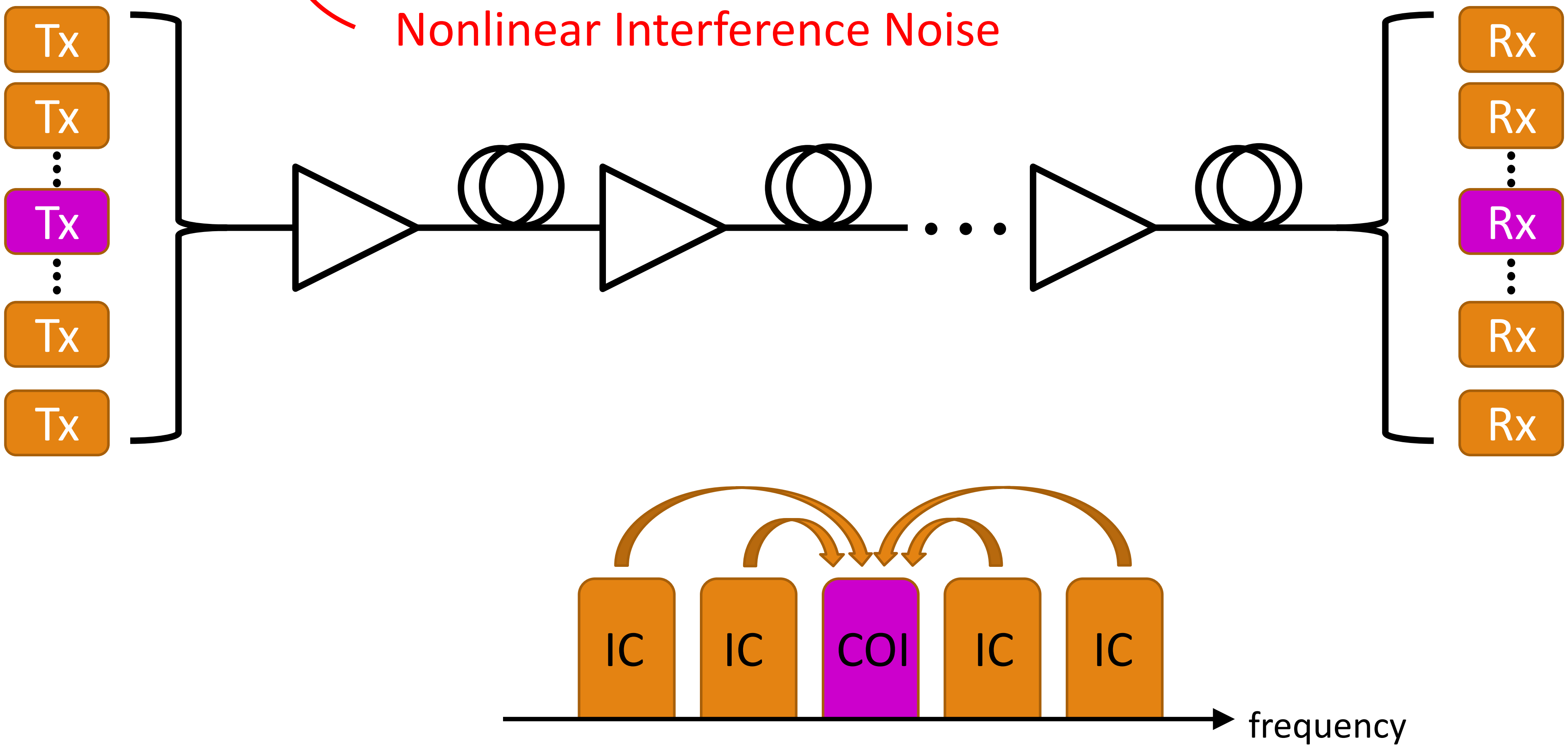
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Nonlinear interference noise in optical fibers- properties, measurement, and applications

Ori Golani

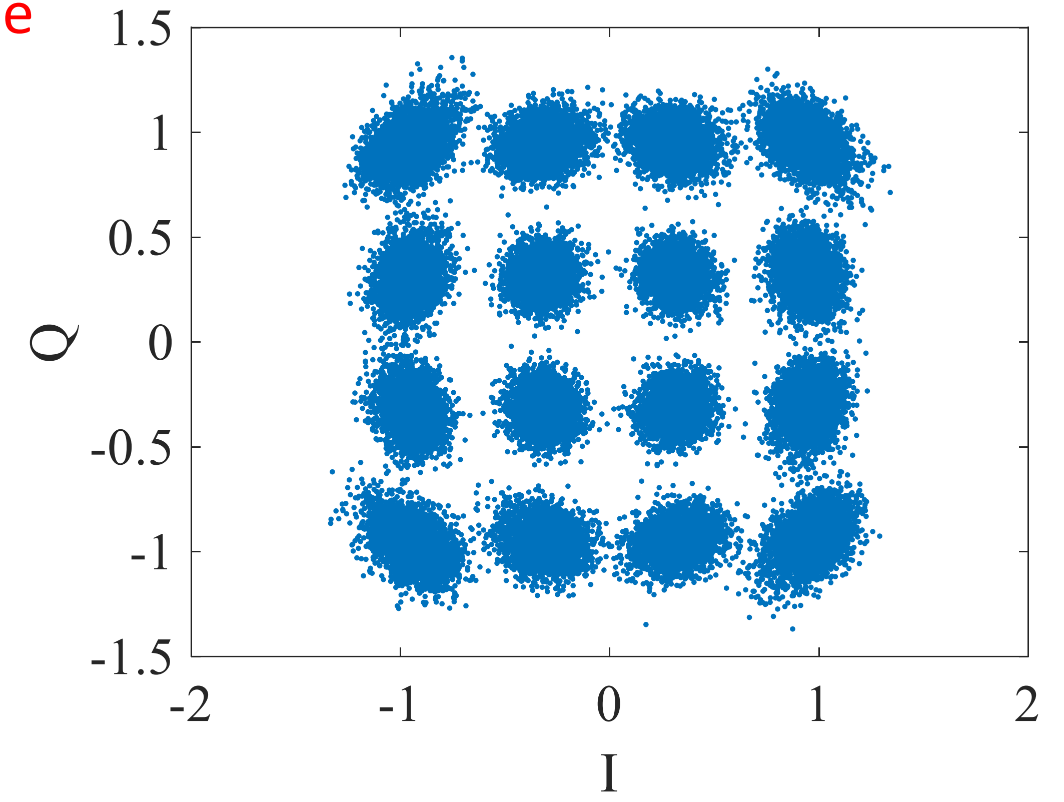
What is NLIN?

Nonlinear Interference Noise

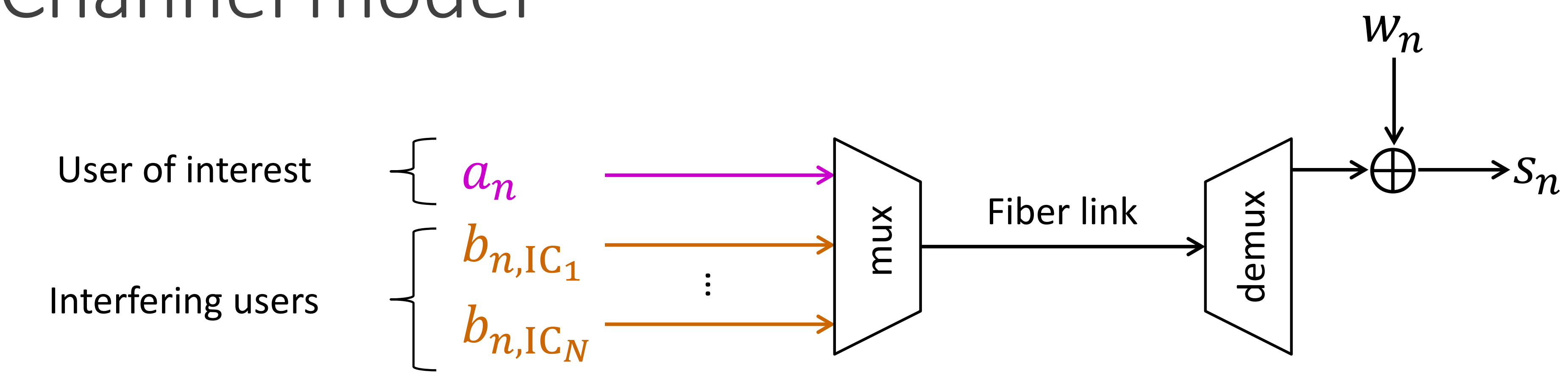


What is NLIN?

Nonlinear Interference Noise



Channel model



$$s_n = a_n + w_n + \underbrace{\sum_{IC} \sum_{h,k,l} i\gamma X_{h,k,l}\, b_h b_k^* a_l}_{\text{Nonlinear interference}}$$

Received signal

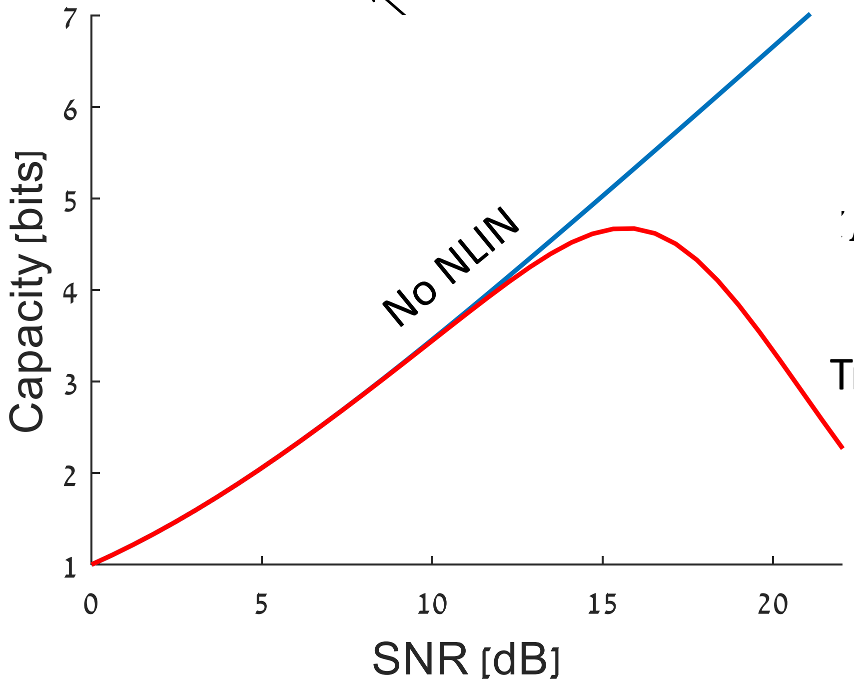
Transmitted symbol

AWGN

Treating NLIN- interference as noise

$$s_n = a_n + w_n + \sum_{IC} \sum_{h,k,l} i\gamma X_{h,k,l}\, b_h b_k^* a_l$$

$$= a_n + w_n + v_n$$



Gaussian,

P^3

Treatment as AWGN

Stochastic ISI model of NLIN

Total NLIN contribution:

$$\mathrm{NLIN} = \sum_{IC} \sum_{h,k,l} i\gamma X_{h,k,l}\, b_h b_k^* a_l$$

$$= \sum_{l} \underbrace{\left[\sum_{IC} \sum_{h,k} i\gamma X_{h,k,l}\, b_h b_k^* \right]}_{\text{Sum on unknown ICs}} a_{n-l} = \sum_{l} R_l^{(n)} a_{n-l}$$

What is this model good for?

$$\Delta a_n = \sum_{IC} \sum_{h,k,l} i\gamma X_{h,k,l}\, b_h b_k^* a_l$$

Nonlinear problem

$$\Delta a_n = \sum_{l} R_l^{(n)} a_{n-l}$$

Linear Time varying

- NLIN behaves like a doubly-selective linear channel- we can use tools from RF communication
- If the ISI coefficients, $R_l^{(n)}$, change slow enough, we can track them and mitigate their effect

Characterization of time-varying ISI model

Characterizing the statistics of the ISI coefficients $R_l^{(n)}$

- Temporal auto-correlation functions (how do they change over time)
- Cross-correlation between different elements

Analytical approach- solve a lot of integrals

Experimental approach- get the statistics from a transmission experiment

Characterization: analytical approach

The channel coefficients are unknown, but we can describe their statistics

$$R_l^{(n)} = \sum_{IC} \sum_{h,k} i\gamma X_{h,k,l}\, b_h b_k^*$$

Autocorrelation function:

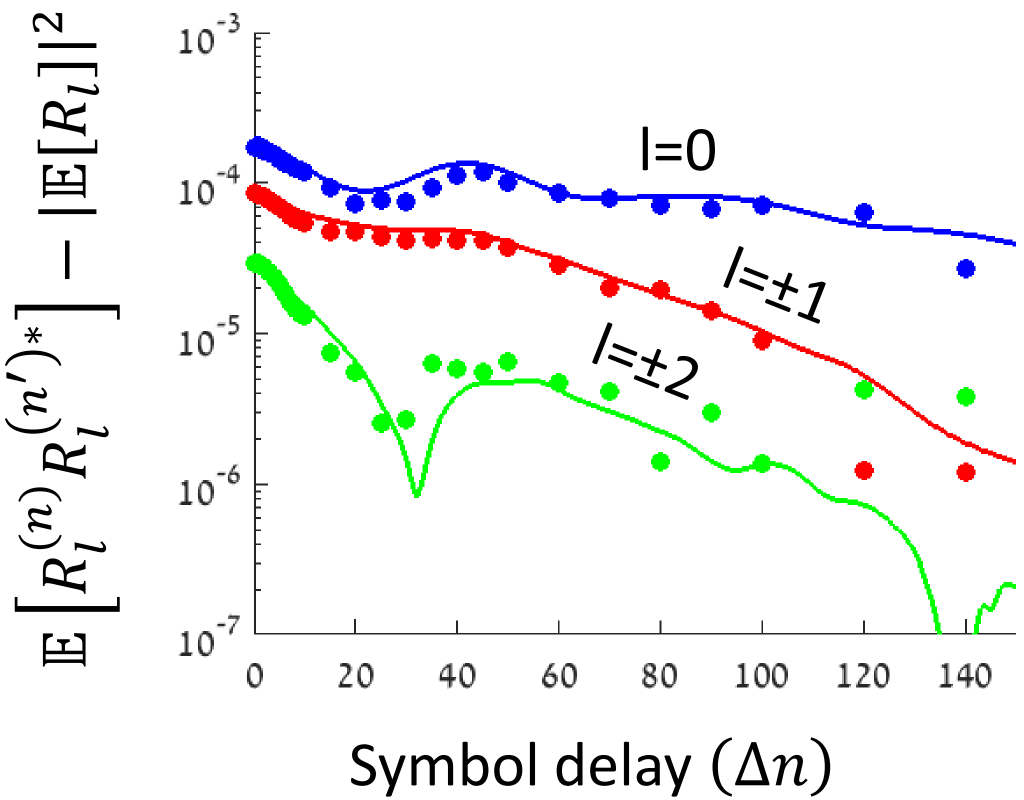
$$\mathrm{ACF}(\Delta n) = \mathbb{E}\left[R_l^{(n)} R_l^{(n+\Delta n)*}\right]$$

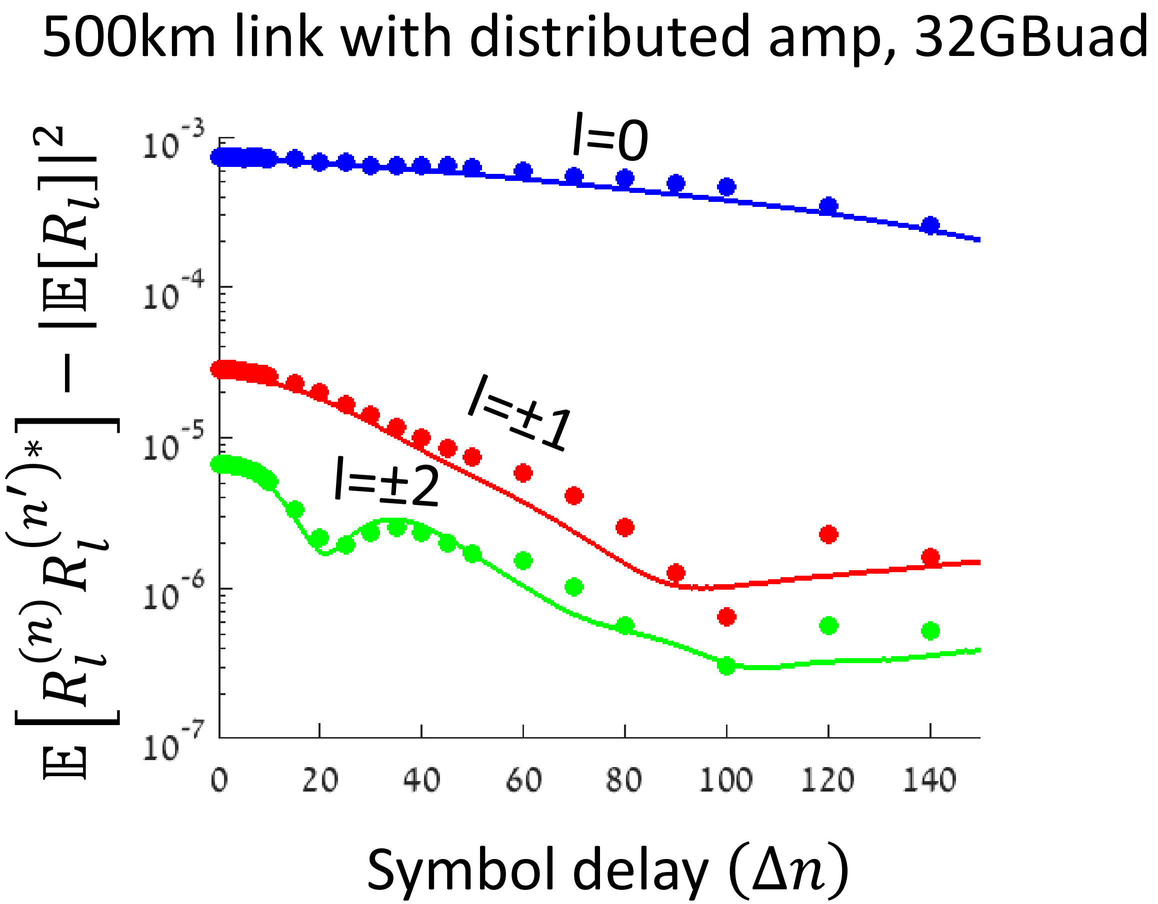
$$= \sum_{IC} \sum_{h,k} i\gamma X_{h,k,l} X^*_{h'+\Delta n,k'+\Delta n,l}\, \mathbb{E}[b_h b_k^* b_{h'} b^*_{k'}]$$

Surprisingly, we can find these functions analytically (with some numeric integration…)

- Dependent on: link structure, bandwidth & frequency of ICs, modulation format…

Characterization: analytical approach





Dots= SSFM results, lines= model predictions

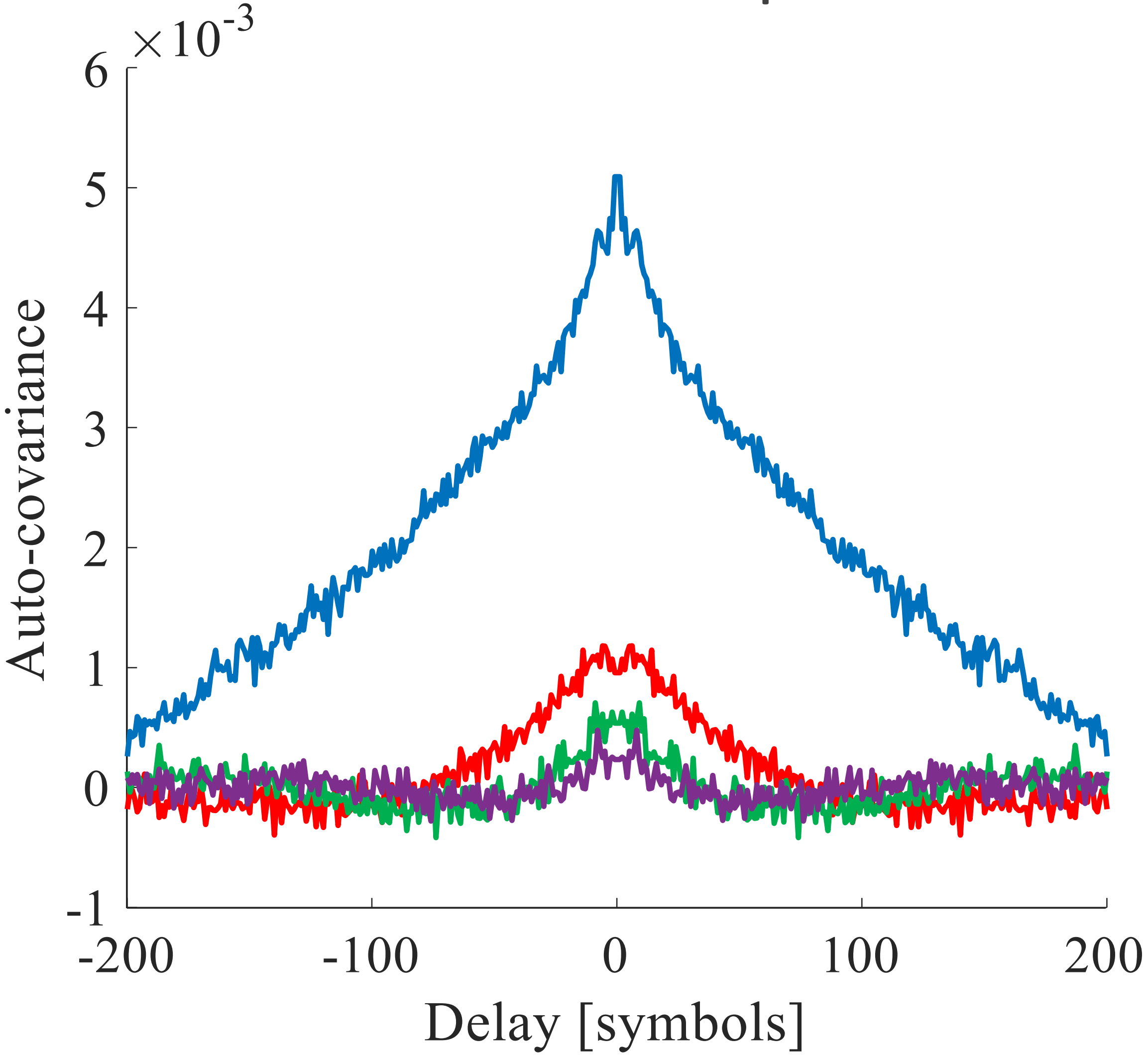
Golani et al, “Correlations and phase noise in NLIN- modelling and system implications,” OFC 2016

Characterization: experimental approach

$$s_n = a_n + iR_0^{(n)} a_n + iR_1^{(n)} a_{n-1} + iR_2^{(n)} a_{n-2} \ldots + w_n$$

Measuring ISI coefficient: $$\frac{s_n - a_n}{a_{n-L}} = iR_L^{(n)} + residual$$

Characterization: experimental approach



20x101km link, 7 WDM channels, 40GBuad

Zero order:

First order:

Second order:

Third order:

Unbounded (phase noise):

$$\frac{s_n - a_n}{a}$$

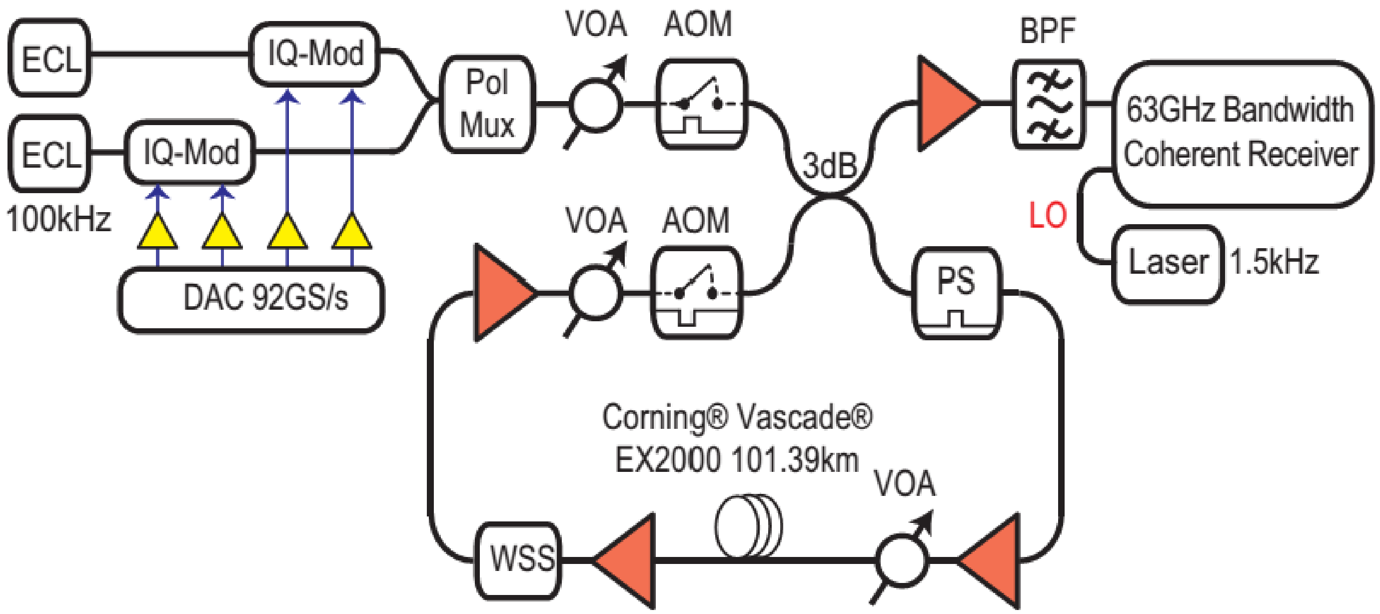
$$\frac{s_n - a_n}{a_{n-1}}$$

$$\frac{s_n - a_n}{a_{n-2}}$$

$$\frac{s_n - a_n}{a_{n-3}}$$

The summation is infinite, but the variance of coefficients drops rapidly

Experimental setup



Recirculating loop experiment:

- 64-QAM, dual polarization
- 40GBaud
- 101km spans
- 42.5GHz channel spacing

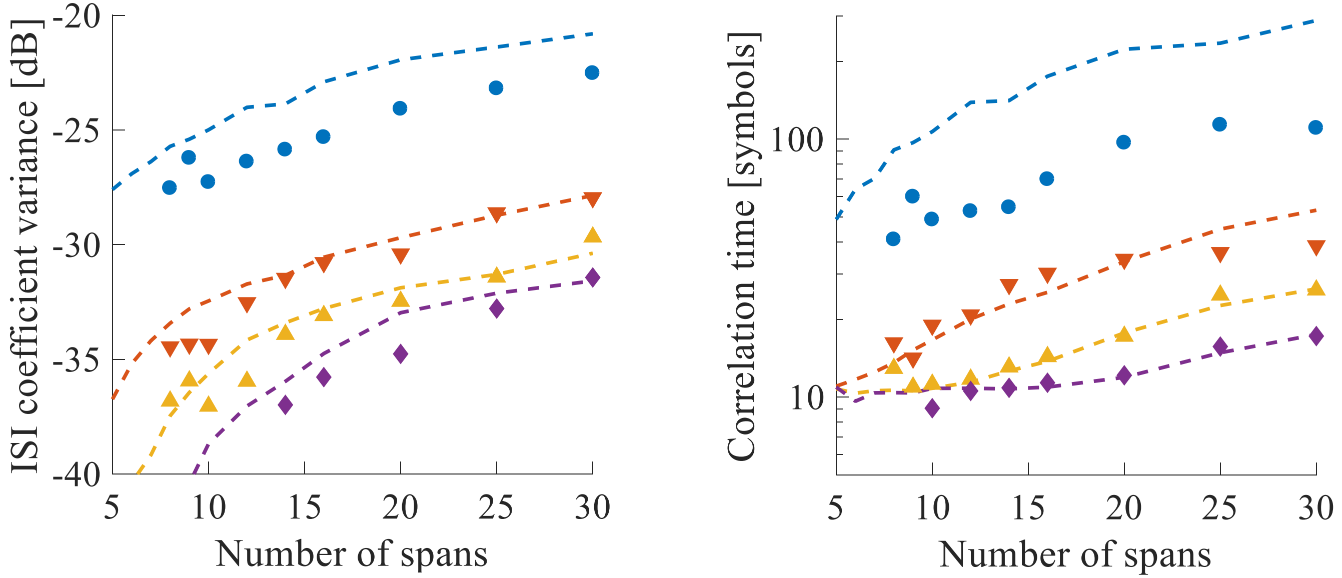
Joint work with UCL,

Golani et al, “Experimental characterization of the time correlation properties of nonlinear interference noise,” ECOC 2017

Results- measuring the ACFs

Effect of transmission distance:

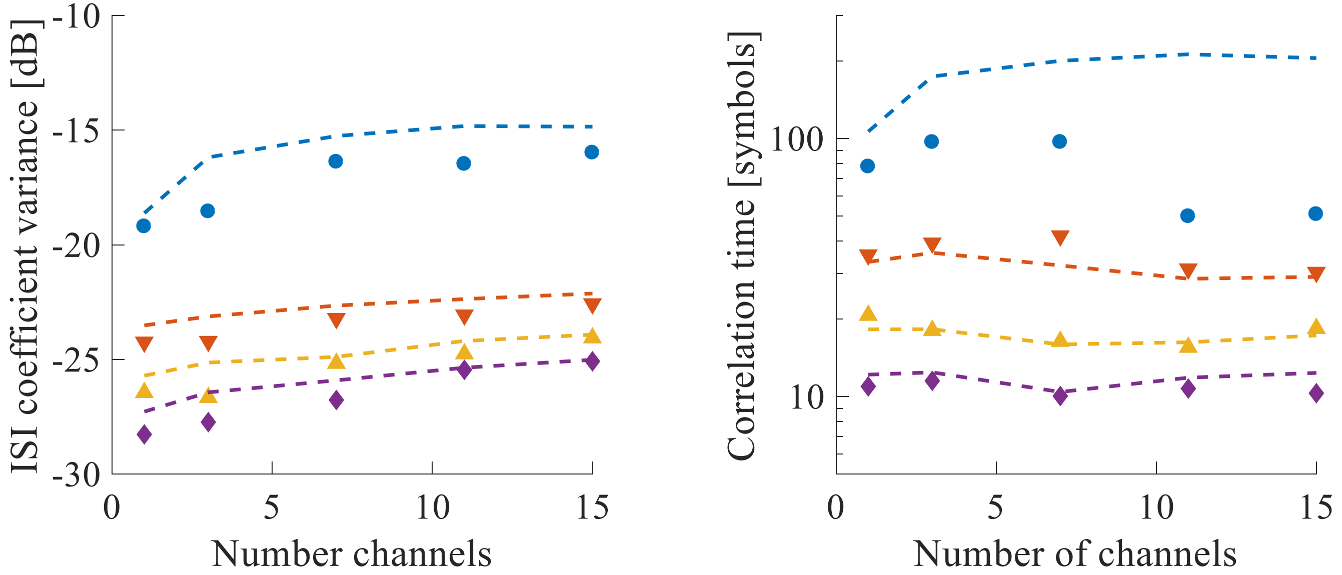
*7 WDM channels



0th order
1st order
2nd order
3rd order

Effect of number of ICs:

*2000km link



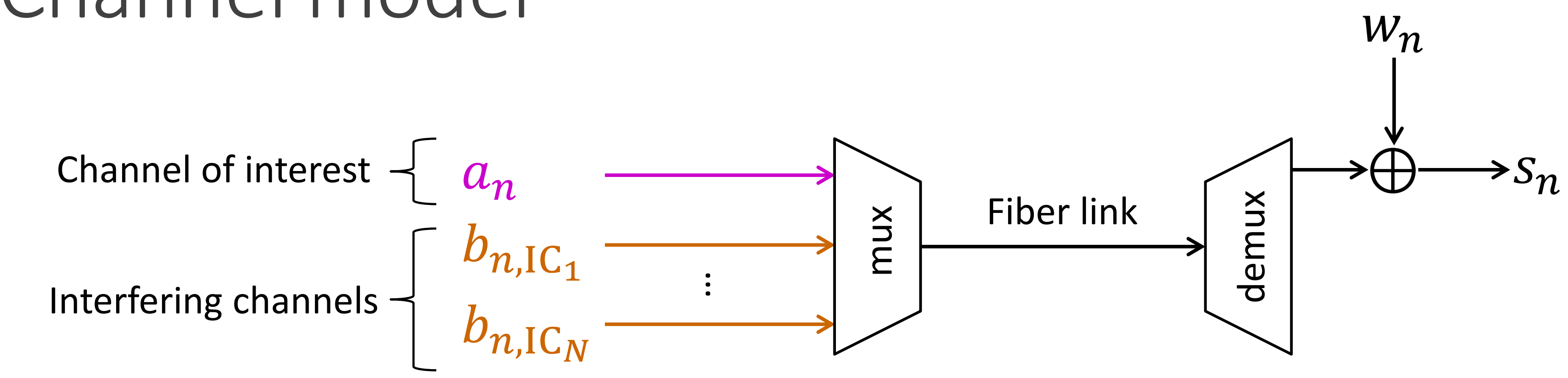
Can also find cross correlations and other moments from these measurements

Applications of time-varying ISI model

Simulation and performance estimation

- “Virtual lab” tool- a fast alternative to split-step simulations
- Predict system performance in the presence of nonlinearity, including interaction between NLIN and the receiver’s DSP

Channel model



$$s_n = a_n + w_n + \underbrace{\sum_{IC}\sum_{h,k,l} i\gamma X_{h,k,l}\, b_h b_k^* a_l}_{\text{Nonlinear interference}}$$

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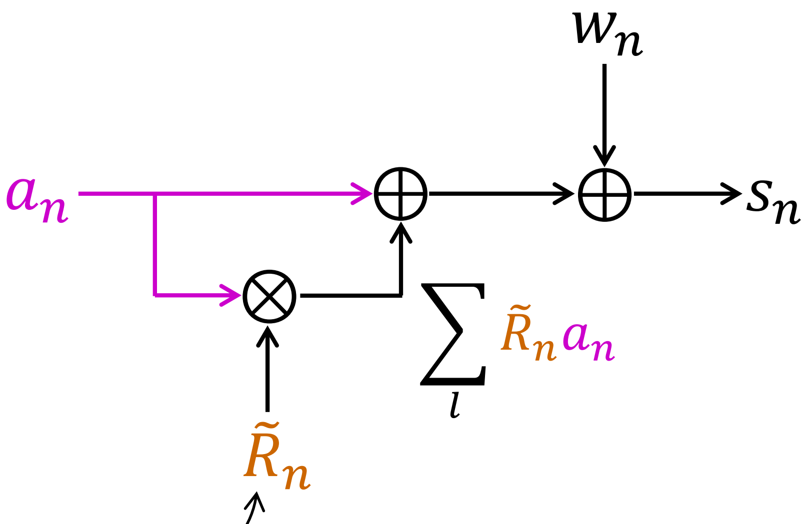
Simplified channel model



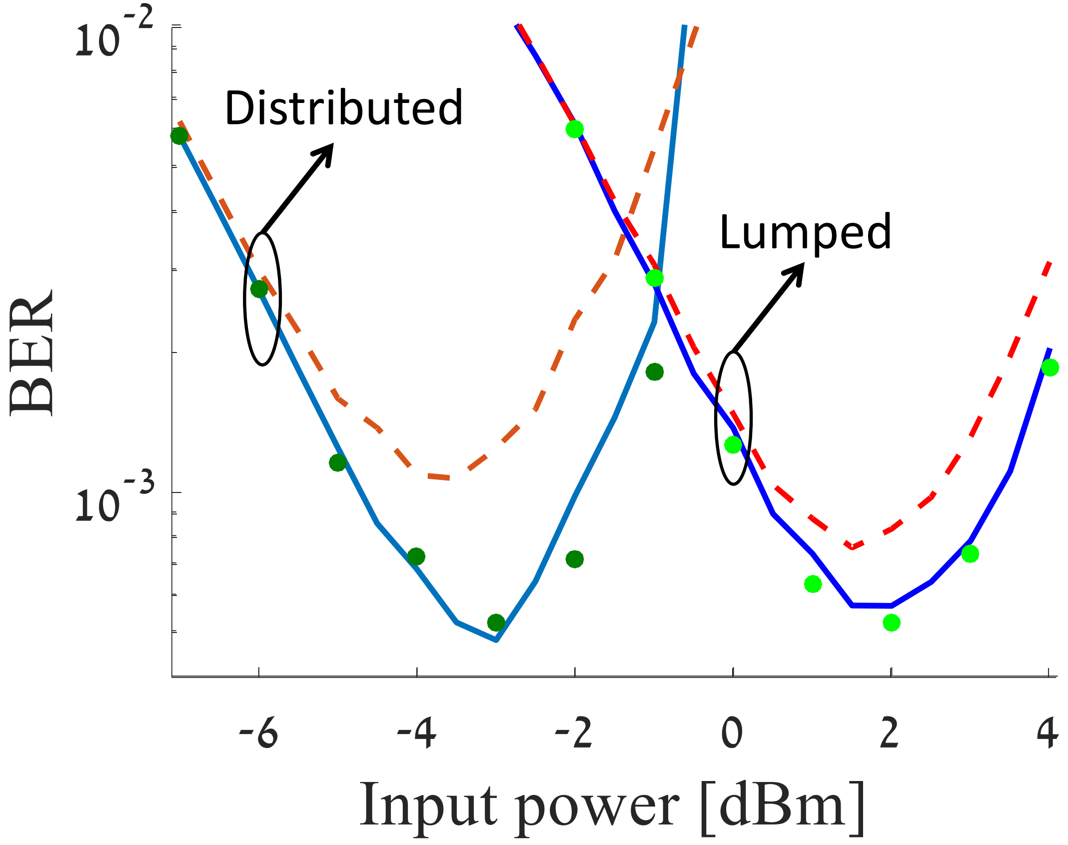
Elements $\tilde{R}_n$ are created artificially

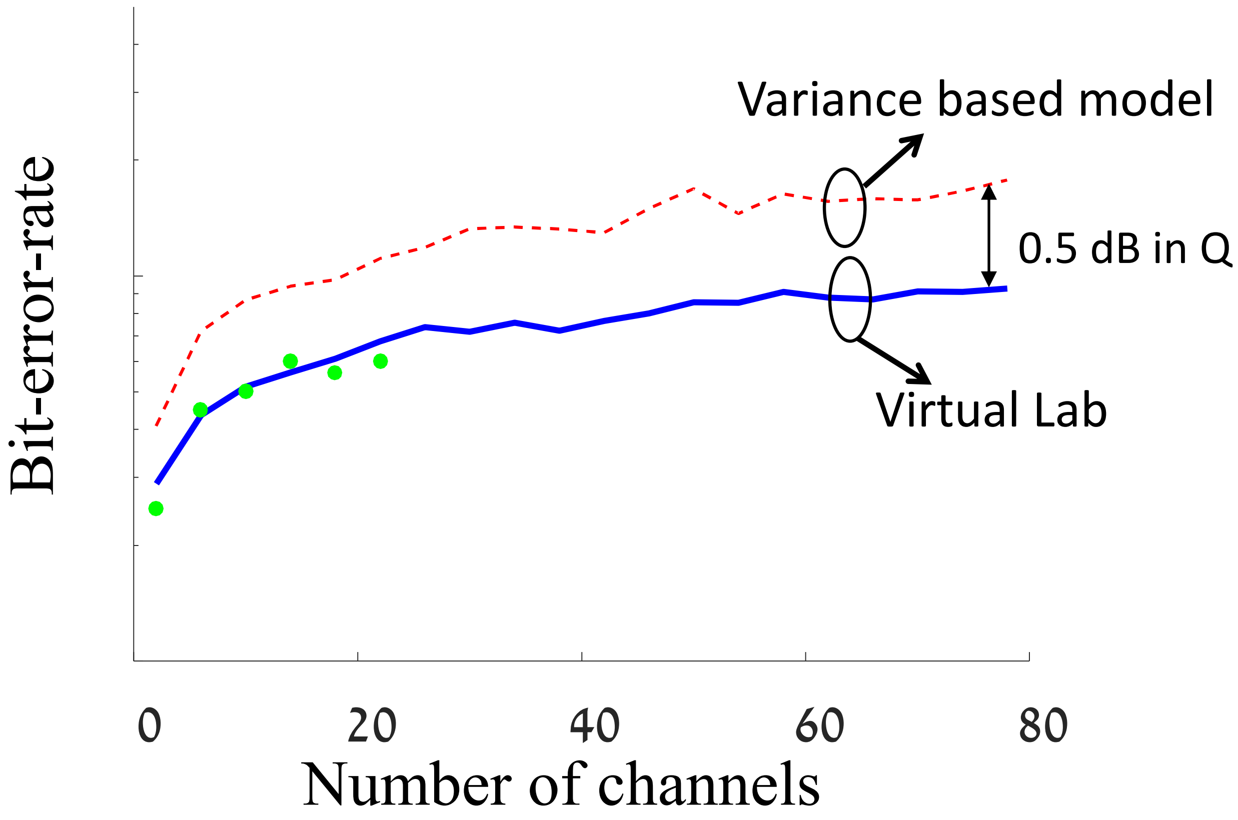
If the statistics of the artificial $\tilde{R}_n$ are the same as those of R_n, the simplified channel model will behave like the original model

O. Golani at Al, “Modeling the Bit-Error-Rate Performance of Nonlinear Fiber-Optic System,” JLT (2016)

O. Golani at Al, “Correlations and phase noise in NLIN- modelling and system implications,” OFC (2016)

A virtual lab for performance assessment





Performed with 11 WDM channels, 500km link

Dots= SSFM results, solid lines= model predictions, dashed lines= AWGN model

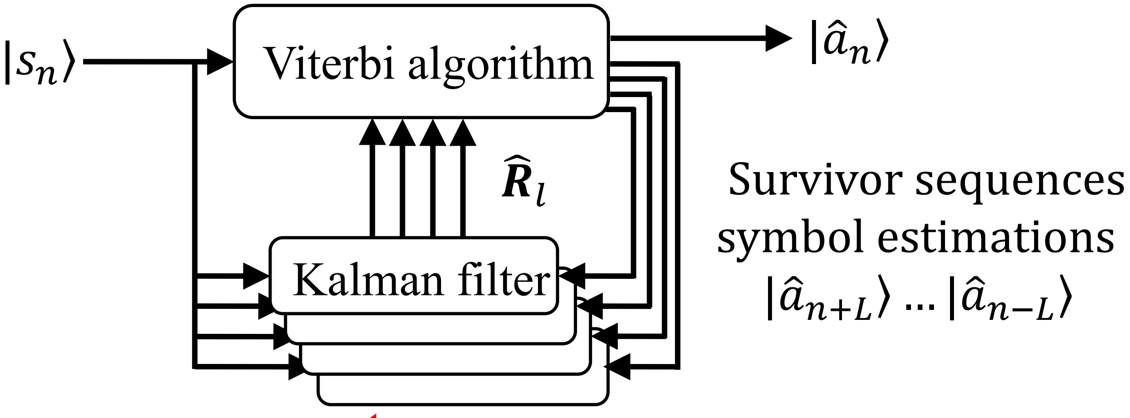
Applications of time-varying ISI model

Design algorithms for nonlinearity mitigation

- Use explicit knowledge of the statistics of NLIN to design equalizers tailored for nonlinearity mitigation

NLIN mitigation using equalization

We can use explicit knowledge of ISI statistics to design better equalizers.
The equalizer evaluates the ISI coefficients, and attempts to cancel their effect.



$|s_n\rangle$

Viterbi algorithm

$|\hat{a}_n\rangle$

$\hat{\boldsymbol{R}}_l$

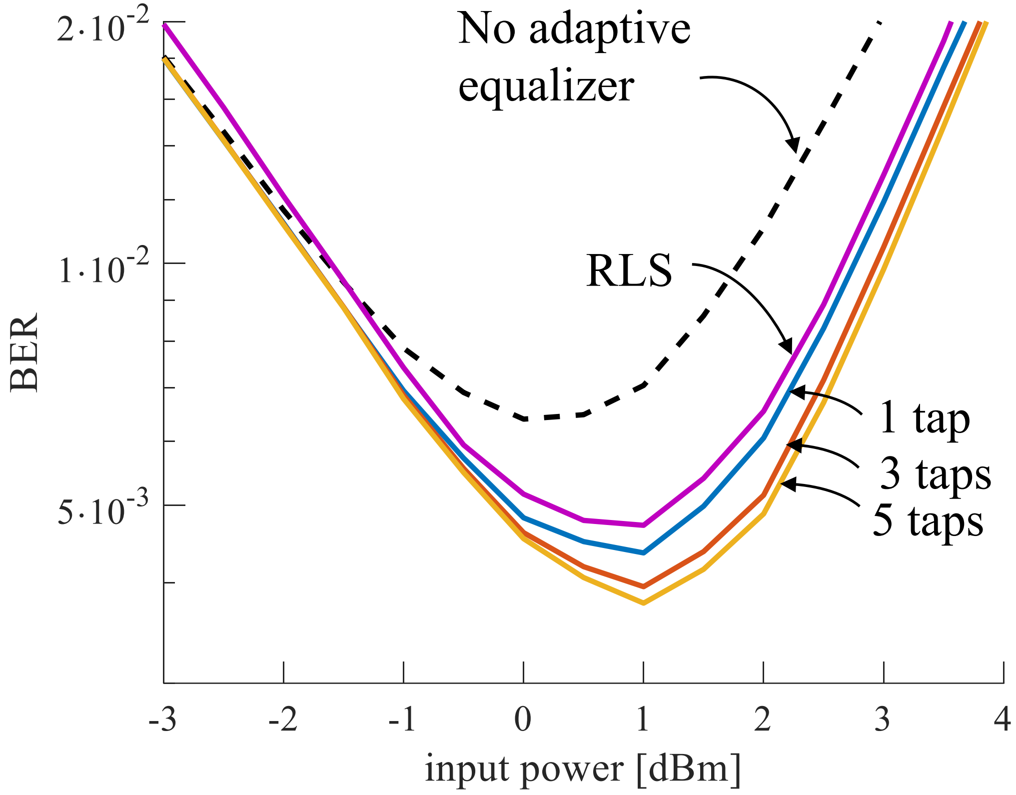
Kalman filter

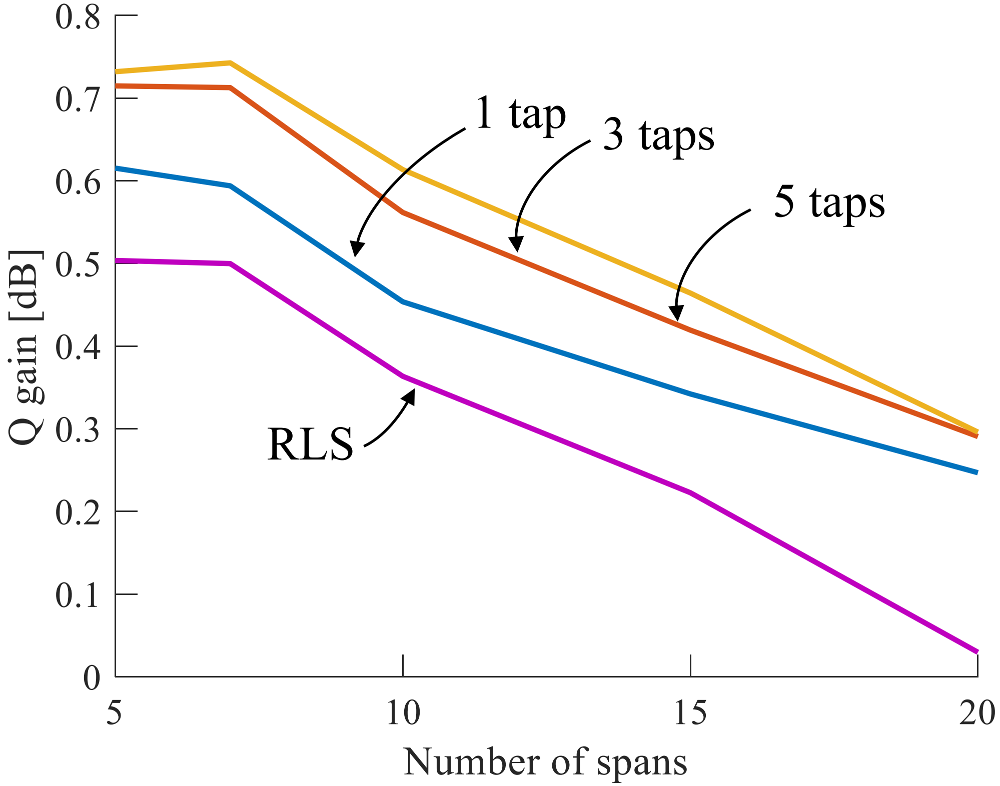
Survivor sequences
symbol estimations
$|\hat{a}_{n+L}\rangle \ldots |\hat{a}_{n-L}\rangle$

Filter uses the statistics of NLIN

O. Golani at Al., “Kalman-MLSE equalization of nonlinear noise,” OFC (2017)
O. Golani at Al., “Equalization Methods for NLIN Mitigation,” submitted to JLT

Application of statistical characterization: NLIN mitigation





5 tap filter requires to measure the ISI coefficients $R_{-2} \ldots R_2$

Conclusions

- The time varying-ISI model: a powerful tool to treat fiber nonlinearity
- Key idea: converting a nonlinear problem into a linear-time varying model
- Can use this model to import techniques from RF communication to optical communication

Thanks for listening!