Research Problems in Signal Processing and Telecommunications

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Research Problems

<u>Interplay between Information Theory and Signal Processing</u>

- De Bruijn's Identity
- Equivalence between Stein's lemma, heat equation and De Bruijn's identity
- Extensions of de Bruijn's Identity
- Applications in Information Theory:
  - Costa's Entropy Power Inequality
  - Entropy Power Inequality
  - Extremal Inequality
  - Information Theoretic Inequalities
- Applications in Signal Processing:
  - Bayesian Cramer-Rao Lower Bound (BCRLB)
  - Fisher Information Inequality
  - A New Lower Bound tighter than BCRLB
  - Cramer-Rao Lower Bound (CRLB)

Cramèr-Rao Lower Bound

Example (Finding optimal training sequences for joint frequency offset and channel estimation)

Under a frequency selective fading channel,

$$\mathbf{y} \;=\; \psi_\theta + \mathbf{w},$$

where $\psi_\theta = \mathbf{X}_{\omega_0}\mathbf{D}\mathbf{h}$, $\mathbf{y} = [y_0, \cdots, y_{n-1}]^T$, $\mathbf{w} = [w_0, \cdots, w_{n-1}]^T$, $\mathbf{h} = [h_0, \cdots, h_{m-1}]^T$,

$$\mathbf{X}_{\omega_0} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{i\omega_0} & \cdots & 0 \\ \vdots & \cdots & \ddots & \vdots \\ 0 & \cdots & 0 & e^{i(n-1)\omega_0} \end{bmatrix}, \mathbf{D} = \begin{bmatrix} d_0 & d_{-1} & \cdots & d_{1-m} \\ d_1 & d_0 & \cdots & d_{2-m} \\ \vdots & \cdots & \ddots & \vdots \\ d_{n-1} & d_{n-2} & \cdots & d_{n-m} \end{bmatrix},$$

Example (Cont.)

Main Techniques:

1. Cramèr-Rao inequality:

$$J(\mathbf{w}) \succeq J(\mathbf{w}_G)$$

2. Worst additive noise lemma:

$$I(\mathbf{w} + \mathbf{z}_G; \mathbf{z}_G) \succeq I(\mathbf{w}_G + \mathbf{z}_G; \mathbf{z}_G)$$

3. Min max optimization

Entropy Extremal Inequalities

What is an Extremal Inequality ?

- Entropy Power Inequality (EPI) : (Shannon, 1948)

$$\begin{aligned} N(X+W) &\geq N(X)+N(W), \\ h(X+W) &\geq h(\tilde{X}_G+\tilde{W}_G), \\ h(a_1X+a_2W) &\geq a_1^2h(X)+a_2^2h(W), \end{aligned}$$

  where $h(\cdot)$ is differential entropy, $N(\cdot)$ denotes entropy power, and $a_1^2+a_2^2=1$.

- An extremal inequality: (Liu, Viswanath, 2007)
  Under the covariance constraints $\mathbf{\Sigma}_X \preceq \mathbf{R}$,

$$\begin{aligned} h(X)-\mu h(X+W_G) &\leq h(X_G^*)-\mu h(X_G^*+W_G), \\ h(X+V_G)-\mu h(X+W_G) &\leq h(X_G^*+V_G)-\mu h(X_G^*+W_G), \end{aligned}$$

  where $\mathbf{\Sigma}_V, \mathbf{\Sigma}_W \succ 0$, $\mu \geq 1$, and $\mathbf{R}$ is a positive semi-definite.

Channel Enhancement Technique & KKT Conditions

(Weingarten, Steinberg, Shamai, 2006)

- Channel Enhancement:

$$V_G, \quad W_G \qquad \Longrightarrow \qquad \tilde{V}_G, \quad \tilde{W}_G,$$

  where $\mathbf{\Sigma}_V \succeq \mathbf{\Sigma}_{\tilde{V}}, \mathbf{\Sigma}_W \succeq \mathbf{\Sigma}_{\tilde{W}}$.

- KKT(Karush-Kuhn-Tucker) conditions:

$$\begin{aligned}
\frac{1}{2}\left(\mathbf{\Sigma}_{X^*} + \mathbf{\Sigma}_V\right)^{-1} + \mathbf{K}_V &= \frac{\mu}{2}\left(\mathbf{\Sigma}_{X^*} + \mathbf{\Sigma}_W\right)^{-1} + \mathbf{K}_W \\
\mathbf{K}_V \mathbf{\Sigma}_{X^*} &= 0 \\
\mathbf{K}_W \left(\mathbf{R} - \mathbf{\Sigma}_{X^*}\right) &= 0
\end{aligned}$$

An Alternative Proof

Main techniques

- Worst Additive Noise Lemma
- Data Processing Inequality
- Moment Generating Function
- Entropy Power Inequality

Developing a Unifying Framework

Information Theoretic Inequalities

- CRLB or Cramér-Rao Inequality
- Maximizing differential entropy
- Worst additive noise lemma
- Entropy Power Inequality
- Extremal Inequality

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- “A Note on the Secrecy Capacity of the Multiple-Antenna Wiretap Channel,” *IEEE Trans. Inf. Theory*, vol. 55, no. 6, pp. 2547- 2553, Jun. 2009.

Publications

- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “On the equivalence between Stein and De Bruijn identities,” *IEEE Transactions on Information Theory*, Accepted.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “Gaussian Assumption: the Least Favorable but the Most Useful,” *IEEE Signal Processing Magazine*, Accepted.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “An Alternative Proof of an Extremal Inequality,” *IEEE Transactions on Information Theory*, Submitted.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “A Unifying Variational Perspective on Perspective on Proving Some Fundamental Information Theoretic Inequalities,” *IEEE Transactions on Information Theory*, Submitted.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “On the equivalence between Stein and De Bruijn identities,” ISIT, July 2012.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “An Information Theoretic Perspective over an Extremal Entropy Inequality,” ISIT, July 2012.
- Sangwoo Park, Erchin Serpedin, and Khalid Qaraqe, “New Perspectives, Extensions and Applications of De Bruijn Identity,” SPAWC, June 2012 (Nominated as Best Student Paper Award).

Additional Research Problems

- MinMax Optimal Designs $\min_{X \in \Omega} \max_{Y \in G_\tau} F(X, Y)$
- Signal Processing for Smart Grids
- Computational Biology, Bioinformatics, Genomics
- Antenna Array Processing (Radar)
- Estimation and Detection Problems in Image Processing
- Synchronization, Tracking, Estimation

Other Research Areas

- Geophysical (seismic) signal processing
- Biomedical Image Processing (MRI)
- Compressive Sampling

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Panel AICT: Advances in Signal Processing and Networking Technologies

SIGNAL PROCESSING IN OPTICAL COMMUNICATIONS TODAY

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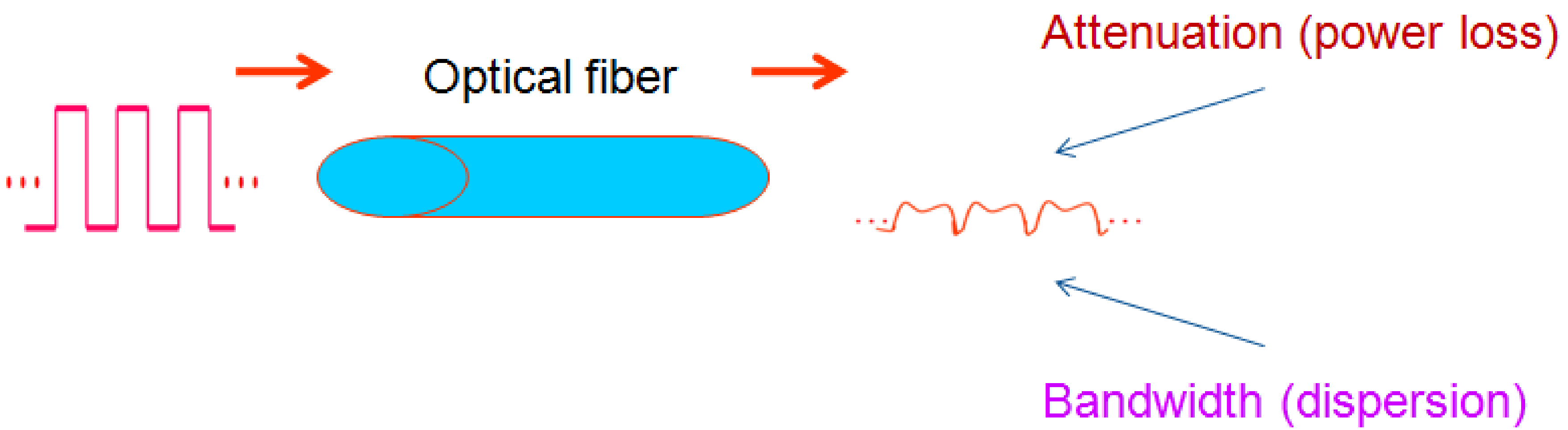
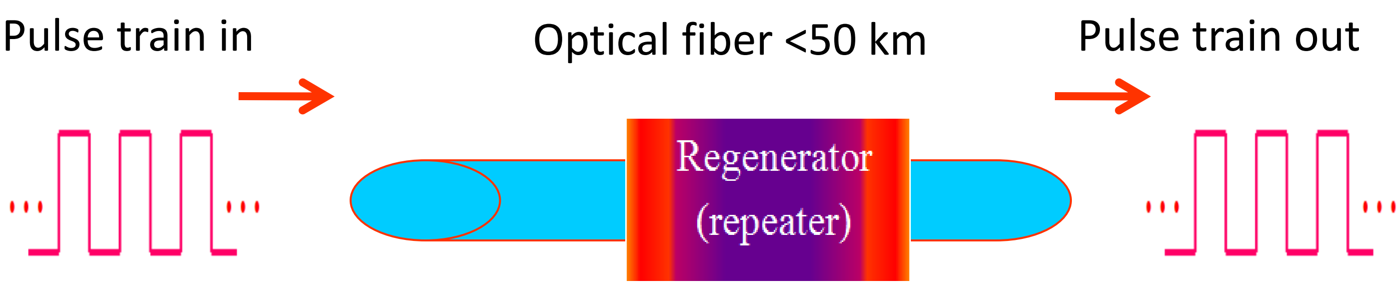
Two main signal impairments in optical communications

- Transmission of optical signal over an optical fiber suffers from two main impairments: *attenuation* due to loss of power and bandwidth decrease due to *dispersion*.



Electronics vs. optics in communications

The solution to both—attenuation and dispersion—problems could be the use of electro-optical regenerator (shown).

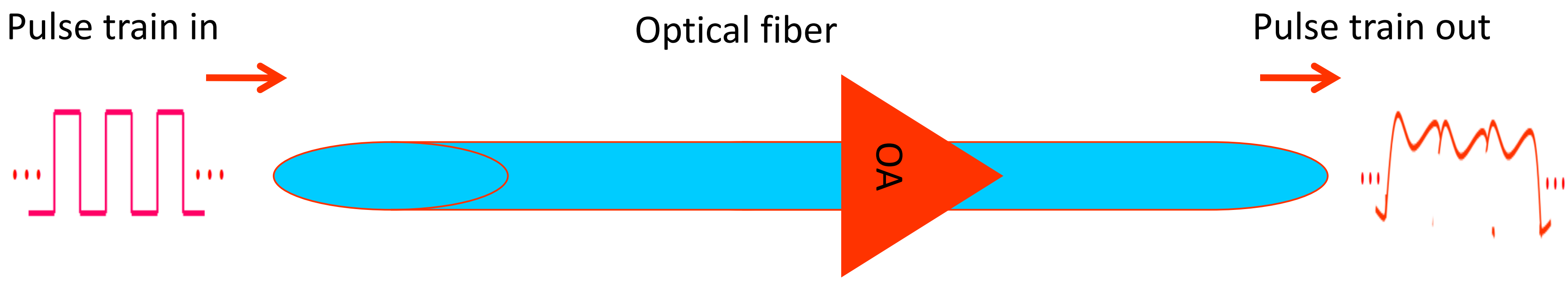


However, electro-optical devices introduce more problems than solutions and optical-network designers consider these devices only as a last resort.

In fact, optical communications technology persistently has tended to replace electronic components by optical ones to take the full advantage of optics; ***all-optical networks*** has always been a goal of this development. But for the last years the trend has been reversed and electronics has replaced some optical modules. Why? How?

Attenuation

- To combat with attenuation, we use optical amplifiers (OAs).

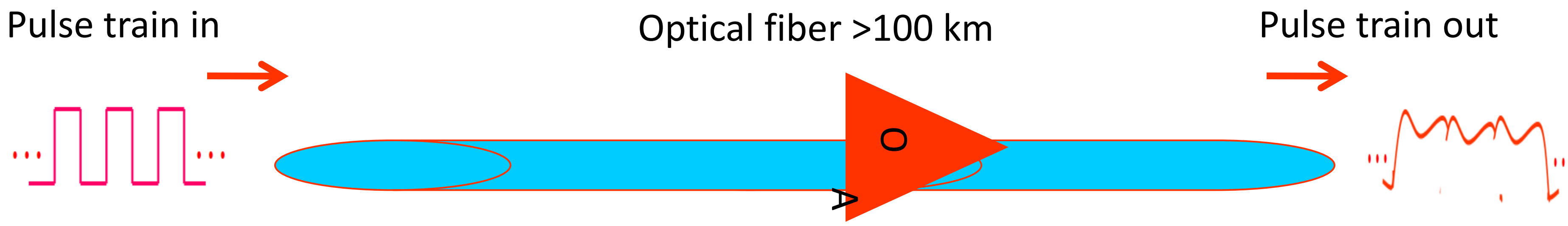


•Problem: We must limit the maximum transmission power , P, to minimize nonlinear phenomena, which results in restriction of transmission distance and also restricts the possibility to directly improve OSNR by increasing the signal power.

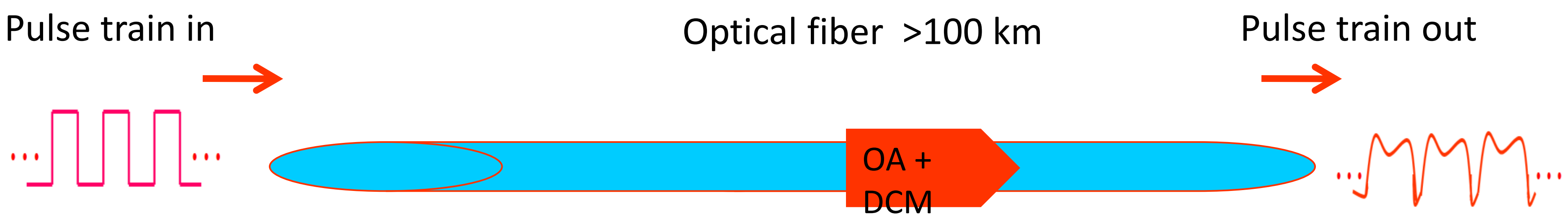
•Refractive index of optical fiber consists of linear and nonlinear parts with respect to E' that is, $n(\omega,E) = n_1(\omega) + n_2E^2$.

Dispersion

Optical amplifier compensates for losses, but now the *transmission distance is limited by dispersion.*

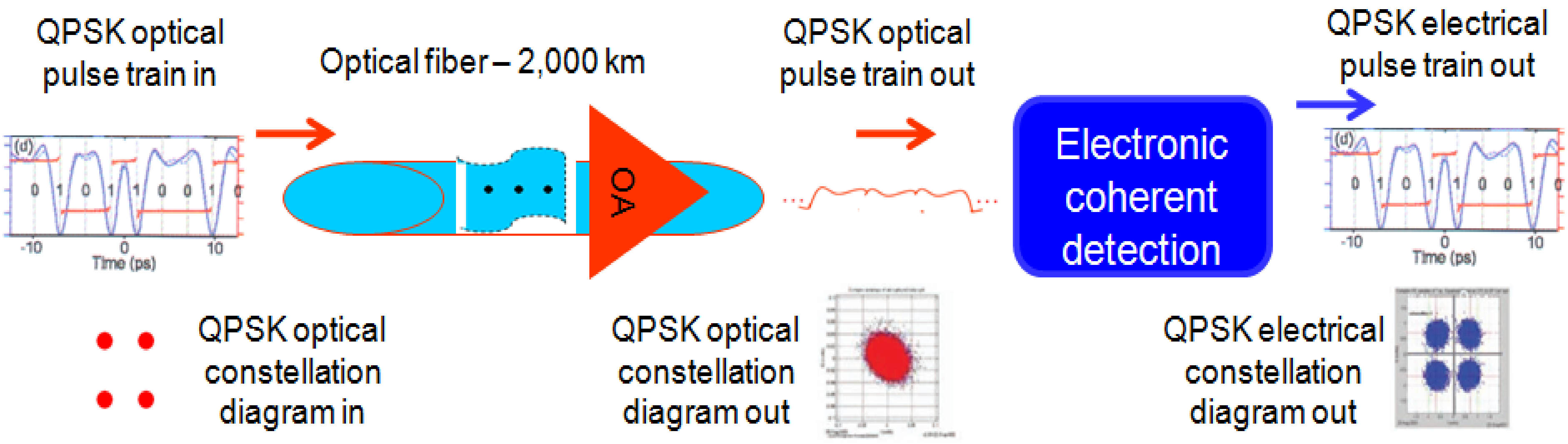


To combat with dispersion, we use optical dispersion-compensating modules, DCM (shown) and dispersion-management techniques to compensate for both chromatic dispersion, CD, and polarization-mode dispersion, PMD. However, over the long distance the dispersion accumulates and eventually the designers had to use the electro-optical regenerators. Today we encounter new problem: **Existing optical networks based on DCM and dispersion management can't support transmission at 100 Gb/s.**



Dispersion and coherent technology

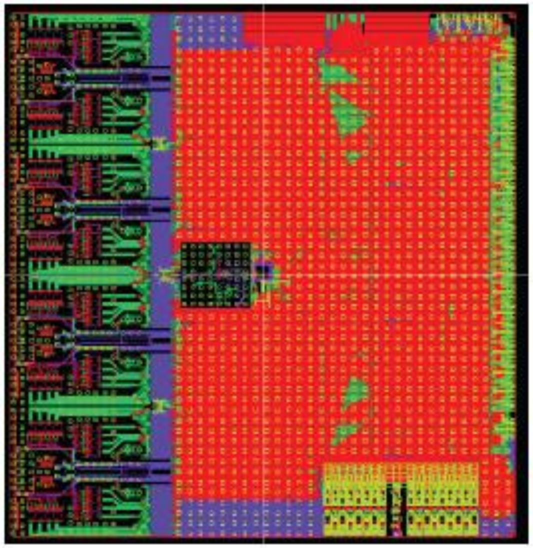
- **Solution:** Coherent transmission technology.



Coherent transmission replaces an optical DCM in the link with DSP electronics in the receiver, thus providing dispersion compensation in electronic domain. Though optical amplification is still necessary, the transmission distance has increased thanks to coherent detection.

High-speed electronics in optical communications

- Key enabler of coherent technology—and the 100-Gb/s operation therefore—is high-speed electronics. This electronics is everywhere from front-ends to clock recovery circuits to digital phase detectors to data converters (ADC, DAC). **But the heart of coherent technology is digital signal processing (DSP) units providing digital filtering of optical communications signals in real time.**

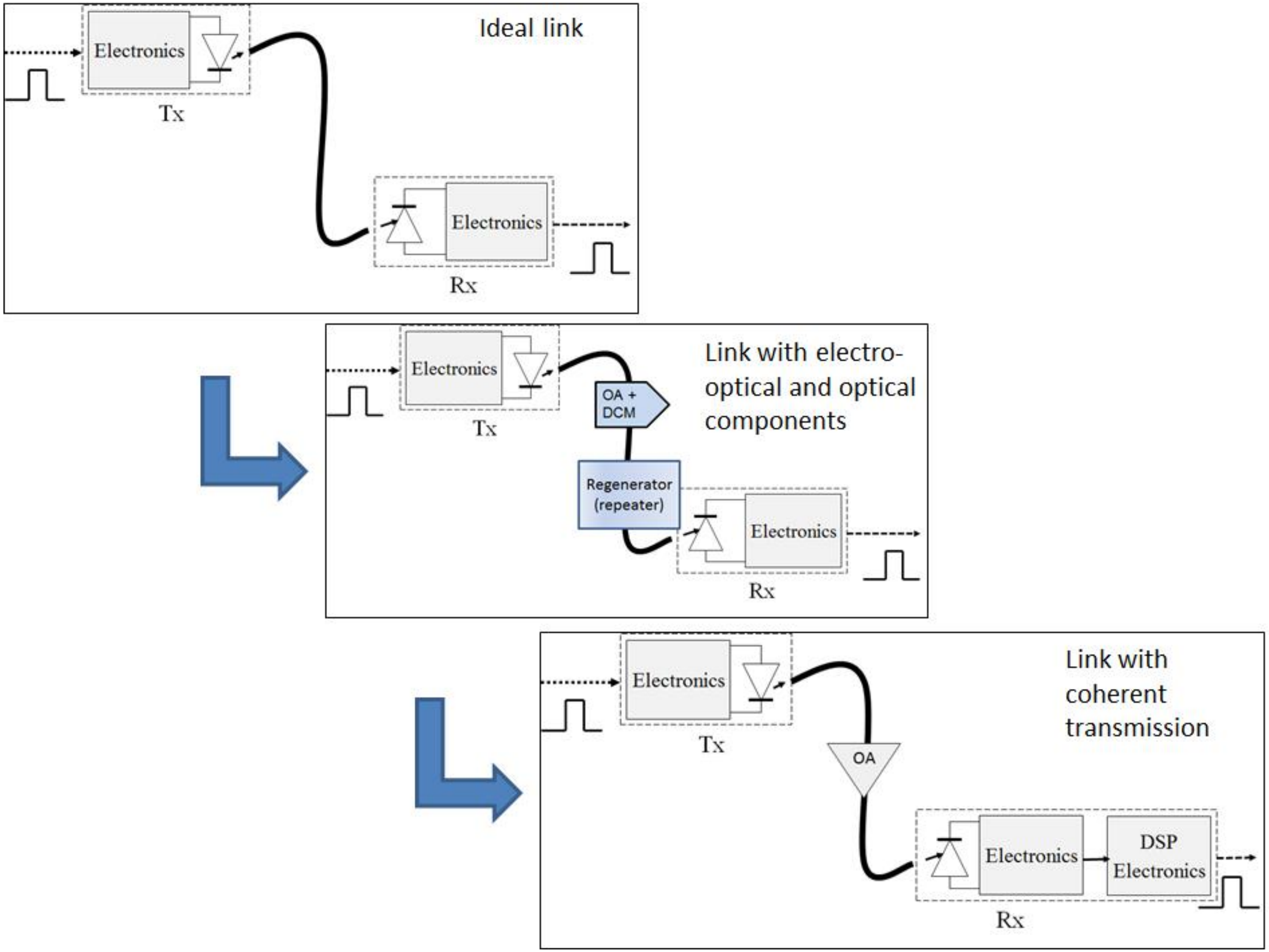


CMOS receiver ASIC with four 23 Gsample/s ADCs and DSP executing 12 trillion ($12x10^{12}$) operations per second.

[www.ciena.com]

Coherent technology – back to the ideal link

Optics and electronics in optical communications: Coherent transmission technology assigns the important function of dispersion compensation to electronics in the interface cards, thus making the optical link closer to the ideal configuration



The Upgrading of the System's Performance in the Presence of Fading by Using Diversity Techniques and Sampling in Two Time Instants

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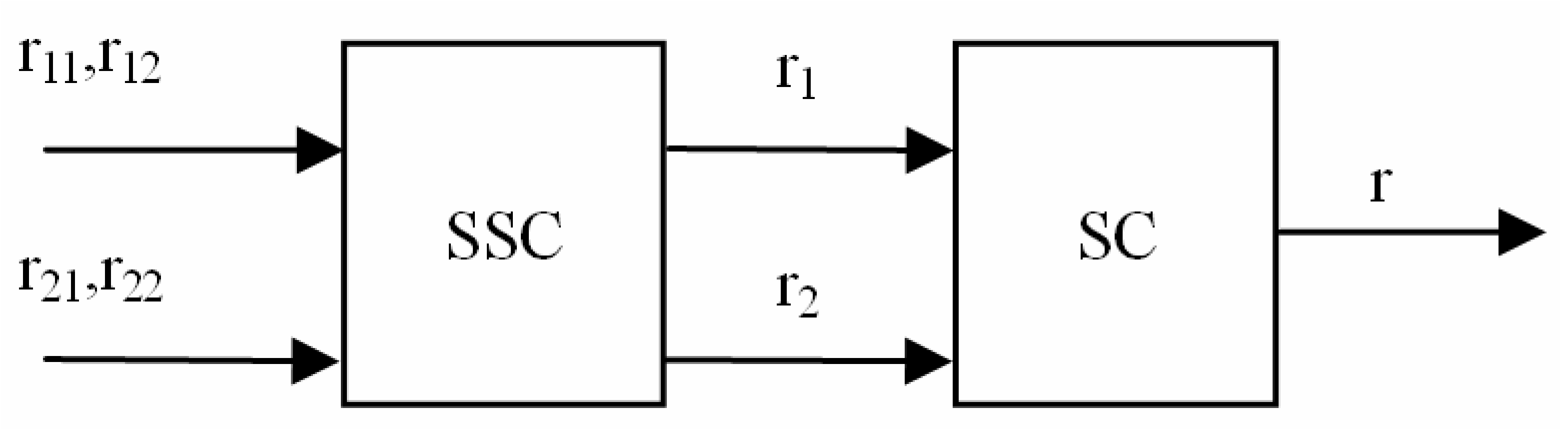
Characteristics of the SSC Combiner

- Model of the system at one time instant
- Model of the system at two time instants

Determination of

- Joint probability density function for SSC Combiner Output Signal at Two Time Instants in Fading Channel
- Probability density function of signal derivatives at the output of SSC combiner at two time instants



System model for complex dual SSC/SC combiner

- The level crossing rate and the average fade duration are also very often used in designing of wireless communication systems as measures for their quality.
- To obtain second order system characteristics the expressions for signal derivatives are need

Conclusion

- It is obtained improvement of characteristics of complex combiner at two time instants comparing with classical combiners

Conclusion

- Complex combiner is not economical in the case of strongly correlated signals because it does not give better performance than MRC combiner

Panel AICT: Advances in Signal Processing and Networking Technologies

Modelling of traffic control mechanisms

Mariusz Głąbowski

Traffic representation

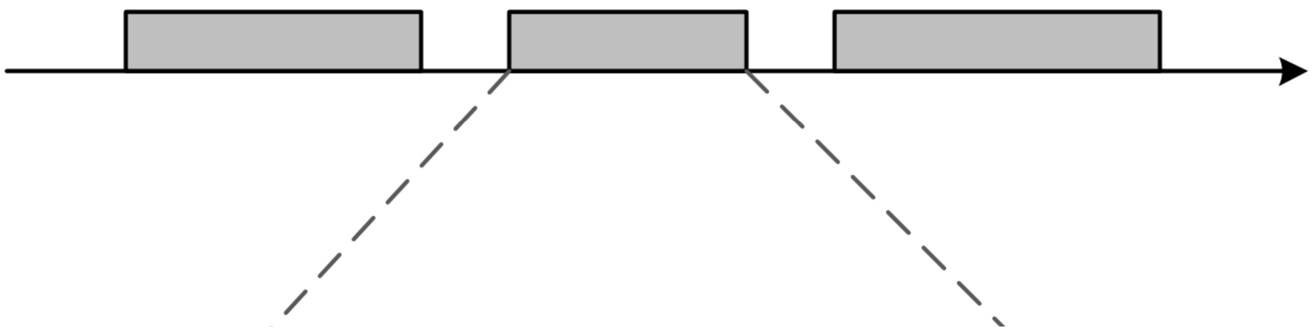
- Packet technologies
  – imposes a hierarchical approach to traffic representation in networks
    - Sessions – calls – streams level
    - Packet level

Traffic representation

- Packet level
  - very complex structure of streams
  - in the simplest cases
    - modelled by traffic sources of the types of IMP, IBP, MMPP
  - in more complex cases (commonly found in packet networks)
    - modelled by by fractal traffic sources (self-similar sources)

Traffic representation – call level

Call level → Poisson stream*



Packet level → VBR stream (IPP, IBP, MMPP, SSS)

* Bonald T., Roberts J., *Internet and the Erlang Formula*, **ACM Computer Communications Review**, vol. 42, no. 1, 2012, pp.23-30.

Parameterization of call streams

Equivalent bandwidth

The equivalent bandwidth is a fixed value that determines the volume of resources that the network allocates to a given call for the required quality of service to be ensured.

Principle of equivalent bandwidth determination

The effect of service of VBR call in the network =

=

= the effect of service of CBR call, determined by the equivalent bandwidth

Parameterization of call streams

Basic Bandwidth Unit (allocation unit)

$$R_{\mathrm{BBU}} = \mathrm{GCD}\,(R_1, R_2, \ldots, R_M)$$

Bandwidth discretization

Number of BBUs required by class i call: $t_i = R_i / R_{\mathrm{BBU}}$

Capacity of the system expressed in BBUs: $V = C / R_{\mathrm{BBU}}$

State-dependency - division

Dependency resulting from call streams

- Engset stream, Pascal stream;

Dependency resulting from system structure

- Limited Availability Group, Overflow systems;

Dependency resulting from CAC function operation

- threshold mechanisms, compression mechanisms.

Current activities

Analytical Modelling of Multiservice Queuing Systems

- CARMNET project