Performance of Modal Signaling vs. Medium Dielectric Variability

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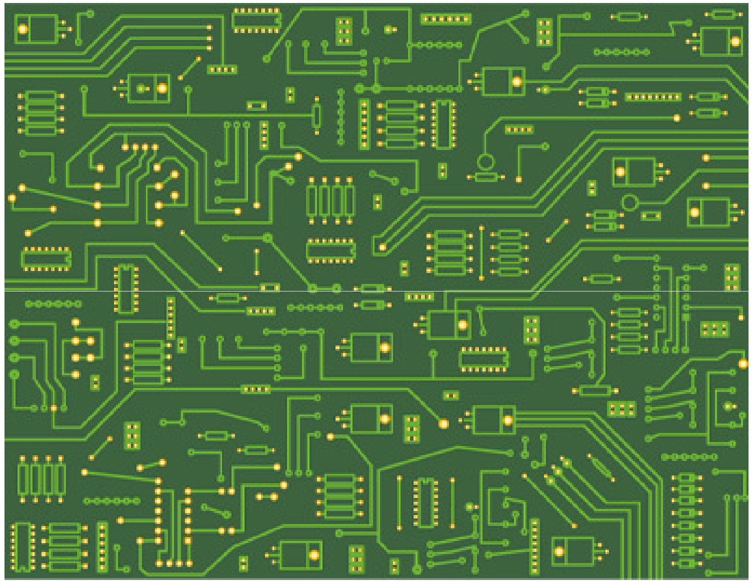
Crosstalk in high-density systems

- The **shrinking** of device sizes is leading to very **high levels of density** in PCB microstrip configurations

- In order to cope with the demand for **large data throughput**, signal speed is also increased

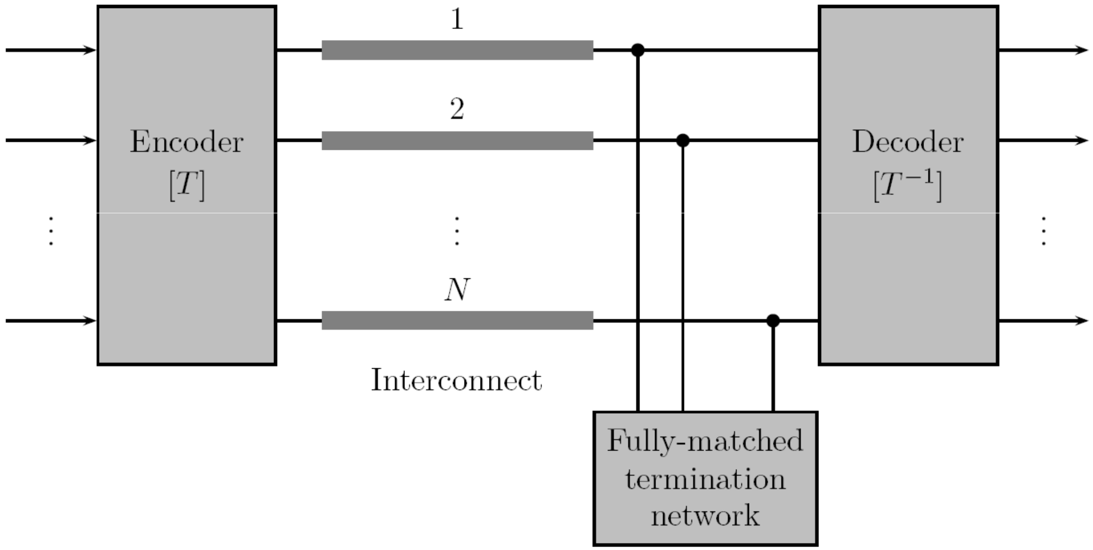


- In such situation, **crosstalk** induced between adjacent conductors is often the **limiting factor**

- In recent years, research work has been focused on solutions to **reduce crosstalk levels** in high-speed links

Modal signaling transmission scheme

- A transmission scheme known as "**modal signaling**" has been developed and proposed in literature to **mitigate crosstalk** [1,2]



- MS consists in **encoding** transmitted signals in order to achieve a transmission being theoretically **free of crosstalk**

[1] F. Broydé, E. Clavelier, "A New Method for the Reduction of Crosstalk and Echo in Multiconductor Interconnections," *IEEE Trans. Circ. Syst.* (2005)
[2] P. Milosevic, J.E. Schutt-Ainé, W. T. Beyene, "Crosstalk Mitigation of High-Speed Interconnects with Discontinuities Using Modal Signaling," EPEPS 2010

Modal signaling overview

- Crosstalk is due to the fact that each signal propagates with ***different modes***, which then recombine at the receiver giving raise to crosstalk
- The underlying idea is then to feed a **single mode** rather than a single physical conductor
- To accomplish this, physical signals are **encoded** using the line's **modal transformation matrix** $\mathbf{T}$

original input signals

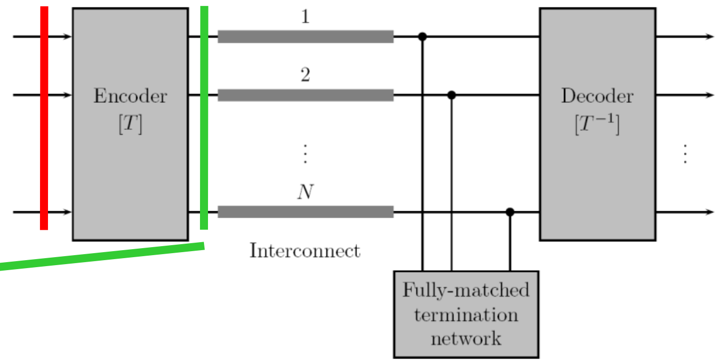
$$\boxed{\mathbf{V}_S}$$

encoded signals

$$\boxed{\mathbf{V}_E = \mathbf{T}\mathbf{V}_S}$$

interconnect modes

$$\boxed{\mathbf{V}_m = \mathbf{T}^{-1}\mathbf{V}_E \equiv \mathbf{V}_S}$$

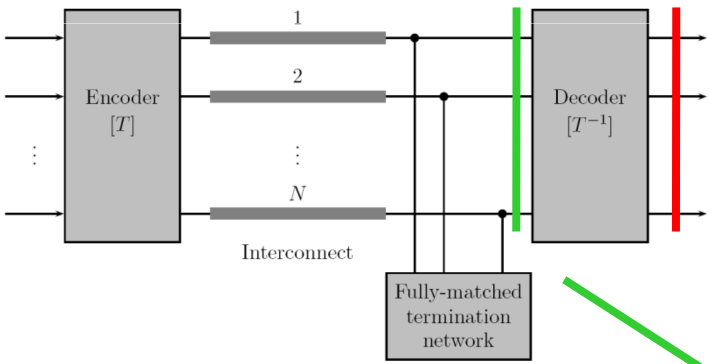


Interconnect modes mimic original source signals!

Modal signaling overview (cont'd)

- A **matched termination network** is also required to avoid reflections at the end of the line

- Finally, to retrieve the original signal, the **inverse transformation** $\mathbf{T}^{-1}$ is applied at the receiver



decoded signals =
original input signals
(after crosstalk-free propagation)!!

$$\boxed{\mathbf{V}_L = \mathbf{T}^{-1}\mathbf{V}_D = \mathbf{V}_m \sim \mathbf{V}_S}$$

$$\boxed{\mathbf{V}_D = \mathbf{T}\mathbf{V}_m}$$

signals at decoder

Role of the interconnect properties

- Modal transformation matrices depend on the **material and geometrical properties** of the interconnect

- Therefore, design of encoders/decoders must **accurately capture these properties** to mimic the actual transformations describing signal propagation along the line

- How sensitive is modal signaling to **(random) perturbations of the physical properties** of the interconnect?

- What happens if **actual properties differ** from those assumed in the design phase, or change during operation (e.g., due to temperature fluctuations)?

Stochastic analysis of modal signaling feasibility

- In order to address the previous questions, a **stochastic analysis** is necessary
- The model presented by the authors for the efficient **stochastic analysis of multiconductor interconnects** [3] is suitable for this purpose
- The model is based on **polynomial chaos** technique and allows to include possible cross-sectional variations into the standard framework of transmission-line theory

The goal of this paper is to provide an efficient tool to **analyze modal signal feasibility** based on polynomial chaos approach

[3] I. S. Stievano, P. Manfredi, F. G. Canavero, "Parameter Variability Effects on Multiconductor Interconnects via Hermite Polynomial Chaos," *IEEE Trans. on Comp. Pack. & Man. Tech.* (2011)

Polynomial chaos overview

- Step #1 is the approximation of stochastic per-unit-length parameters associated to the stochastic cross-section as a series of **orthogonal polynomials**

Coefficients

$$\mathbf{L}(\underbrace{\boldsymbol{\xi}}_{\text{Random variables}}) \cong \sum_{k=0}^{P} \overbrace{\mathbf{L}_k}^{} \underbrace{\phi_k(\boldsymbol{\xi})}_{} \qquad \mathbf{C}(\boldsymbol{\xi}) \cong \sum_{k=0}^{P} \overbrace{\mathbf{C}_k}^{} \underbrace{\phi_k(\boldsymbol{\xi})}_{}$$

Orthogonal polynomials

- Expansion coefficients can be computed by means of **Gaussian quadratures** and samples of the per-unit-length parameters

- Choice of orthogonal polynomials is related to the **distribution** of the random variables $\boldsymbol{\xi}$

Polynomial chaos overview (cont'd)

- **Expansion** and **projection** of the original equations lead to an **augmented set** of differential equations

$$\begin{cases} \frac{d}{dz}\tilde{\mathbf{V}}(z,s) & = & -s\tilde{\mathbf{L}}\tilde{\mathbf{I}}(z,s) \\ \frac{d}{dz}\tilde{\mathbf{I}}(z,s) & = & -s\tilde{\mathbf{C}}\tilde{\mathbf{V}}(z,s) \end{cases}$$

P+1 larger

- New equations are **deterministic** and therefore solvable with the standard procedure for multiconductor transmission lines

- Solution of such equations gives polynomial chaos coefficients for voltage and current variables, defining an **analytical expression** that allows a **fast computation** of statistical parameters

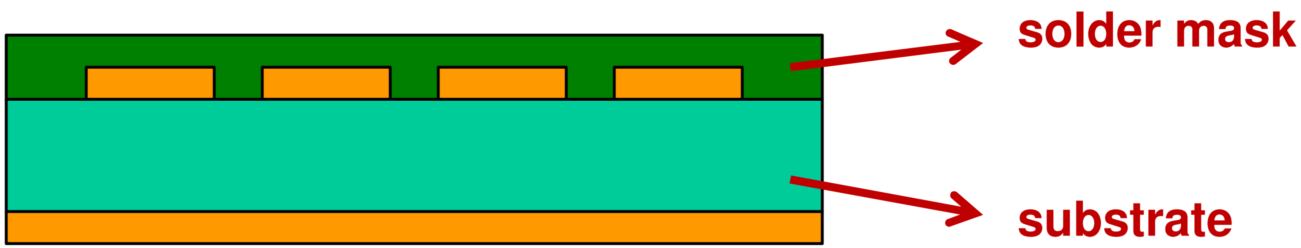
$$\tilde{\mathbf{V}} = [\mathbf{V}_0, \mathbf{V}_1, \mathbf{V}_2, \ldots]$$

$$\mathbf{V}(s,\xi) = \mathbf{V}_0(s)\phi_0(\xi) + \mathbf{V}_1(s)\phi_1(\xi) + \mathbf{V}_2(s)\phi_2(\xi) + \ldots$$

Analytical!!

Structure under investigation

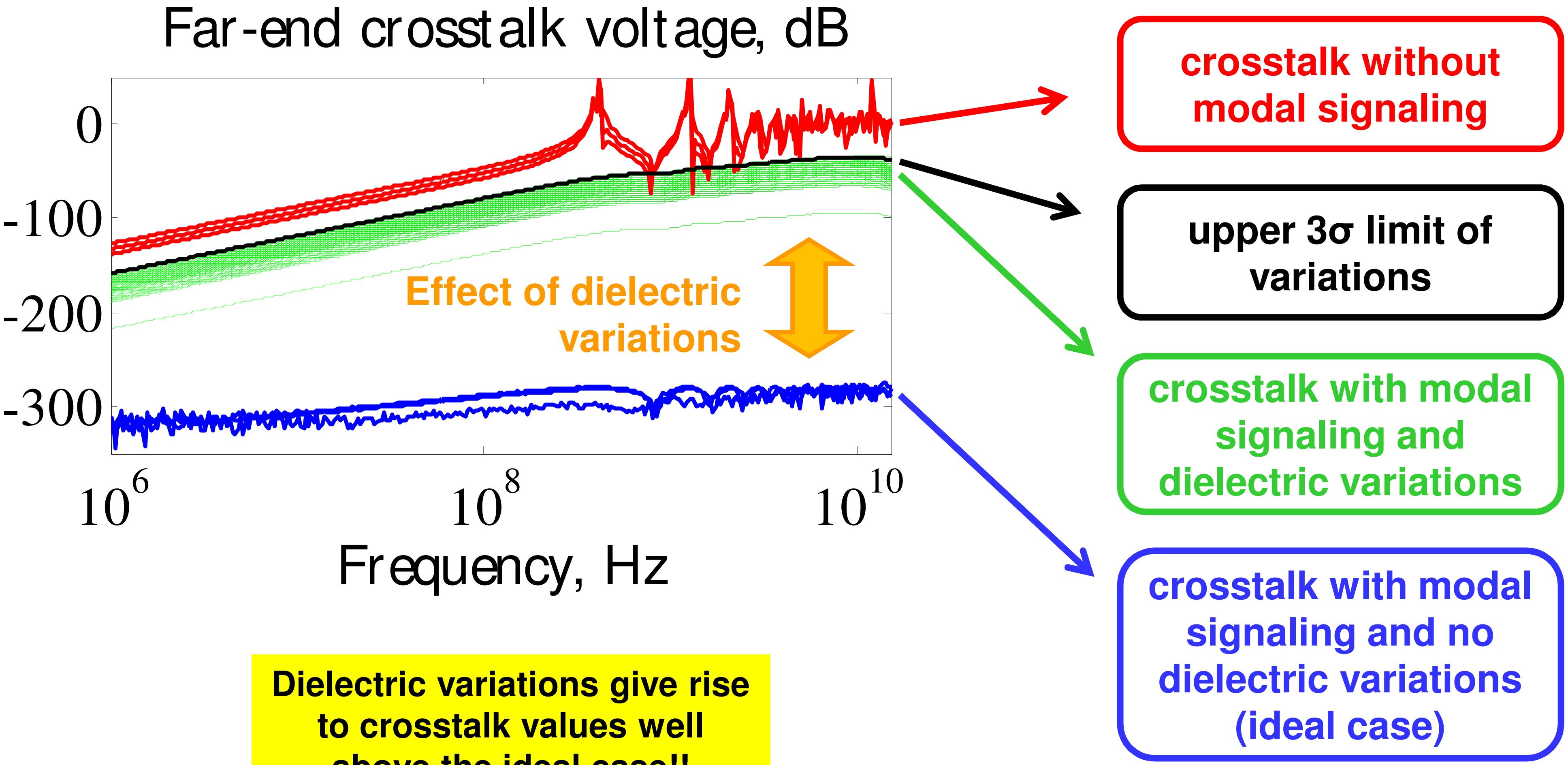
- As a practical example, the performance of modal signaling is investigated for a PCB structure with four traces



- **Independent variations** (± 10% @ 3σ) are ascribed to the **dielectric constants** of substrate and solder mask

- For the sake of simplicity, the interconnect is assumed to be **lossless**. A lossy line would imply **frequency-dependent** transformation matrices and, consequently, frequency-dependent encoders/decoders

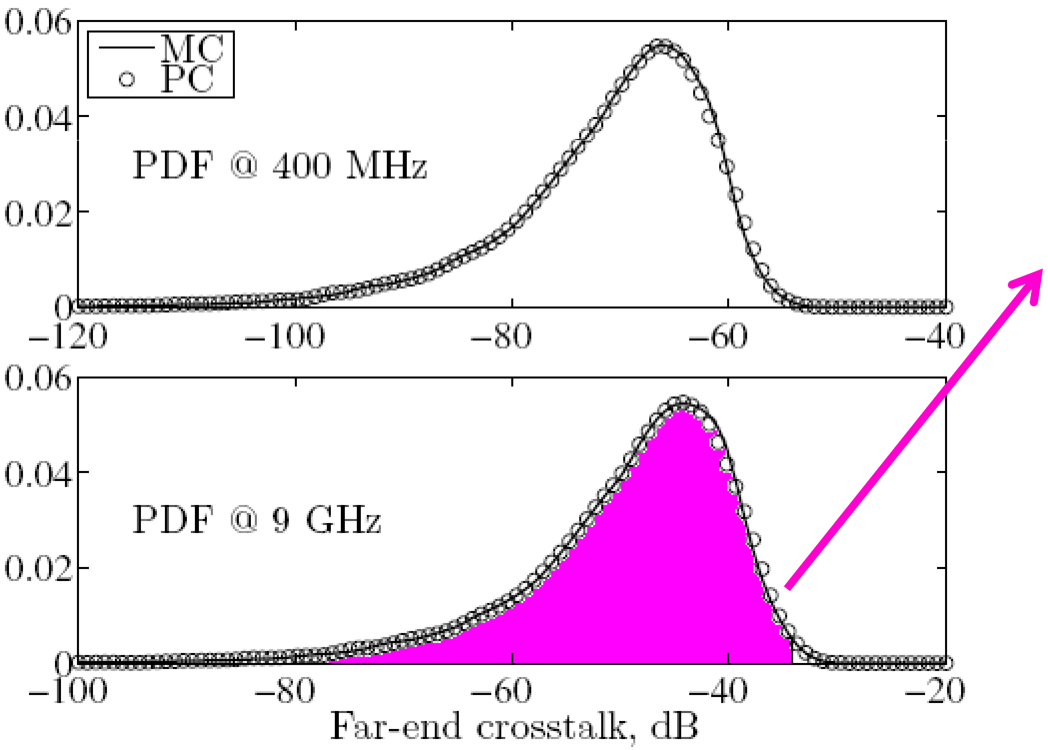
Effects of dielectric variations



Dielectric variations give rise to crosstalk values well above the ideal case!!

Crosstalk distribution

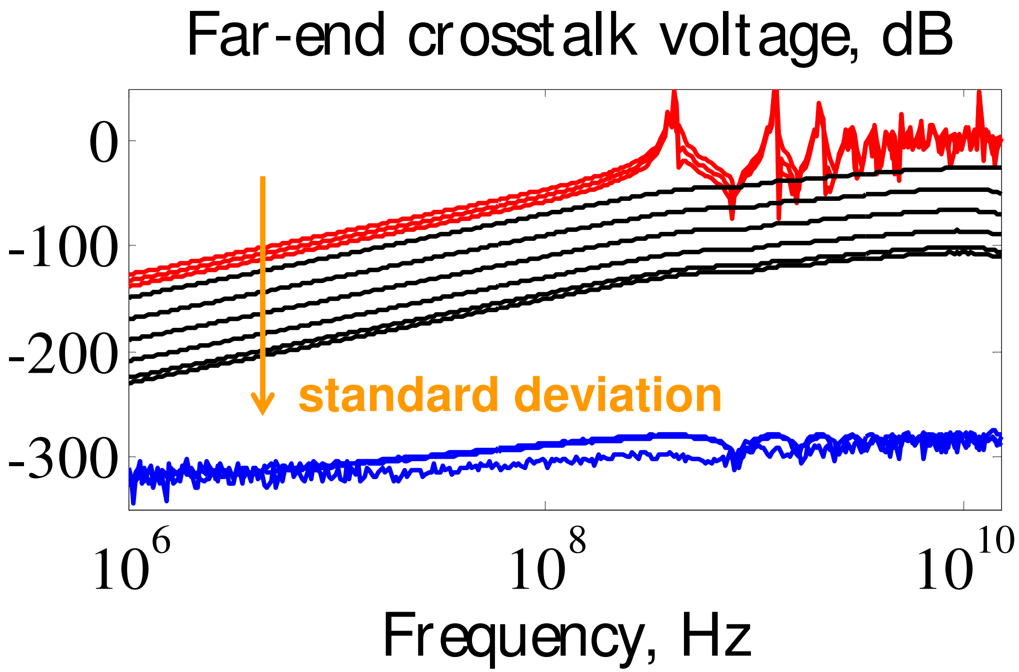
- **Probability density function** (PDF) allows to assess crosstalk distribution and to compute its confidence bounds at a given frequency
- PDFs can be obtained from polynomial chaos solution as well



- We can for instance conclude that 99% of crosstalk at 9 GHz will be below -35 dB
- Comparison with **Monte Carlo** simulation validate the prediction provided by polynomial chaos

Effect of standard deviation magnitude

- A standard deviation as large as 10% in the permittivity can cause big shifts in crosstalk levels
- To assess **sensitivity** to small deviations, the standard deviation of permittivity variations has been swept from 0.0001% (1 ppm) to 10%
- 3σ level of crosstalk increases with standard deviation of permittivity
- A 1 ppm tolerance on dielectrics still produces a remarkable crosstalk with respect to the ideal case



Discussion about polynomial chaos efficiency

- **Monte Carlo** approach needs a **large number of samples** to achieve convergence (typically between 10k and 50k)
- **Polynomial chaos** requires a **single solution** of a larger system
- Computational times for the proposed application:

Method	Simulation	Speed-up
MC (20 000 samples)	2 h 16 min	-
PC (45-time larger system)	57 s	~ 140x

Conclusions

- Overview of **modal signaling** transmission scheme for **crosstalk mitigation** in high speed links
- Analysis of modal signal **feasibility** in presence of **random variations** in the interconnect parameters
- **Efficient stochastic analysis** achieved by means of polynomial chaos methodology
- Numerical results shows a **significant impact of dielectric variations**

Thank you for your attention!!

Q&A

Appendix (1)

- The Hermite polynomials form a complete basis for $\mathbb{R}$

$$< \phi_k , \phi_j >= k! \delta_{kj}$$

- Definition of the scalar product

$$< \phi_k , \phi_j >= \int_{-\infty}^{+\infty} \phi_k(\xi) \phi_j(\xi) \exp\left(-\xi^2/2\right) / \sqrt{2\pi}\, d\xi$$

same as gaussian PDF!

- Function expansion

$$f(\xi) \cong \sum_{k=0}^{P} \alpha_k \phi_k(\xi); \quad \alpha_k = \frac{< f , \phi_k >}{< \phi_k , \phi_k >}$$

Appendix (2)

- 2-dimensional Hermite polynomials (basis for $\mathbb{R}^2$)

$$\phi_k(\xi_1,\xi_2) = \phi_m(\xi_1)\phi_n(\xi_2)$$

$$\phi_{0,1,2,3,4,5,\ldots}(\xi_1,\xi_2) = 1,\quad \xi_1,\quad \xi_2,\quad \xi_1^{\,2}-1,\quad \xi_1\xi_2,\quad \xi_2^{\,2}-1,\quad \ldots$$

- Scalar product

$$<\phi_k,\phi_j> = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\phi_k(\xi_1,\xi_2)\phi_j(\xi_1,\xi_2)\exp\left(-\xi_1^2/2-\xi_2^2/2\right)/2\pi\, d\xi_1 d\xi_2$$

Appendix (3)

- **PC accuracy assessment**