Carrier phase recovery for optical coherent *M*-QAM communication systems using harmonic decomposition-based maximum loglikelihood estimators

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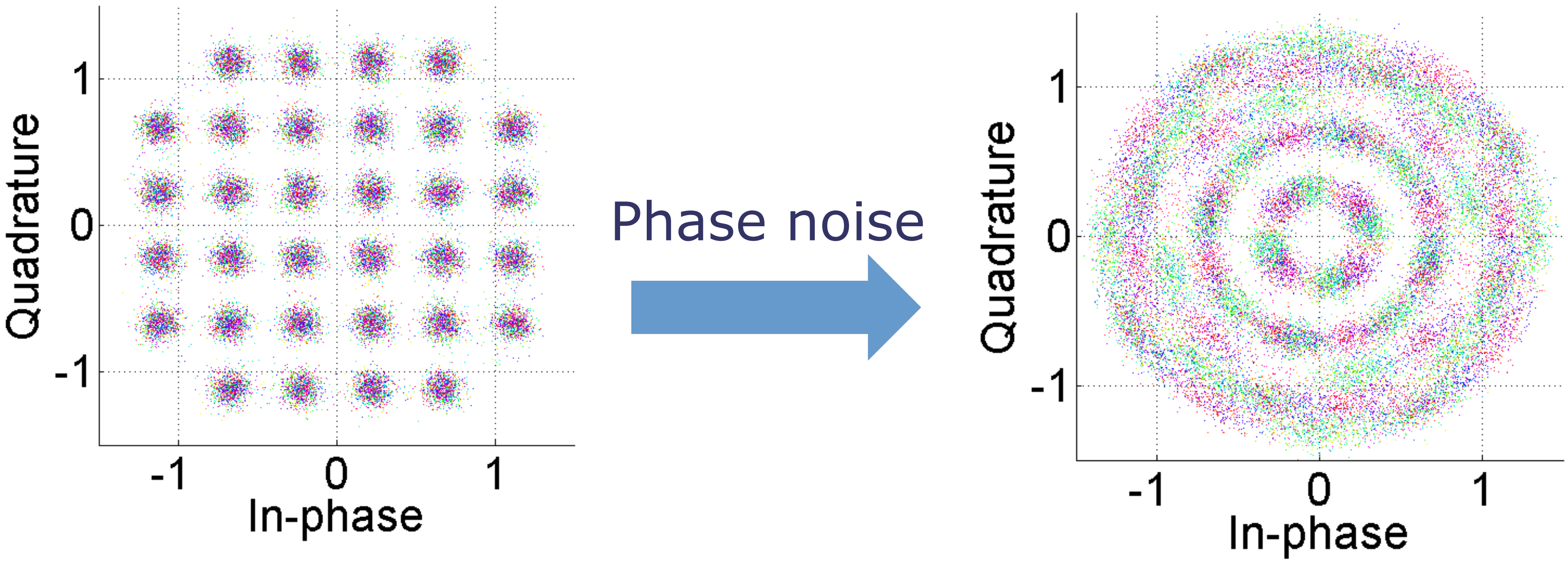
Effect of laser phase noise



- 32-QAM
- SNR = 20.8 dB
- Normalized linewidth $\Delta\nu T_B = 10^{-5}$

Outline

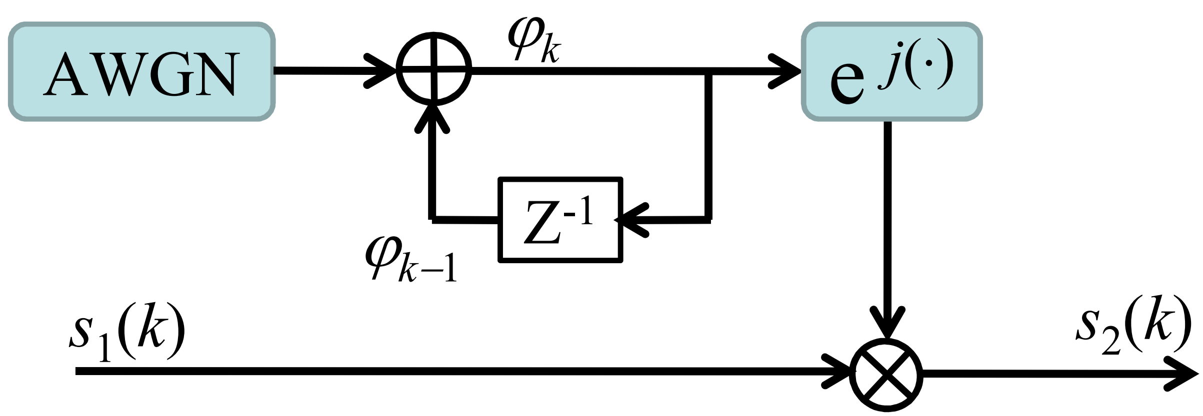
- ➢ Introduction
  - ✓ Influence of laser phase noise on optical coherent systems
  - ✓ Feedforward methods for carrier phase recovery (CPR)
- ➢ Proposed method for feedforward CPR
  - ✓ Method description
  - ✓ Simulation model
  - ✓ Numerical results and discussion
- ➢ Conclusions

Feedforward carrier phase recovery

- Minimum distance blind phase search (BPS)
  T. Pfau et al., J. Lightw. Technol. 27, 989, 2009.
- Modified BPS with multistage compensation
  X. Zhou et al., IEEE Photon. Technol. Lett. 26, 1863, 2014.
- Viterbi-Viterbi monomial based and maximum likelihood estimator (VVMPE-ML)
  S. Dris et al., Proc. of OFC 2013, paper OTu3I.3.
- Based on QPSK partitioning
  S. M. Bilal et al., Proc. of OFC 2014, paper M2A.8.
- <u>Proposal</u>
  Based on circular harmonic expansion* and cascaded with maximum likelihood estimator (CHE-ML)

* *A. V. Petrov et al., Proc. of ICC 2013, p. 4756.*

Laser phase noise model



➢ **Laser linewidth**: discrete time random walk

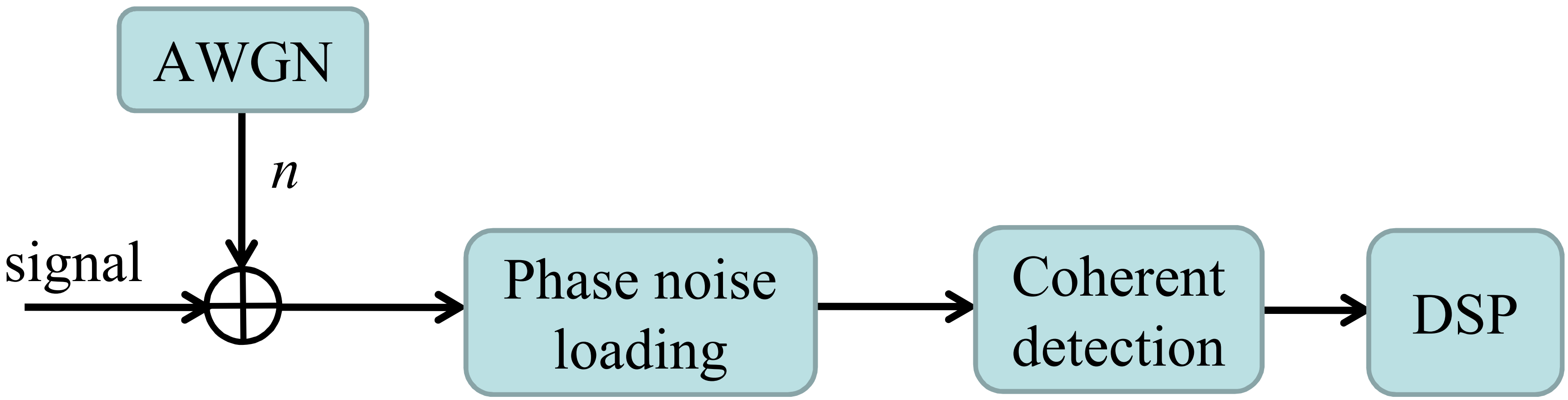
$$\varphi_k = \varphi_{k-1} + \Delta_k$$

- Δ_k – Gaussian random variable with zero mean and variance $\sigma_\varphi^2 = 2\pi \Delta\nu T_B$
- T_B – QAM symbol duration
- $\Delta\nu$ – laser linewidth

Parameters for simulations

- Number of symbols: ~ 130 000 (2^{17})
- Differential encoding
- Additive white Gaussian noise (AWGN)
- SNRs for 1 dB penalty at 10^{-3} FEC limit for *M*-QAM

	16-QAM	32-QAM	64-QAM	128-QAM
SNR (dB) (E_b/N_0)	18.4	20.8	24.5	26.6



Description of the method (1)

1. Maximum likelihood estimation of $\phi(k)$ knowing the received signal

$$x(k) = r(k)\, e^{j\phi(k)} + n(k)$$

AWGN

$$\mathrm{LLF}\left(\phi(k) \,|x(k)\right) = \log\left[\frac{1}{2\pi\sigma^2 M}\sum_{m=1}^{M}\exp\left(-\frac{\left|x(k)\, e^{-j\phi(k)} - C_m\right|^2}{2\sigma^2}\right)\right]$$

M constellation size

C_m ideal values of the symbols on the constellation

σ^2 AWGN variance

2. Averaging over observed sequence $\{x(k)\}$ and using Fourier series expansion*

$$\mathrm{LLF}\left(\phi(k) \,|\, \{x(k)\}\right) \approx \Re\left[e^{-j4\phi(k)}\sum_{k=1}^{N_1} A_4\left(r(k)\right) e^{-j4\varphi(k)}\right]$$

$$= \Re\left[e^{-j4\phi(k)} F_4\left(\{x(k)\}\right)\right]$$

** A. V. Petrov et al., Proc. of ICC 2013, p. 4756*

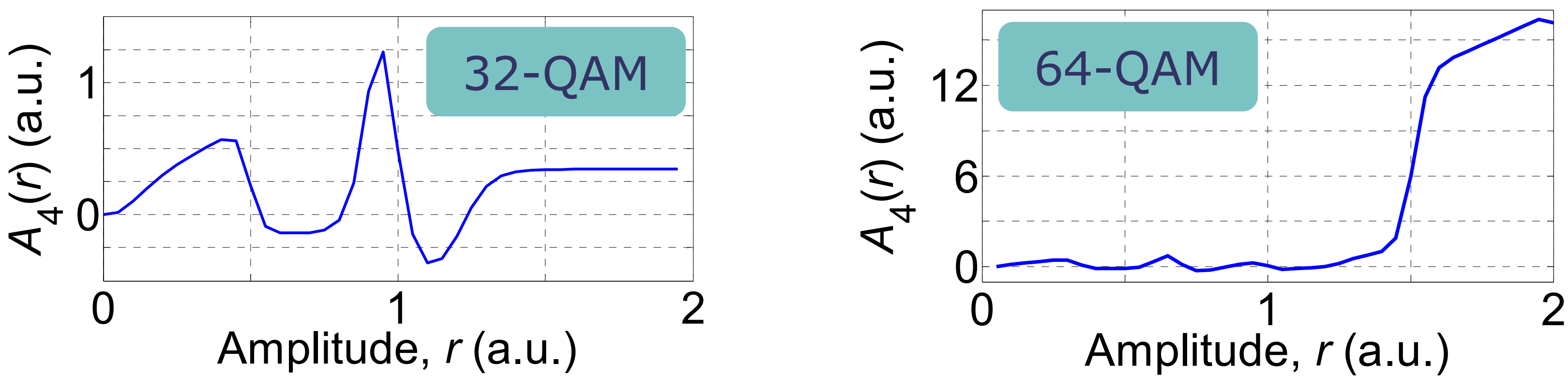
Description of the method (2)

$$\mathrm{LLF}\left(\phi\left(k\right) \mid \left\{x\left(k\right)\right\}\right) = \Re\left[e^{-j4\phi(k)} F_4\left(\left\{x\left(k\right)\right\}\right)\right]$$

3. Carrier phase noise estimated by

$$\hat{\phi} = \frac{1}{4} \arg F_4\left(\left\{x\left(k\right)\right\}\right)$$

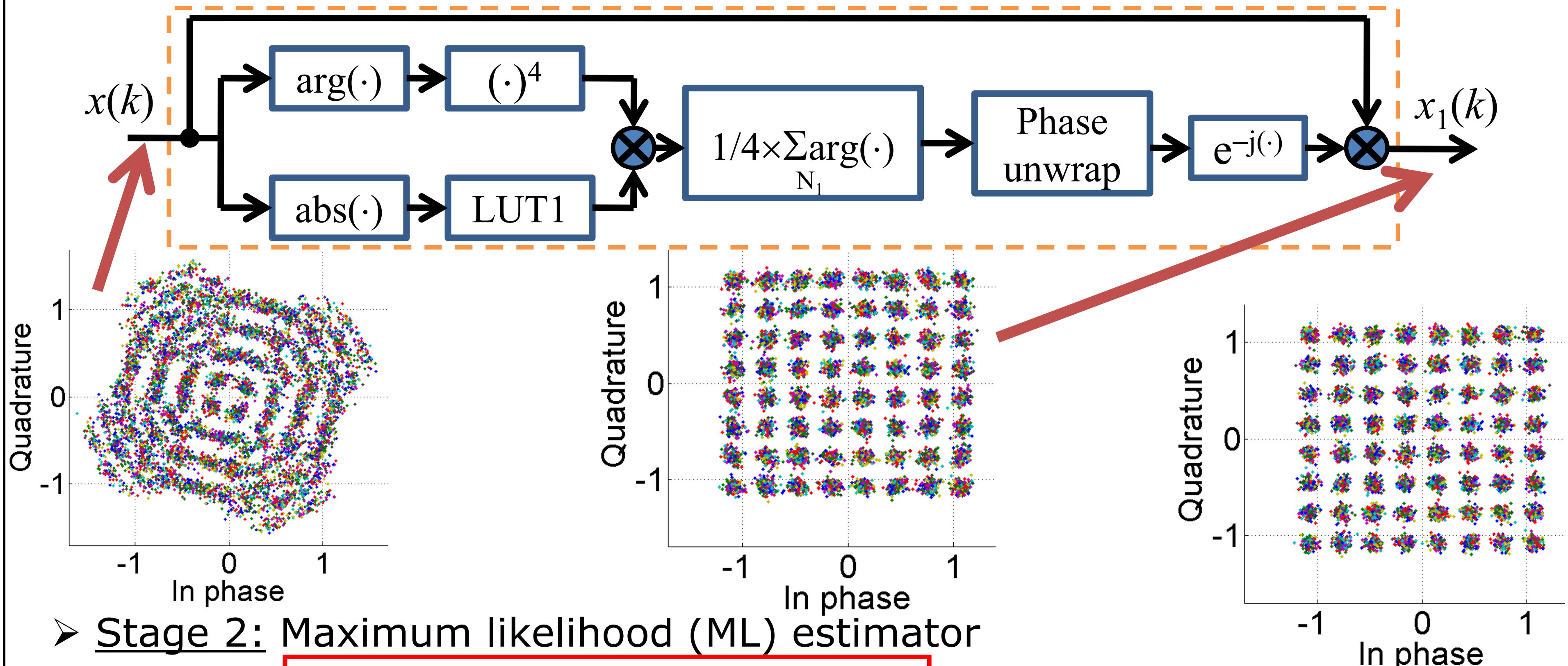
where $A_4\left(r\left(k\right)\right)$ is retrieved using a look up table



* *A. V. Petrov et al., Proc. of ICC 2013, p. 4756*

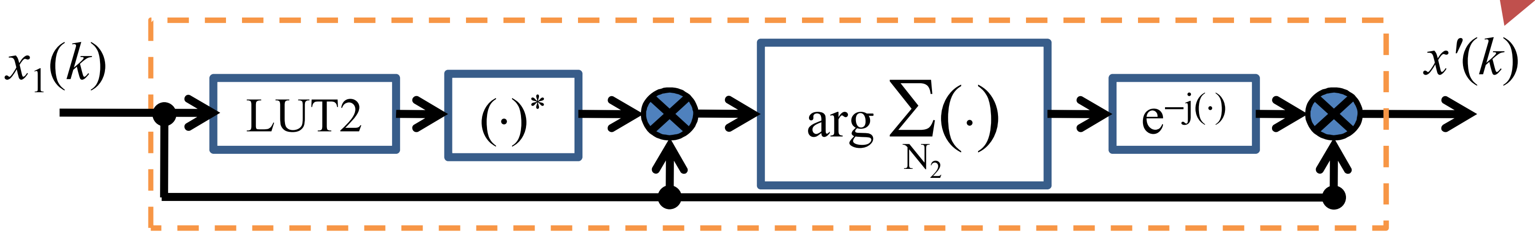
Block diagram

- Stage 1: Circular harmonic expansion (CHE) estimator



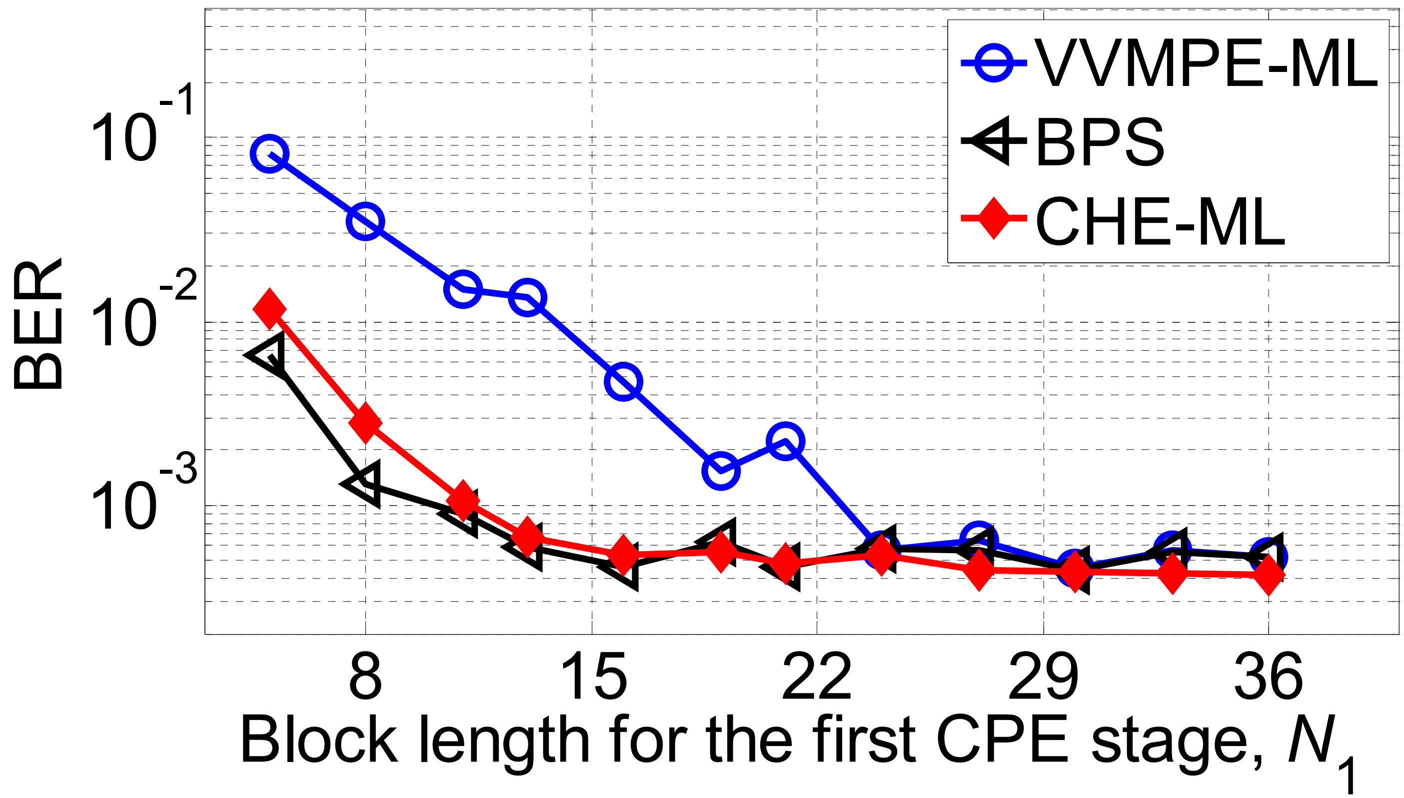
- Stage 2: Maximum likelihood (ML) estimator

$$\widehat{\phi_{ML}} = \arg\left[\sum_{k=1}^{N_2} DD\left(x_1\left(k\right)\right)^* x_1\left(k\right)\right]$$



Block length N_1 optimization

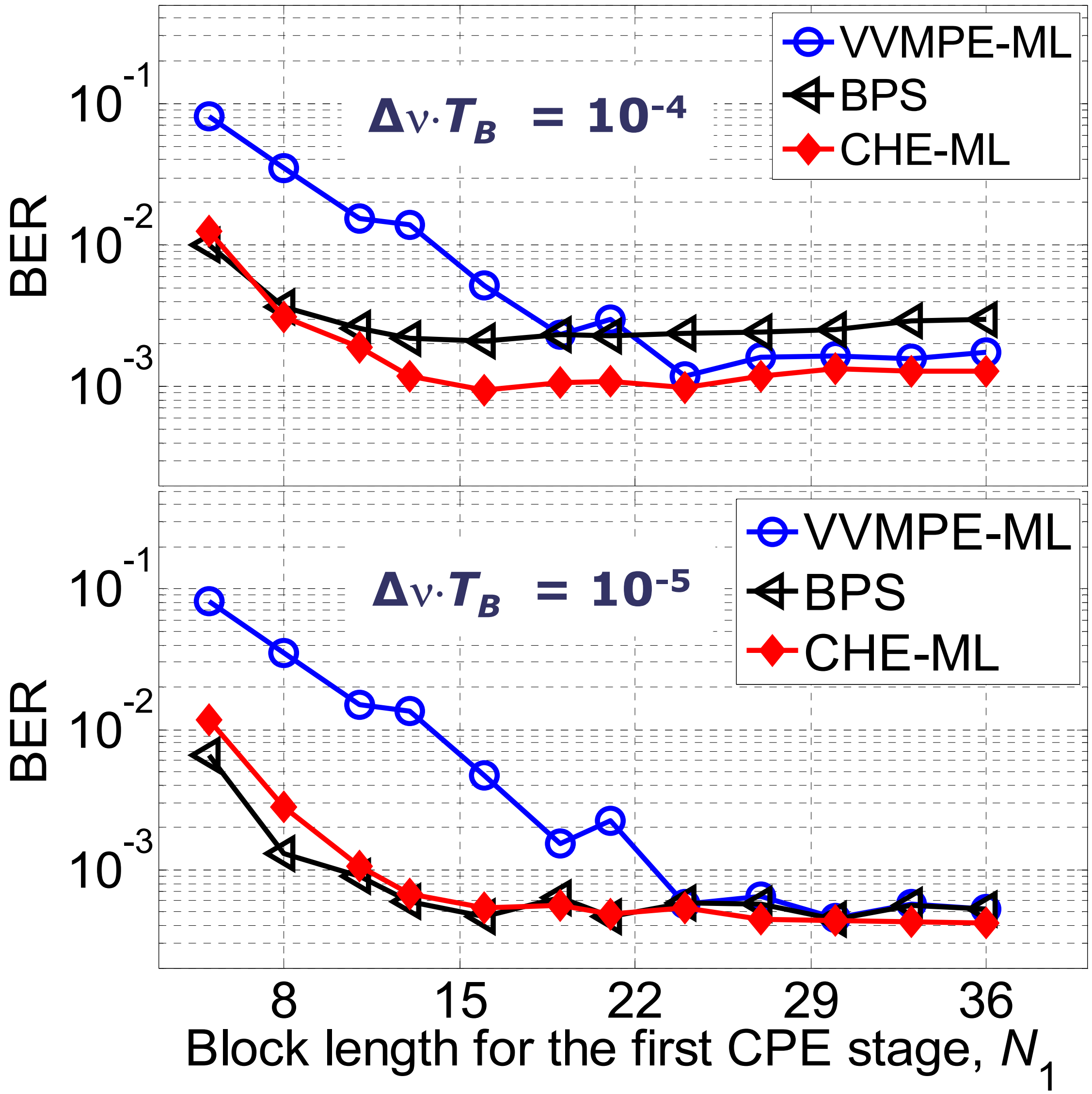
16-QAM
$\Delta\nu \cdot T_B = 10^{-5}$



- VVMPE-ML converges slowly to the optimum BER value
- BPS and CHE-ML convergence speeds are similar

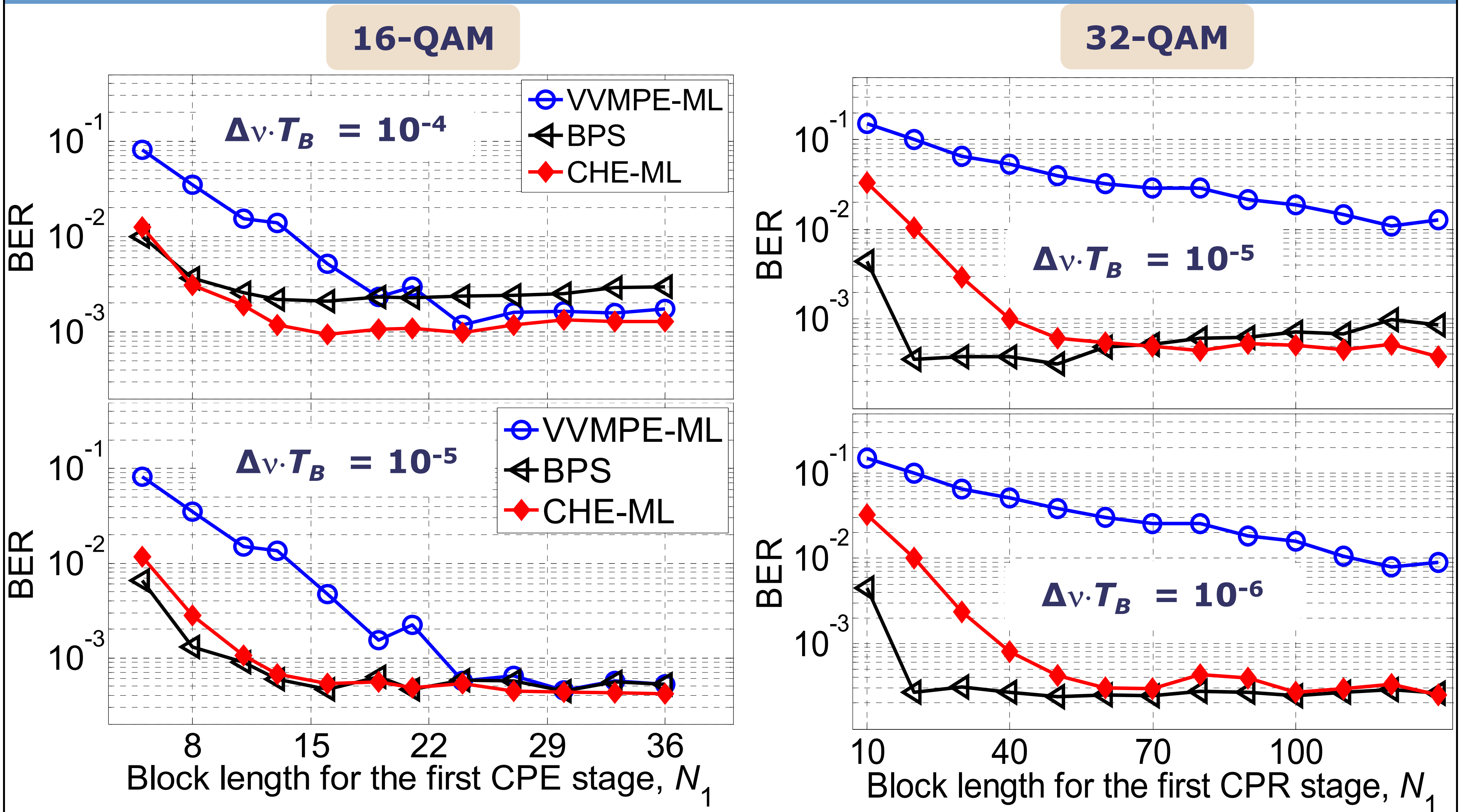
Block length N_1 optimization

16-QAM



When phase noise increases (10^{-5} -> 10^{-4}), the linewidth tolerance is slightly degraded for BPS compared to VVMPE-ML and CHE-ML

Block length N_1 optimization

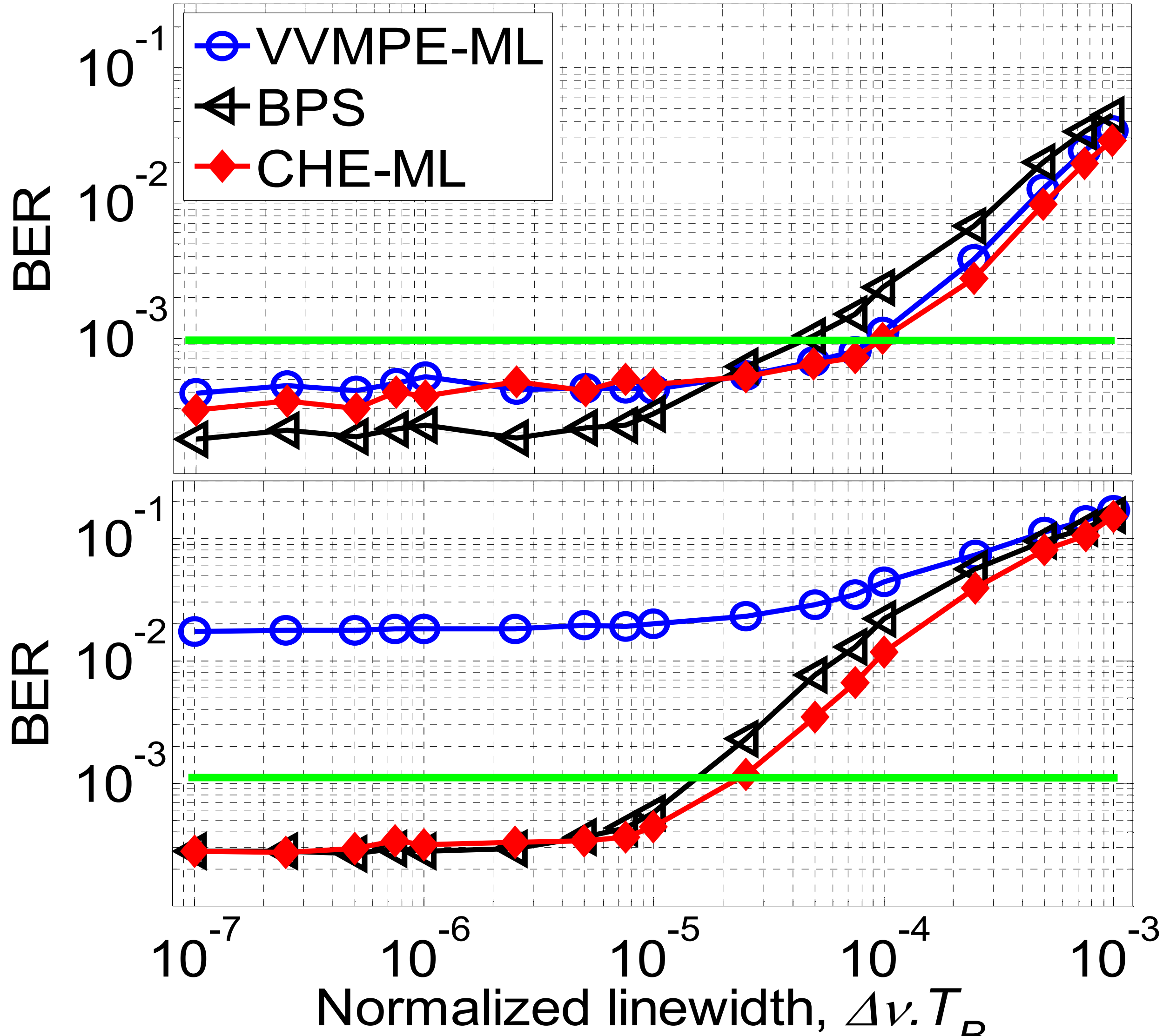


- Optimum block lengths are similar with different phase noise
- VVMPE-ML ineffective with cross M-QAM

BER versus normalized linewidth for 16-, 32-QAM

16-QAM

32-QAM

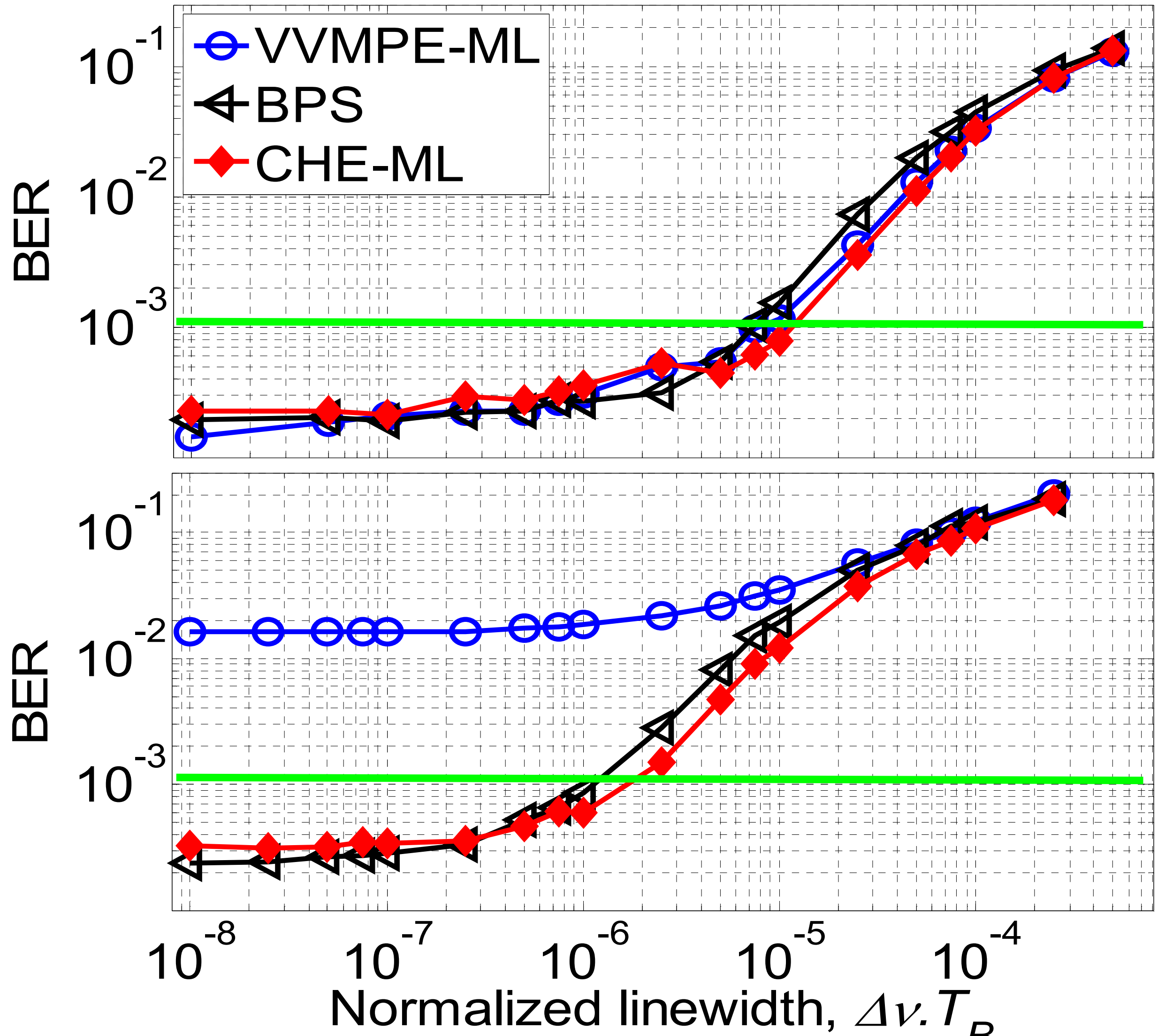


Maximum tolerated linewidths of 1 MHz and 680 kHz for 40 Gbaud 16- and 32-QAM, respectively

BER versus normalized linewidth for 64-, 128-QAM

64-QAM

128-QAM



Maximum tolerated linewidths of 520 and 70 kHz for 40 Gbaud 64- and 128-QAM, respectively

Conclusions

- Feedforward carrier phase recovery based on harmonic decomposition of a loglikelihood function
- Numerical validation up to 128-QAM showing its compatibility with commercial ECLs ($\Delta\nu \sim$ 100 kHz)
  - ✓ Work with both square and cross M-QAM
  - ✓ Linewidth tolerance of 70 kHz for 40 Gbaud 128-QAM signals
- Perspective: using more significant terms in the decomposition to achieve a better estimation

Acknowledgements

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
MINISTÈRE
DE L'ENSEIGNEMENT SUPÉRIEUR
ET DE LA RECHERCHE

Région
BRETAGNE

Questions:

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