Intra-Channel Nonlinear Effects in 40 Gbit/s Optical Communication Systems Over G.652 Fibers

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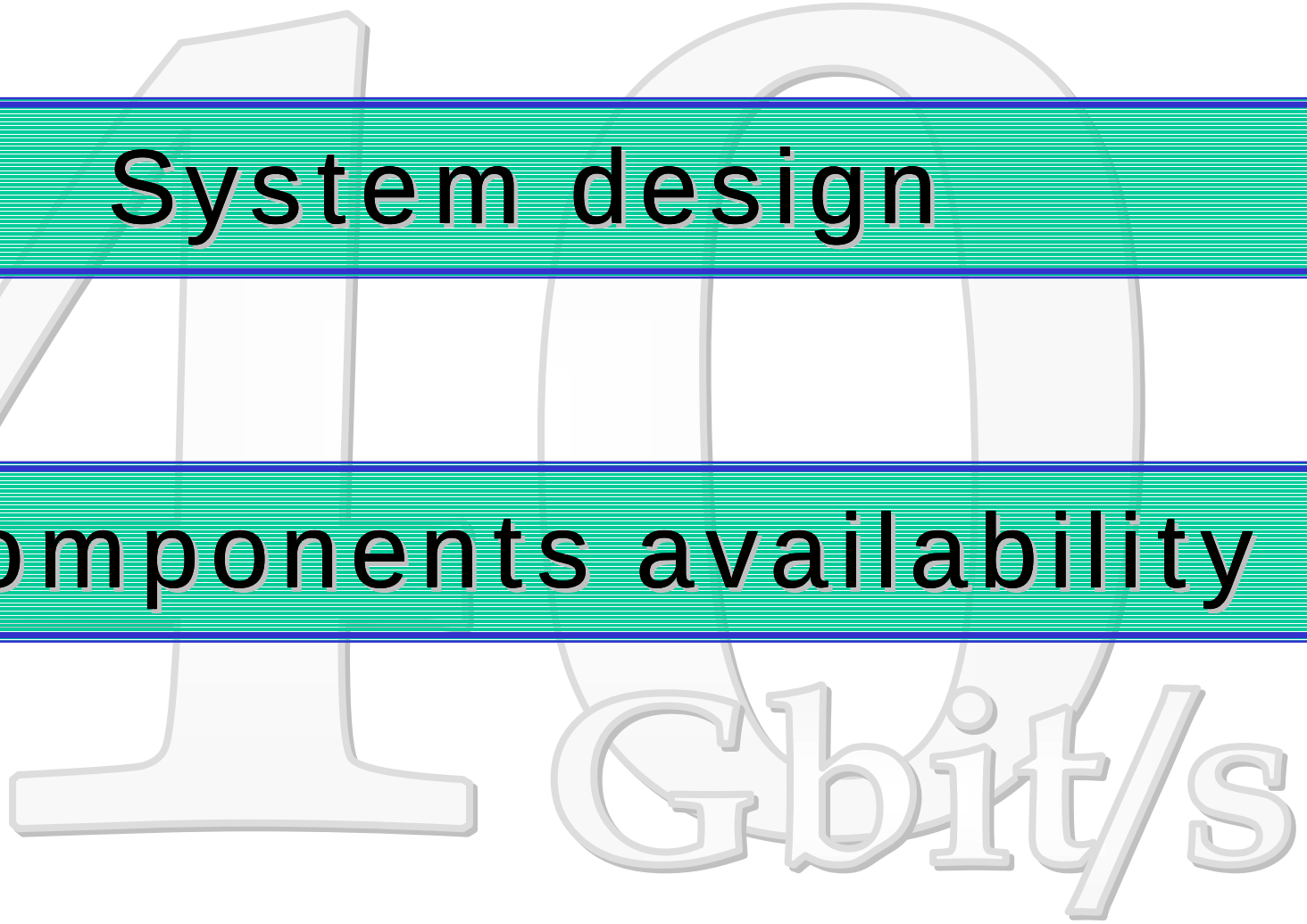
The 40 Gbit/s Problem...

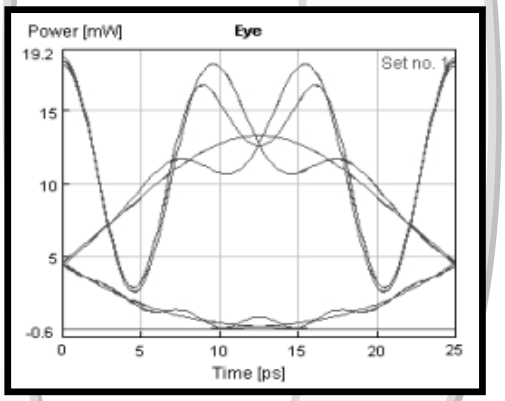
System design

Components availability



Signal Distortion in High-Speed Optical Communication Systems over G.652 Fibers

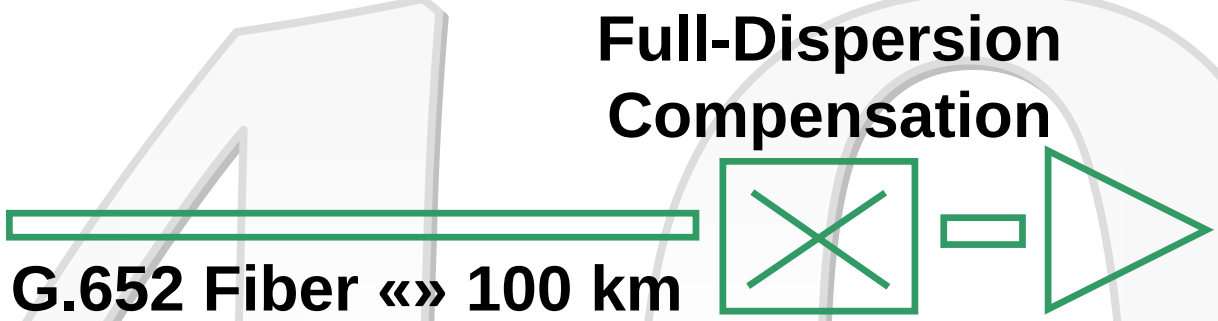
- **Chromatic Dispersion (17 ps/nm/km)**
  - **40 Gbit/s system**
  - **5 ps Gaussian pulses**
  - **After 1.8 km**
  - **BER < 10^{-14}**



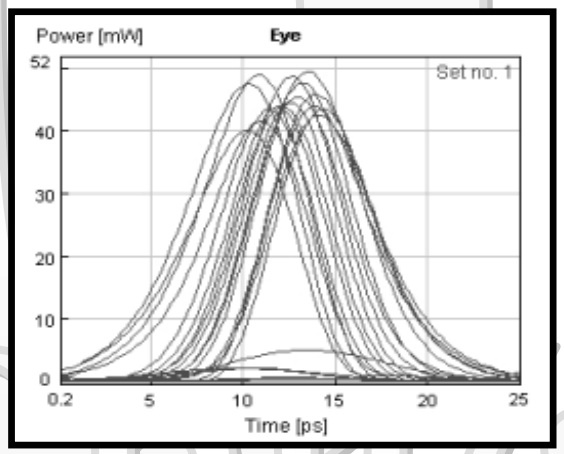
The pulses broadening is about β_2 / T_0 per kilometer

- **Fiber Nonlinear Behavior (1.3 W^{-1}/km)**

Full Dispersion Compensation

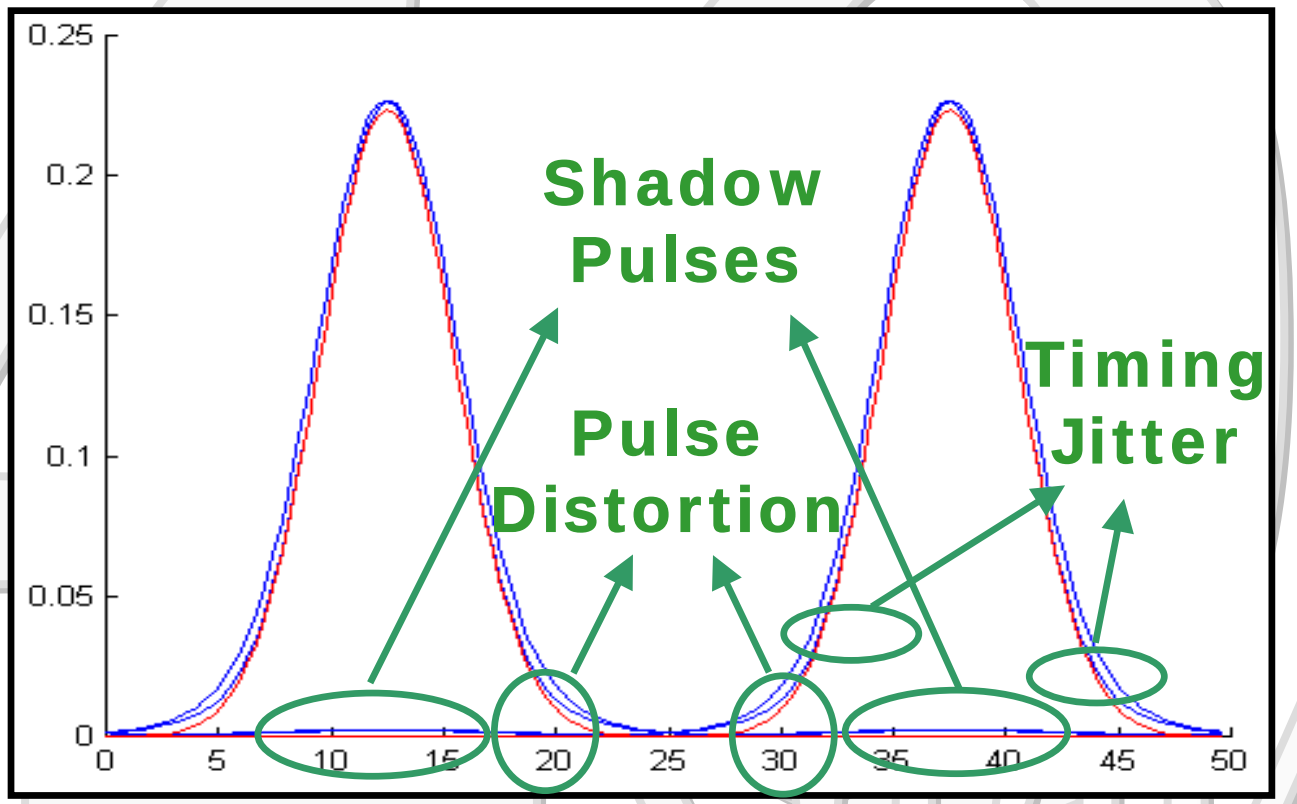


- 40 Gbit/s system
- 5 ps Gaussian pulses
- 100 km Span
- After 1200 km
- BER < 10^{-9}



Fiber Nonlinearities Limit the Maximum Transmission Distance to 1200 km

Two Pulses Propagation



Nonlinear Schrödinger Equation

Solution of the form $u = u_0 + \Delta u$

Linear solution

Nonlinear perturbation

$$i \cdot \frac{\partial \Delta u}{\partial z} - \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \gamma \cdot |u_0 + \Delta u|^2 \cdot u_0 + \gamma \cdot |u_0 + \Delta u|^2 \cdot \Delta u + i \cdot \frac{\alpha}{2} \cdot \Delta u = 0$$

$$|u_0 + \Delta u|^2 \approx |u_0|^2 \qquad |u_0 + \Delta u|^2 \cdot \Delta u \approx 0$$

$$i \cdot \frac{\partial \Delta u}{\partial z} - \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \gamma \cdot |u_0|^2 \cdot u_0 + i \cdot \frac{\alpha}{2} \cdot \Delta u = 0$$

Two Pulses Propagation

$$u_0 = u_1 + u_2$$

SPM

$$\frac{\partial \Delta u}{\partial z} + i \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \frac{\alpha}{2} \cdot \Delta u = i \cdot \gamma \cdot \left\{ |u_1|^2 \cdot u_1 + |u_2|^2 \cdot u_2 \right\}$$

IXPM

$$+ i \cdot \gamma \cdot \left\{ 2 \cdot |u_2|^2 \cdot u_1 + 2 \cdot |u_1|^2 \cdot u_2 \right\}$$

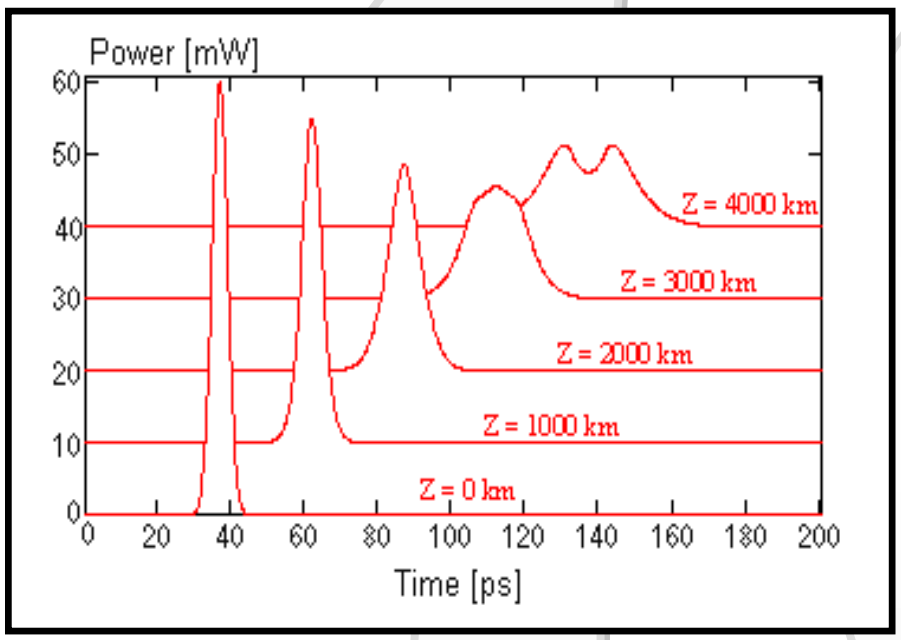
IFWM

$$+ i \cdot \gamma \cdot \left\{ u_1 \cdot u_2^* \cdot u_1 + u_2 \cdot u_1^* \cdot u_2 \right\}$$

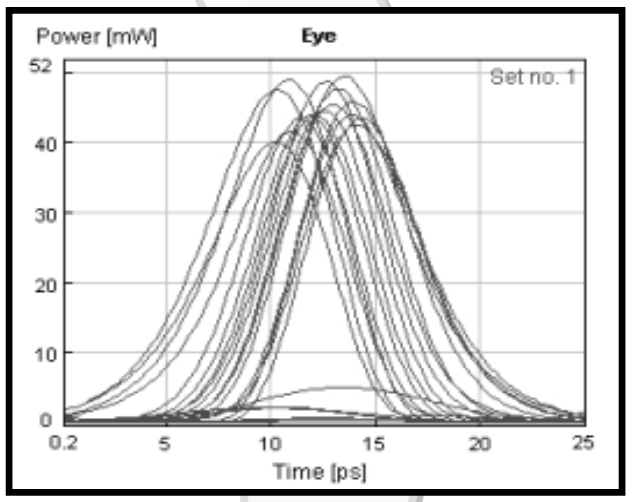
Due to the chromatic dispersion $u_1 \cdot u_2 \neq 0$

Self-Phase Modulation

Single Pulse Propagation



Sequence Propagation



After 1200 km

The SPM effect is not the main degradation effect

Two Pulses Propagation

$$u_0 = u_1 + u_2$$

SPM

$$\frac{\partial \Delta u}{\partial z} + i \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \frac{\alpha}{2} \cdot \Delta u = i \cdot \gamma \cdot \left\{ |u_1|^2 \cdot u_1 + |u_2|^2 \cdot u_2 \right\}$$

IXPM

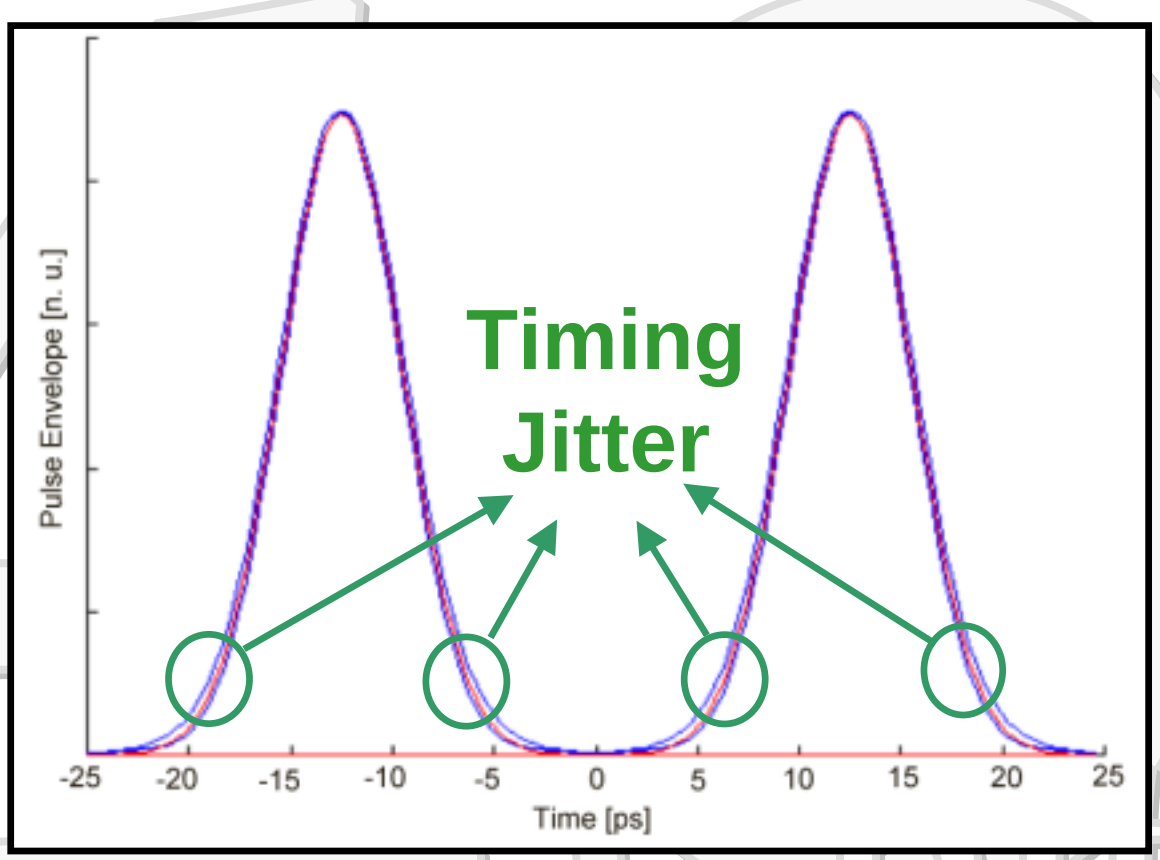
$$+ i \cdot \gamma \cdot \left\{ 2 \cdot |u_2|^2 \cdot u_1 + 2 \cdot |u_1|^2 \cdot u_2 \right\}$$

IFWM

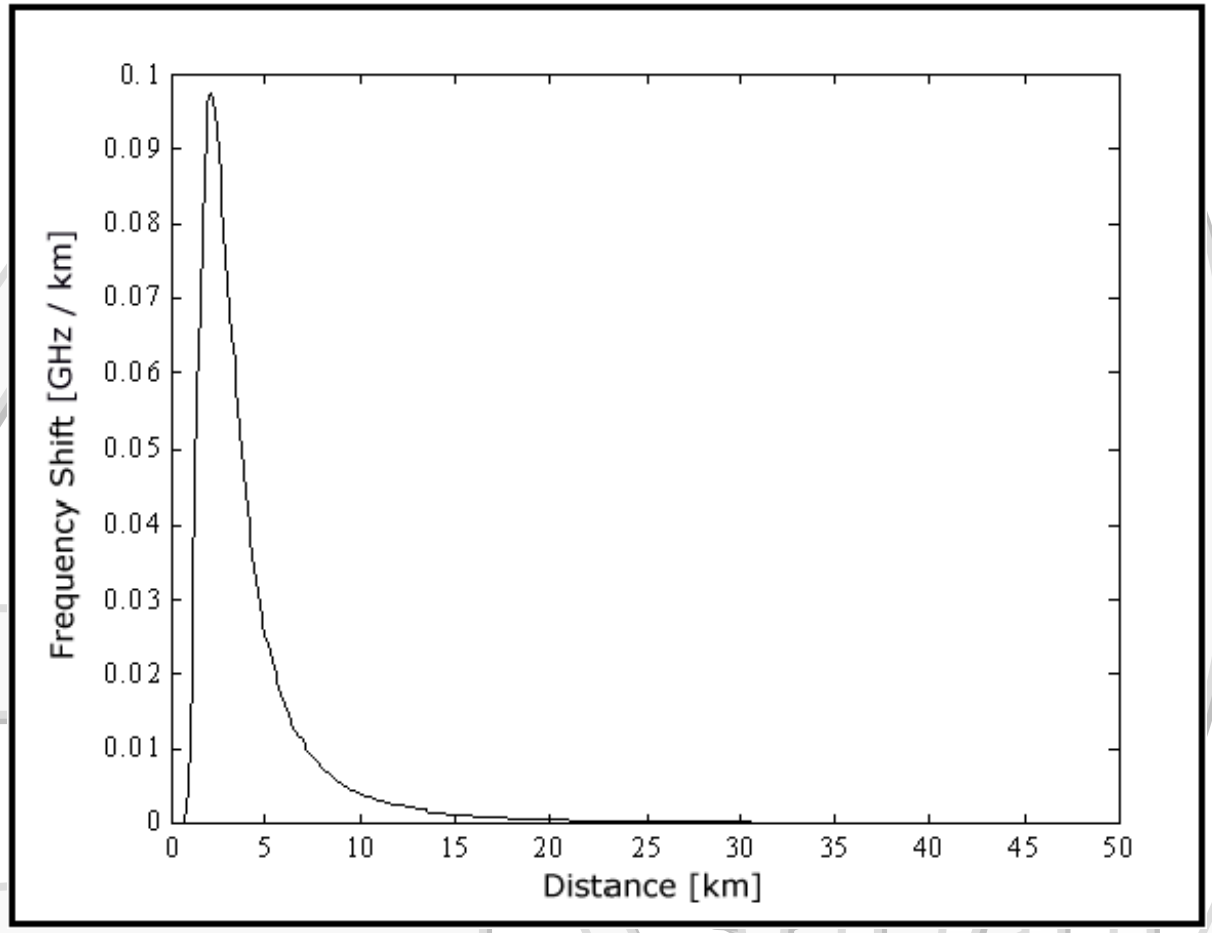
$$+ i \cdot \gamma \cdot \left\{ u_1 \cdot u_2^* \cdot u_1 + u_2 \cdot u_1^* \cdot u_2 \right\}$$

Dispersion + IXPM

IXPM


Timing
Jitter
Pulse Envelope [n. u.]
-25
-20
-15
-10
-5
0
5
10
15
20
25
Time [ps]

IXPM


Frequency Shift [GHz / km]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
30
35
40
45
50
Distance [km]

Two Pulses Propagation

$$u_0 = u_1 + u_2$$

$$\frac{\partial \Delta u}{\partial z} + i \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \frac{\alpha}{2} \cdot \Delta u = i \cdot \gamma \cdot \left\{ |u_1|^2 \cdot u_1 + |u_2|^2 \cdot u_2 \right\}$$

SPM

IXPM

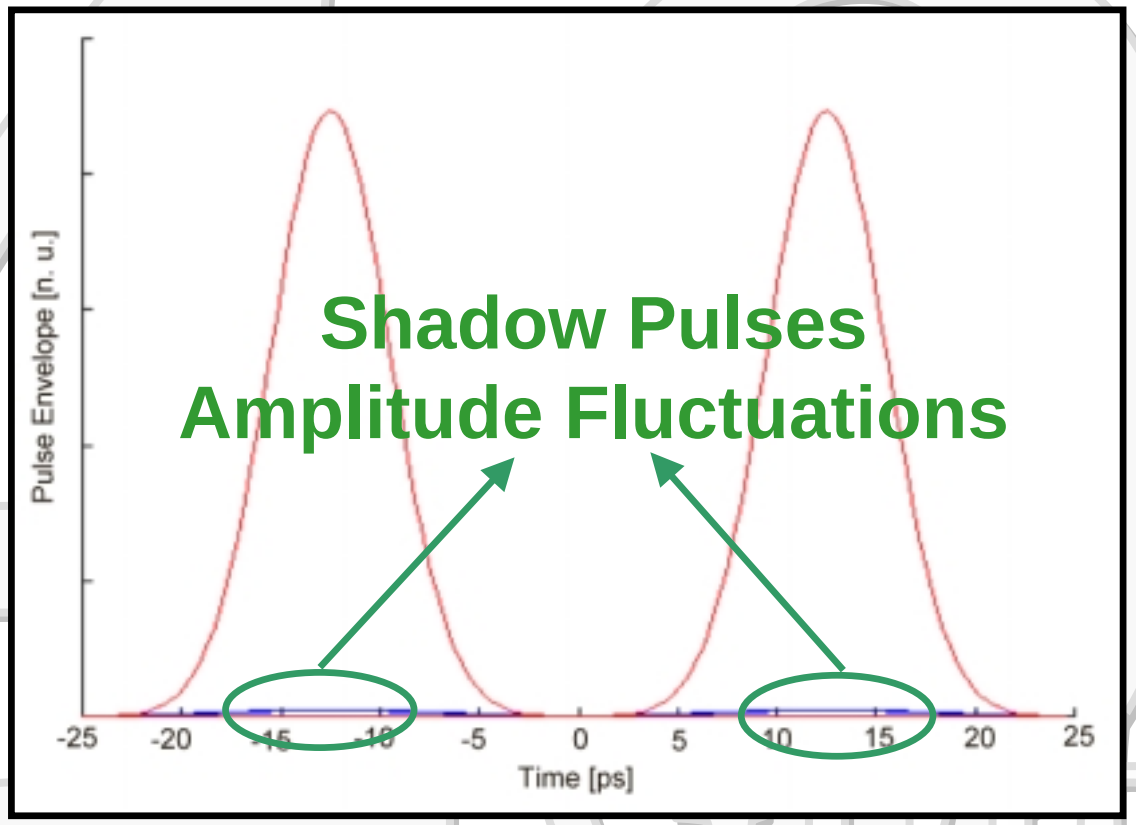
$$+ i \cdot \gamma \cdot \left\{ 2 \cdot |u_2|^2 \cdot u_1 + 2 \cdot |u_1|^2 \cdot u_2 \right\}$$

IFWM

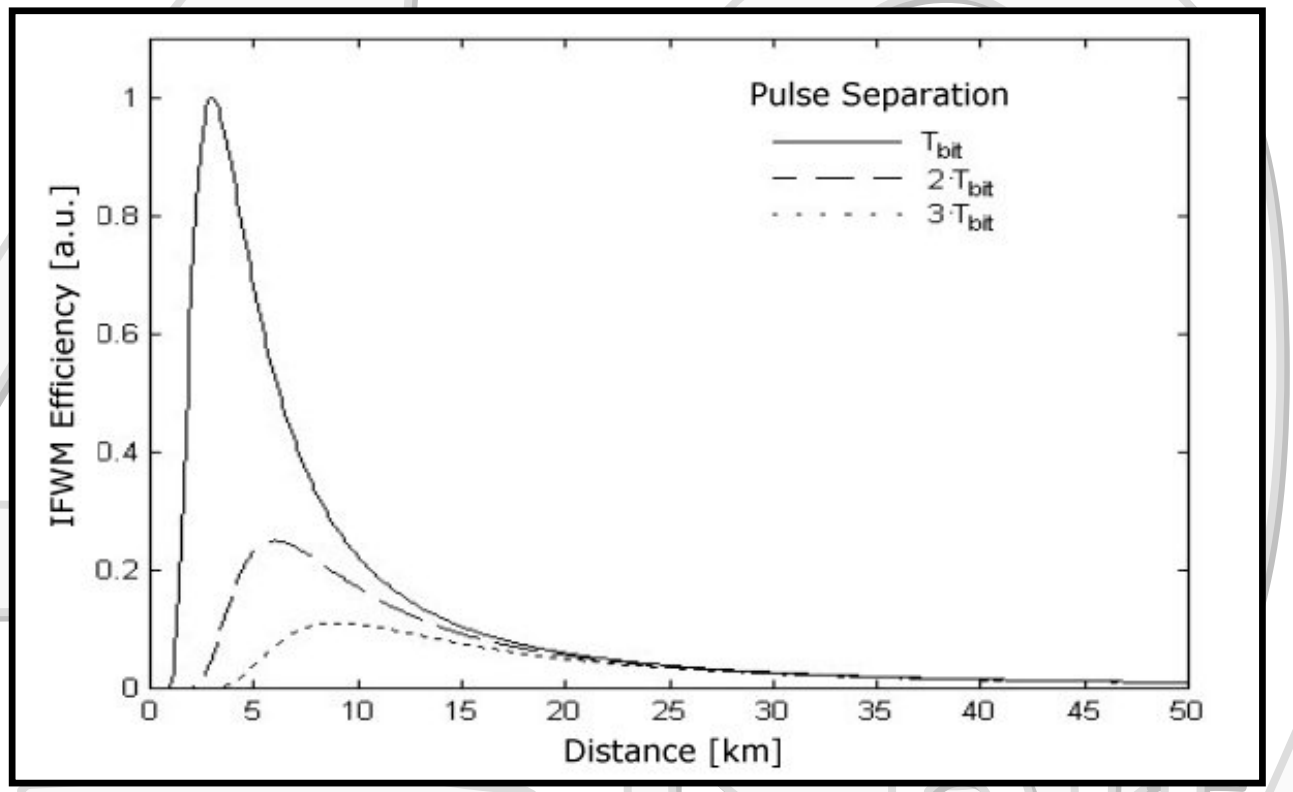
$$+ i \cdot \gamma \cdot \left\{ u_1 \cdot u_2^* \cdot u_1 + u_2 \cdot u_1^* \cdot u_2 \right\}$$

Dispersion + IFWM

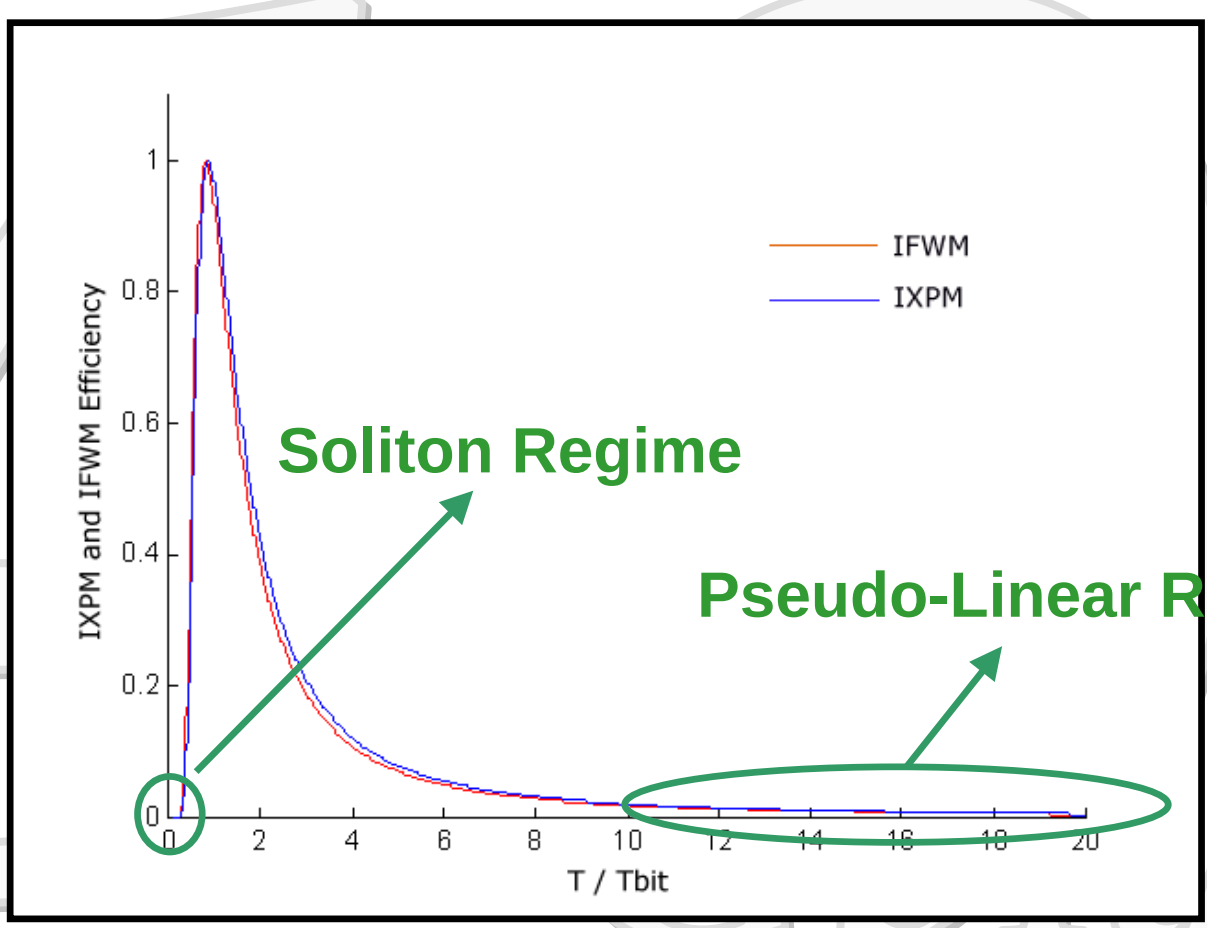
Intra-Channel Four Wave Mixing



Intra-Channel Four Wave Mixing

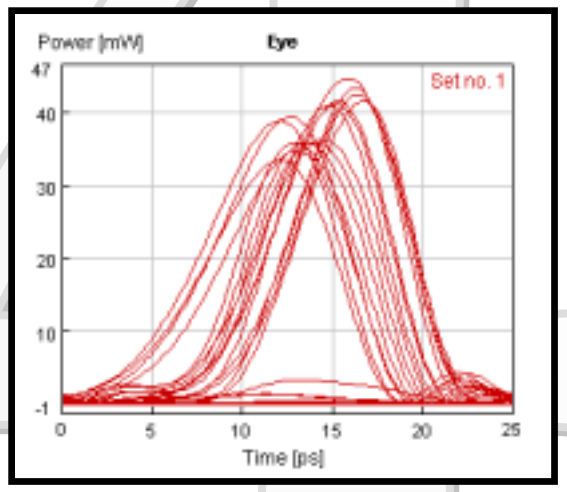


Intra-Channel Nonlinear Effects Efficiency

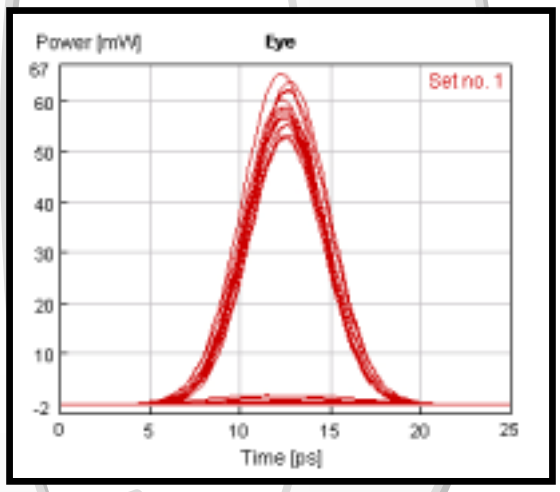


500 km Point-to-Point Link

Dispersion Compensated Span-by-Span

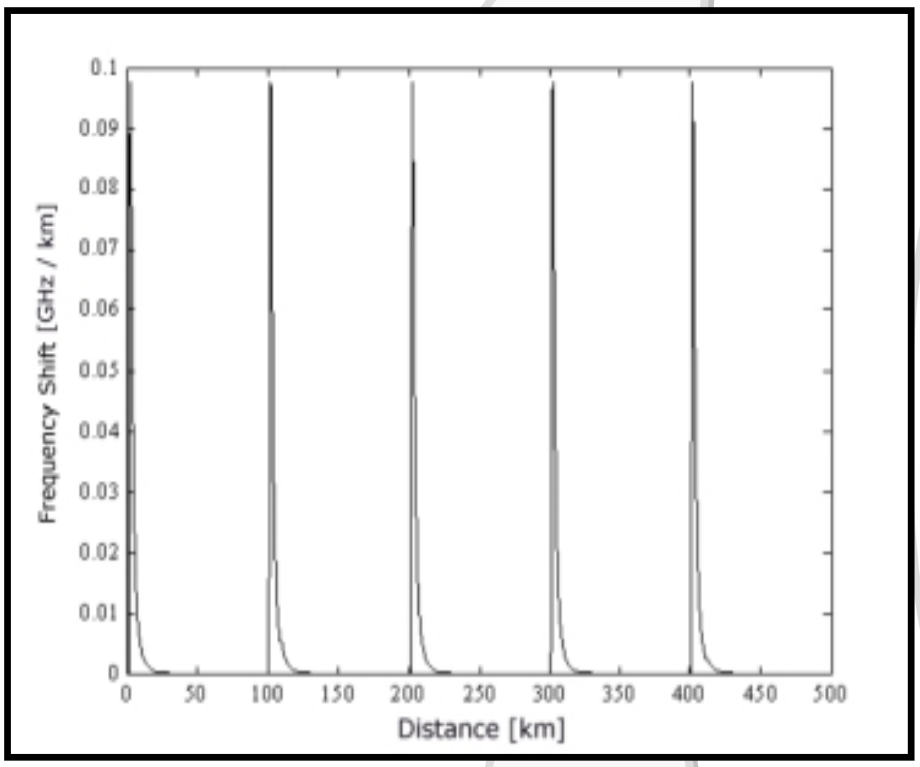


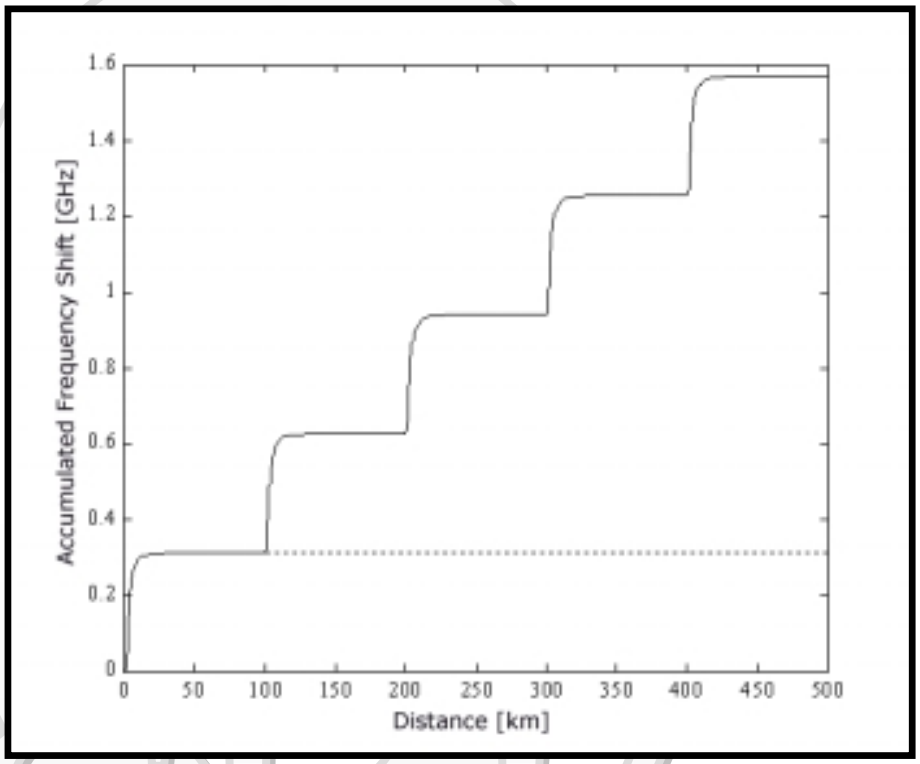
Dispersion Compensated Before the Receiver



40 Gbit/s

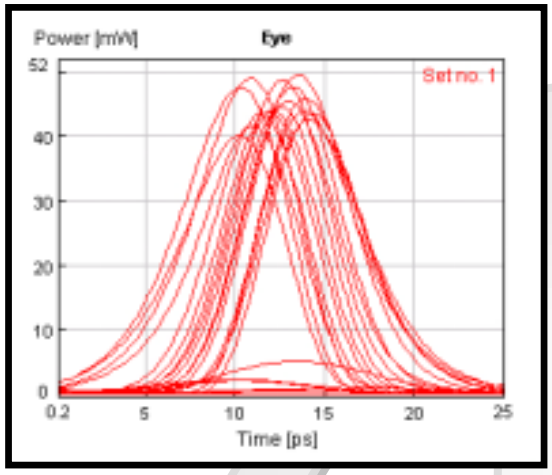
500 km Point-to-Point Link





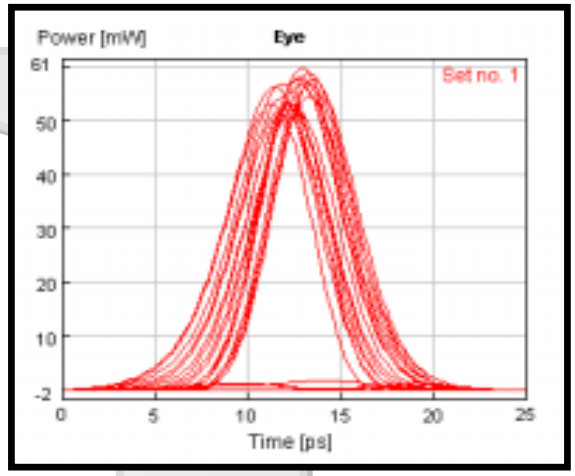
Gbit/s

Pre-Chirp + Post-Chirp

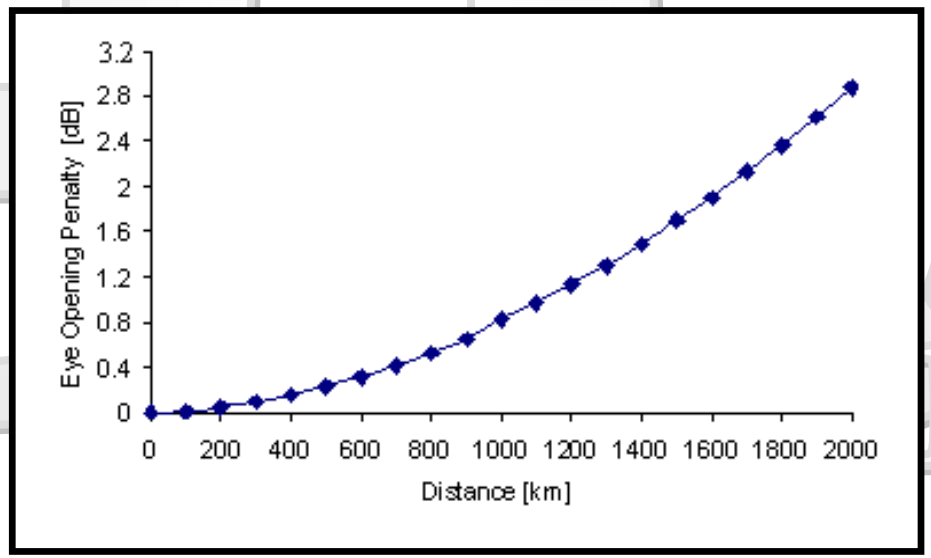


Without Pre-Chirp

Eye Diagrams
After 1200 km



With Pre-Chirp



Conclusions

- **Intra-Channel Nonlinear Effects Induce Pulse Distortion (SPM), Timing Jitter (IXPM), Shadow Pulses and Amplitude Fluctuations (IFWM)**
- **Intra-Channel Nonlinear Effects Can Be Mitigated Operating in the Pseudo-Linear Regime**
- **A Pre-Chirp and Post-Chirp Technique Allows to Operate in the Highly Dispersive Regime in All-Optical Networks**