Advanced Optical Modulation Formats in High-speed Lightwave System

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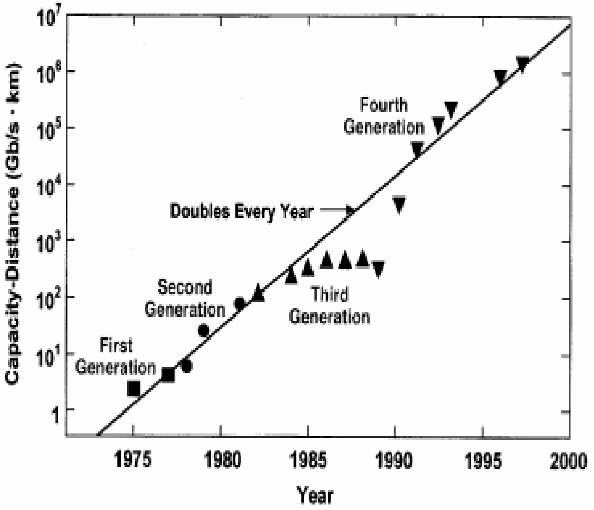
Outline

- Introduction
- Signal Propagation in Optical Fibers
- Overview of Optical Modulation Formats
- Impact of Optical Modulation Formats on Different Fibers
- A simplified model about SPM in dispersion-managed optical system
- Conclusion
- Future Work

Introduction

- Lightwave communication started in 1970s.
- Four generations of developing phases so far.
- Next-generation of lightwave system:
  - High-speed datarate per wavelength, e.g. 40Gbps
  - Operating wavelength-range extending from C-band to L-band and S-band
  - Closer channel spacing
- Modulation is becoming a key issue



Signal Propagation in Optical Fibers

- Nonlinear Schrödinger Equation:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial T^3} = i\gamma \left[|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T}(|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right]$$

$$T = t - z / v_g = t - \beta_1 z$$

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} = i\gamma |A|^2 A$$

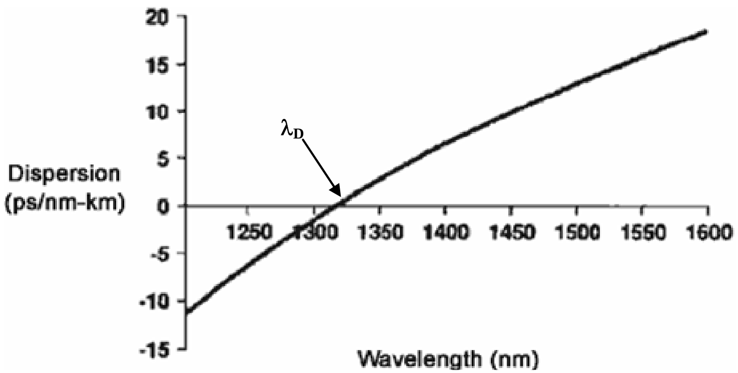
Signal Propagation in Optical Fibers (contd.)

- Linear Effects:
  - Optical Loss

$$P_T = P_0 \exp(-\alpha L)$$

  - Chromatic Dispersion

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \approx -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$



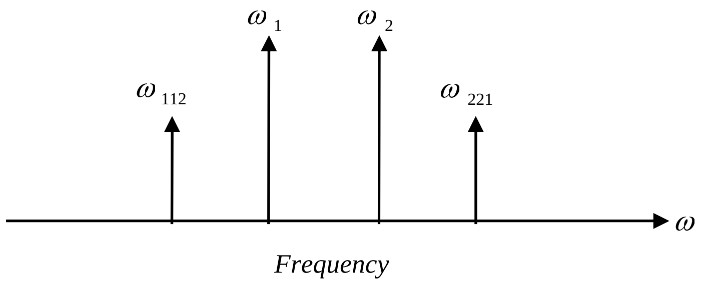
Signal Propagation in Optical Fibers (contd.)

- Nonlinear Effects:
  - SPM & XPM

$$\phi_{NL} = n_2 k_0 L(|E_1|^2 + 2|E_2|^2) \qquad \gamma = \frac{n_2 \omega_0}{c A_{eff}}$$

  - Four-wave Mixing (FWM)
    - Phase matching condition

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k$$



Signal Propagation in Optical Fibers (contd.)

- Split-step Fourier Transformation (SSFT)

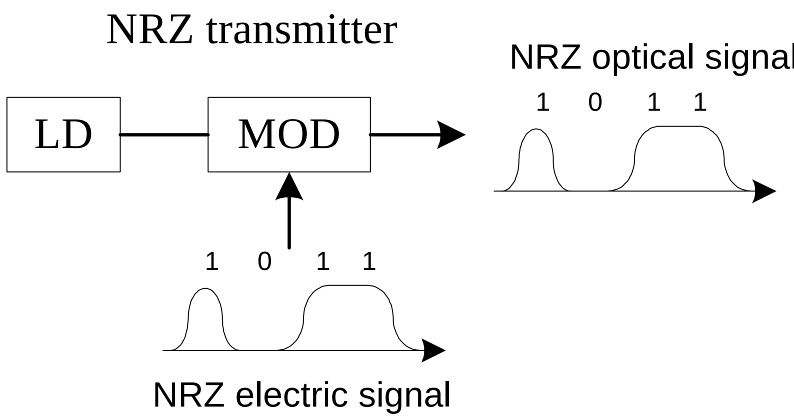
$$\frac{\partial A(z,T)}{\partial z} = \left(\widehat{D} + \widehat{N}\right)A$$

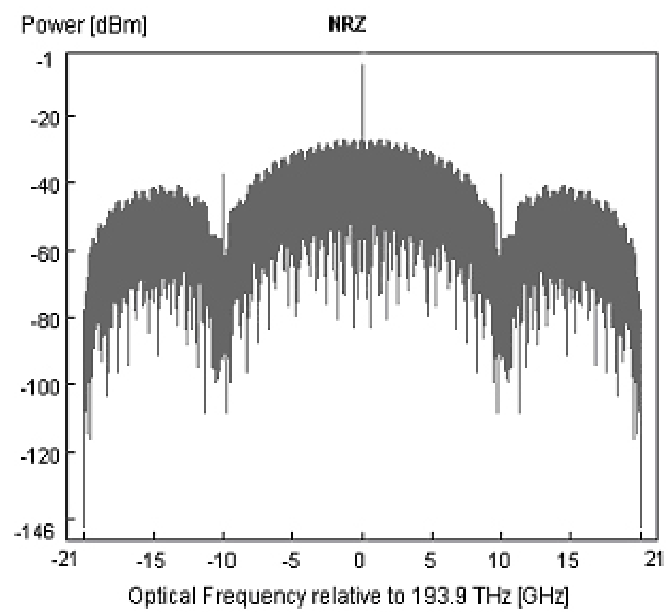
$$\widehat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} - \frac{\alpha}{2} \qquad \widehat{N} = i\gamma\left|A\right|^2$$

$$A(z+h_n,T) = \exp\left(h_n\hat{N}\right)F^{-1}\left\{\exp\left[h_n\widehat{D}(i\omega)\right]F\left[A(z,T)\right]\right\}$$

Overview of Optical Modulation Formats **(contd.)**

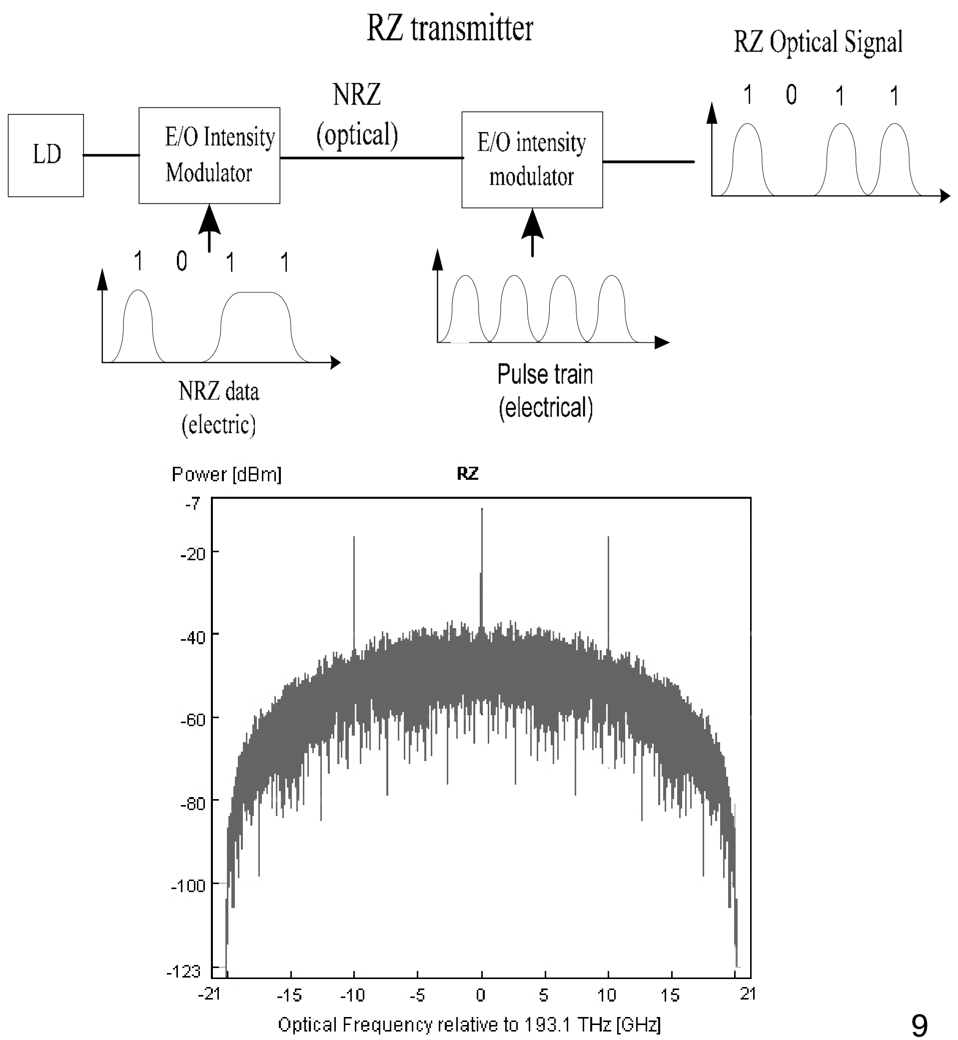
- NRZ-OOK
  - Most compact spectrum
  - Poor tolerance to dispersion and nonlinearities
  - Simplest configuration of transceivers





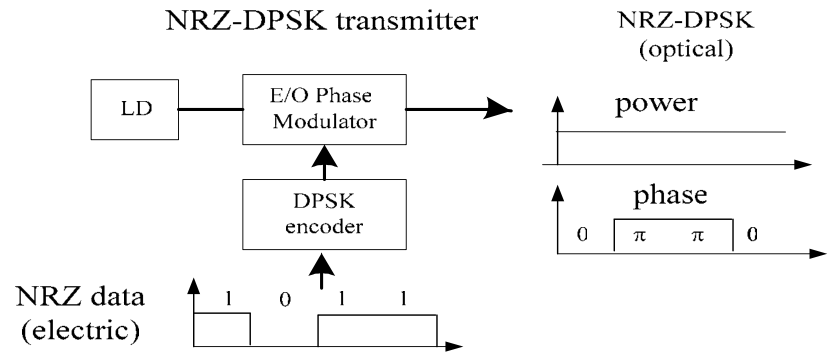
Overview of Optical Modulation Formats (contd.)

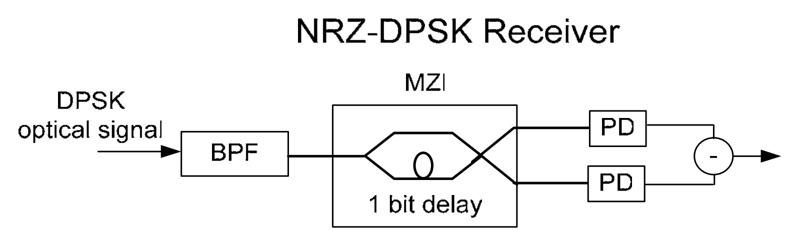
- RZ-OOK
  - Shorter signal width than its bit period
  - Improved tolerance to nonlinearities because of its regular RZ signal pattern

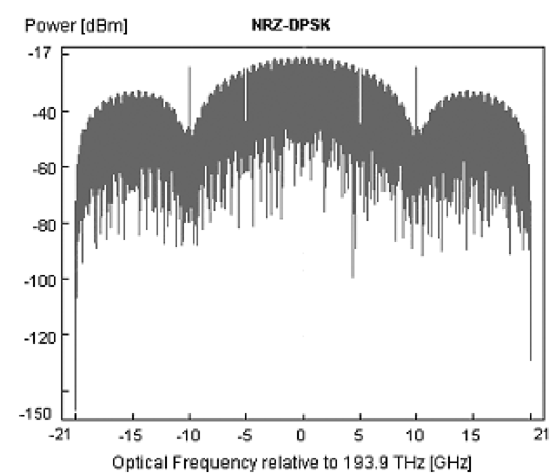


Overview of Optical Modulation Formats (contd.)

- NRZ-DPSK
  - Constant optical power
  - No carrier component in optical spectrum
  - 3dB better receiver sensitivity by using a balanced receiver

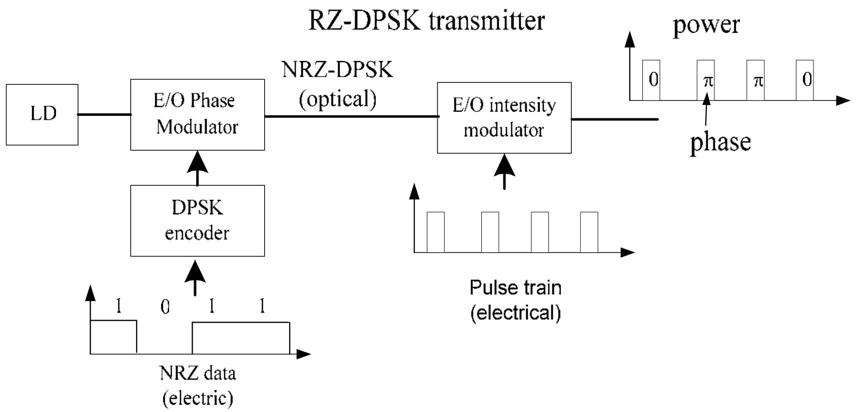


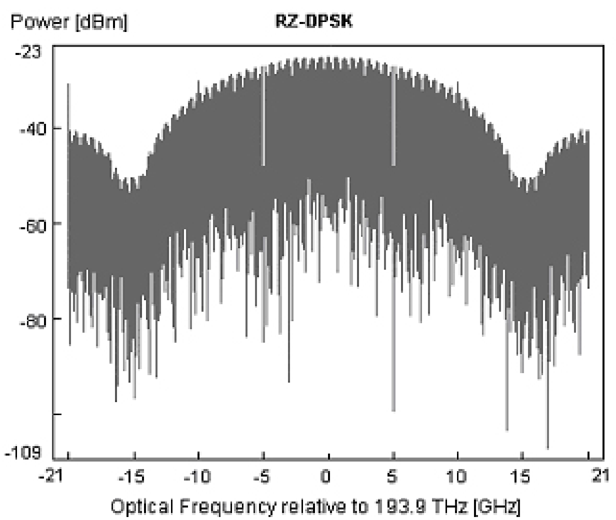




Overview of Optical Modulation Formats **(contd.)**

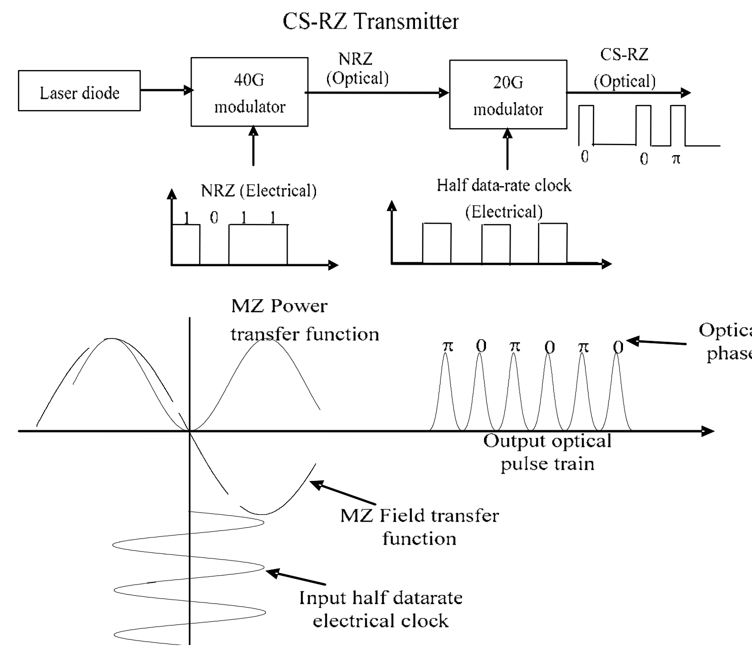
- RZ-DPSK
  - RZ shape of optical signal
  - No carrier component
  - 3dB better receiver sensitivity
  - Better nonlinearity tolerance than its NRZ counterpart

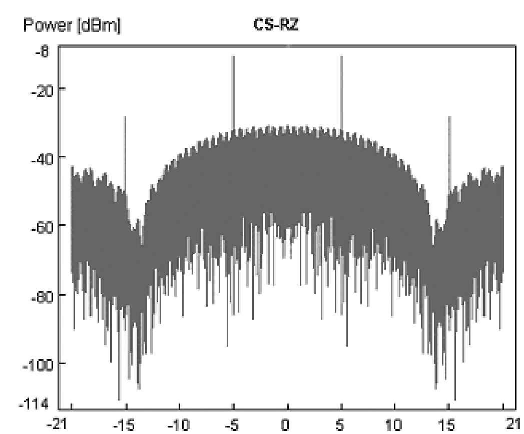




Overview of Optical Modulation Formats (contd.)

- CS-RZ
  - π phase shift between adjacent bits
  - No carrier component, two clock signals half datarate away of the carrier
  - Configuration of transmitter is easier than RZ-OOK



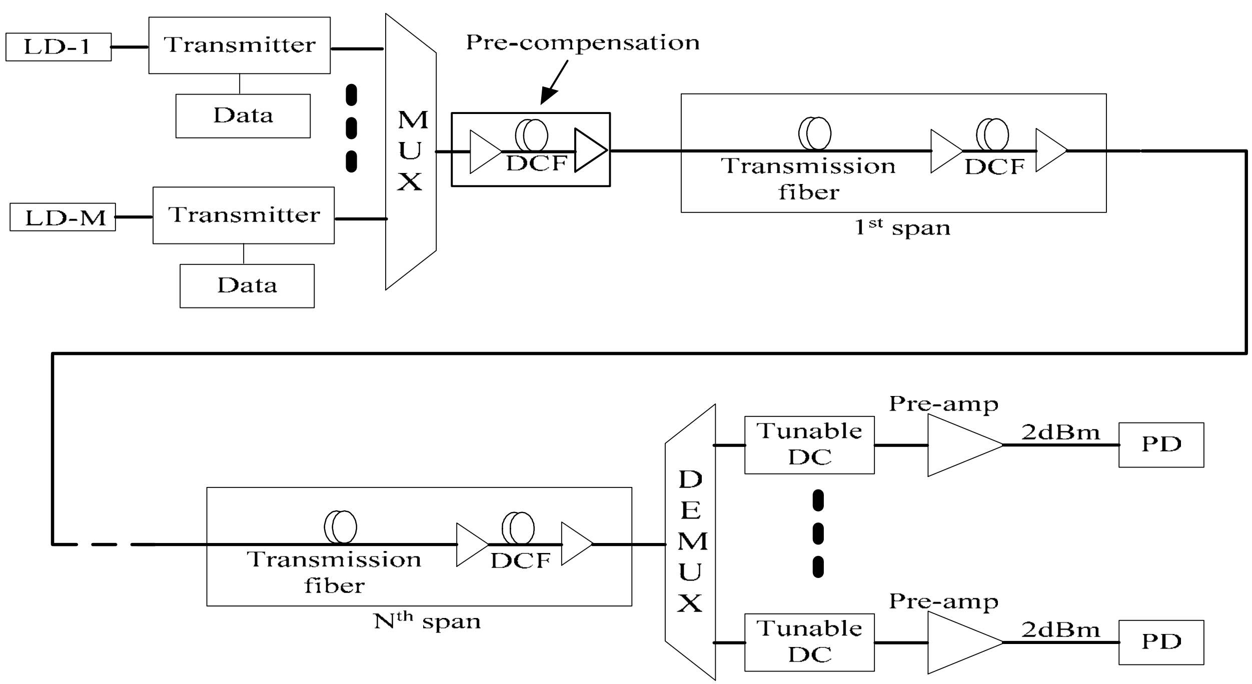


Impact of Optical Modulation Formats on Different Fibers **(contd.)**

- Motivation
  - Linear and nonlinear degrading effects are becoming severe in high-speed optical systems
  - System performance are influenced by both modulation formats and fiber types
  - The choice of transmission fiber could be dependent on the modulation format and datarate of system

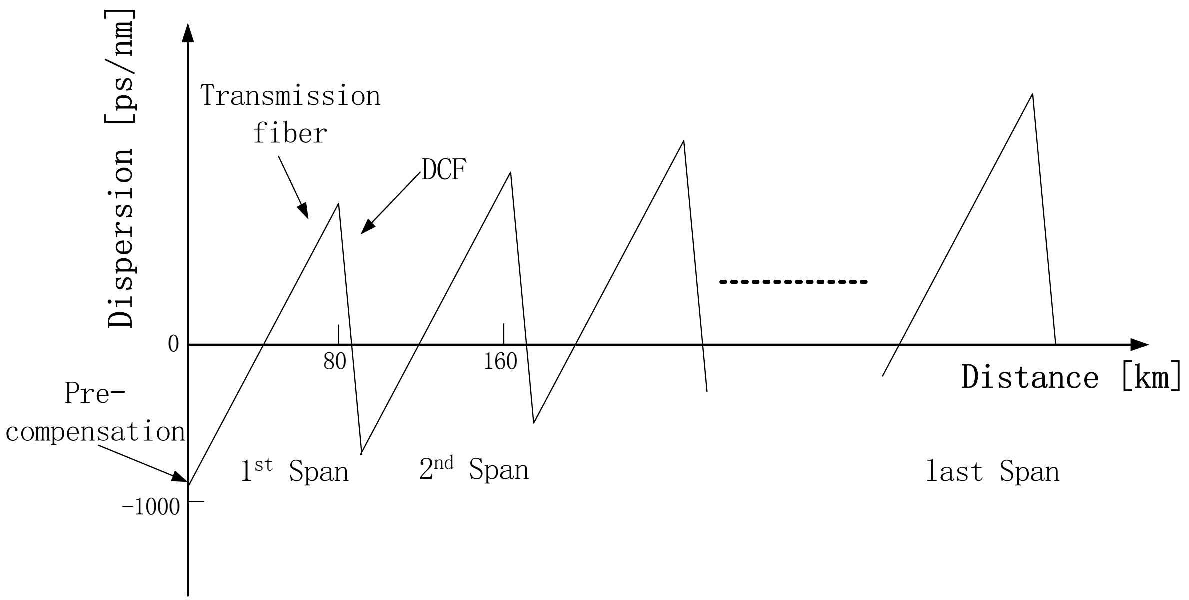
Impact of Optical Modulation Formats on Different Fibers (contd.)

- System Setup
  - 1.6 Tb/s of capacity, 40Gbps/ch×40ch or 10Gbps/ch×160ch
  - Spectral efficiency is 0.4b/s/Hz
  - Ideal dispersion slope compensation
  - Optical loss totally compensated by in-line EDFAs
  - using tunable DC after Demux in non-central channels



Impact of Optical Modulation Formats on Different Fibers (contd.)

- Dispersion Map
  - Pre-compensation optimized in single-channel case ranging from -1000ps/nm to 0ps/nm
  - Total residual dispersion is 0ps/nm in central channel
  - Residual dispersion compensation distributes evenly in each span



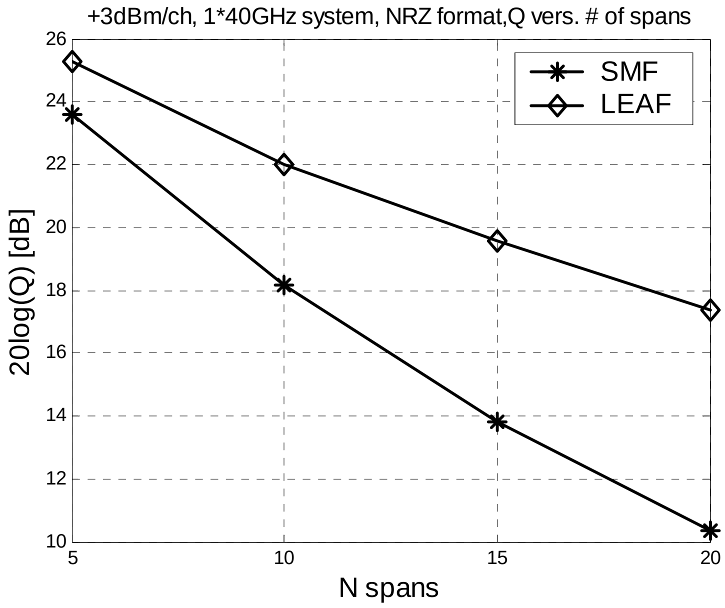
Impact of Optical Modulation Formats on Different Fibers (contd.)

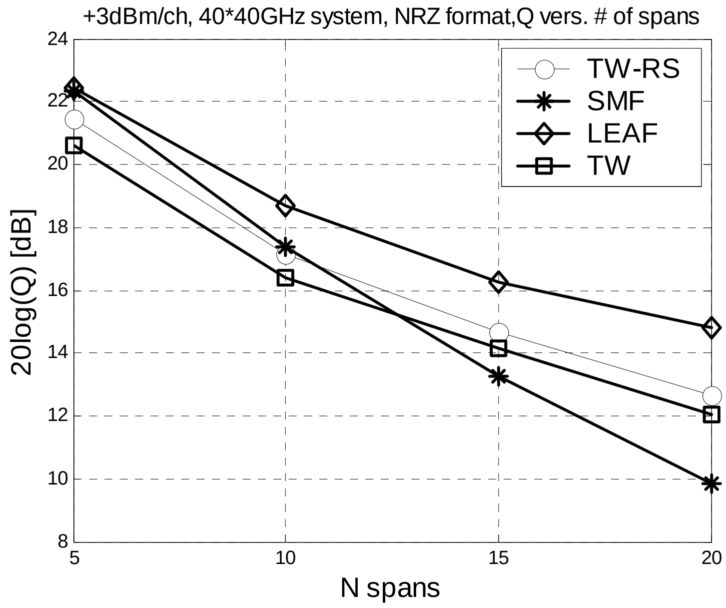
- Four modulation formats: NRZ, CS-RZ, NRZ-DPSK and RZ-DPSK
- Four kinds of transmission fibers: standard SMF, TW, TW-RS and LEAF ($\gamma = \frac{n_2 \omega_0}{c A_{eff}}$)

	Dispersion *D* @ 1550nm [ps/nm/km]	Dispersion slope *S* @1550nm [ps/nm^2/km]	Nonlinear refractive index n_2 [10^{-20} m^2/W]	Effective core area A_{eff} [μm^2]	Fiber attenuation α [dB/km]
SSMF	17	0.058	2.8	80	0.25
DCF for SSMF	-90	$0.058 \times \frac{-90}{17}$	4.3	14.3	0
TW	3.5	0.08	3.45	45	0.25
DCF for TW	-90	$0.08 \times \frac{-90}{3.5}$	4.3	14.3	0
TW-RS	4.4	0.045	3.2	55	0.25
DCF for TW-RS	-90	$0.045 \times \frac{-90}{4.4}$	4.3	14.3	0
LEAF	3.7706	0.11	3.0	72	0.25
DCF for LEAF	-90	$0.11 \times \frac{-90}{3.7706}$	4.3	14.3	0

Impact of Optical Modulation Formats on Different Fibers (contd.)

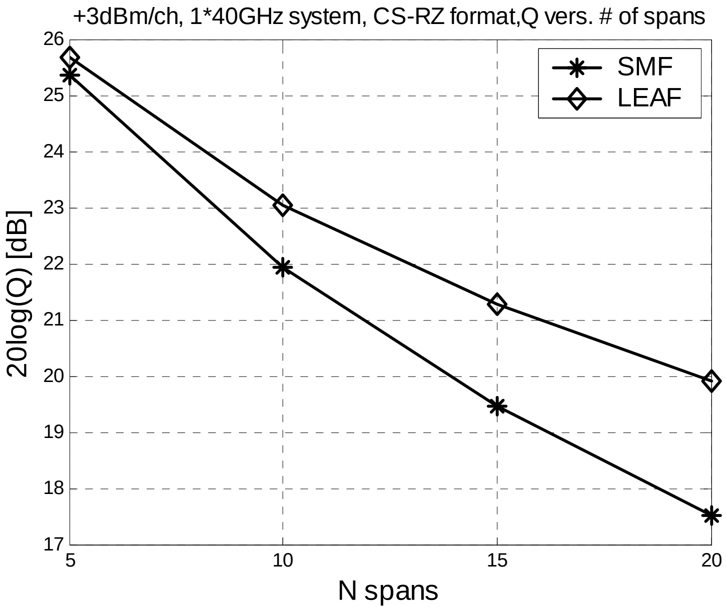
- 40Gbps Optical System, NRZ-OOK
  - LEAF outperforms SSMF in single-channel system
  - SSMF is beneficial in WDM system because of its large local dispersion *D*

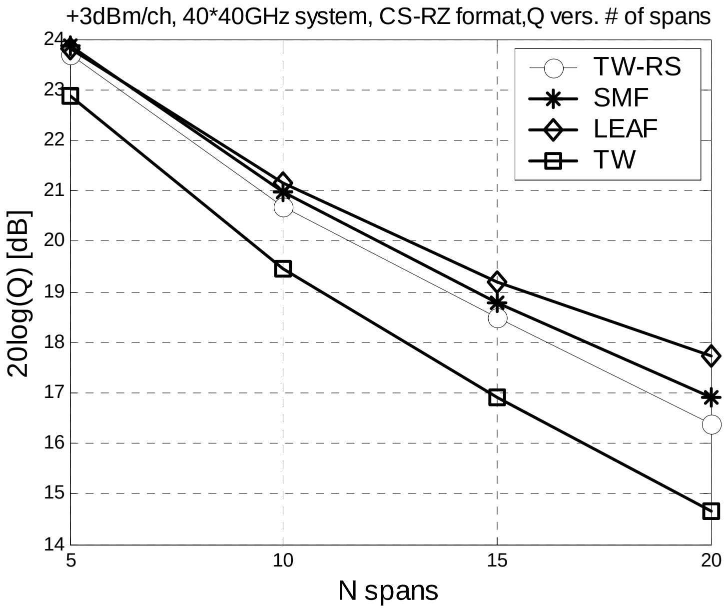




Impact of Optical Modulation Formats on Different Fibers (contd.)

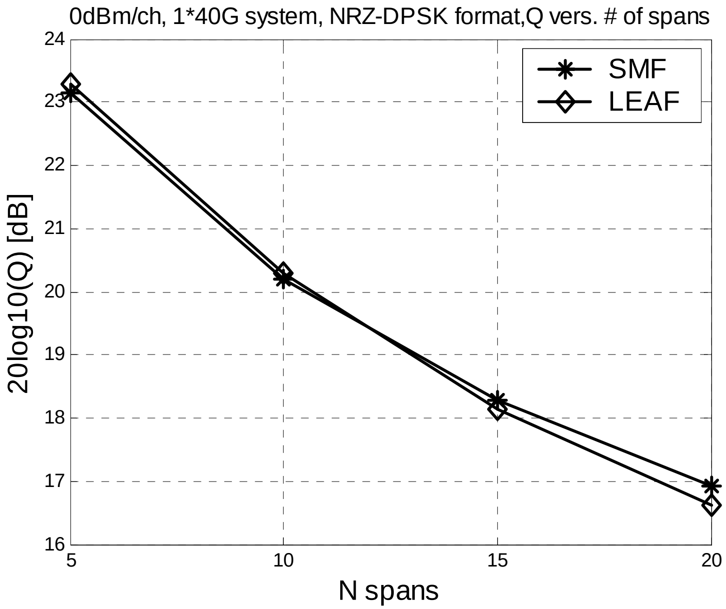
- 40Gbps Optical System, CS-RZ
  - More tolerant to nonlinear degrading effects than NRZ
  - Performance of SSMF and LEAF is similar to that of NRZ case

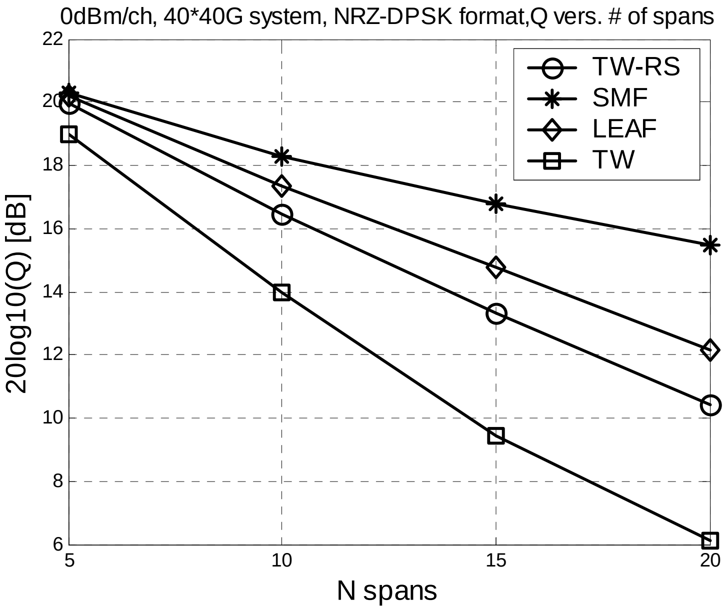




Impact of Optical Modulation Formats on Different Fibers (contd.)

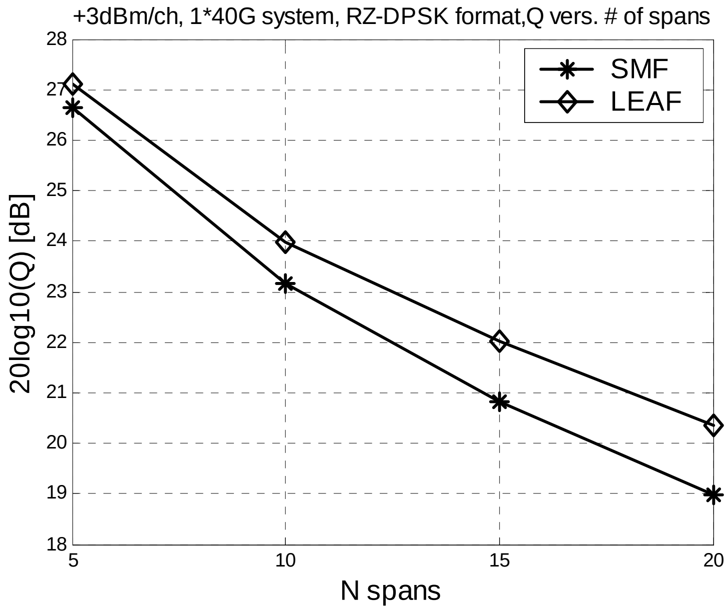
- 40Gbps Optical System, NRZ-DPSK
  - SPM is not significant because of constant optical power of NRZ-DPSK
  - SSMF outperforms LEAF because of its larger *D*

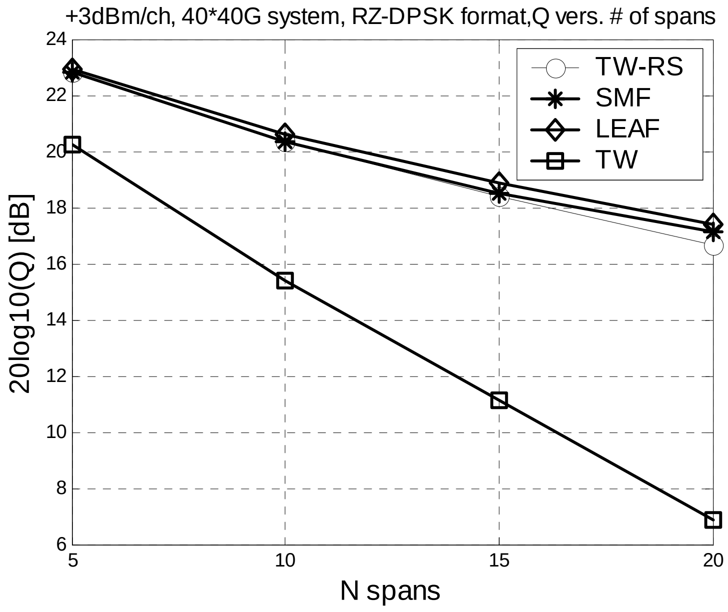




Impact of Optical Modulation Formats on Different Fibers (contd.)

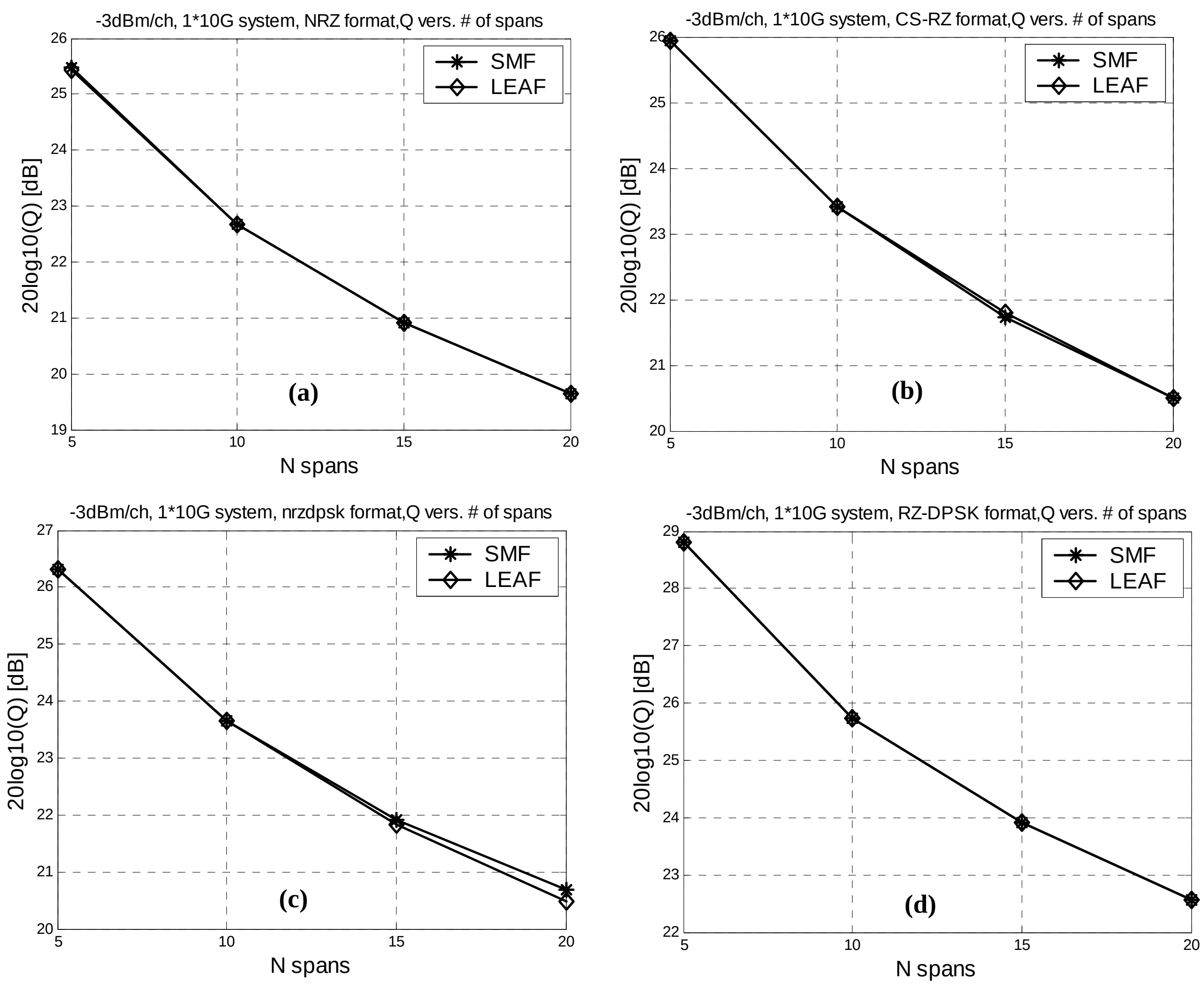
- 40Gbps Optical System, RZ-DPSK
  - Best tolerance of nonlinearity among investigated formats
  - All fibers except TW have similar performance in WDM System





Impact of Optical Modulation Formats on Different Fibers **(contd.)**

- 10Gbps Optical System, Single-channel

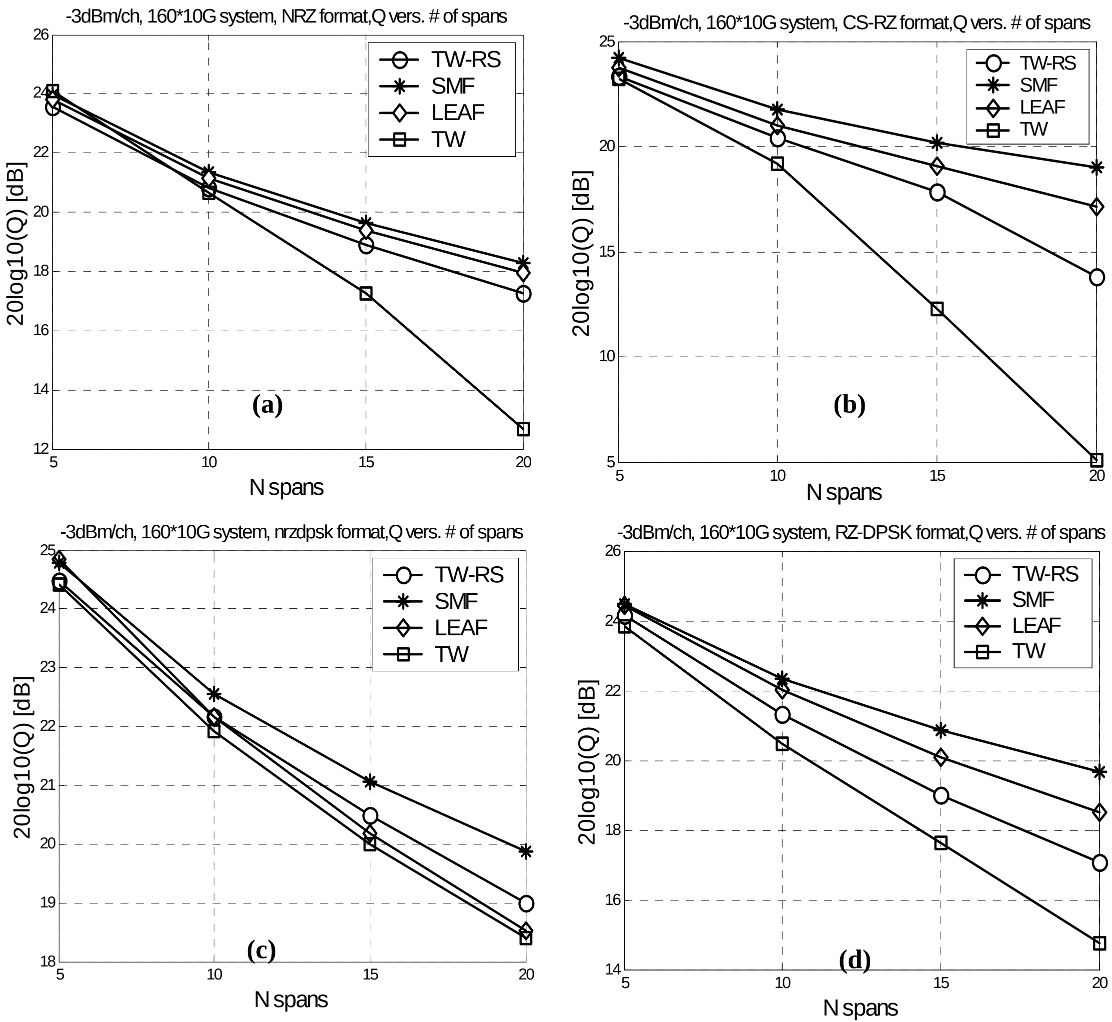


Impact of Optical Modulation Formats on Different Fibers (contd.)

- 10Gbps Optical System, Single-channel
  - All kinds of fibers shows nearly identical performance for all investigated modulation formats
  - SPM is not a big concern in 10Gb/s system

Impact of Optical Modulation Formats on Different Fibers (contd.)

- 10Gbps Optical System, 160ch, 25GHz channel spacing



Impact of Optical Modulation Formats on Different Fibers **(contd.)**

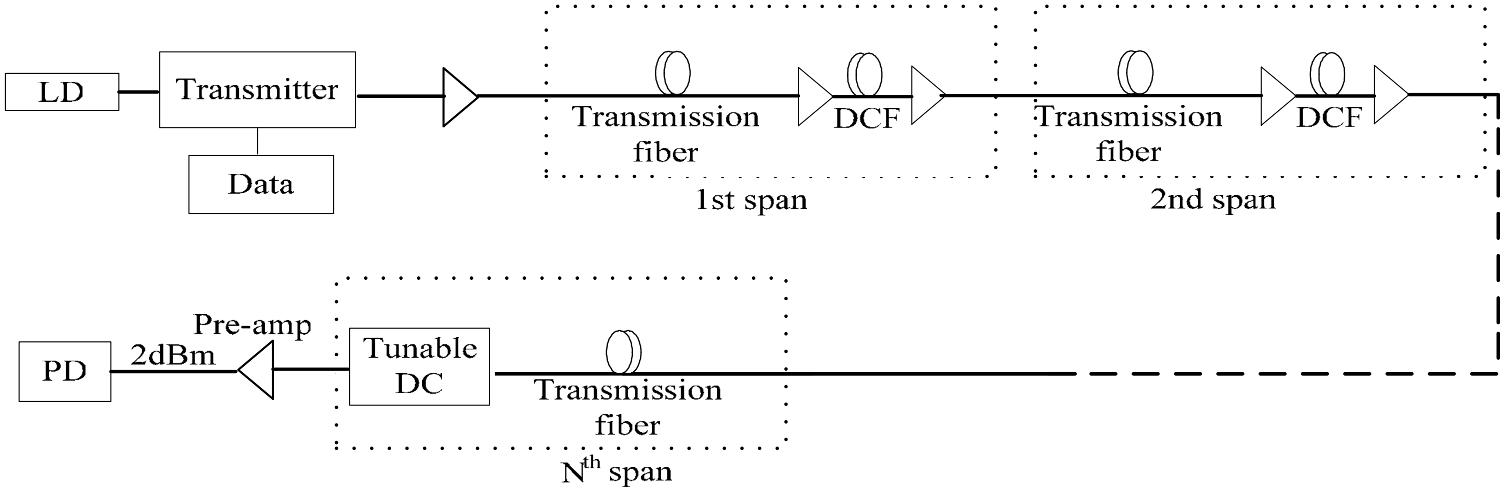
- 10Gbps Optical System, 160ch, 25GHz channel spacing
  - XPM & FWM are the dominant degrading effect in the system because of the narrow channel spacing
  - SSMF outperforms other fibers for all formats because of its larger *D*

A simplified model about SPM in dispersion-managed optical system

- Motivation
  - SPM is one of the dominant degrading factors in high-speed (e.g. 40Gbps) optical system
  - A simplified model is helpful in the design of system concerning the limit induced by SPM
  - SPM-limited system performance maybe dependent on datarate and modulation formats

A simplified model about SPM in dispersion-managed optical system **(contd.)**

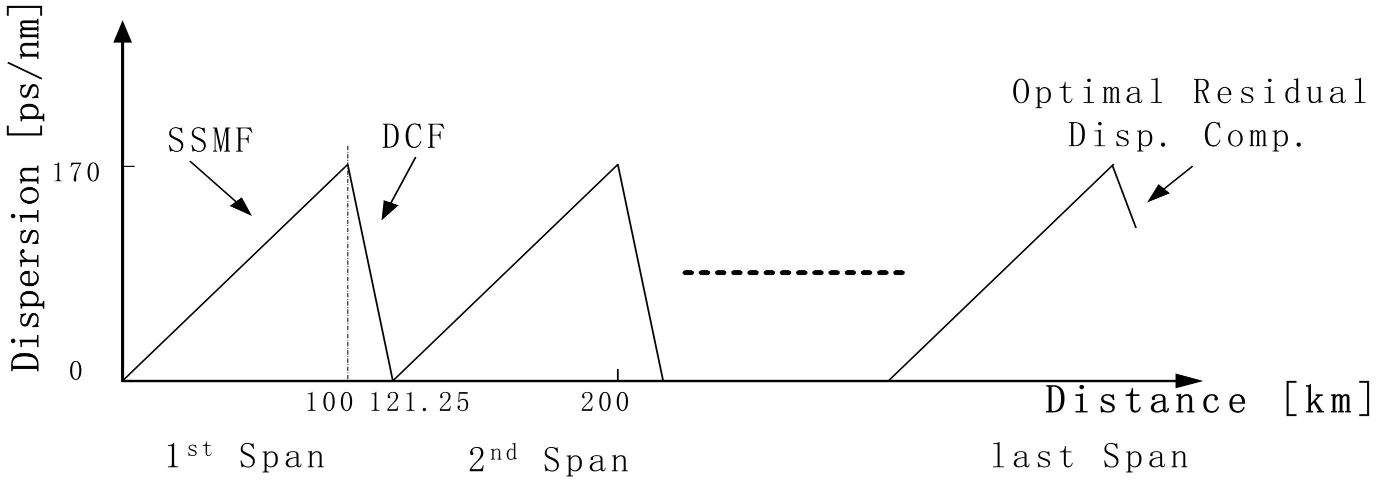
- System Setup



	SSMF	**DCF**
Dispersion parameter D [s/m^2]	17e-6	-80e-6
Nonlinear index n_2 [m^2/W]	2.43e-20	4.3e-20
Core area A_{eff} [m2]	72e-12	14.3e-12
Attenuation α [dB/km]	0.2	0.5

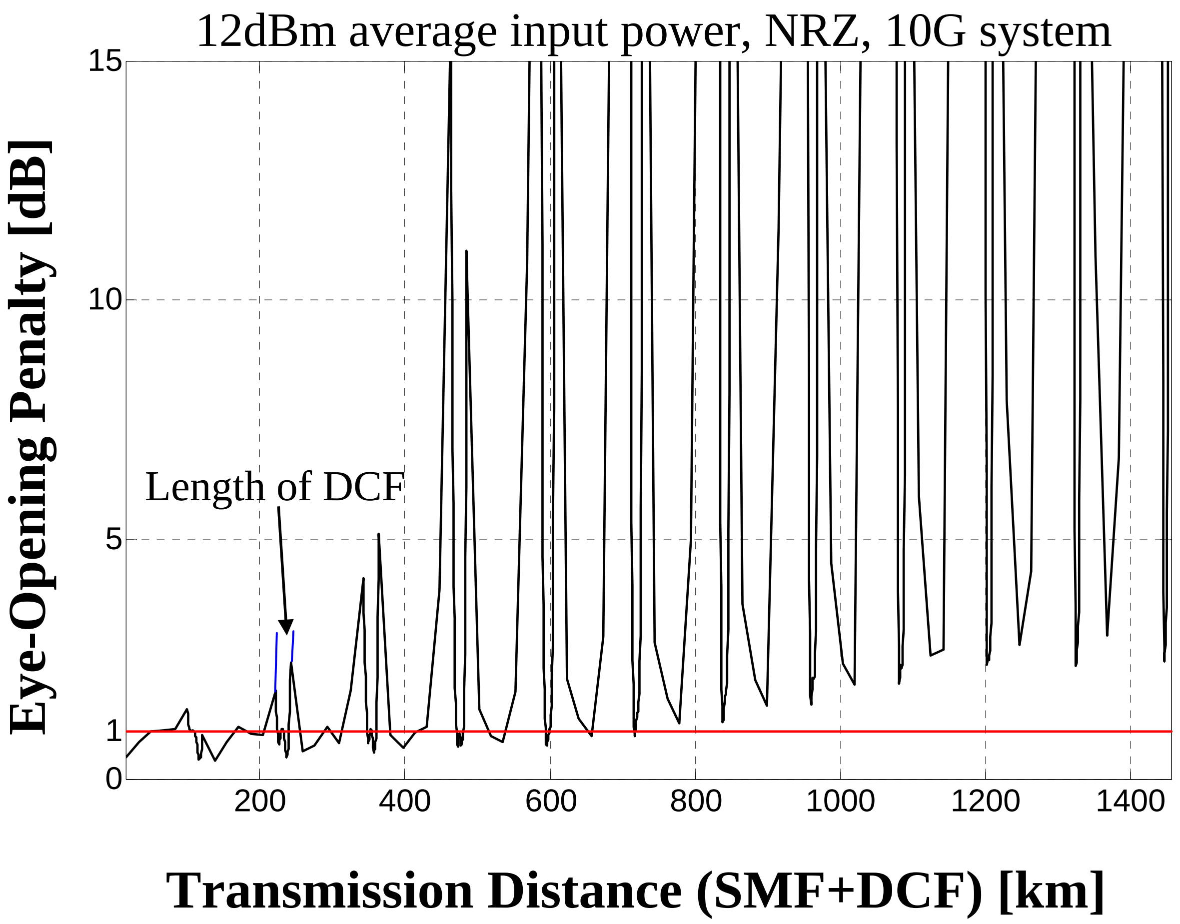
A simplified model about SPM in dispersion-managed optical system **(contd.)**

- Dispersion Management
  - 100% per-span dispersion compensation in-line
  - Optimum dispersion compensation for the system by optimizing the length of DCF in the last span



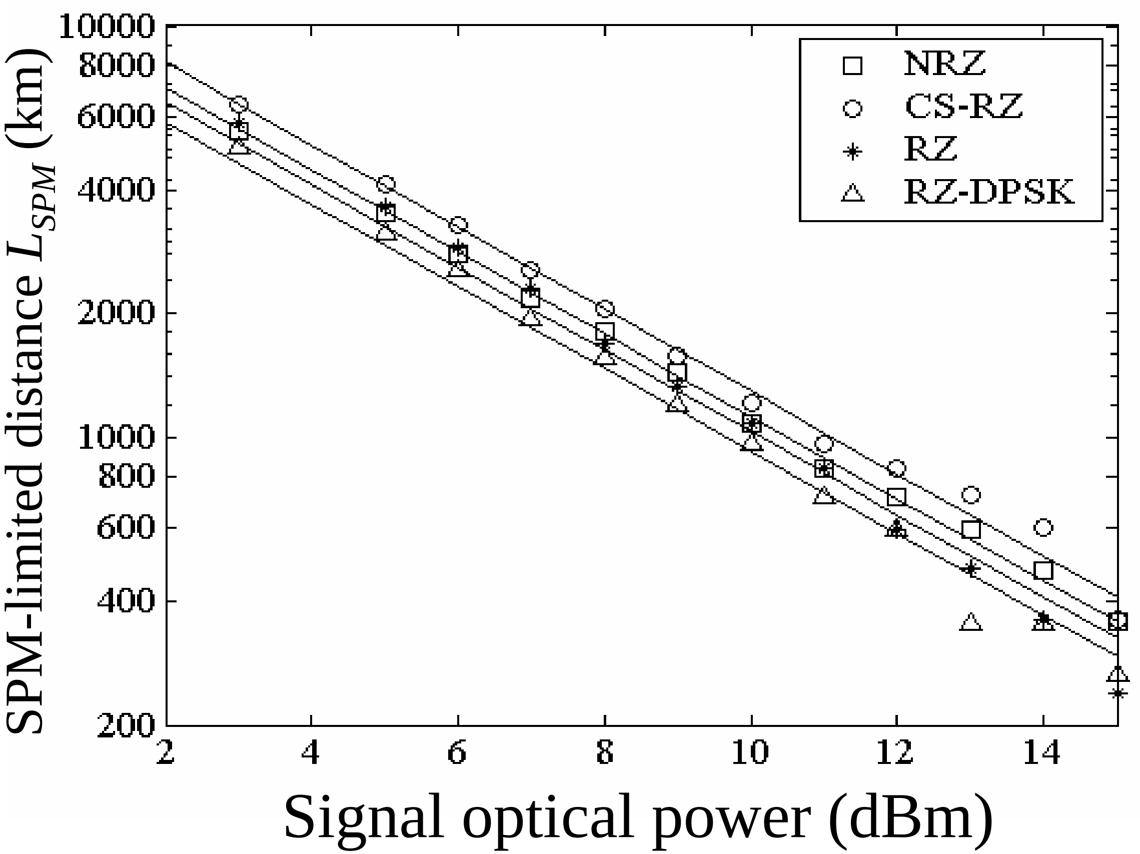
A simplified model about SPM in dispersion-managed optical system **(contd.)**

- Definition of SPM-Limit on Transmission Distance L_{spm}



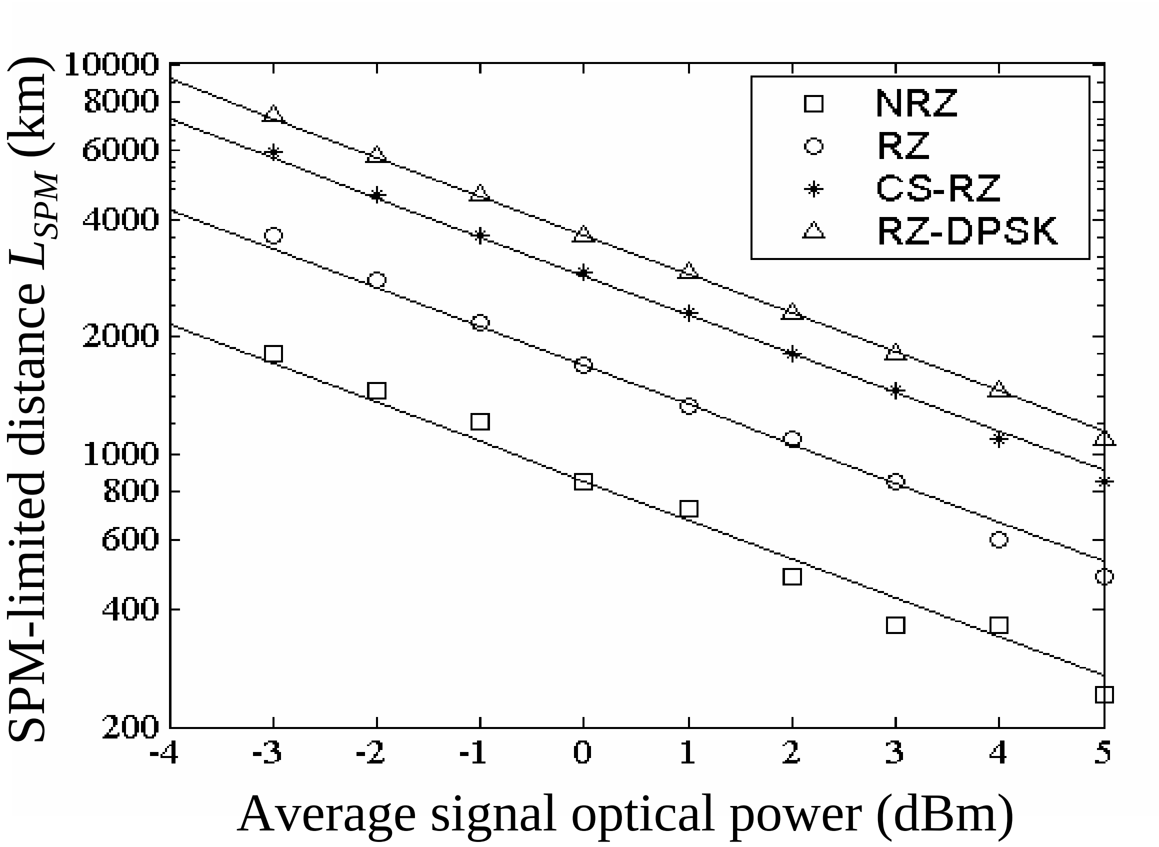
A simplified model about SPM in dispersion-managed optical system **(contd.)**

- SPM-limited maximum transmission distance at 10Gb/s
  $\text{Log}(L_{SPM}) = -P(\text{dBm}) + C$



A simplified model about SPM in dispersion-managed optical system **(contd.)**

- SPM-limited maximum transmission distance at 40Gb/s
  $\text{Log}(L_{SPM}) = -P(\text{dBm}) + C$



A simplified model about SPM in dispersion-managed optical system (contd.)

- Impact of Modulation Formats
  - $L_{SPM} \cdot P = C$ holds For all modulation formats, where *C* is a constant depending on modulation formats.
  - No obvious difference in *C*-value (< 20%) for different formats in 10Gb/s system.
  - In 40Gb/s system, RZ-DPSK shows the best SPM-induced nonlinearity tolerance, about 400% increase of transmission distance compared to NRZ format.

Power- L_{SPM} product C for different modulation formats in $[mW \cdot km]$

Data-rate	NRZ	RZ	CS-RZ	RZ-DPSK
10 Gb/s	11222	10294	12926	9254
40 Gb/s	855	1683	2864	3636

A simplified model about SPM in dispersion-managed optical system **(contd.)**

- Limit Induced by ASE-noise
  - ASE noise generated by inline EDFAs is another major limitation.
  - SNR-limited receiver *Q*-value is directly proportional to the square-root of optical signal power:

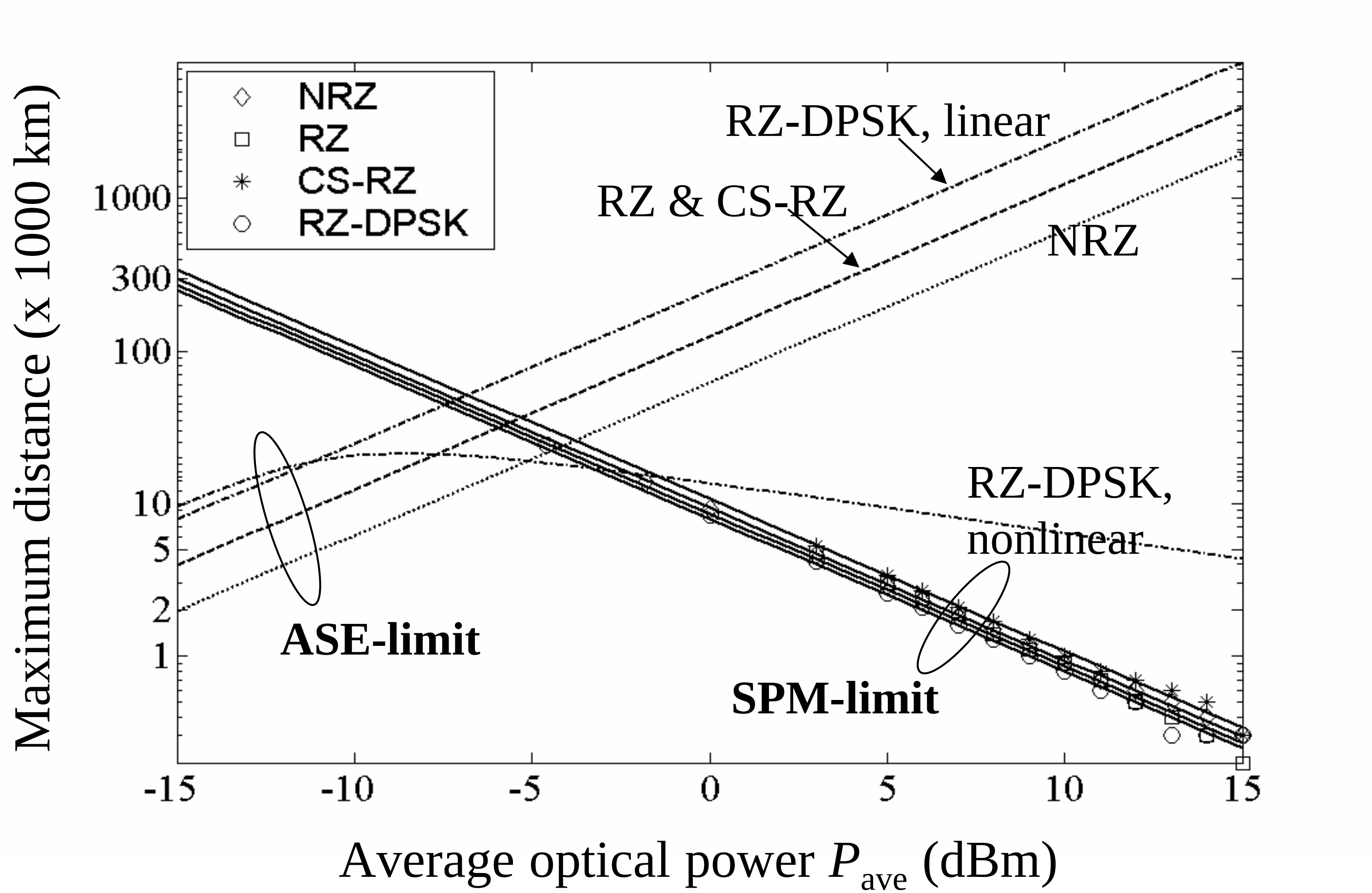
$$Q = \sqrt{\frac{\lambda P_{in}^{(1)}}{2NhcF_{eff}(G_{eff}-1)B_e}}$$

  - RZ-DPSK is vulnerable to Gordon-Mollenauer effect where ASE optical intensity noise can be converted into phase noise through fiber nonlinearity.

$$Q = \frac{\pi}{2\sqrt{2(\sigma_L^2 + \sigma_{NL}^2)}}$$

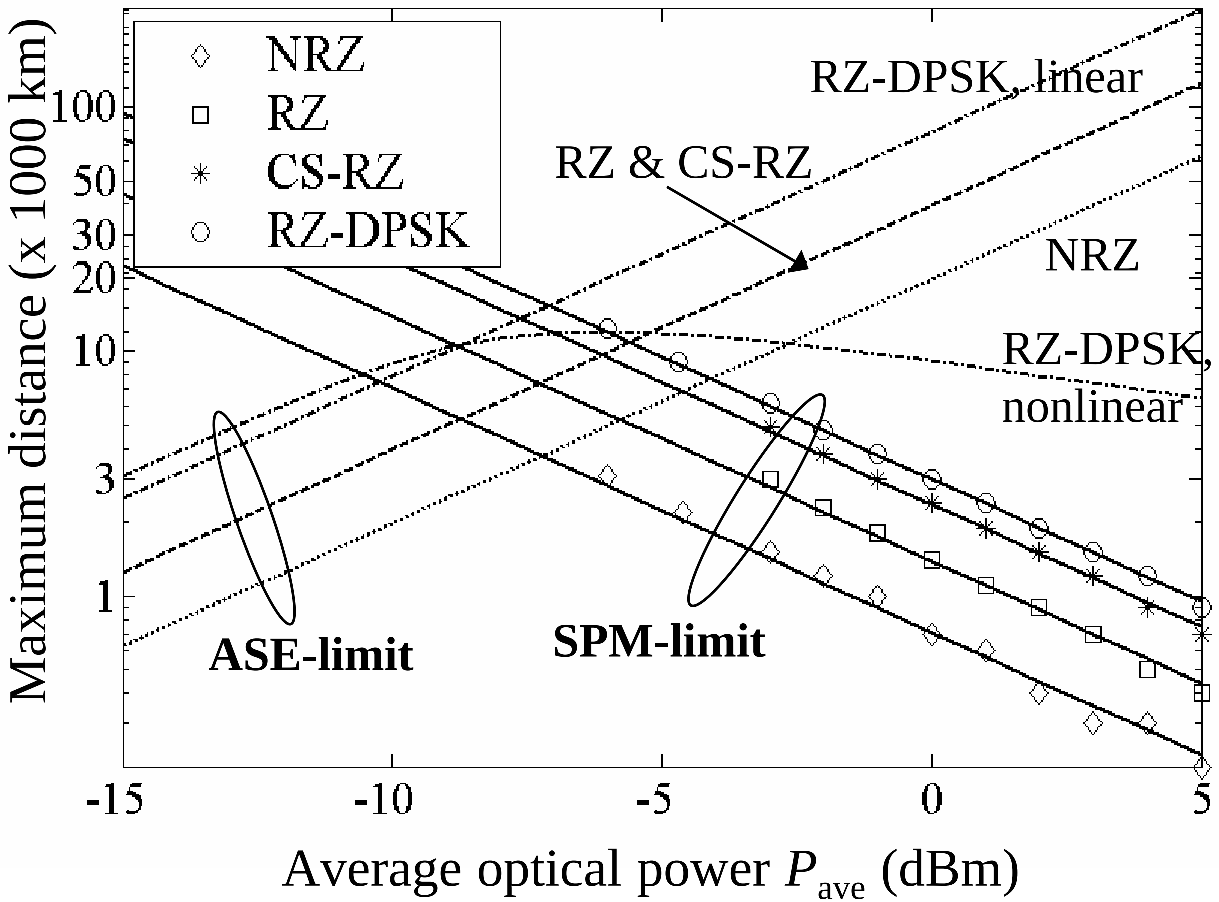
A simplified model about SPM in dispersion-managed optical system **(contd.)**

- Limit Induced by ASE-noise at 10Gb/s



A simplified model about SPM in dispersion-managed optical system (contd.)

- Limit Induced by ASE-noise at 40Gb/s



Conclusion

- Impact of modulation formats on different fibers are compared
  - In 10Gbps WDM system, XPM & FWM are the major source of degrading effects; SSMF outperforms other fibers
  - In 40Gbps WDM system, SPM is the major source of degrading effect if NRZ is used; Using advanced modulation format like DPSK, SSMF is still a competitive transmission fiber
- A first-order rule about SPM is found: $L_{SPM} \cdot P = C$
  - RZ-DPSK shows the best tolerance to SPM-induced distortion w/o consideration of nonlinear phase noise at 40Gb/s datarate.
  - At 10Gb/s, all the modulation formats exhibit similar SPM-tolerance. At this datarate, RZ-DPSK is most susceptive to nonlinear phase noise.

Future Work

- In the future, there are several things could be done:
  - Multiple-level signaling like DQPSK compared to the binary signaling concerning both performance and commercial realization
  - Compensation of nonlinearity in electrical domain

Thanks!