Low-Complexity Linewidth-Tolerant Carrier Phase Estimation for 64-QAM Systems Based on Constellation Transformation

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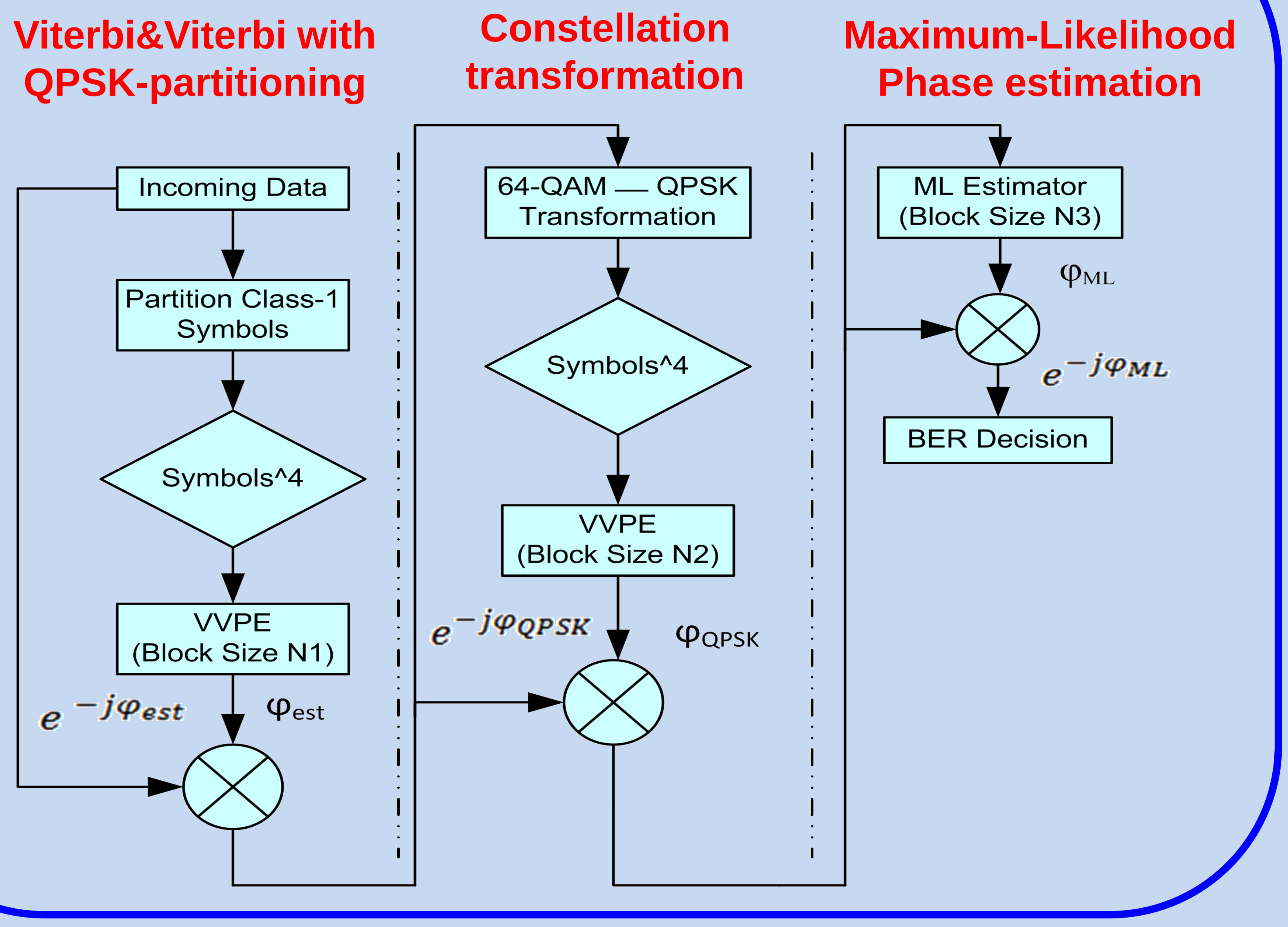
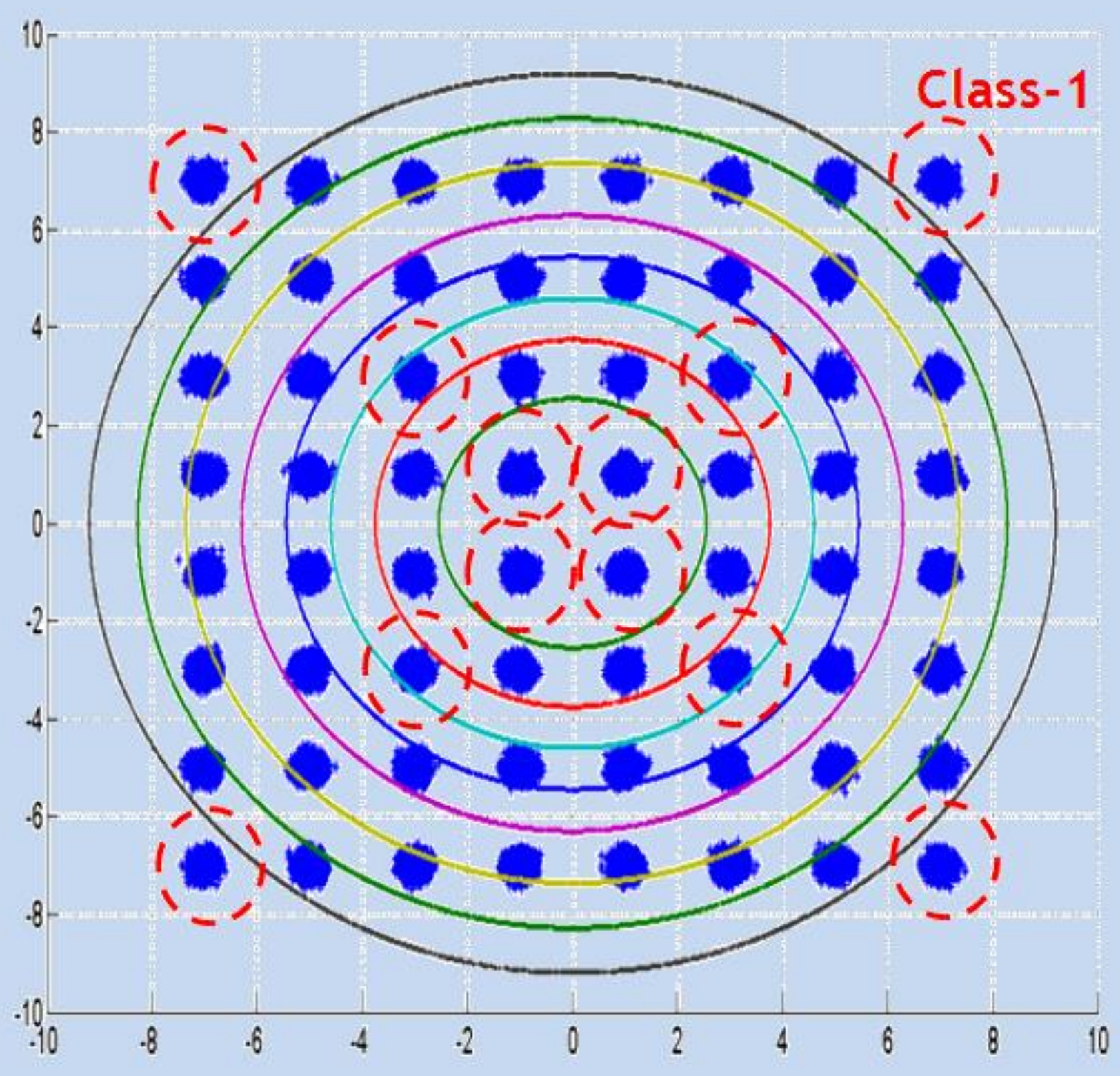
Abstract - *A novel three-stage digital feed-forward carrier recovery algorithm based on the transformation of 64-QAM constellation into QPSK is proposed. For 1 dB penalty at BER=10^{-2}, it can tolerate a linewidth-times-symbol-rate product of $4.5 \cdot 10^{-5}$, making it possible to operate 32-Gbaud optical 64-QAM systems with current commercial tunable lasers.*

Block diagram of the algorithm



QPSK partitioning and MLE stages



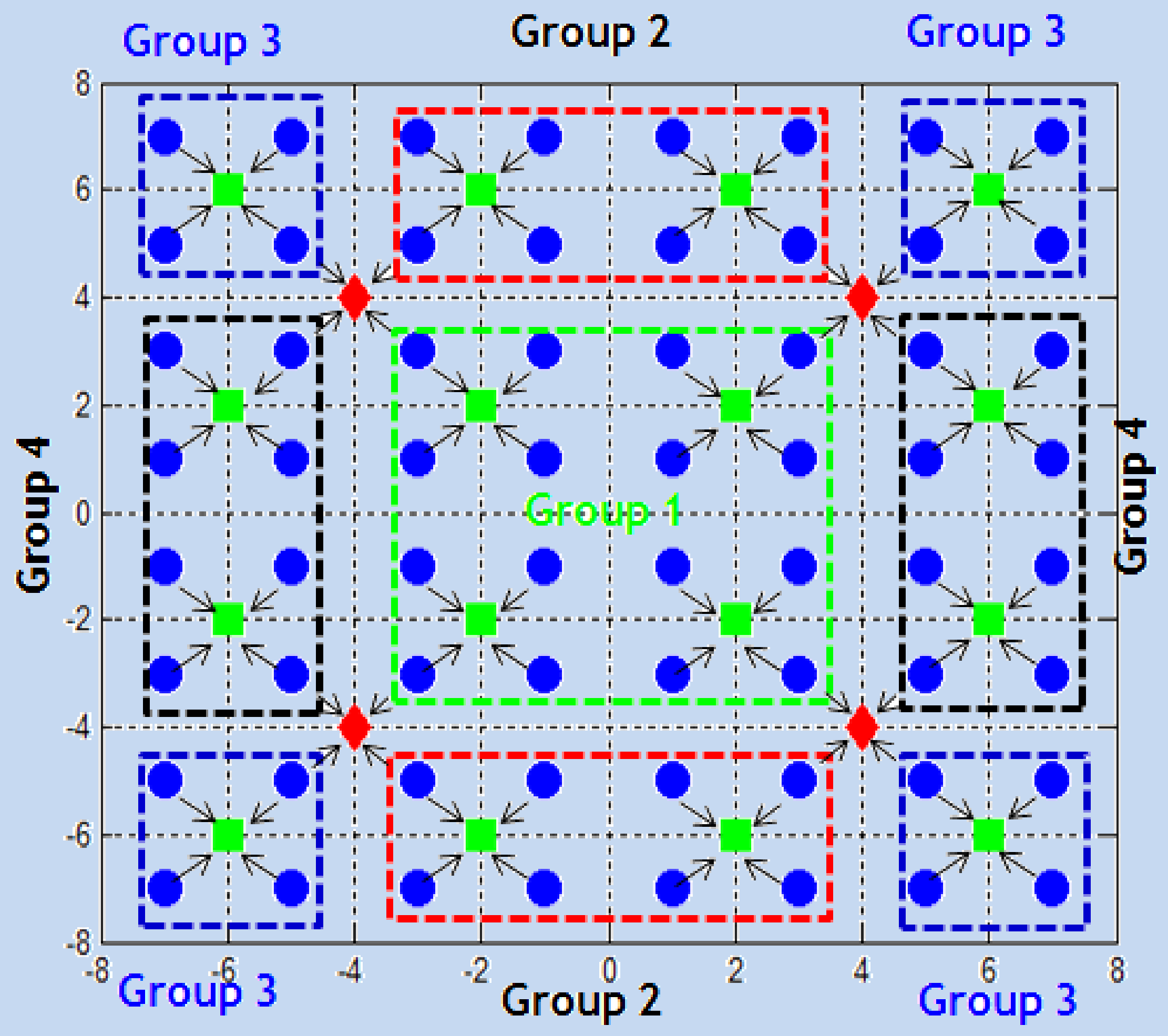
- Class-1 symbols have modulation angles equal to $\pi/4 + m \cdot \pi/2$ ($m = 0\ldots3$).
- 12 out of the 16 symbols lying at the vertices of squares are used in the Viterbi&Viterbi algorithm:

$$\varphi_{est,class1} = \frac{1}{4}\arg\sum_{k=1}^{N_1}\frac{X_k^4}{\left|X_k^4\right|}$$

- Performance of the estimators can be further improved by adding an MLE stage:

$$\varphi_{ML} = \tan^{-1}\left(\frac{\text{imag}(z)}{\text{real}(z)}\right) \quad \text{with} \quad z = \frac{1}{4}\arg\sum_{k=1}^{N_2} x_k \cdot y_k$$

64-QAM –> QPSK Constellation Transformation



From 64-QAM to 16-QAM:

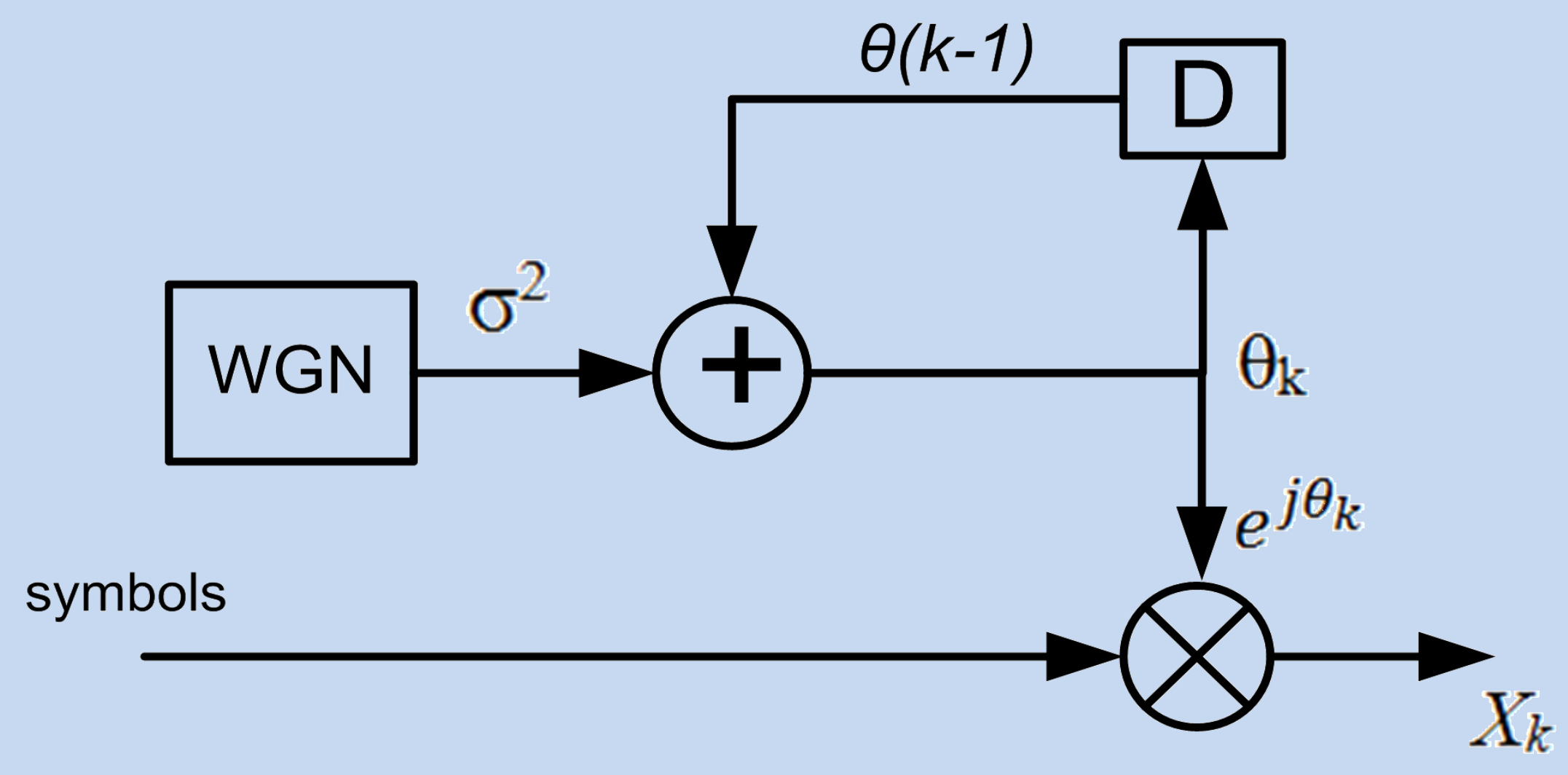
$$\begin{aligned} Y = {} & Y_{1r} - \text{sgn}\left(Y_{1r} - 2\,\text{sgn}\left(Y_{1r}\right)\right) + j\left(Y_{1i} - \text{sgn}\left(Y_{1i} - 2\,\text{sgn}\left(Y_{1i}\right)\right)\right) + \\ & + Y_{2r} - \text{sgn}\left(Y_{2r} - 2\,\text{sgn}\left(Y_{2r}\right)\right) + j\left(Y_{2i} - \text{sgn}\left(Y_{2i} - 6\,\text{sgn}\left(Y_{2i}\right)\right)\right) + \\ & + Y_{3r} - \text{sgn}\left(Y_{3r} - 6\,\text{sgn}\left(Y_{3r}\right)\right) + j\left(Y_{3i} - \text{sgn}\left(Y_{3i} - 6\,\text{sgn}\left(Y_{3i}\right)\right)\right) + \\ & + Y_{4r} - \text{sgn}\left(Y_{4r} - 6\,\text{sgn}\left(Y_{4r}\right)\right) + j\left(Y_{4i} - \text{sgn}\left(Y_{4i} - 2\,\text{sgn}\left(Y_{4i}\right)\right)\right) \end{aligned}$$

From 16-QAM to QPSK:

$$\begin{aligned} Y = {} & Y_r - \text{sgn}\left(Y_r - 2\,\text{sgn}\left(Y_r\right)\right) + \\ & + j\left(Y_i - \text{sgn}\left(Y_i - 2\,\text{sgn}\left(Y_i\right)\right)\right) \end{aligned}$$

- The constellation transformations are applied after frequency offset compensation between the LO and transmitter laser and after an initial phase noise correction using a coarse estimate (achieved using the Viterbi&Viterbi algorithm based on QPSK partitioning)

Simulation Setup and results

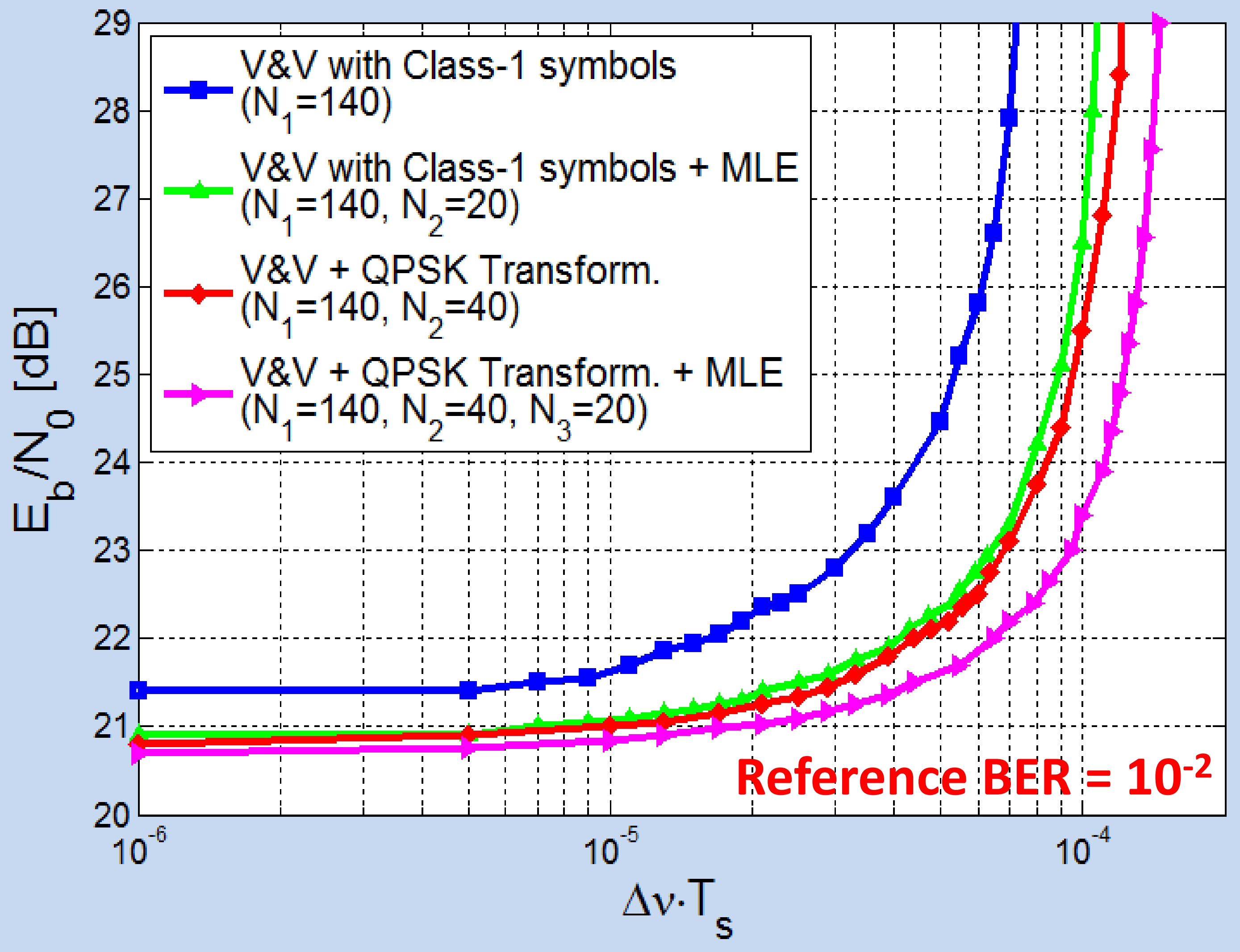


$$y_k = x_k e^{j\theta_k} + \eta_k$$

$$\theta_k = \sum_{i=-\infty}^{k} \nu_i$$

$$\sigma_f^2 = 2\pi\Delta\nu T_s$$

- x_k is the data symbol that belongs to the set: $(\pm a \pm j.b)$, $a,b \in \{1,3,5,7\}$.
- η_k is the AWG noise.
- θ_k is the laser phase noise, modeled as a Wiener process.
- $\Delta\nu$ is the combined laser linewidth of Tx laser and local oscillator.
- T_s is the symbol period.



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Conclusion: A novel low complexity algorithm for carrier phase estimation of 64-QAM has been presented and its performance analyzed through numerical simulations.

A linewidth times symbol duration product ($\Delta\nu \cdot T_s$) equal to $4.5 \cdot 10^{-5}$ is tolerated for 1-dB penalty at BER equal to 10^{-2}.

Assuming the industry-standard symbol rate of 32 GBaud, this means that a total combined linewidth of over 1.3 MHz could be tolerated, making it possible to operate optical 64-QAM systems with current commercial tunable lasers.