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Accelerating 56G PAM4 Link Equalization Optimization Using Machine Learning-based Analysis

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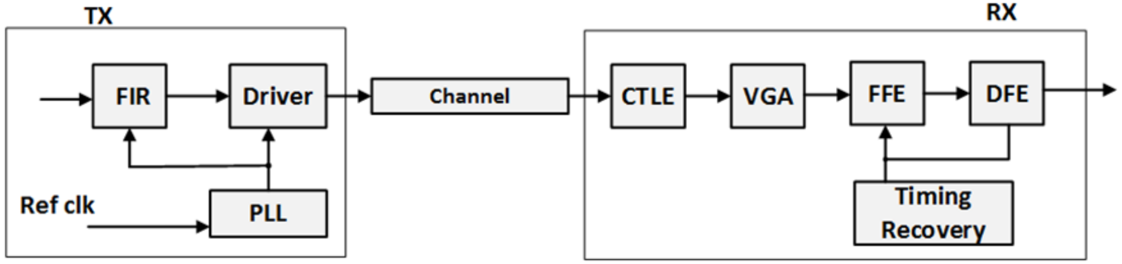
Agenda

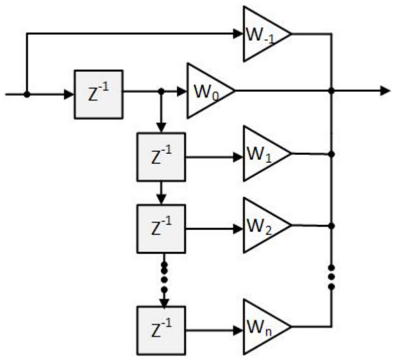
- Introduction
- Proposed methodology: Equalization optimization based on PCA analysis
- Application to High-speed Links
  -8G PCIe SerDes
  -56G PAM4 SerDes
- Conclusion

Introduction

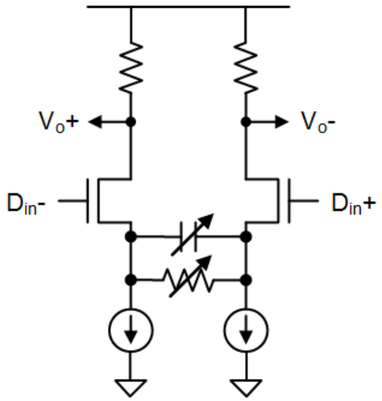
- Various equalization schemes are adopted in today’s high-speed serial links
- Adaptive equalizers are designed to compensate varying channels and environmental conditions.
- Auto-adaptation is critical to relieve the burden of manually searching for optimal settings.
- Large number of adaptive parameters poses better potential to recover the link performance, however, the high tuning dimensionality causes more challenges.



FIR



CTLE



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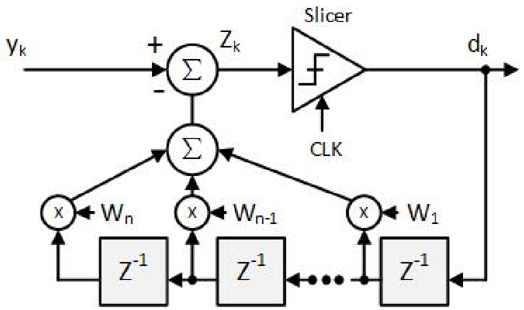

Equalizer Adaptation Challenges

- High tuning dimensionality
- Tuning time is bounded by the protocols (i.e. 3s for IEEE 802.3cd), may not have enough time to fully use the adaptation capability before run out of time.
- Algorithm highly relies on the equalization architecture and interface protocol requirements.
- A lot of equalizers rely on LMS (least-mean-squares) algorithm, which is slow in convergence.
- Algorithm has some assumption on channel conditions for generating the adaptation sequences, may not be efficient for various channel conditions.
- Individual adaptation target for each block, relation among parameters is not revealed.

Timing is limited

Algorithm is non-trivial

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Equalization optimization based on PCA analysis

- **Objective**

Reduce tuning dimensions of equalizers through Principal Component Analysis (PCA), and perform optimization in the reduced principal component space to accelerate adaptation.

- **Principal component analysis (PCA)**

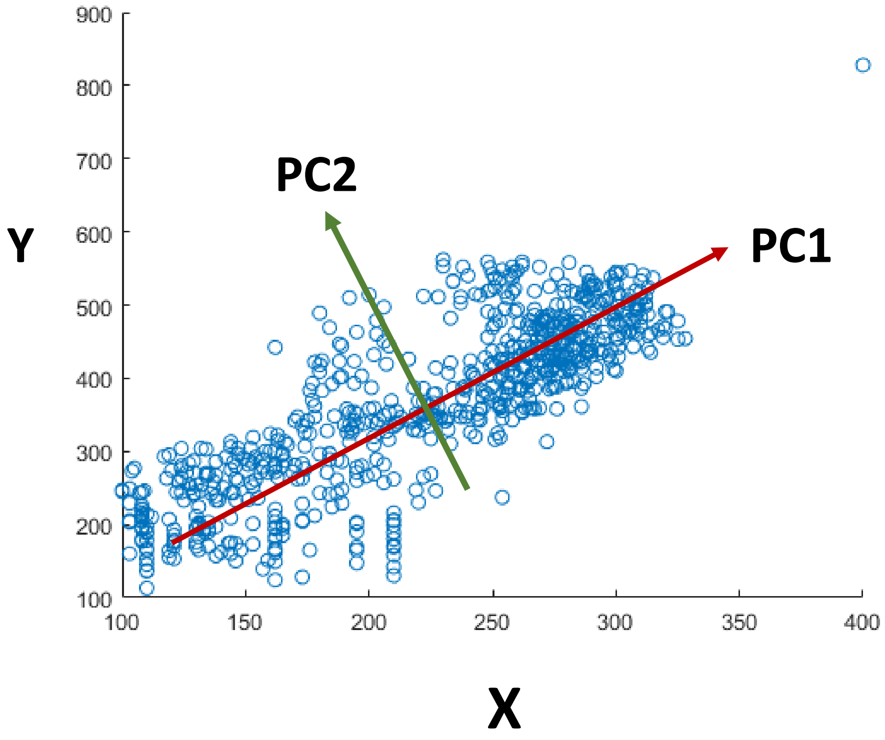
- Perform feature selection of finding the critical tuning parameters.
- Generate tuning vector for adaptation instead of one parameter at a time.
- Allow the existing SerDes algorithm take advantage of tuning vectors
- Minimize the algorithm changes in the existing SerDes architecture

PCA for Dimensionality Reduction

- PCA uses the eigenvector of the covariance matrix to reduce the variable dimensions.
- Keeping only k eigenvectors, corresponding to the k largest eigenvalues.
- Each principle component is a linear combination of the original vectors

$$\mathrm{PC1} = a_1X + a_2Y + a_3Z, \ldots \qquad \mathrm{PC2} = b_1X + b_2Y + b_3Z, \ldots$$

- The coefficient a_1,a_2, a_3 … and b_1, b_2, b_3,… are calculated so that the covariance matrix is diagonal



Optimization based on PCA analysis

- Principle components (PCs) are used as tuning vectors.
- Select the most critical PCs to generate reduced principal component space.
- Optimization objectives are not specific.
- Perform optimization in the reduced principal component space by using PCs as the tuning vectors, in order to find the optimal solution until it converges.
- The PCA based optimization is a general methodology, not limited by specific optimization solvers.

Optimization based on PCA analysis

Original Design Space → *PCA Analysis* → **Principal Component Space** → *Select the first k Principal components* → **Reduced Principal Component Space**

Find: $y^* = \arg\min_{y} f(y)$

Subject to: $y_L \le y \le y_U$

y standardized equalizer adaptive parameters

$y \in \mathbb{R}^n$

Find: $z^* = \arg\min_{z} f(Az)$

Subject to: $y_L \le Az \le y_U$

A is the eigenvector matrix

$$z = A^{\mathrm{T}} y$$

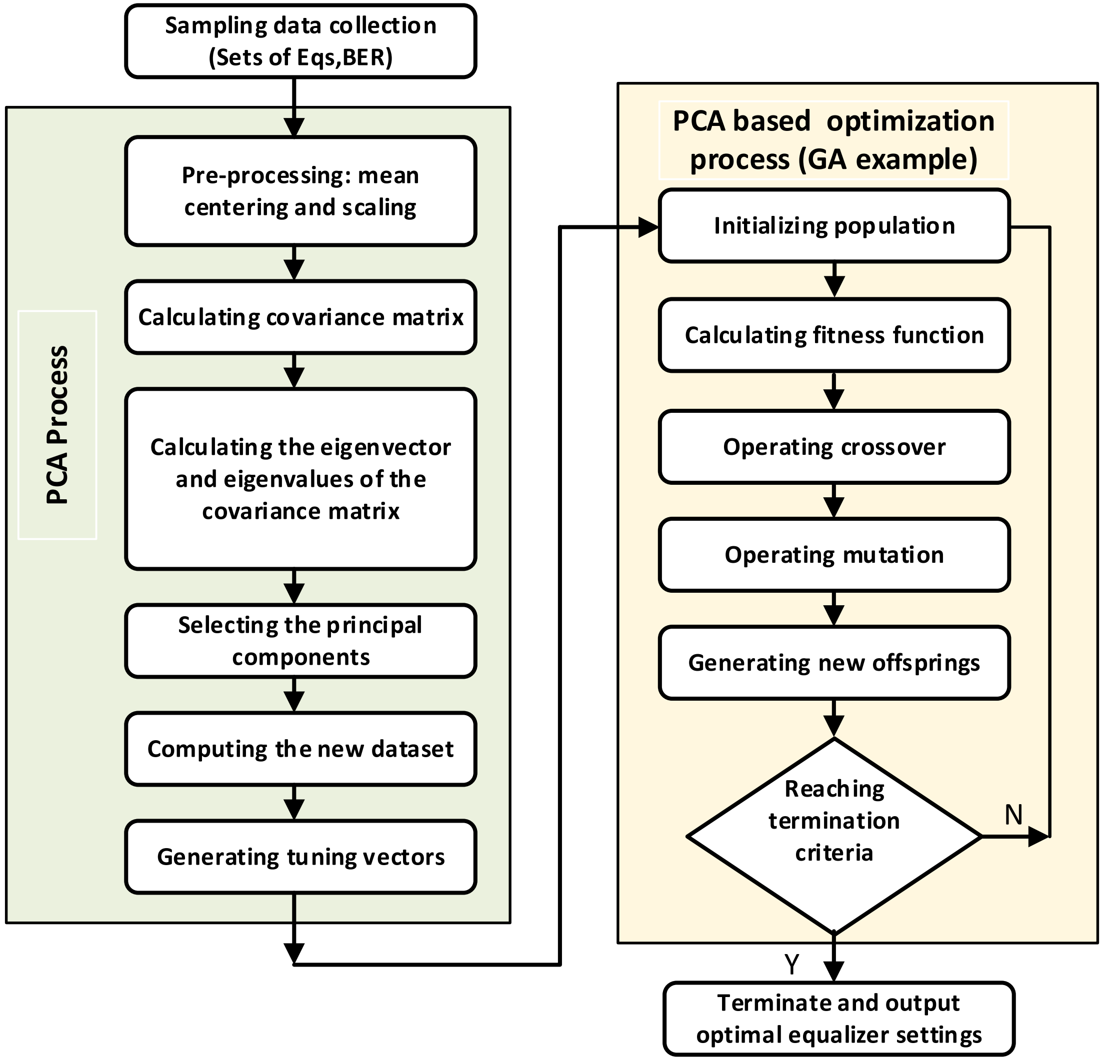
$A \in \mathbb{R}^{n \times n}$

Find: $z_k^* = \arg\min_{z_k} f(A_k z_k)$

Subject to: $y_L \le Az \le y_U$

$A_k \in \mathbb{R}^{n \times k}$

Proposed Flow for Equalization Optimization



- The PCA based optimization is a general methodology which can work with various solvers.
- Genetic Algorithm (GA) is selected in case studies to solve the integer programming problem.

Benefits of the New Method

- Perform feature selection of finding the critical tuning parameters.
- Allow the existing SerDes algorithm take advantage of tuning vectors instead of one parameter at a time, minimize the algorithm changes to the existing SerDes architecture.
- Not limit to specific tuning objective.
- Not limit to specific optimization solver.
- Include the impacts from all the components in the links, i.e. PHYs, PCB channels, connectors etc., to generate tuning vectors per the channel conditions.
- Select the parameters for dimension reduction by detecting the underlying data relations, without a need of knowing details in the equalizer design.
- A general solution for equalization optimization.

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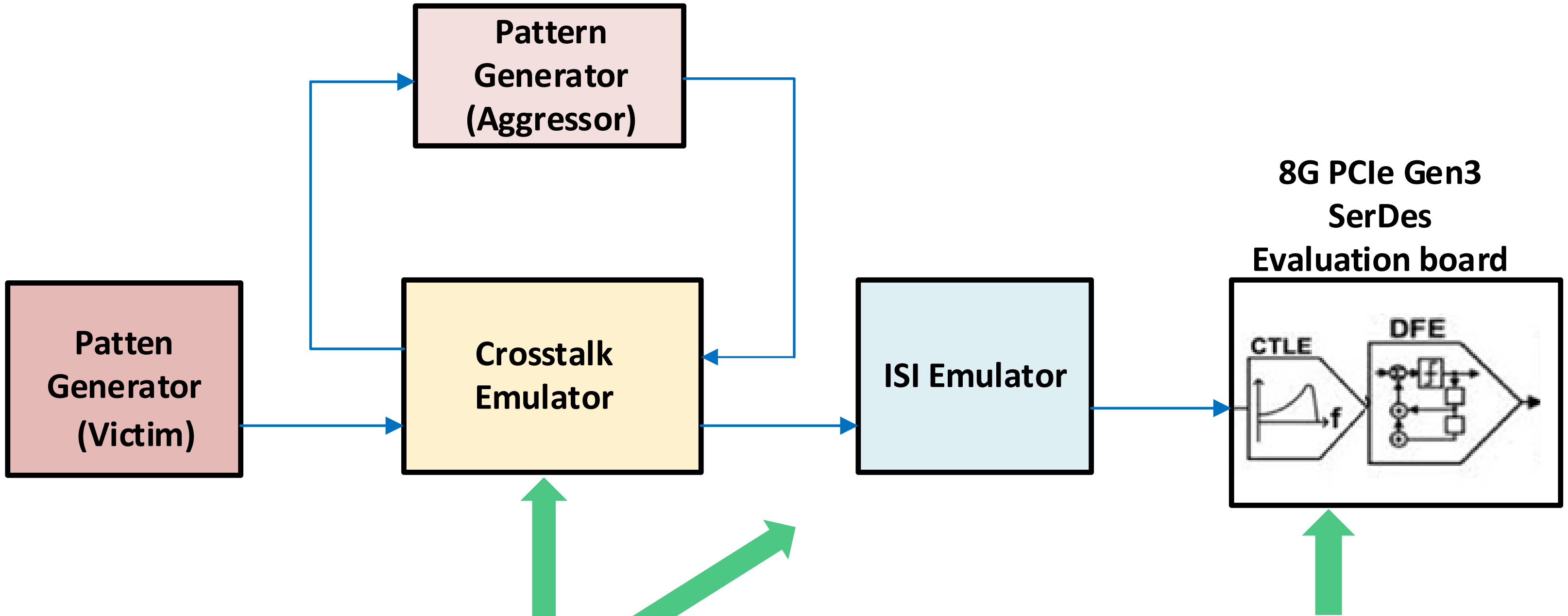
x_{5-40}

Case I. 8G SerDes -Test Setup



- Swept ISI and crosstalk conditions.
- Channel insertion loss varies from 6-24dB@4GHz
- Crosstalk coupling varies from 0-100%.

10 dimensional tunable equalizer parameters.

x	Description
x_{1-4}	Rx CTLE control parameter 1-4
x_{5-10}	Rx DFE control parameter 5-10

Case I. 8G SerDes Case-PCA Analysis

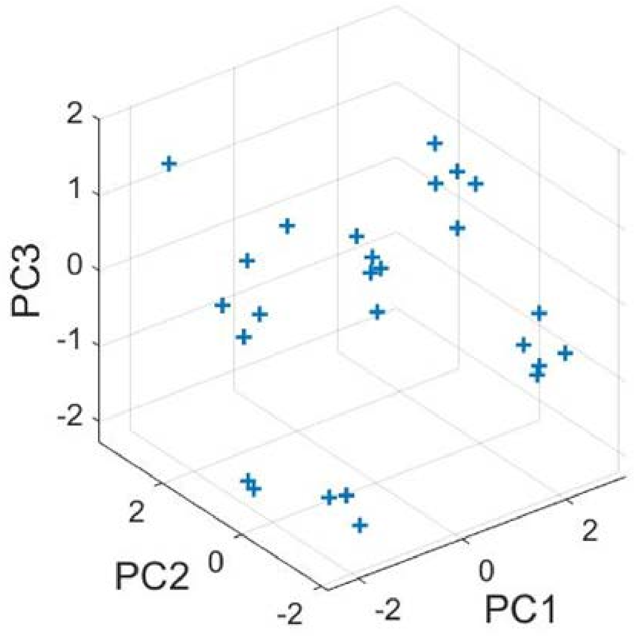
- Sample: 25 sets of converged equalizer values were collected.
- The proposed PCA process was performed and the principal components were generated.

The first 6 principal components and the corresponding coefficients

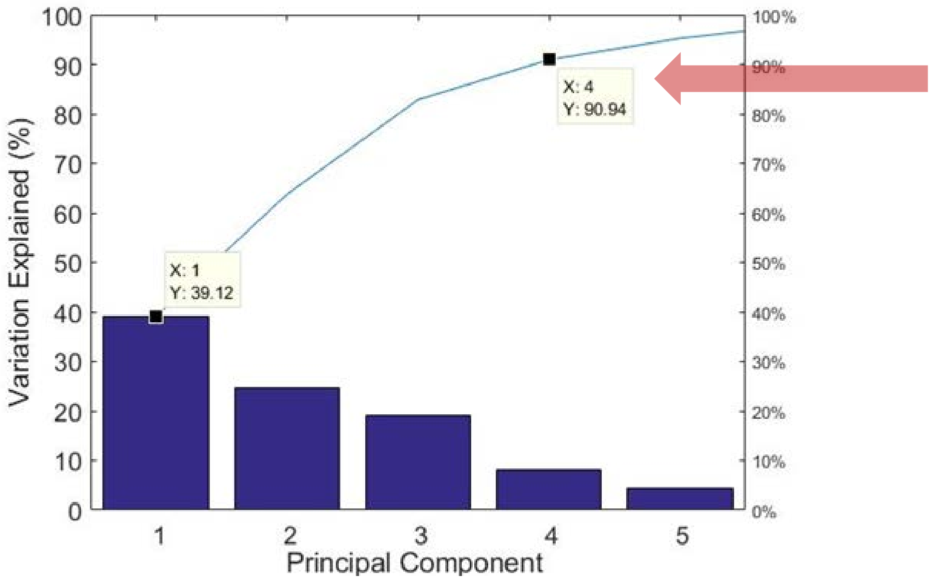
x	PC1	PC2	PC3	PC4	PC5	PC6
x_1	-0.009	-0.4355	-0.1781	0.8236	0.2739	0.024
x_2	-0.3333	-0.3511	0.4291	-0.1282	0.1171	-0.0283
x_3	0.2219	0.4308	-0.4738	0.1557	-0.1003	0.1433
x_4	0	0	0	0	0	0
x_5	0.3283	-0.4193	0.0765	-0.0634	-0.5087	0.6661
x_6	-0.4902	-0.0448	-0.1686	0.1401	-0.1927	0.1646
x_7	-0.2501	0.4936	0.2417	0.2594	0.0754	0.4978
x_8	0.0711	0.2613	0.5907	0.4157	-0.4517	-0.2576
x_9	0.4082	0.0884	0.3417	-0.0256	0.6161	0.3047
x_{10}	0.5072	-0.0633	0.035	0.1288	-0.1267	-0.3166

Case I. 8G SerDes Case-PCA Analysis (cont')

Data plot in PC1, PC2, PC3 space.

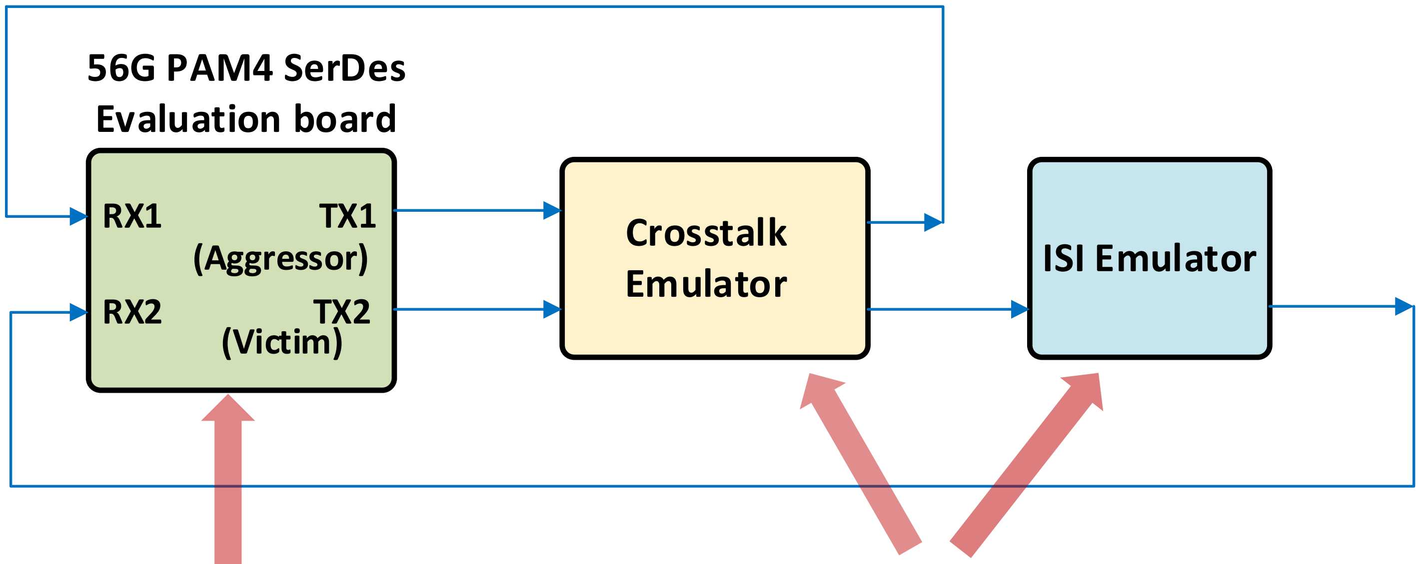


Percentage of variation coverage by the first 5 PCs and accumulated percentage



90.94% by the first 4 PCs

Case II. 56G PAM4 SerDes Case - Test Setup



- 25 dimension of RX tuning parameters

x	Description
x_{1-6}	Rx CTLE control parameter 1-6
x_{7-11}	Rx FFE control parameter 1-5
x_{12-25}	Rx DFE control parameter 1-14

- Swept ISI and crosstalk conditions.
  - Channel insertion loss varies from 6-21dB@14GHz
  - Crosstalk coupling varies from 0-100%.

Case II. 56G PAM4 SerDes Case-PCA Analysis

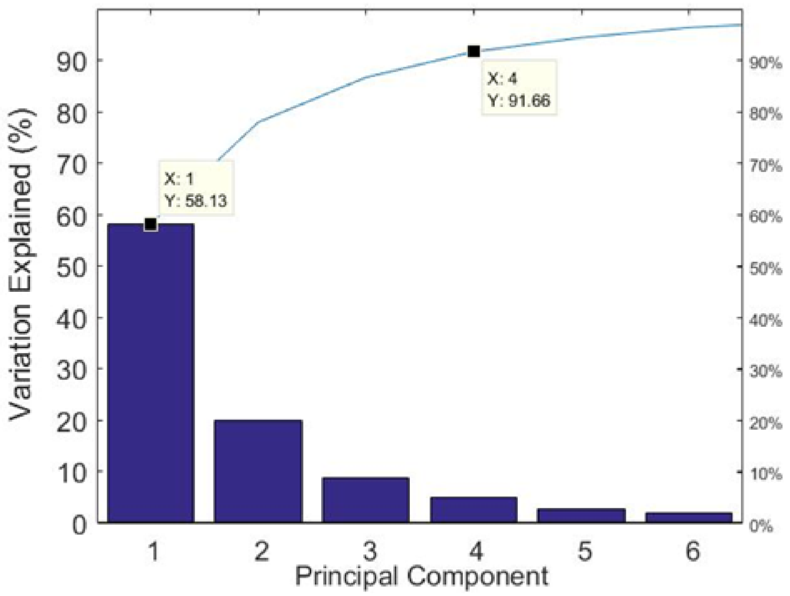
- Samples: 36 sets of converged equalizer values were collected.
- The proposed PCA process was performed and principal components were generated.

The first 6 PCs and the corresponding coefficients

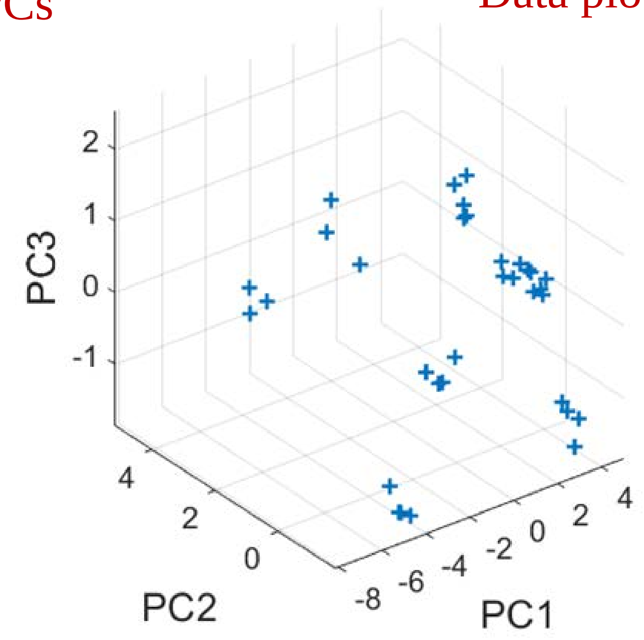
	PC1	PC2	PC3	PC4	PC5	PC6
x_1	-0.2965	0.0556	-0.0322	0.1519	-0.2629	-0.0784
x_2	0.213	-0.013	-0.4169	0.3793	-0.4381	-0.1588
x_3	0	0	0	0	0	0
x_4	-0.2965	0.0556	-0.0322	0.1519	-0.2629	-0.0784
x_5	0	0	0	0	0	0
x_6	0	0	0	0	0	0
x_7	0.2938	0.0821	0.06	-0.1871	0.0985	0.1912
x_8	-0.2912	-0.1014	0.0163	0.2177	0.0712	-0.1351
x_9	-0.2613	0.0175	-0.2692	0.2715	0.1975	0.2151
x_{10}	0	0	0	0	0	0
x_{11}	-0.2138	0.1045	-0.3614	0.3356	0.5288	0.1606
x_{12}	0	0	0	0	0	0
x_{13}	0	0	0	0	0	0
x_{14}	0.2388	0.1949	-0.3463	-0.147	0.1361	-0.1563
x_{15}	0.299	-0.0184	-0.0743	0.0226	0.143	0.0716
x_{16}	0.2763	-0.0214	-0.3181	0.0885	0.1723	0.0222
x_{17}	0.2231	-0.3152	-0.1673	0.206	-0.1374	-0.1431
x_{18}	0.2581	-0.2236	-0.0876	0.1141	-0.2106	-0.0228
x_{19}	0.1165	0.47	-0.0671	0.0348	-0.2296	0.1604
x_{20}	0.2167	-0.244	0.1709	0.2337	-0.0117	0.6598
x_{21}	0.1022	0.4787	-0.0224	0.0206	-0.0791	0.0589
x_{22}	0.1081	0.4675	0.0846	0.108	0.085	-0.1498
x_{23}	0.2377	-0.1006	0.2745	0.2505	0.3704	-0.5423
x_{24}	0.1241	0.1974	0.488	0.5703	-0.0313	0.0587
x_{25}	0	0	0	0	0	0

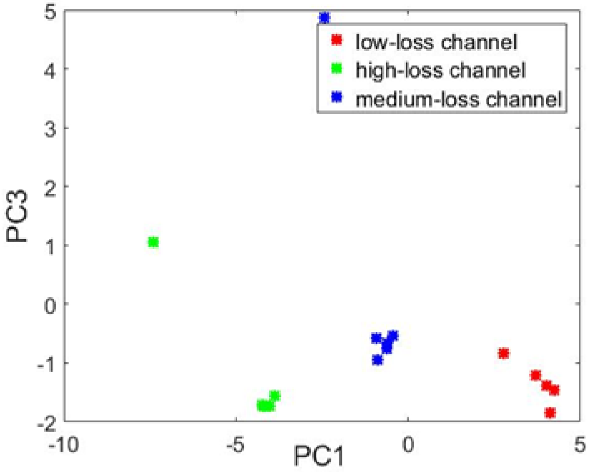
Case II. 56G PAM4 SerDes Case-PCA Analysis(cont.)

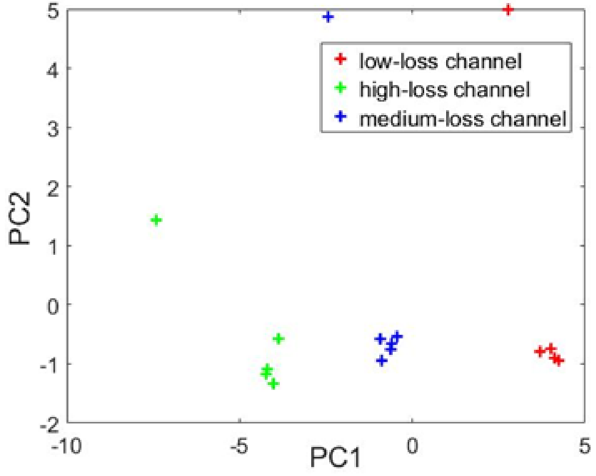
Percentage of variation coverage by the first 6 PCs



Data plot in 3D/2D PC space







-The first principal component covers 58.13% variations
-The first 4 principal components cover 91.66% variations
-Sample data were projected in the PC space,
in which the scatters of the points are related to the channel loss.

Case II. 56G PAM4 SerDes Case - Optimization

- **Optimization problem definition**

Equalization optimization was performed based on the PCA results, in order to find the optimal raw BER performance.

- **Parameters**

Selected partial adaptive parameters and bound their ranges as the Table shows. Other adaptive parameters were fixed at the baseline.

x	Description	x_L	x_U
x_1	Rx CTLE control parameter 1	0	6
x_2	Rx CTLE control parameter 2	4	8
x_3	Rx CTLE control parameter 3	0	6
x_4	Rx FFE control parameter 1	-2	-6
x_5	Rx FFE control parameter 2	6	10
x_6	Rx FFE control parameter 3	0	4
x_7	Rx FFE control parameter 4	0	4
x_8	Rx DFE control parameter 1	10	12
x_9	Rx DFE control parameter 2	4	6

- **Dimension reduction**

The first 4 PCs were used to generate the tuning vectors for performing optimization in the reduced dimensional space.

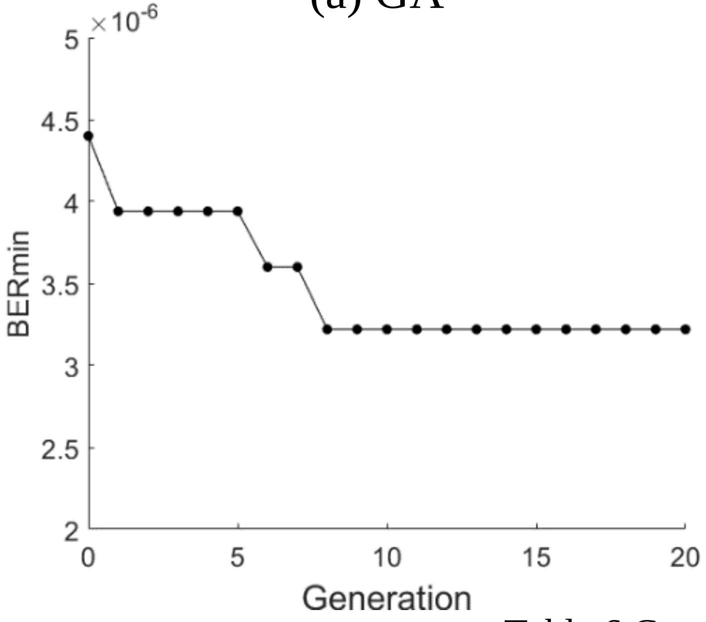
- **GA solver**

- Population of 100 elements (100 samples in the reduced principal component space).
- Crossover fraction is 0.8 (specified 80% of the next generation was produced by crossover operation).
- Mutation adds a random number from a Gaussian distribution to each parent vector.

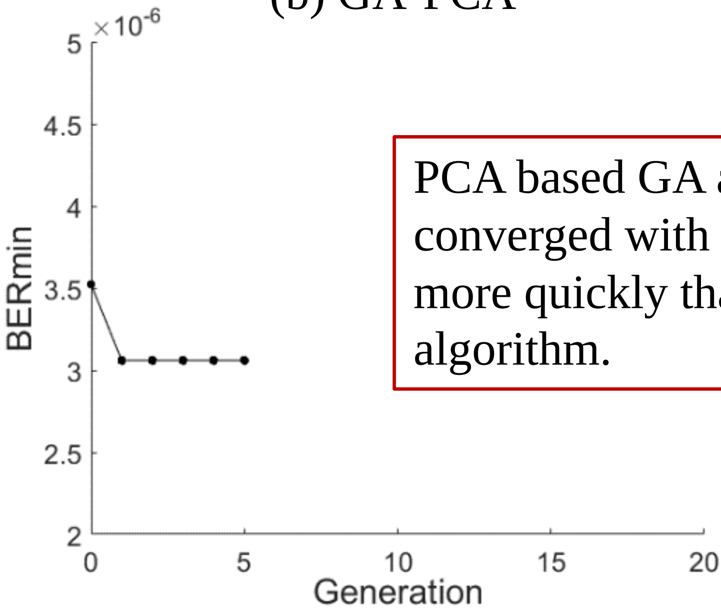
Case II. 56G PAM4 SerDes Case – Optimization (Cont')

Best fitness function versus generation.

(a) GA



(b) GA-PCA



PCA based GA algorithm converged with fewer generations, more quickly than the general GA algorithm.

Table 6 Converged equalizer values

	Optimal x	min BER
GA-PCA	$x_1 = 6, x_2 = 2, x_3 = 2, x_4 = -4, x_5 = 8, x_6 = 1, x_7 = 2, x_8 = 10, x_9 = 5$	3.06e-06
GA	$x_1 = 6, x_2 = 2, x_3 = 2, x_4 = -4, x_5 = 8, x_6 = 2, x_7 = 0, x_8 = 10, x_9 = 5$	3.22e-06

Conclusion

- This paper proposed a new method to reduce the tuning dimensions for the adaptive equalization through principal component analysis (PCA).
- The method is able to do feature selection of finding the critical tuning parameters for the equalizers and to generate tuning vectors for accelerating the link optimization.
- The method allows the existing SerDes algorithm take advantage of tuning vectors instead of one parameter at a time, minimizes the algorithm changes to the existing SerDes architecture.
- The new method was applied to 8G PCIe Gen3 and 56G PAM4 link examples, both demonstrated the new method can effectively reduce the adaptive tuning dimensions.
- We also demonstrated optimizing BER performance of 56G PAM4 link by combing PCA with genetic algorithm (GA). The results show the PCA based GA converged quicker in fewer generations than the general GA method.
- It is the first time to apply machine learning based analysis to reduce the tuning dimensions of adaptive equalizers, without a need of knowing internal details of the equalization design.
- By using machine learning-based analysis, it is a general solution for link optimization.

Thank you!

Questions?