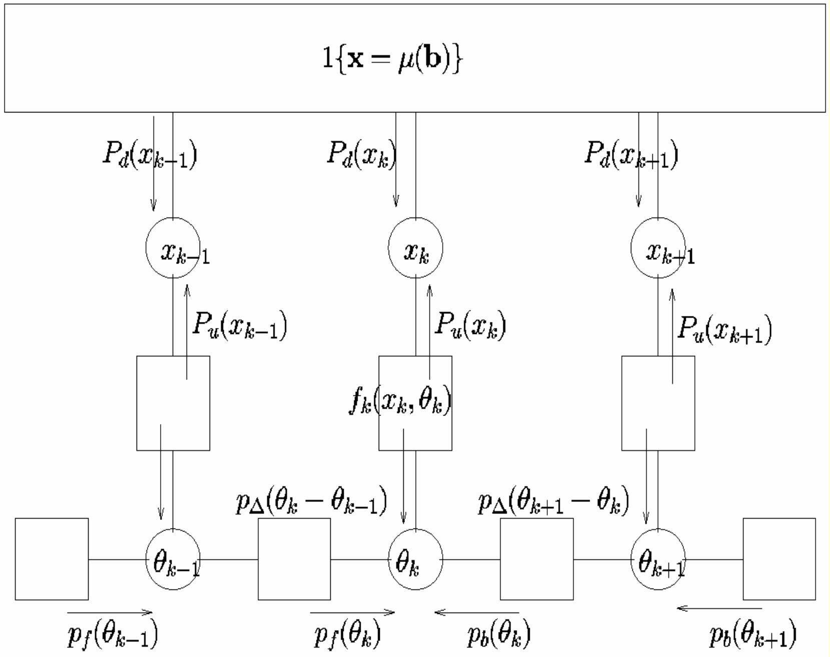
phase noise
(Markov model)

channel observation

$$f_k(x_k,\theta_k) \overset{\Delta}{=} \exp\left\{ -\frac{1}{N_0} |y_k - x_k e^{j\theta_k}|^2 \right\}$$

Factor Graph

- F.G. representation of P(**b**,θ | **y**) :



Sum-Product Algorithm equations

$$P_u(x_k) \propto \int_0^{2\pi} p_f(\theta_k) p_b(\theta_k) f_k(x_k,\theta_k) \, d\theta_k \, .$$

$$p_d(\theta_k) \propto \sum_{x \in X} P_d(x_k=x) f_k(x_k=x,\theta_k) \, .$$

$$p_f(\theta_k) \propto \int_0^{2\pi} p_d(\theta_{k-1}) p_f(\theta_{k-1}) p_\Delta(\theta_k - \theta_{k-1}) \, d\theta_{k-1}$$

$$p_b(\theta_k) \propto \int_0^{2\pi} p_d(\theta_{k+1}) p_b(\theta_{k+1}) p_\Delta(\theta_{k+1} - \theta_k) \, d\theta_{k+1}$$

- variables :
  - constellation symbols x_k ; phase error θ_k ; code bits (hidden in the Code factor)
- factors :
  - code ; f_k ;phase transition ;
- messages :
  - up and down probabilities on symbols x_k
  - forward and backward probabilities on phase error θ_k

Finding Practical Algorithms

- The phase error is a continuous random variable
  - the Sum Product Algorithm involves integrals of continuous pdf
  - not practicable for implementation
  - ⇒ find discrete parameterization of the pdfs.

- discretization of [0;2π] uniformly in *L* values
  - BCJR on a phase trellis
  - becomes optimal with large values of L (L ~ 8*constellation size)
  - high complexity

- Tikhonov approximation (CBC algorithm)
  - Proposed by Colavolpe, Biglieri, Caire, 2004
  - Observe that $P_d(\theta_k)$ is a linear combination of Gaussian pdf

$$p_d(\theta_k) \propto \sum_{x \in X} P_d(x_k=x) f_k(x_k=x,\theta_k) \,.$$

=> Approximated by the **Gaussian pdf at minimum divergence** defined by its mean and variance values $(\alpha_k \,;\, \beta_k)$

$$\alpha_k \overset{\Delta}{=} \sum_{x \in X} x \, P_d(x_k=x) \qquad\qquad \beta_k \overset{\Delta}{=} \sum_{x \in X} |x|^2 \, P_d(x_k=x) \,.$$

CBC equations

- The pdf $P_d(\theta_k)$ is then entirely represented with one complex parameter u_k (through a Tikhonov distribution)

$$u_k = \frac{2\, y_k \alpha_k^*}{N_0 + \beta_k - |\alpha_k|^2}$$

- The same applies to $P_f(\theta_k)$ and $P_b(\theta_k)$, defined with a_k and b_k resp.

$$a_k = \frac{a_{k-1} + u_{k-1}}{1 + \sigma_\Delta^2\, |a_{k-1} + u_{k-1}|} \qquad b_k = \frac{b_{k+1} + u_{k+1}}{1 + \sigma_\Delta^2\, |b_{k+1} + u_{k+1}|}$$

  - is computed recursively
  - σ_Δ is matched to the phase noise variance

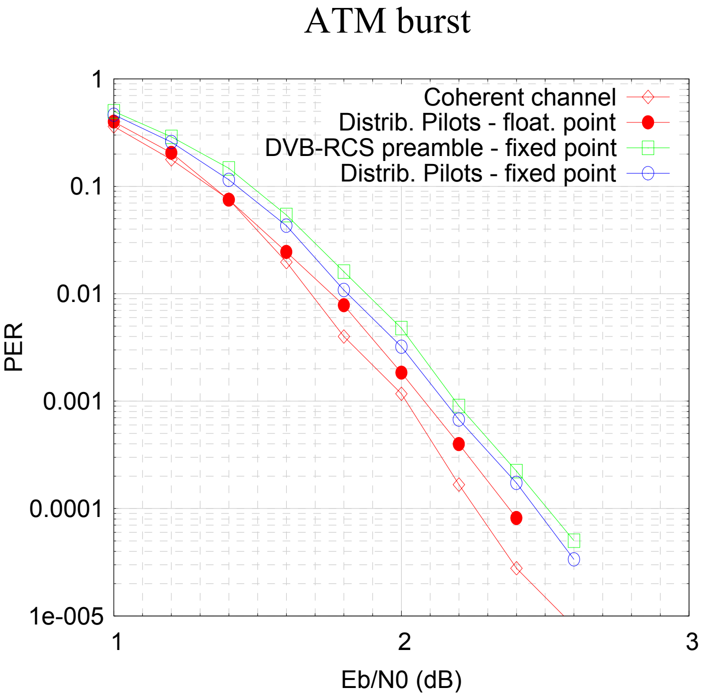
- $P_u(x_k)$ is obtained with :

$$P_u(x_k) \propto \exp\left\{ -\frac{|x_k|^2}{N_0} \right\} I_0\left(\left| a_k + b_k + 2\frac{y_k\, x_k^*}{N_0} \right| \right)$$

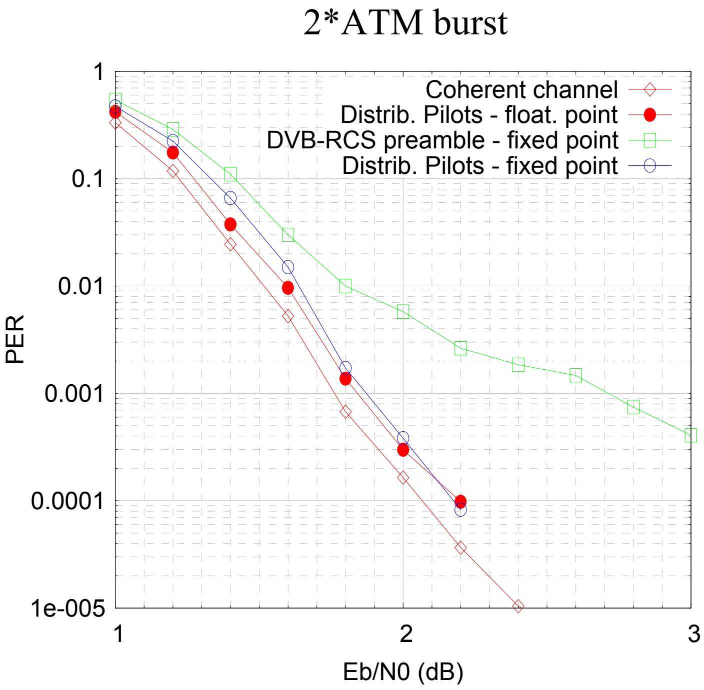
  - In practice log(Pu) is needed ; log(I0(x)) simplifies into x-2
  - If $|x^2|$ is constant (QPSK or 8PSK), the first factor can be omitted

Application to DVB-RCS – Performance

- ATM cell, 64kbaud, DVB-RCS phase noise mask +6dB
- Two pilot situations are considered :
  - DVB-RCS air interface (48symbols preamble ; no pilots)
  - Distributed pilots (48symbols)



ATM burst

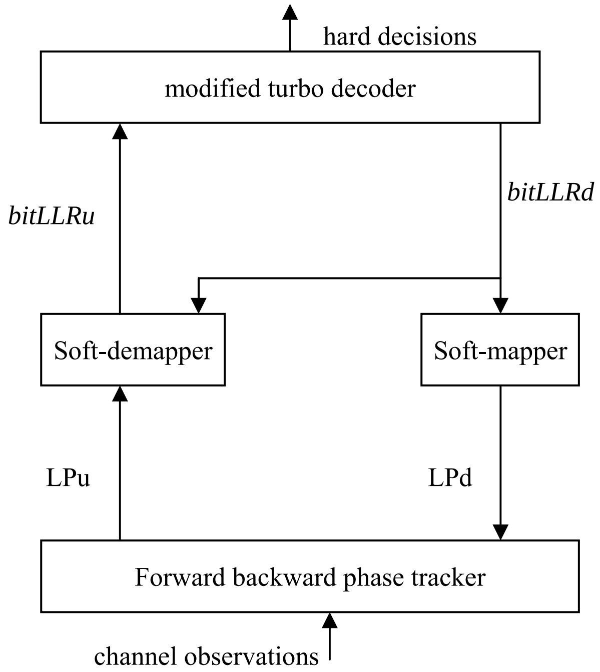


2*ATM burst

- Near coherent performance
- Pilots are needed for 2*ATM cells and longer bursts
- The fixed point performance is within 0.1 dB of the floating point model

Application to DVB-RCS – implementation

- Block diagram
  - modified turbo decoder (produce bitLLRs on redundancy bits)
  - need bit <->symbol conversions
  - sliding window phase tracker



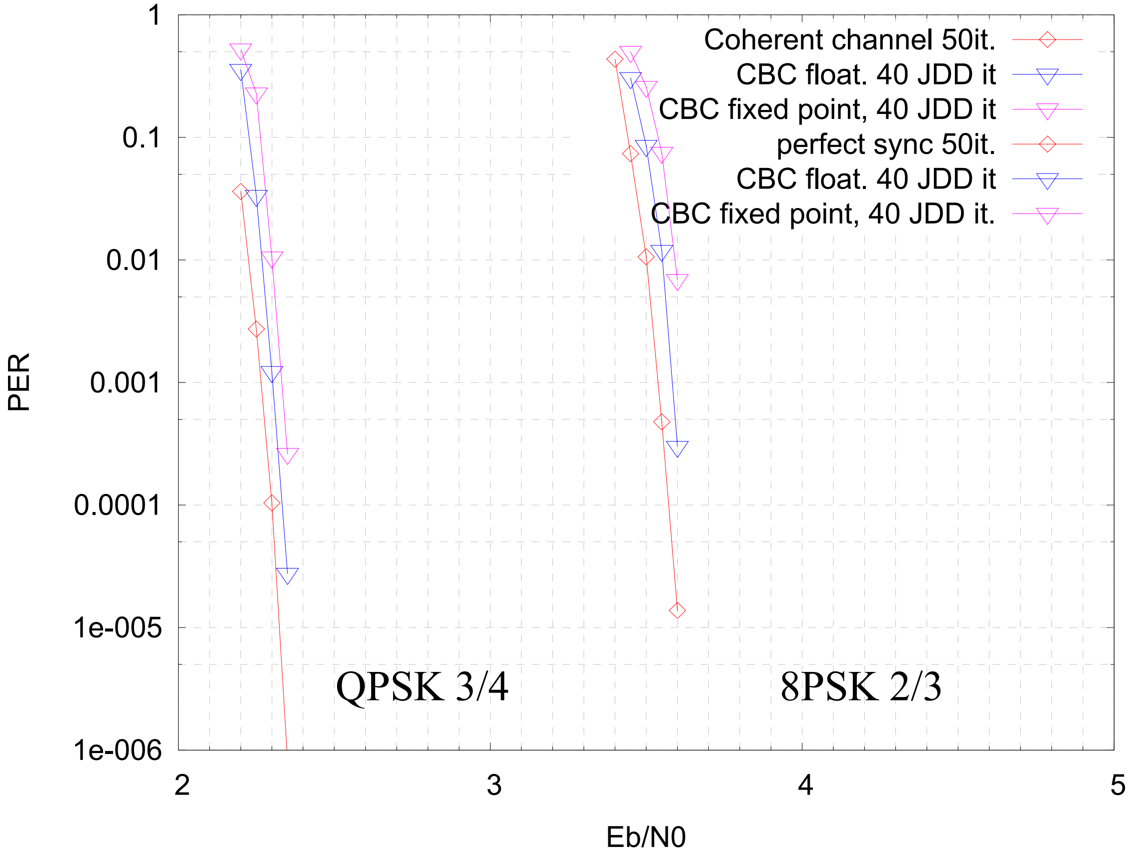
- Complexity (*)
  - 8000 FPGA Logic Elements
  - increase of 40% in logic wrt. turbo decoder
- Throughput (*)
  - depends on the number of JDD iterations
  - 4 Mbit/s with 4 JDD iterations

JDD iterations	8	4	2	0
decoder bitrate (Mbps)	2,96	4,60	6,35	10,26

(*) Examples given with a 10 Mbps commercial decoder Core

Application to DVB-S2 – performance

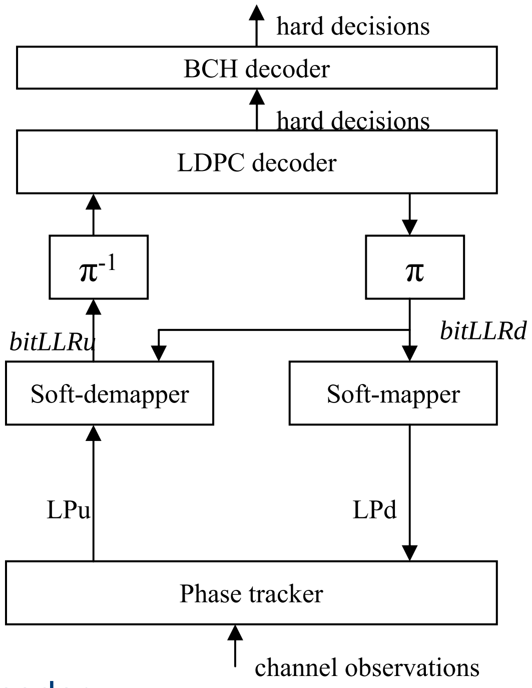
- 64kbit frames, with pilots, 5 Mbaud, consumer-LNB phase noise.



- Near coherent channel performance
- The fixed point performance is within 0.1 dB of the floating point model

Application to DVB-S2 – implementation

- Block diagram
  - modified LDPC decoder
    - updated bitLLRu
    - needs to output bitLLRd
  - interleaver/deinterleaver
  - bit <->symbol conversions
  - sliding window phase tracker



hard decisions

BCH decoder

hard decisions

LDPC decoder

π^{-1}

π

bitLLRu

bitLLRd

Soft-demapper

Soft-mapper

LPu

LPd

Phase tracker

channel observations

- Complexity (*)
  - increase of 15% in logic wrt. the FEC decoder
- Throughput (*)
  - depends on the number of JDD iterations
  - 20 Mbit/s coded with 4 JDD iterations

JDD iterations	20	8	4	0
Coded bitrate (Mbps)	5,44	12,13	20,57	63,00

(*) Examples given with a 20 Mbaud version of the tc4000 commercial Core