Performance and Complexity Comparison of CPE Algorithms for 256-QAM Optical Signals

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Motivation

- Coherent detection enabled the use of high-order modulation formats in optical transmission systems to increase the per-channel bit rate and the aggregate WDM throughput

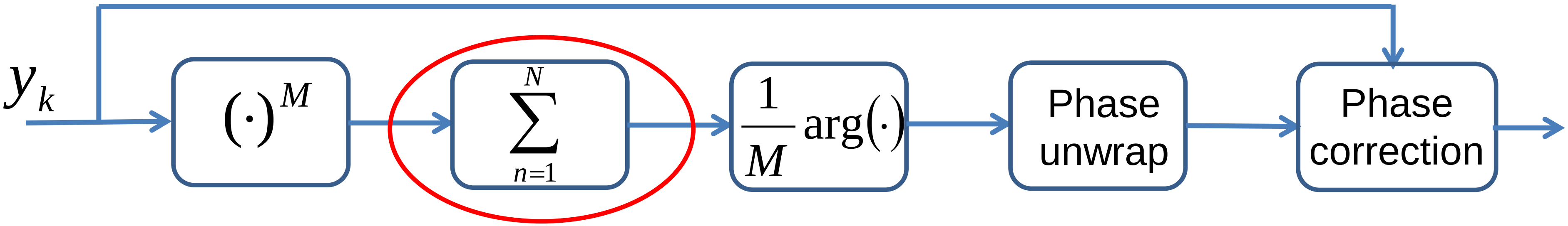
- High-order modulation formats are less tolerant to phase noise

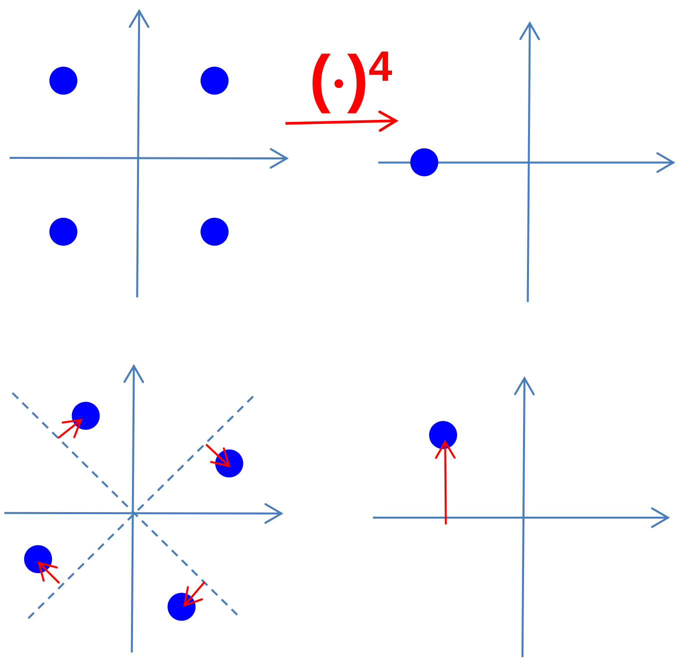
Minimum angle between constellation points on the same ring

QPSK	8-PSK	16-QPSK	16-QAM	64-QAM	256-QAM
90°	45°	22.5°	36.9°	16.3°	7.6°

- More complex carrier-phase estimation (CPE) algorithms are needed

Standard Viterbi&Viterbi algorithm

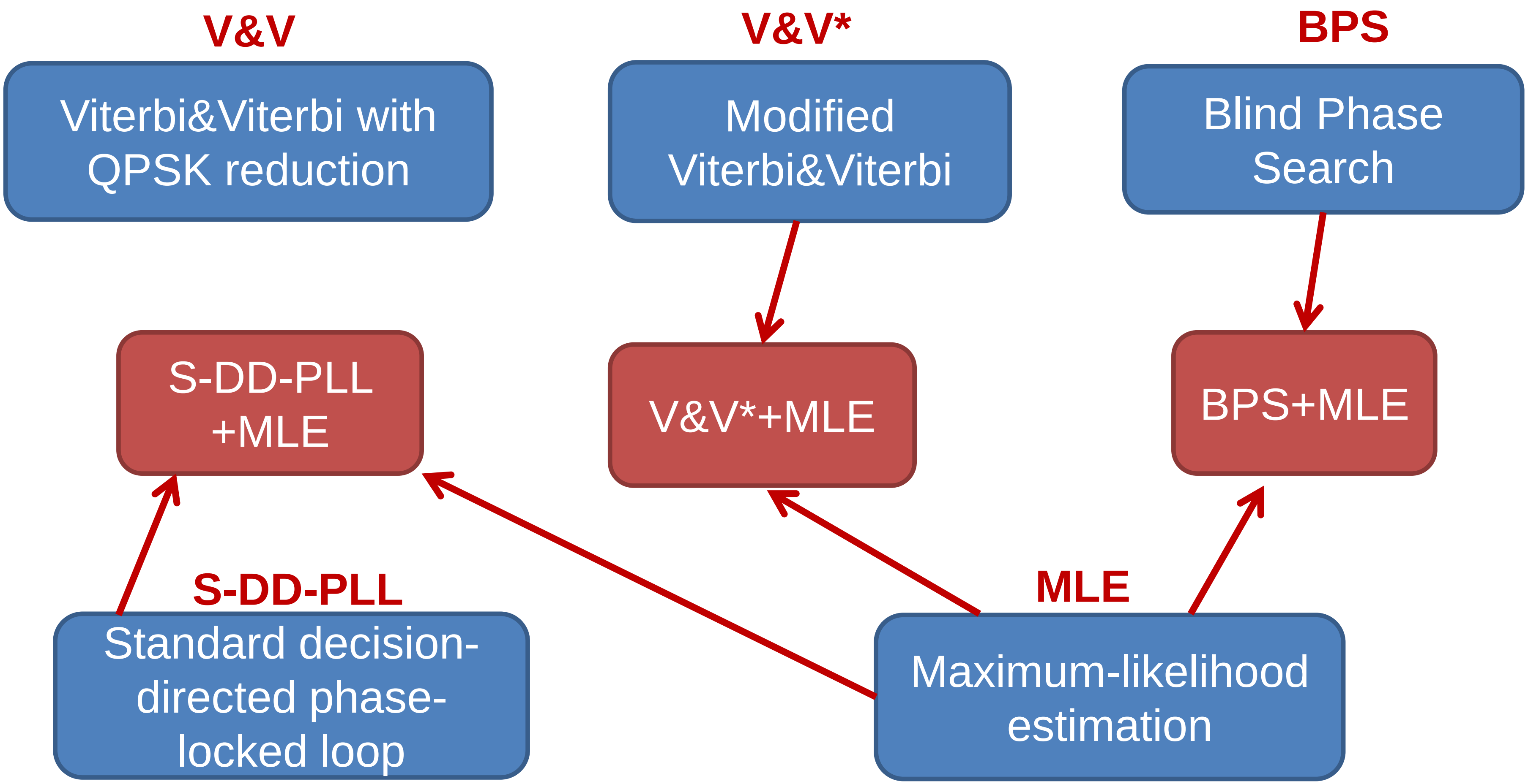




- Feed-forward architecture
- Can be directly applied to M-PSK constellations

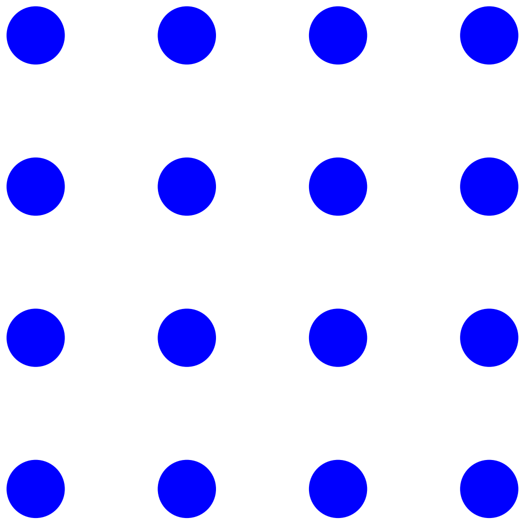
- **Uniform filter of length *N* symbols** (averages the effect of AWGN)

CPE algorithms for squared-QAM constellations



Viterbi&Viterbi algorithm with QPSK reduction (V&V)

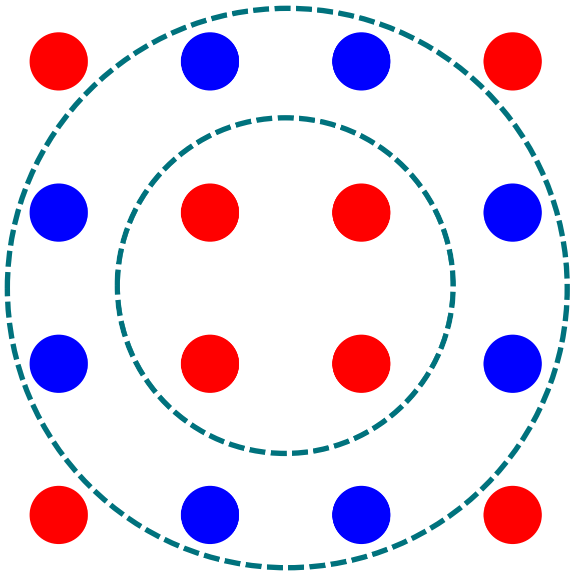
- **16 QAM**



- Only uses symbols that match a QPSK constellation

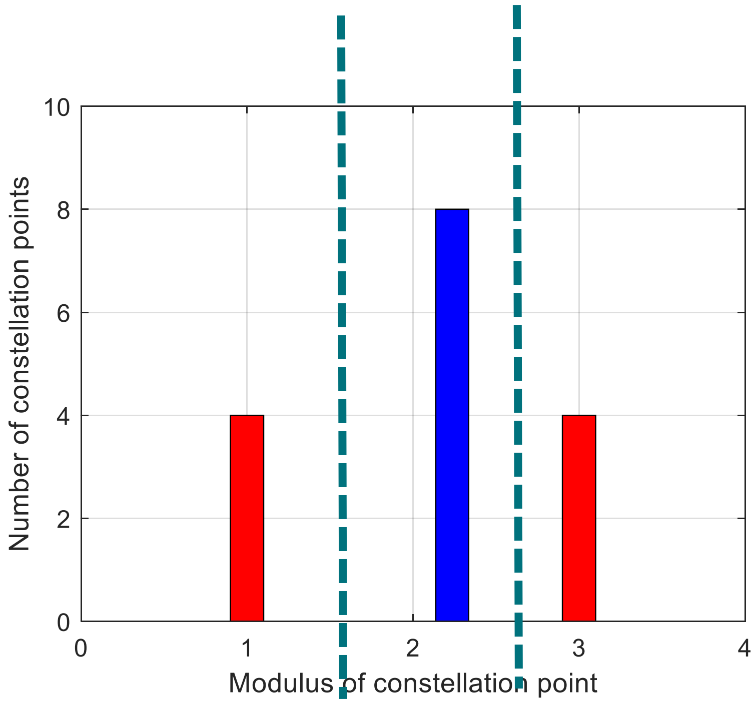
Viterbi&Viterbi algorithm with QPSK reduction (V&V)

- **16 QAM**



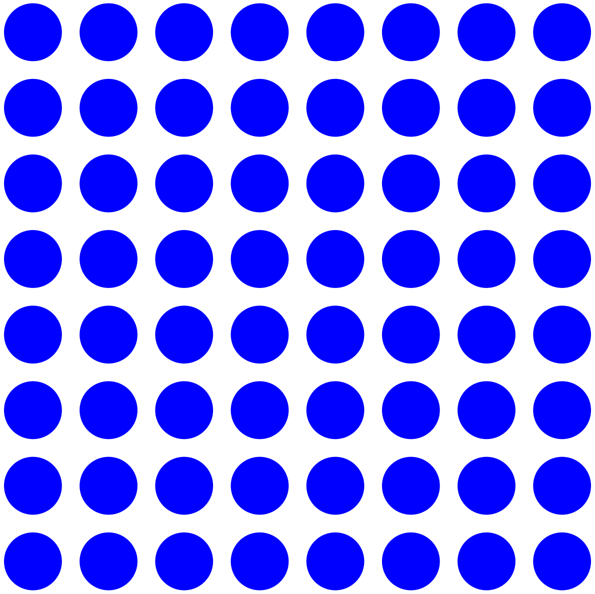
50% of symbols are used

- Only uses symbols that match a QPSK constellation



Viterbi&Viterbi algorithm with QPSK reduction (V&V)

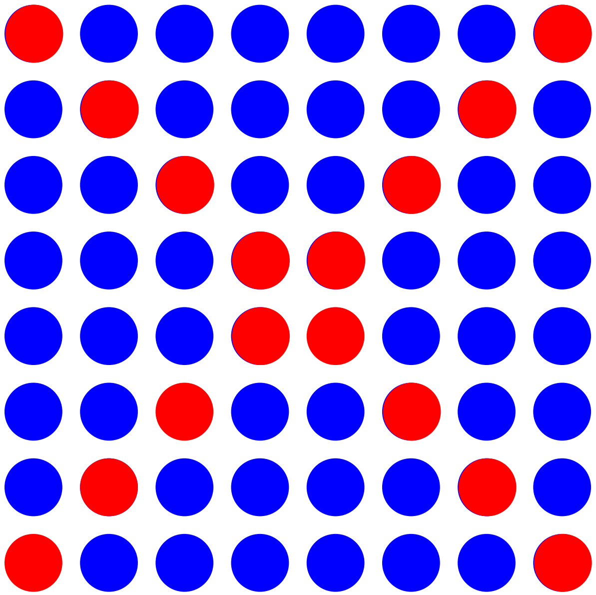
- **64 QAM**



- Only uses symbols that match a QPSK constellation

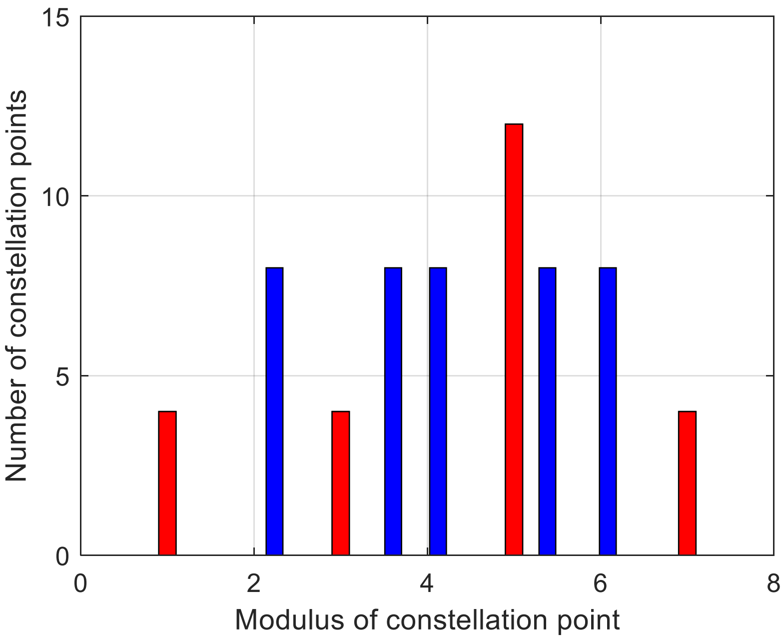
Viterbi&Viterbi algorithm with QPSK reduction (V&V)

- **64 QAM**



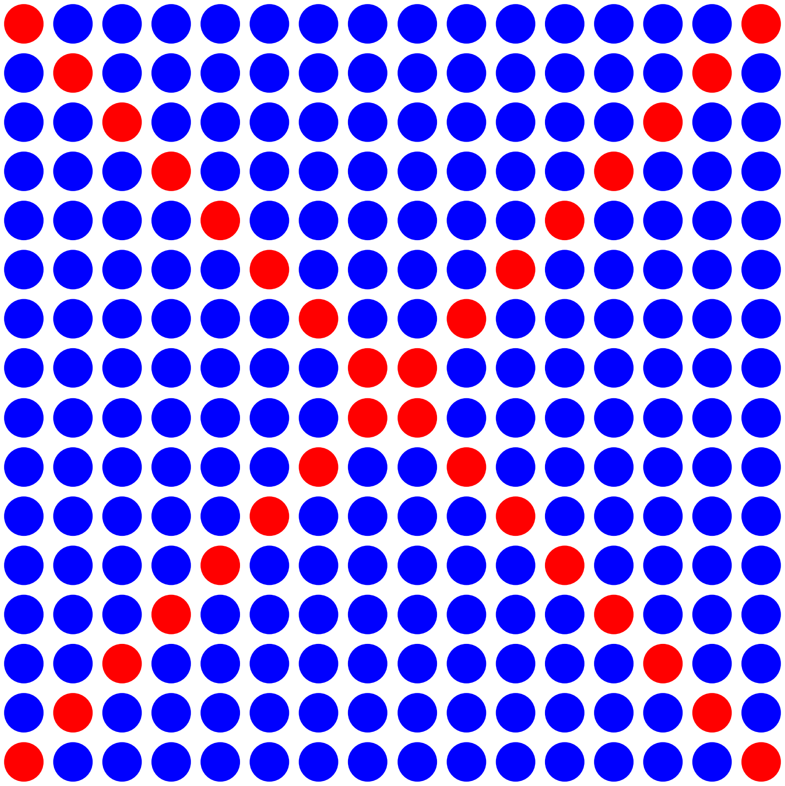
18.75% of symbols are used

- Only uses symbols that match a QPSK constellation

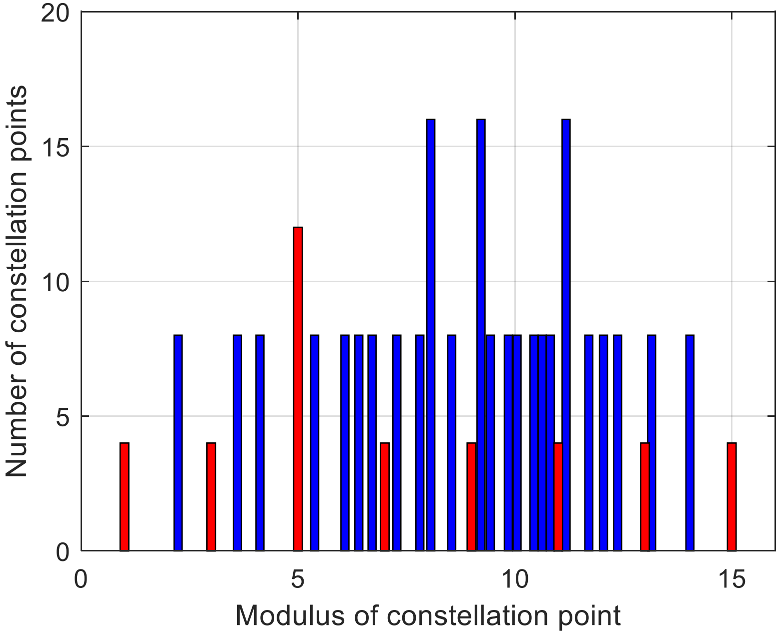


Viterbi&Viterbi algorithm with QPSK reduction (V&V)

- **256 QAM**

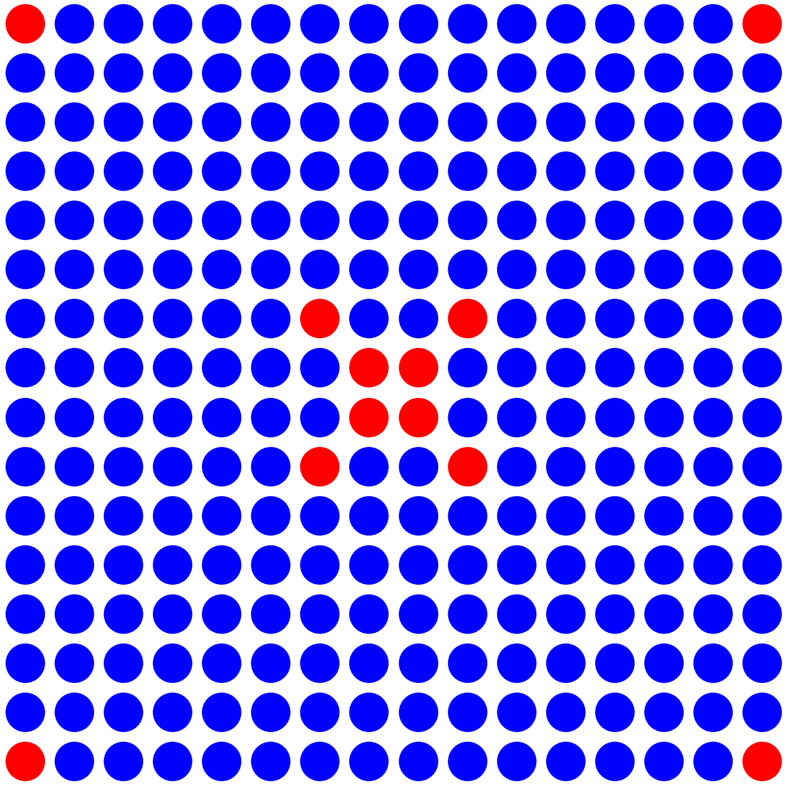


- Only uses symbols that match a QPSK constellation



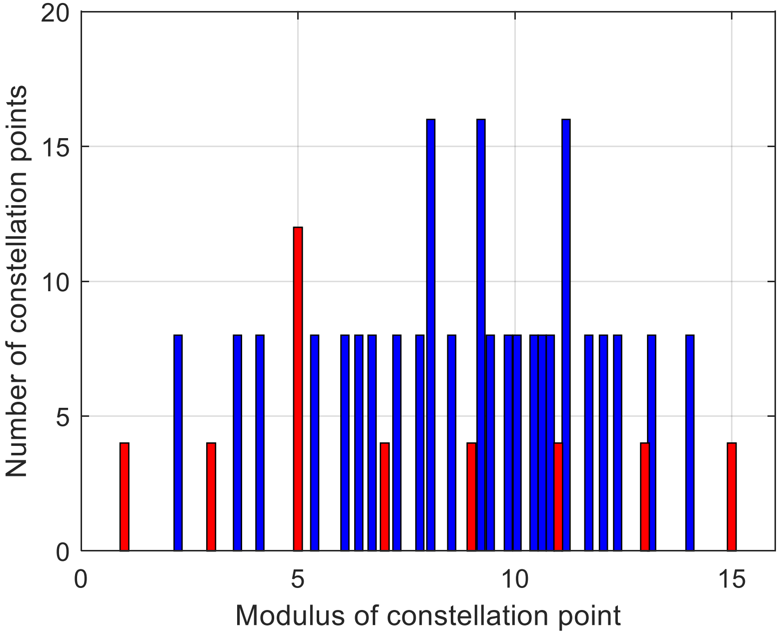
Viterbi&Viterbi algorithm with QPSK reduction (V&V)

- **256 QAM**

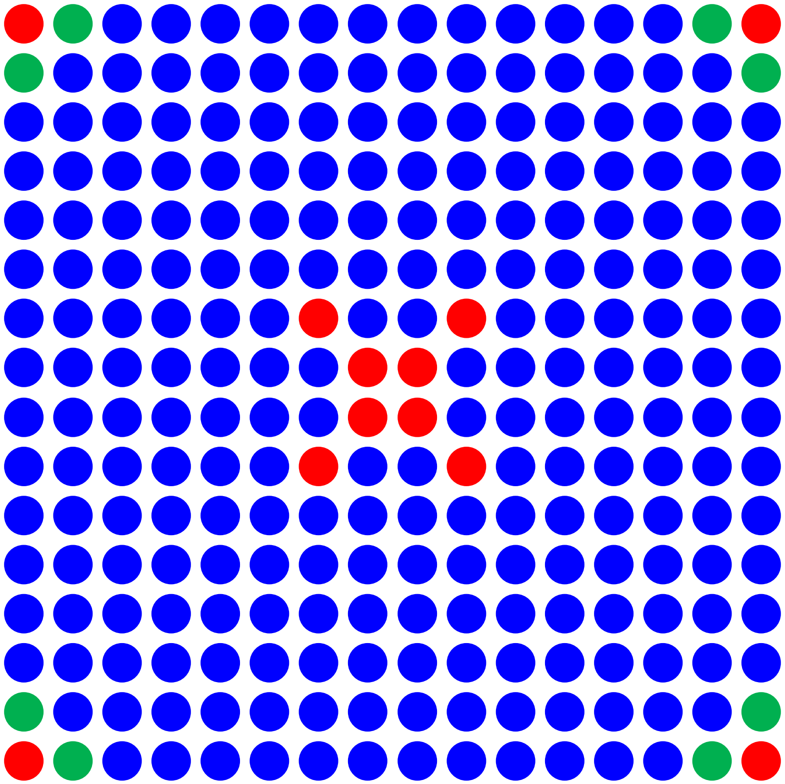


4.7% of symbols are used

- Only 12 out of the 32 symbols lying at the vertices of squares are used.



Modified V&V algorithm (V&V*)



7.8% of symbols are used

- Green symbols lie at an angle of ± 4° from the QPSK constellation.
- If the averaging window is sufficiently long, this ±4° error is averaged out → the estimation of phase noise is only marginally affected by these errors.

Blind-phase search (BPS)

- Feed-forward approach, based on the following steps:
  - Rotation of received sample by ***M* test carrier phase angles**:

$$\varphi_b = \frac{m}{M} \cdot \frac{\pi}{2} \qquad m \in \{0, 1, \ldots, M-1\}$$

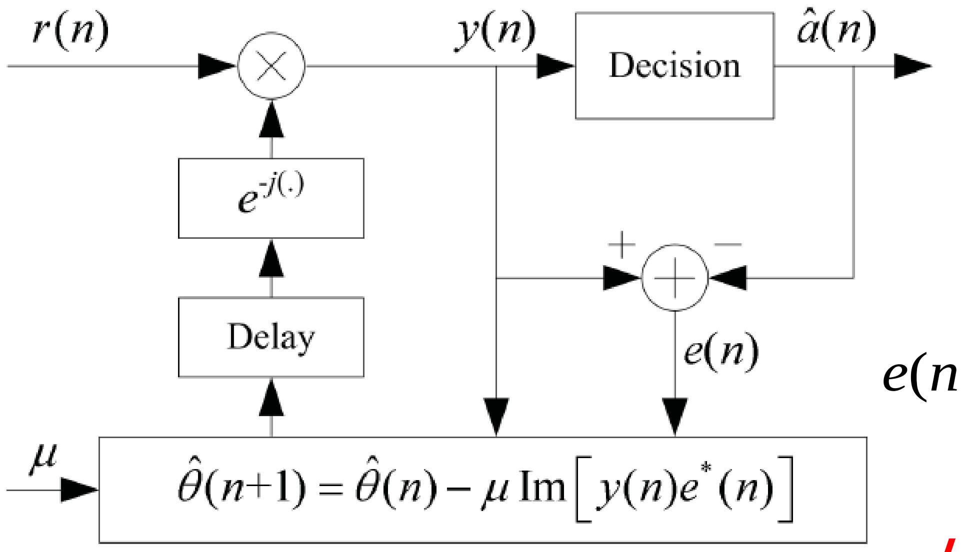
  - Evaluation of the *M* squared distances to the closest constellation point
  - Sum of distances of ***N* consecutive symbols** (to mitigate noise distortion)
  - Identification of the optimum phase value by searching the minimum sum of distance values

T. Pfau et al., "Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations", JLT, vol. 27, no.8, pp.989-999, Apr.2009.

Standard Decision-Directed Phase Locked Loop

- It updates the phase estimation using the error between the output of the equalizer and the corresponding decision.

$$y(n) = r(n) \cdot e^{-j\theta(n)}$$

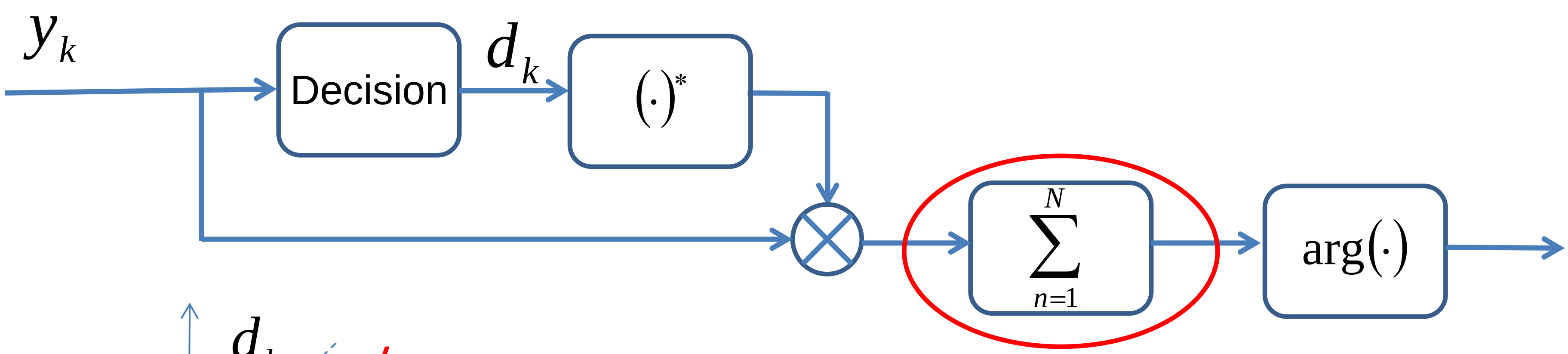


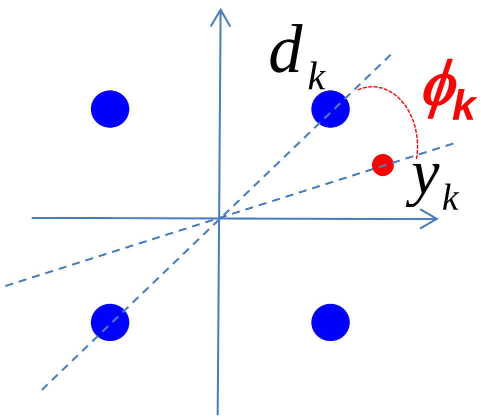
$$e(n) = y(n) - \hat{a}(n)$$

μ **is the update coefficient**

Y. Gao et al., "Modulation-Format-Independent Carrier Phase Estimation for Square M-QAM Systems" , JLT, vol. 25, no. 11, pp. 1073 1077, Jun. 2013.

Maximum Likelihood Estimation (MLE)



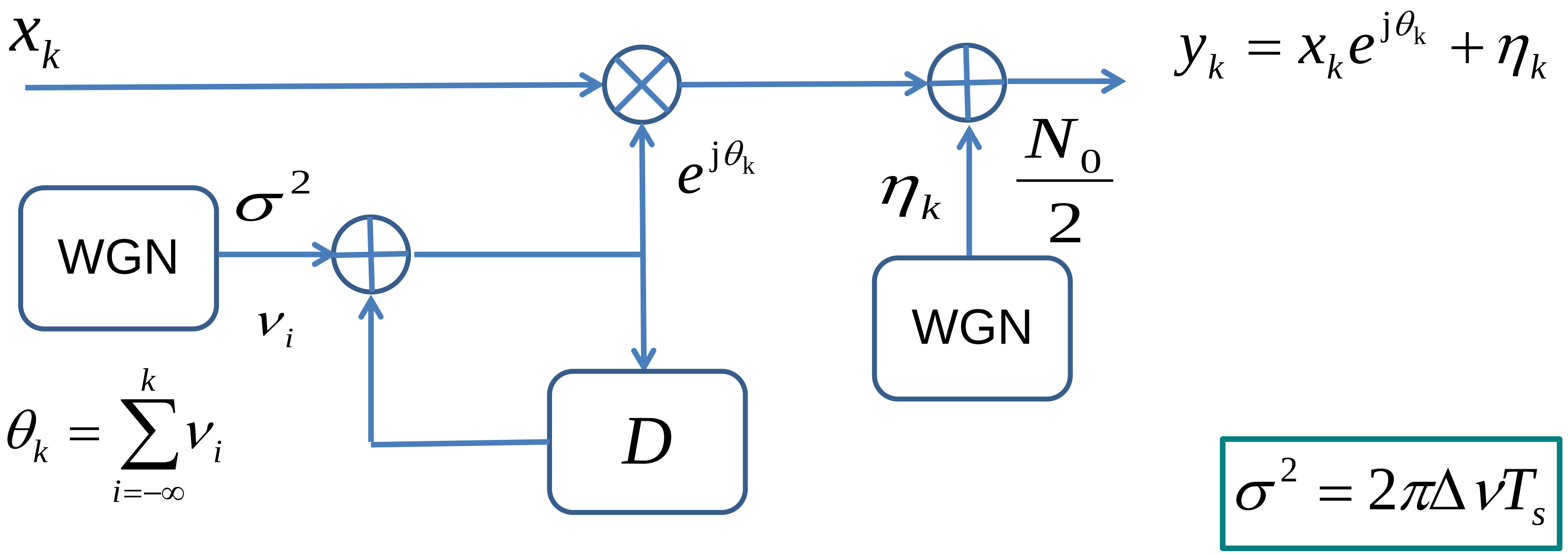


- Usually used as second-stage CPE, after coarse phase estimation
- **Uniform filter of length *N* symbols** (averages the effect of AWGN)

Y. Gao, et al., "Low-complexity two-stage carrier phase estimation for 16-QAM systems … in Proc. OFC/NFOEC, Los Angeles, CA, USA, Mar. 2011, paper OMJ6.

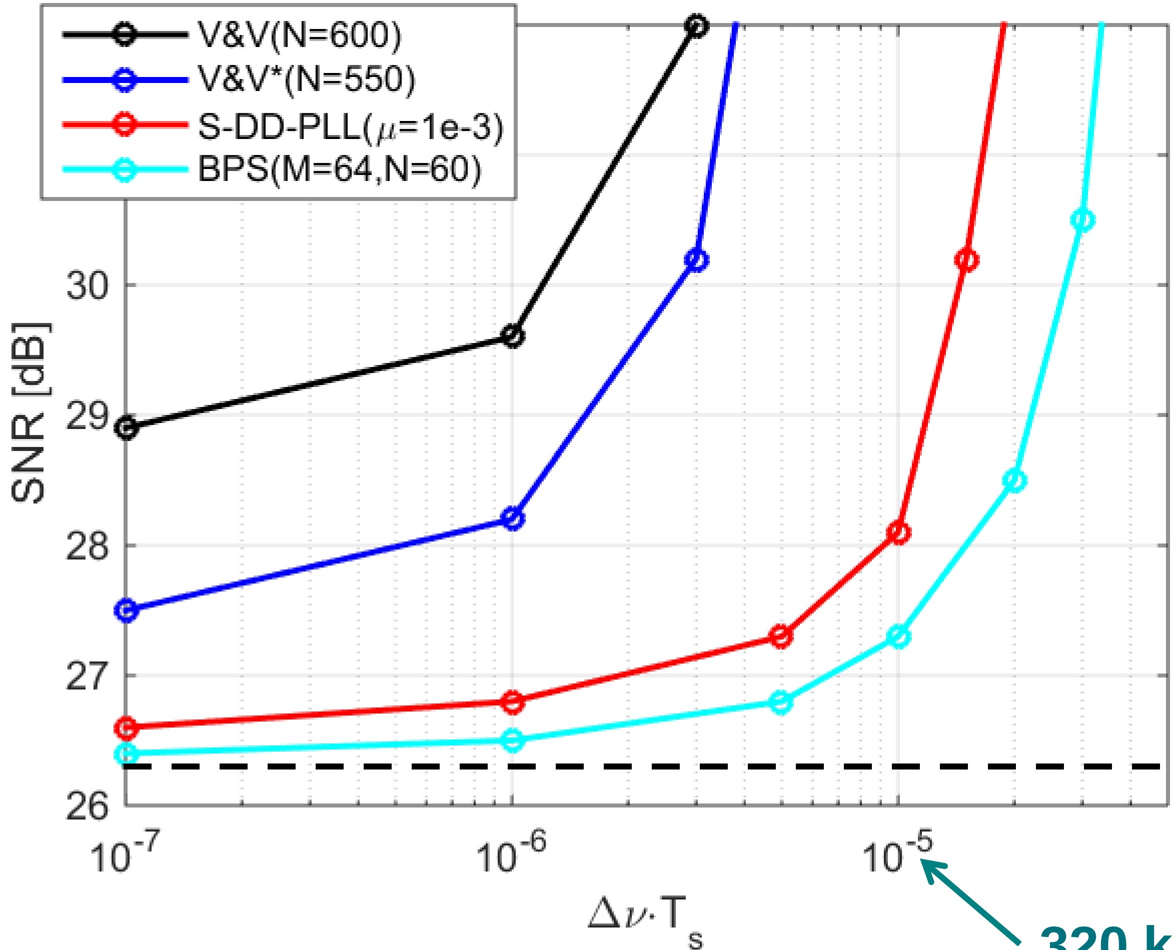
Simulation set-up

- Channel model: AWGN + phase noise
- Signal samples at the output of the digital coherent receiver:



- θ_k is the laser phase noise, modeled as a Wiener process
- $\Delta\nu$ combined laser linewidth of transmitter laser and LO

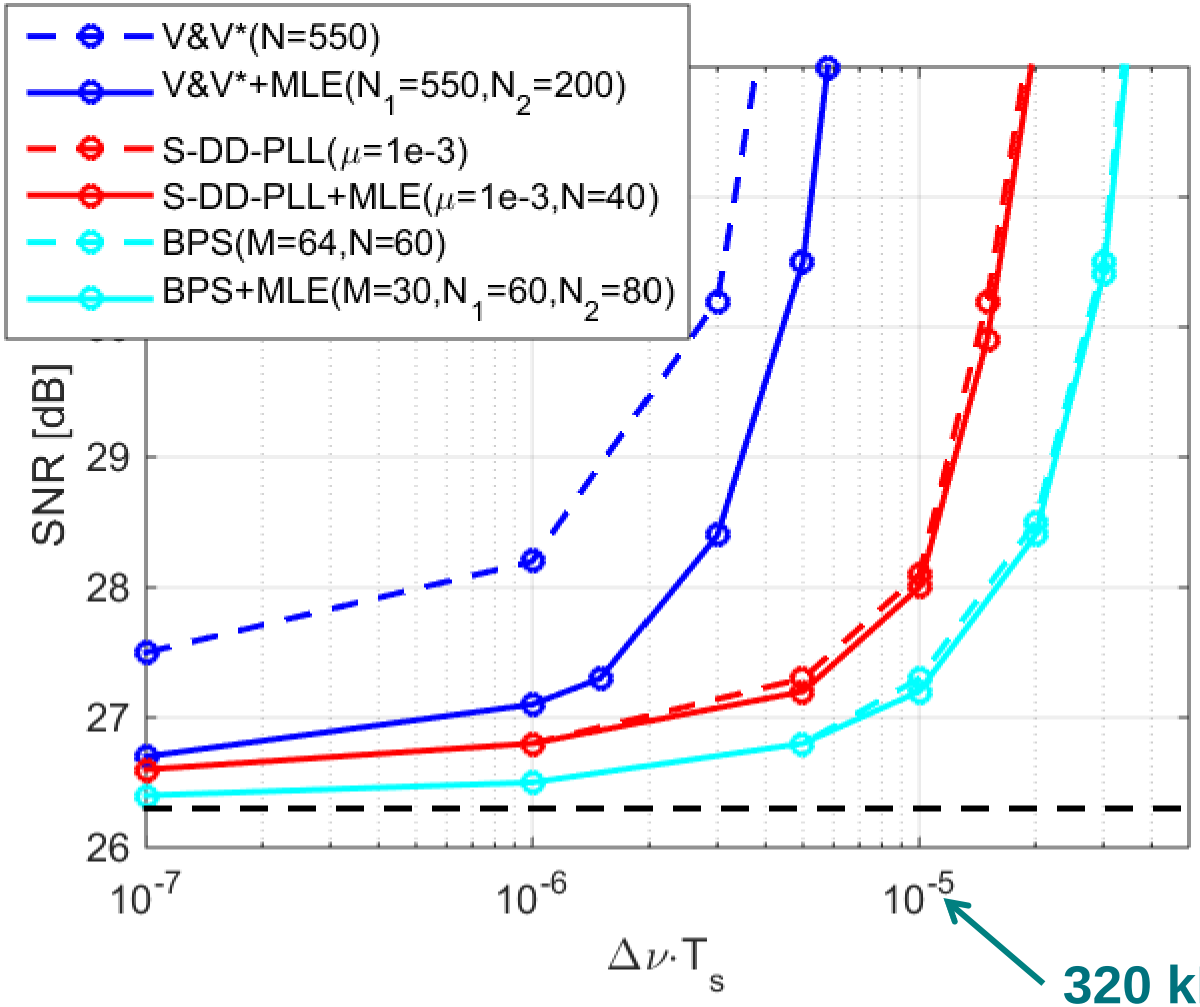
Single-stage algorithms



- Target BER=1e-2
- $$\mathrm{SNR} = \frac{P_{Rx}}{N_0 R_s}$$
- $$R_s = \frac{1}{T_s}$$
- $\Delta\nu$ combined laser linewidth of transmitter laser and LO

320 kHz @32 Gbaud

Dual-stage algorithms



320 kHz @32 Gbaud

- Target BER=1e-2
- $\mathrm{SNR} = \frac{P_{Rx}}{N_0 R_s}$
- $\mathrm{R}_s = \frac{1}{T_s}$
- $\Delta\nu$ combined laser linewidth of transmitter laser and LO

Complexity comparison

CPE	Real Multipliers	Real Adders	Comparators	Look-Up Tables	Decisions
V&V	8N	3N+2	4N+2	1	N_1
V&V*	8N	3N+2	4N+2	1	N_1
V&V*+MLE	$8N_1+N_2$	$3N_1+N_2+1$	$4N_1+7$	2	N_2
BPS	NM+2NM	2NM-M+3	M+1	0	NM+N
BPS+MLE	$N_1M+2N_1M+N_2$	$2N_1M-M+N_2+2$	M+1	1	N_1M+N_2
S-DD-PLL	2N	2N	0	0	2N
S-DD-PLL+MLE	$2N_1+N_2$	$2N_1+N_2-1$	0	1	N_1+N_2

- BPS has the best performance but the highest complexity.
- It's complexity can be reduced by a factor of 2.5 using the BPS-MLE approach, without any loss in performance.

- The actual complexity is strongly dependent on the practical implementation.

Conclusions

- A detailed simulative analysis of different CPE schemes for 256-QAM modulation has been performed.

- Differently from what previously found for 16-QAM and 64-QAM, the best performance for 256-QAM systems is achieved by using BPS algorithms, with the complexity of **BPS+MLE** being almost 2.5 times less than the complexity of BPS.

Thank you!