Linewidth-tolerant Feed-forward Dual-stage CPE Algorithm Based on 64-QAM Constellation Partitioning

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Abstract - A detailed analysis of a novel low-complexity two-stage digital feed-forward carrier recovery algorithm for 64-QAM, based on the rotation of constellation points to remove phase modulation is presented. Its performance and complexity is compared with previously proposed algorithms.

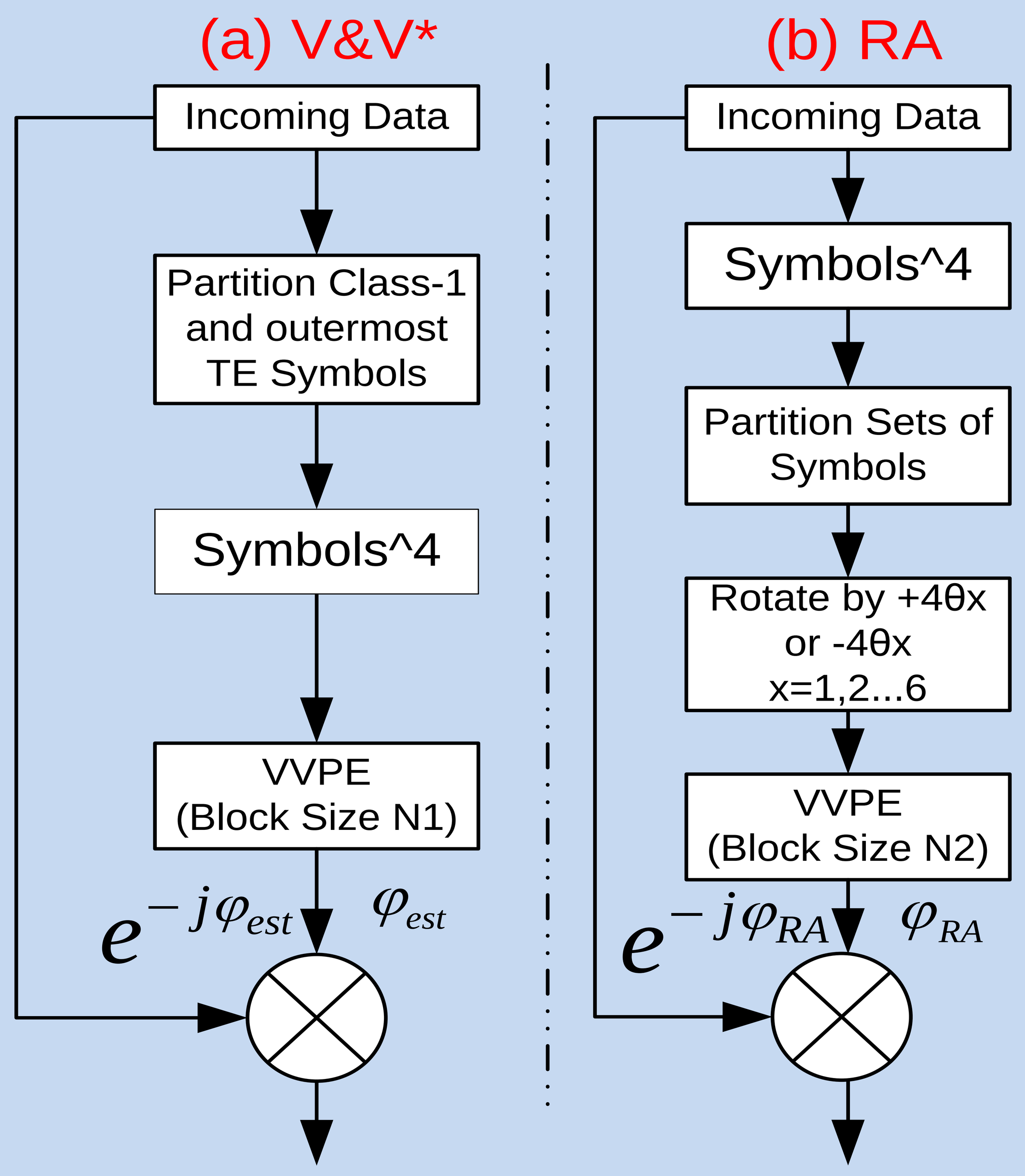


Figure. 1: Block diagram of the proposed technique

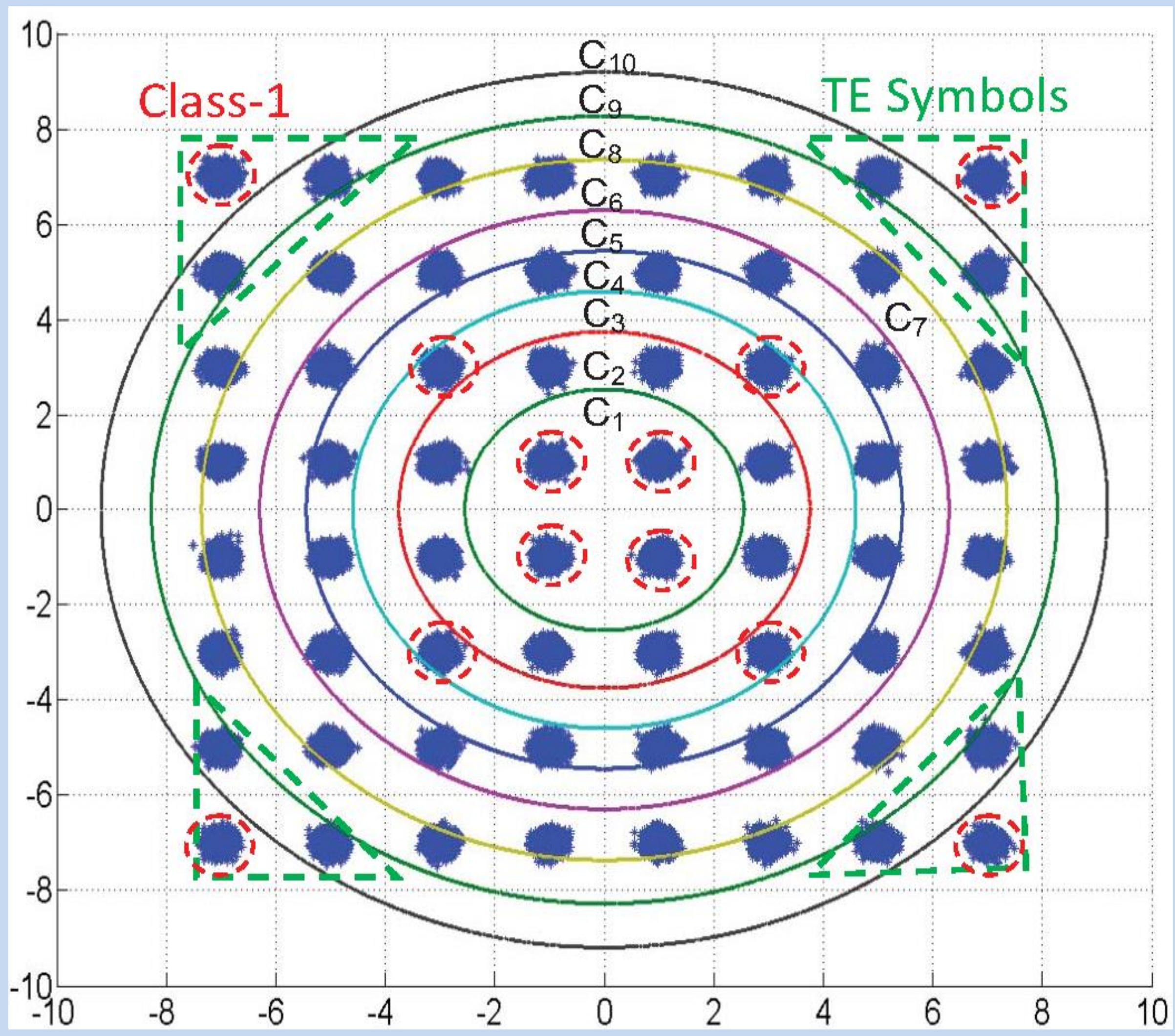


Figure. 2: 64-QAM Constellation with different thresholds for separating symbols of different amplitudes. Symbols used in the first V&V* stage are highlighted by red dashed circles (Class-1 Symbols) and green dashed triangles (Triangle Edge (TE) Symbols).

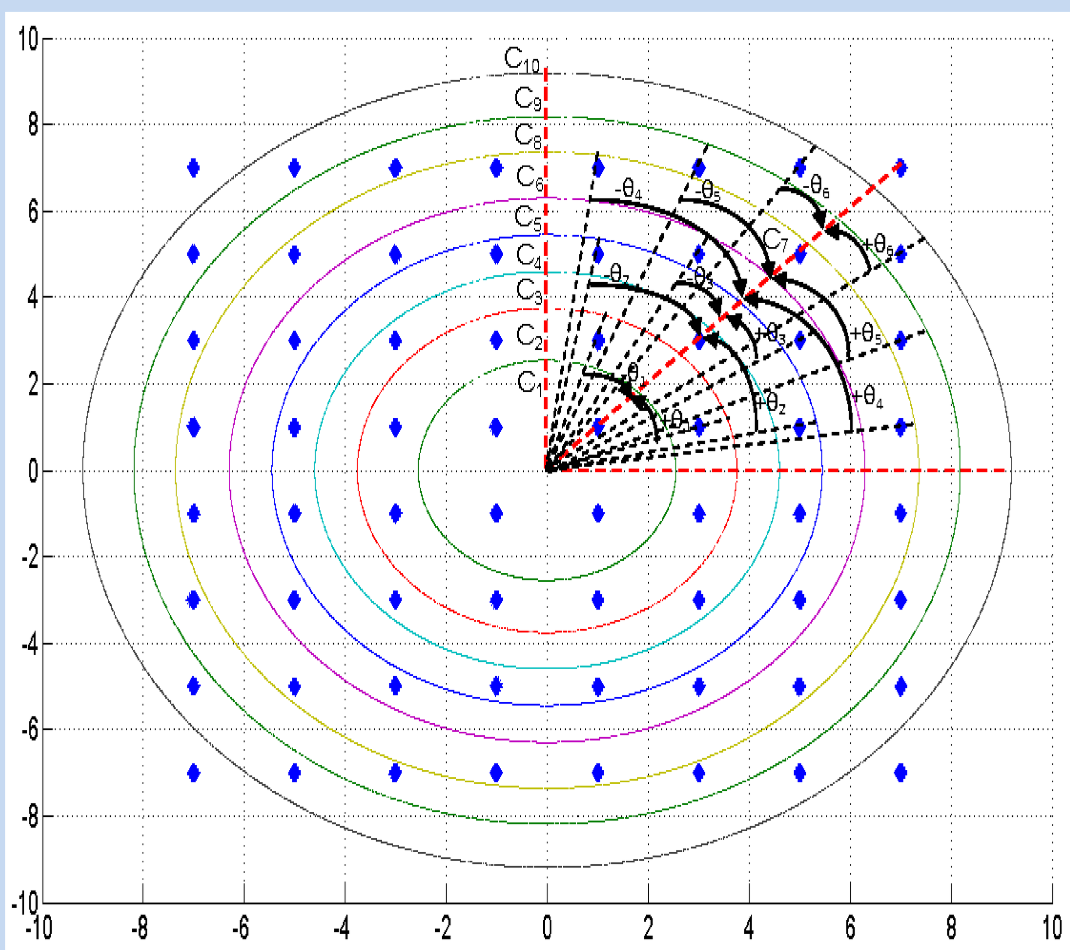


Figure. 3: 64-QAM constellation showing all rings and rotation angles

- Symbols in the rings C_1, C_3, C_7 and C_{10} are QPSK partitioned symbols that lie at modulation angles equal to $\pi/4 + m \cdot \pi/2$ (m=0…3).
- Symbols in the rings C_2, C_4, C_5, C_6, C_8, and C_9 can be categorized into two sets of QPSK symbols with phase rotations $\theta_x=\pm(\pi/4-\tan^{-1}(k_x))$, with $k_x \in \{1/3,1/5,3/5,1/7,3/7,5/7\}$, with respect to the symbols lying in the rings C_1, C_3, C_7 and C_{10}.

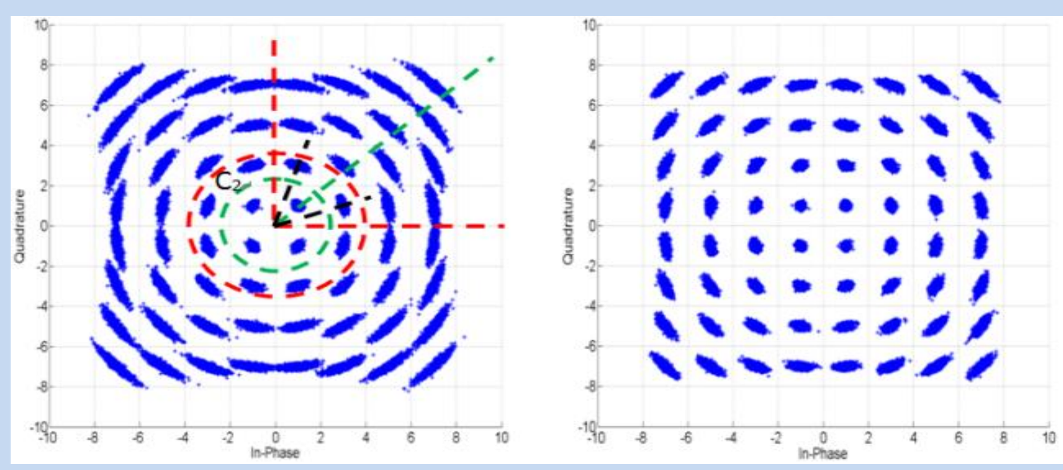


Figure. 4: 64-QAM constellation after coarse (left) and fine (right) carrier phase estimation

- If the residual phase noise after the coarse carrier phase estimation is sufficiently small not to cross the boundaries between the symbols in corresponding rings, these symbols can be properly rotated by θ_x in order to make them fall at an angle equal to $\pi/4 + m \cdot \pi/2$ (m=0…3).
- After the subsequent 4th power operation all the symbols will collapse down to unique positions and, having distinct thresholds, can be easily separated.
- Phase modulation of the rings C_1, C_3, C_7 and C_{10} is directly removed while the phase modulation of the rings C_2, C_4, C_5, C_6, C_8, and C_9 can be removed with:

$$RA_x=C_y\cdot\exp(4j\theta_x\cdot\mathrm{sgn}(\mathrm{Im}(C_y)))$$

where y = 2,4,5,6,8,9, x = 1,2,…6, sgn(.) is the 'signum' function and Im(.) is the imaginary part of the complex valued symbols

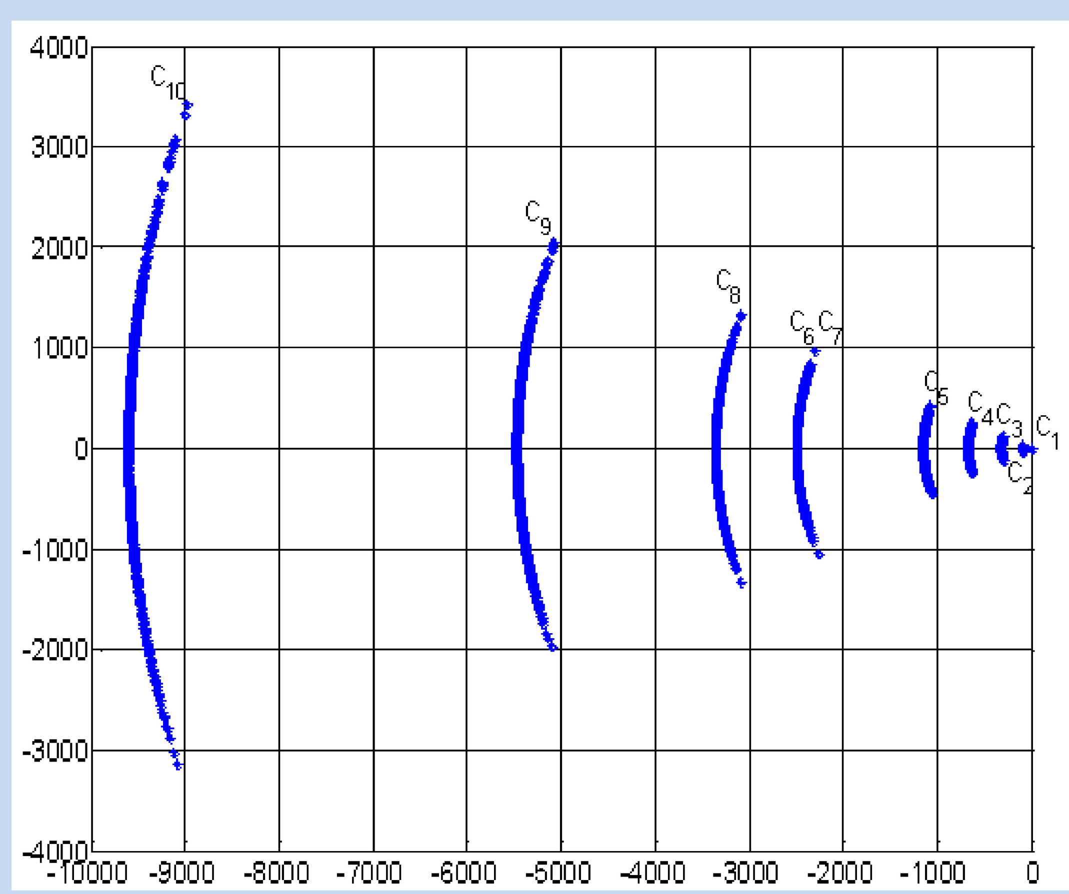


Figure. 5: 64-QAM constellation after fourth power and rotation operation

Simulation model

Received noisy samples:

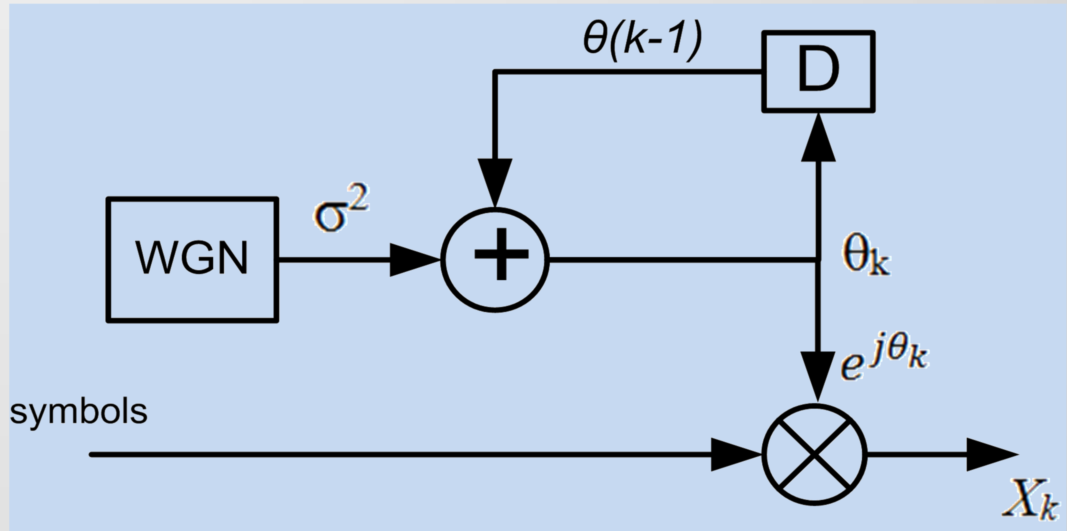
$$y_k = x_k e^{j\theta_k} + \eta_k$$

Phase noise:

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

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

- x_k is the data symbol at time k that belongs to the set $(\pm a \pm j\cdot b)$, with $a,b \in \{1,3,5,7\}$.
- 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 transmitter laser and LO.
- T_s is the symbol period.



Complexity analysis

CPE	Real Multipliers	Real Adders	Comparators	Look-Up Tables	Decisions
V&V*	8N	3N+2	4N+2	1	N
V&V*+CT	$8N_1+6N_2$	$3N_1+3N_2+30$	$4N_1+7$	2	N_2
V&V*+RA	$8N_1+6N_2+36$	$3N_1+3N_2+4$	$4N_1+13$	3	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

Table. 1: Computational complexity for various CPE algorithms

Simulation Results

Case	2	4	6	7	8
CPE	V&V*	V&V*+CT	V&V*+RA	BPS	BPS+ MLE
$\Delta\nu\cdot T_s$ @ 1dB penalty	10^{-5}	$3.7\cdot10^{-5}$	$3.7\cdot10^{-5}$	$5.7\cdot10^{-5}$	$5.4\cdot10^{-5}$
Equivalent linewidth @ 20 Gbaud	0.20 MHz	0.74 MHz	0.74 MHz	1.14 MHz	1.08 MHz

Table. 2: Laser phase noise tolerances and their equivalent linewidths at 20 Gbaud

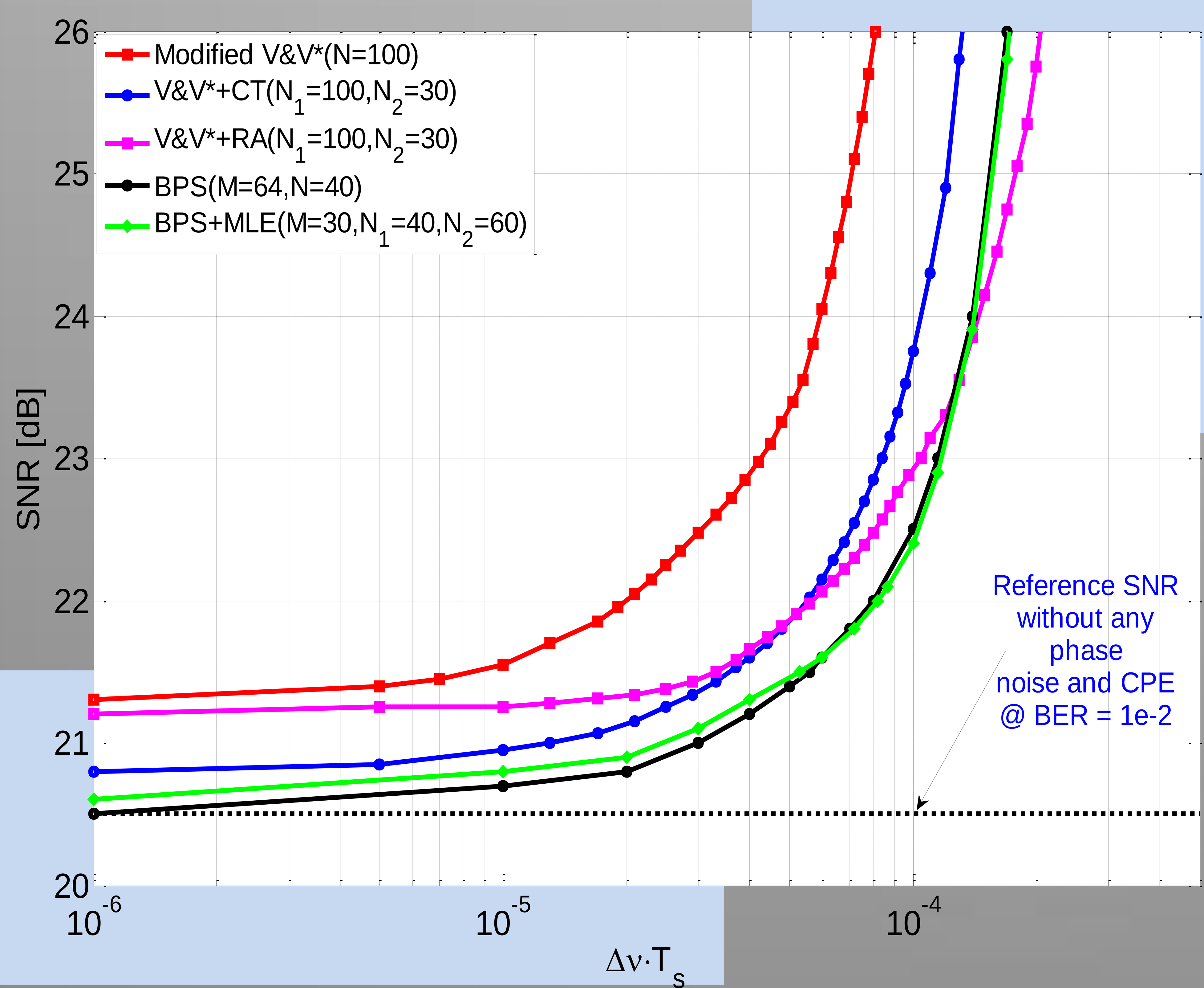


Figure. 6: SNR vs. linewidth times symbol duration ($\Delta\nu\cdot$Ts) product at BER=10^{-2} for different CPE schemes.

Conclusions

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

At high phase noise values, performance of the proposed technique is even better than CT and BPS with approx. the same complexity as CT and almost 9 times less complexity than that of BPS.