Multimode Fiber Link Model for 1300nm Equalized Links

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Outline

- General approach to link simulations
- Description of MMF Link Model
- Use of the Model for Equalized Link Design

General Approach to Link Simulations

Possible Link Simulation Approaches

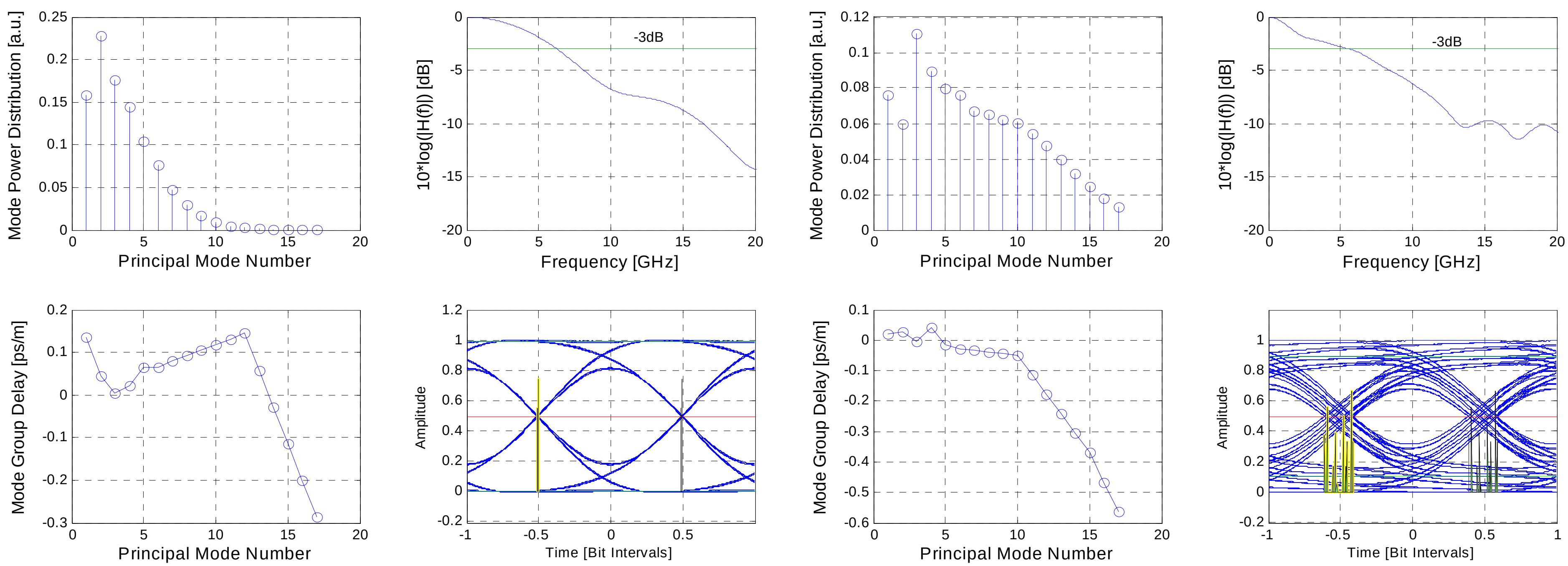
- Use analytical tools – use well known formulas usually based on Gaussian approximation
  - Simple, fast, reasonably accurate, lacks direct capability for accurate analysis of equalized links
  - Easy implementation in Excel, Basic, C/C++, Java, Matlab or other languages
- True Monte Carlo simulation
  - Takes noise into account as signal propagates
  - Accurate, but time consuming, need to know all parameter distributions
    - Can use importance sampling, but difficult to implement
  - Most difficult for implementation, any programming language (Matlab, C/C++, some commercial tools)

Proposed Implementation Approach:

- ✓ Basic quasi-analytical approach (Combines simulation with analysis)
  - Separates the problem into signal and noise part
  - Simulation generates noiseless waveforms at the receiver with all signal distortions taken into effect
  - Given the noise pdf (here Gaussian), calculates the probability of error with a formula based on the system parameters for the given channel
    - Departures from Gaussian in noise distributions can't be easily handled
  - Commercial programs use the quasi-analytical approach
  - Moderate implementation difficulty in Matlab, C/C++ or other languages
  - Implementation in Excel possible by using shared libraries (presentation for March meeting planned)

What is more relevant:
Bandwidth or ISI power penalty

Link 1 Link 2

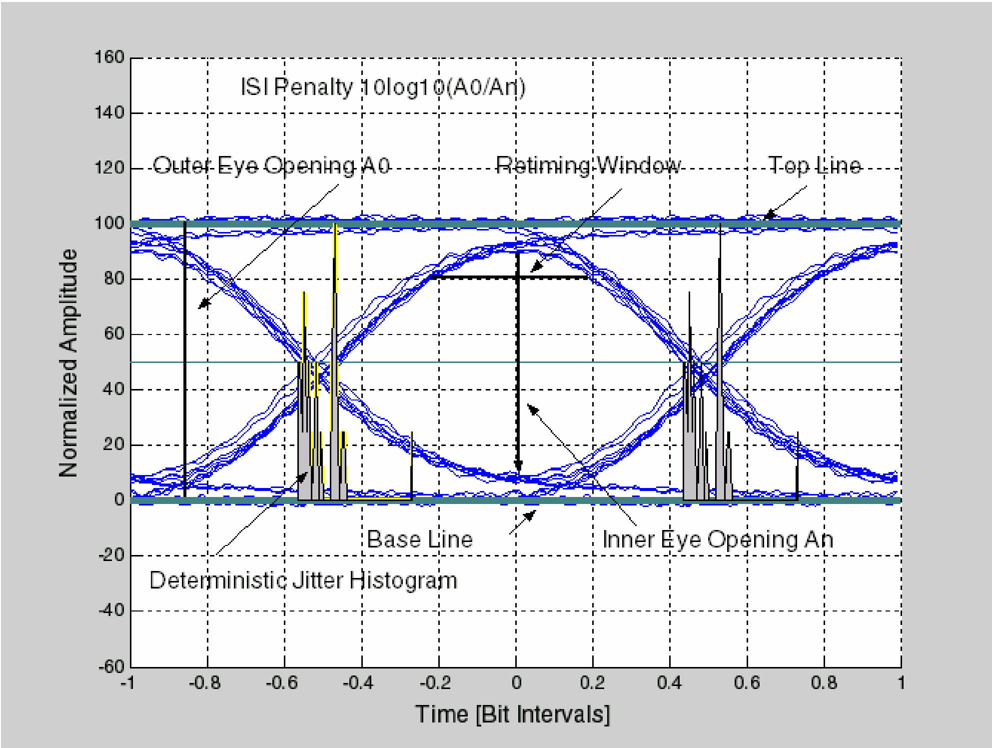


Bandwidth is approximately the same, ISI penalty and DJ very different
Need SIGNAL SHAPES to find ISI penalty

Including Jitter in Simulations

- Complete inclusion (DJ+RJ) not possible because of time constraints
- Duty cycle distortion (DCD), deterministic jitter can be easily added in the model:
  - DCD by modifying the width of the standard pulse shape
  - Input DJ by passing the signal through a filter with very low BW and then going through a limiting amp
- Random jitter
  - Can be added at input, for devices (laser, receiver).
  - Do we want random jitter added ?
    - obscures the signal
    - can’t simulate to BER~1e-12

ISI and DJ Calculation

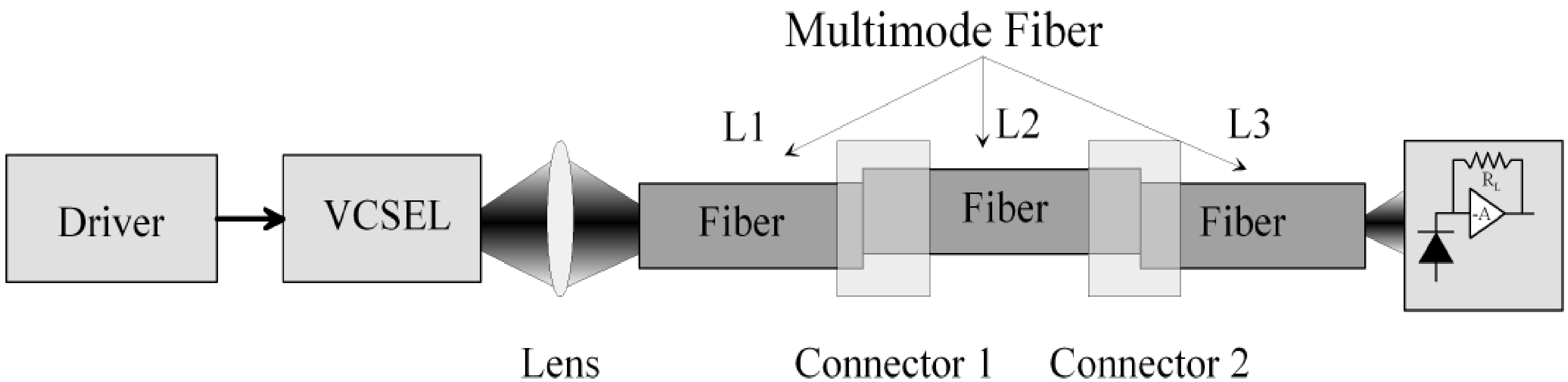


- Finds first top line, base line and threshold, then minimum vertical eye opening
- ISI penalty (optical) = 10*log$_{10}$(An/A0)
- Vertical eye closure calculation is NOT always accurate – uncertainty due to A0
- DJ is determined from zero crossings – accurate when DJ < 0.7 U.I.

Multimode Fiber Link Model

Multimode Fiber Link Model

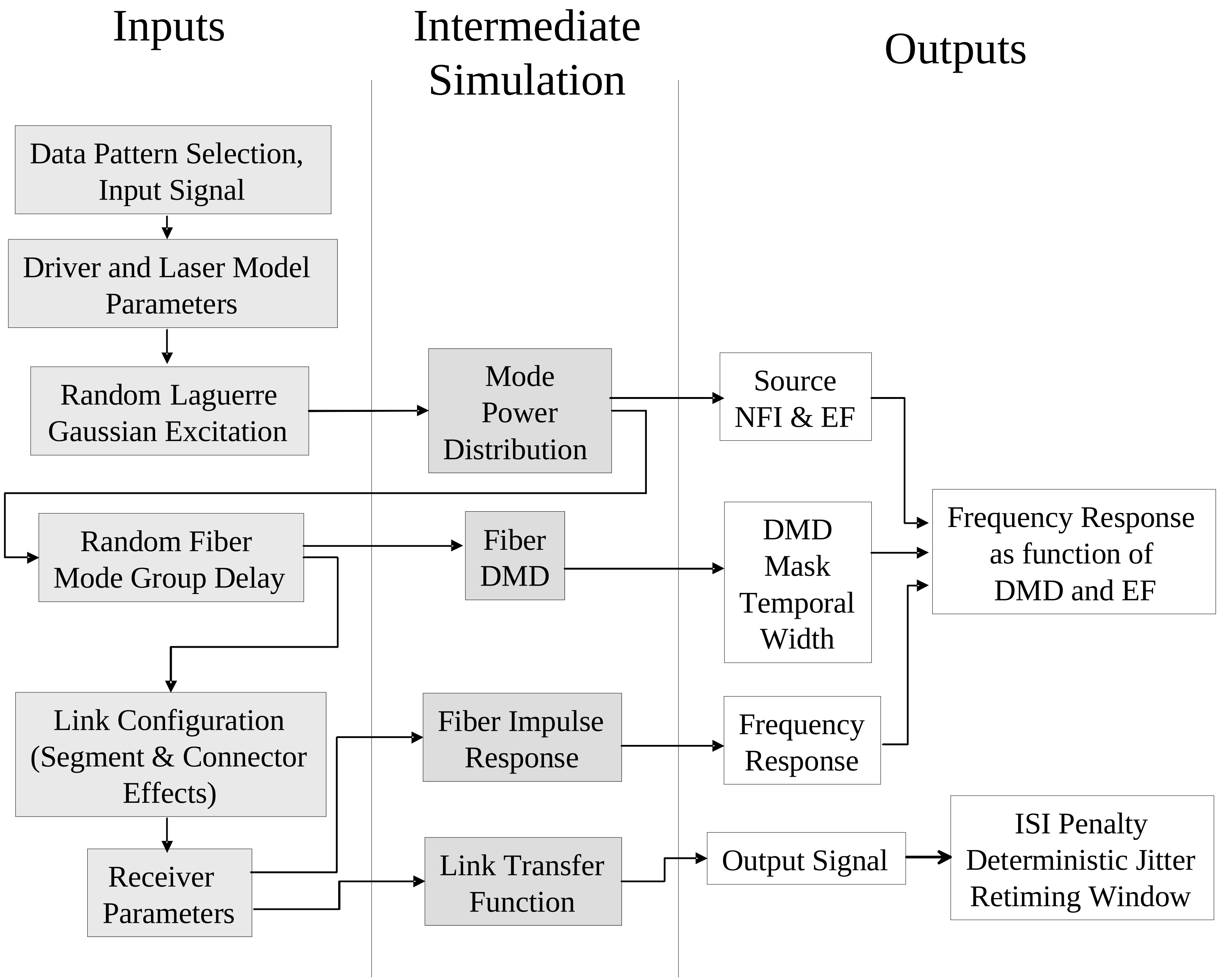
- Structure of MMF Link Model follows typical structure of Ethernet Links
- MMF Link model used by TIA FO-4.2.1 in development of OM3 fiber
  - Theoretical model foundation and development results published in the *Journal of Lightwave Technology* (ref. 1-2).



Simulation Environment and Inputs to IBM MMF Link Model

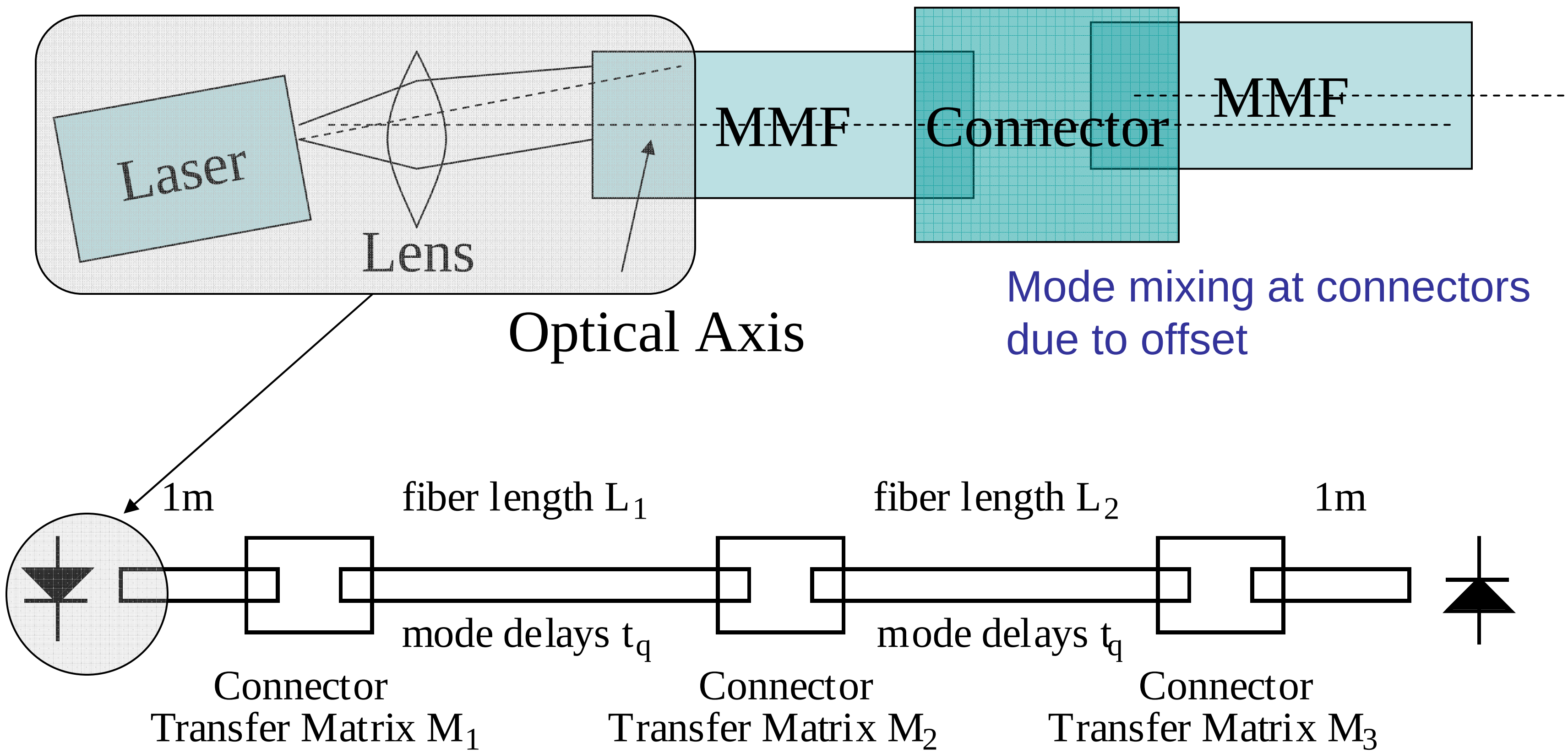
- IBM MMF Link Model implemented in Matlab includes:
  - Solution of Scalar Wave Equation for Fiber Field, mode delays
  - Fiber-fiber connector offset impact
  - Source-fiber lateral, axial and tilt offset impact
  - Calculation of Mode Power Distribution (MPDs) and Encircled Flux at fiber input
- Simulation of overall system behavior and estimation of link performance by evaluating ISI penalty, system bandwidth, deterministic jitter and retiming window
  - Uses linear models for driver, laser and receiver, with worst case parameters taken from IEEE 802.3ae specs
  - Uses fiber mode delays, launch MPDs and Connector transfer function to find overall fiber response
- Performance of a set of 40000 links simulated from the following pool of devices:
  - 2000 TX launch conditions, 5000 fiber DMD profiles and 1000 link configurations (include fiber-fiber connector offsets, 4 link types)
- New dataset at 1300 nm created from delays at 850nm
  - methodology in ref. 2, section VI.B (eq. 6) used to transform delays from 850 nm to 1300 nm values

Simulation Block Diagram

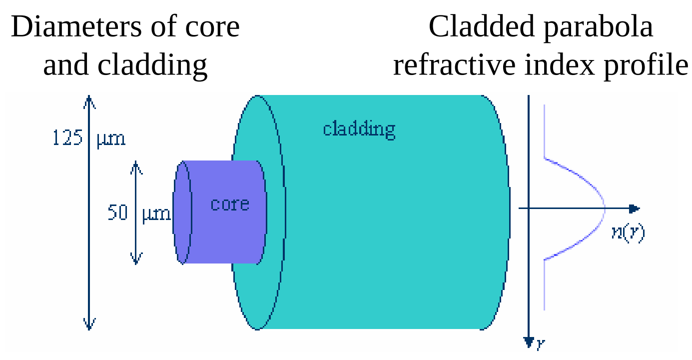


MMF link diagram – detail of laser launch model

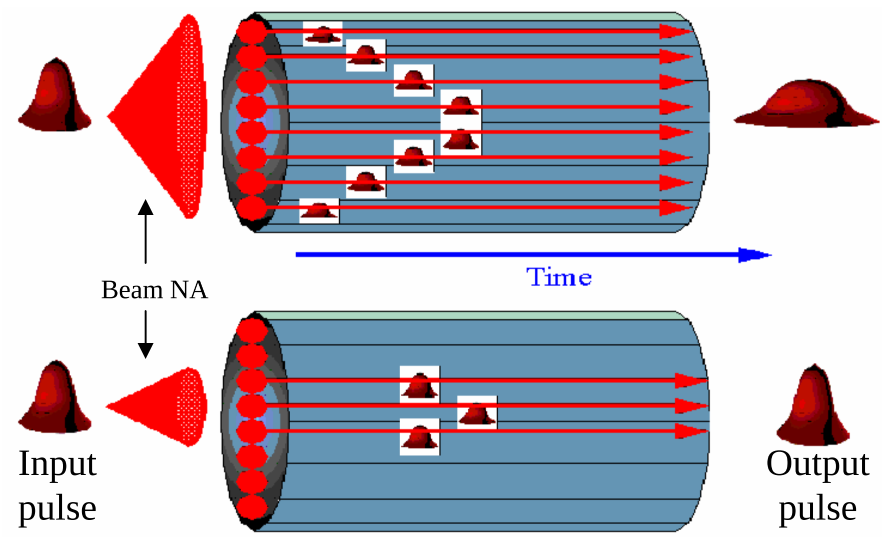
Launch Conditions –
offsets, tilts, beam size



Launch conditions and mode groups in Multimode Fiber (MMF)



Multimode optical fiber



- A multimode fiber can be represented as a waveguide propagating each of the modes in a separate “tube”
- Which modes will be excited and what will be the power distribution between them depends on the launch conditions
- The impulse response of the MMF is a weighted superposition of all modal pulses from each “tube”
- Need to find **coupled power** and **delay times** (or propagation constants) for each mode (mode group)

Fiber model and the scalar wave equation

- The electric field in the fiber assumed to be in the form:

$$\Psi(r,\phi,z) = \psi(r,\phi)\exp(i\beta z) \qquad \psi(r,\phi) = R_{l,q}(r)e^{-il\phi}$$

- Radial component R and propagation constant β are a solution to the scalar wave equation

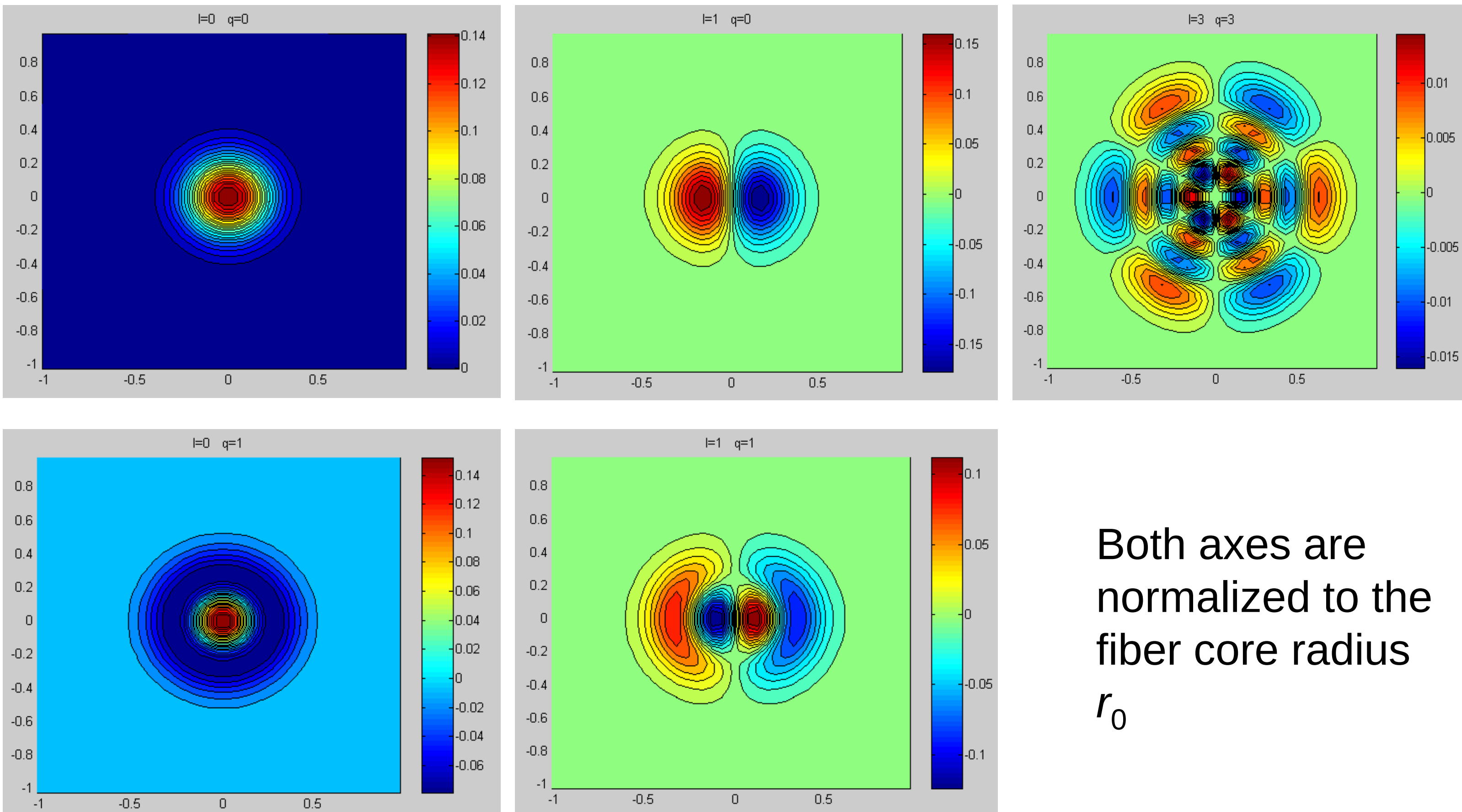
$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + k_0^2 n^2(r) - \frac{l^2}{r^2} - \beta^2\right] R_{l,q}(r) = 0$$

- Numerical solution uses difference instead of differential operators
- The field determined with user defined accuracy, for arbitrary index profile (analytic solution only for parabolic profile)
- Problem reduces to eigenvalue problem, can find **R** and β

$$\mathbf{A} \times \mathbf{R} = (\kappa r_0)^2 \mathbf{R}$$

From here we have the fiber field for calculation of mode power distribution, connector mode mixing effects

Transverse fiber field distributions $R_{l,q}(r,\phi)$



Both axes are normalized to the fiber core radius r_0

q – radial number, l – azimuthal number

Laser electric field model

- Fundamental mode is Gaussian:

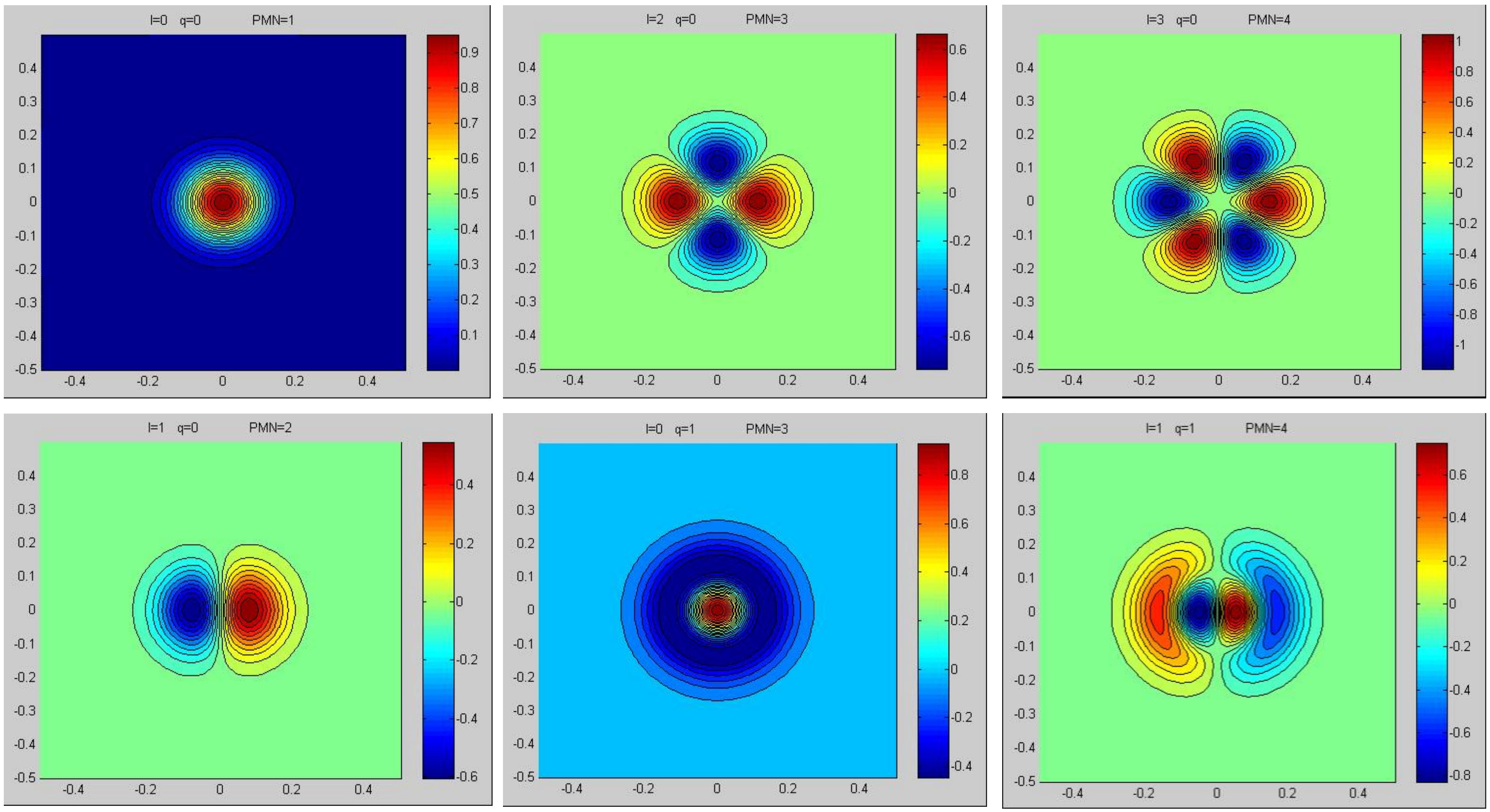
$$E(r) = Ce^{-\frac{r^2}{\omega_0^2}}$$

- Higher-order modes described by Laguerre-Gauss functions:

$$E_{l,q}(r,\phi) = C\left(\sqrt{2}\,\frac{r}{\omega_0}\right)^l L_q^l\left(2\frac{r^2}{\omega_0^2}\right)e^{-\frac{r^2}{\omega_0^2} - il\phi}$$

From here we have the laser field for calculation of mode power distribution in the fiber

Electric field of first 6 laser modes



The spot-size ω_0 is 2.8 μm

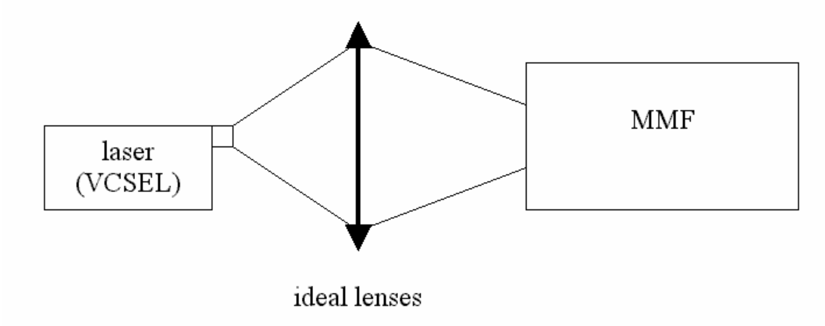
Laser to Fiber Interaction

- Laser beam formed as a superposition of electric fields from laser modes
  - At 1300nm there may be only one mode (mostly DFB sources!)
  - But also need to examine radial overfill launch (ROFL)
- Each laser mode couples into several fiber modes
- Fiber transfer function depends on laser launch conditions (beam properties) as well as optical properties (composition of optical spectrum)

Laser-fiber interaction

Laser mode l_l, q_l is coupled into fiber mode l_f, q_f (overlap integral):

$$c_{l_l,q_l;l_f,q_f} = \int_A E^*_{l_l,q_l}\,\psi_{l_f,q_f}\,dA$$



Modal power distribution (MPD) of the mode group with $PMN = i = 2q_l + l_l + 1$

$$MPD(i) = \sum_{q_l,l_l} S(l_l,q_l)\left(\sum_{\substack{q_f,l_f\\2q_f+l_f+1=i}} |c_{l_f,q_f;l_f,q_f}|^2\right)$$

$S(l_l,q_l)$ is the power coefficient of laser mode l_l, q_l

From here we have the Mode Power Distribution (MPD) in the fiber for fiber transfer function calculation

Computation of the connector transfer matrix

1. Find coupling coefficient between modes of two fibers:

$$c_{l_1,q_1;l_2,q_2} = \int_A \psi^*_{l_1,q_1} \, \psi_{l_2,q_2} \, dA$$

2. Find elements of the connector matrix

$$C_{PMN}(i,j) = \frac{1}{j} \sum_{\substack{1 \\ 2q_1+l_1+1=i}}^{M} \sum_{\substack{1 \\ 2q_2+l_2+1=j}}^{M} | c_{l_1,q_1;l_2,q_2} |^2$$

MPD in receiving fiber:

$$MPD_2(j) = \sum_{i=1}^{N_{\max}} MPD_1(i) C_{PMN}(i,j), \quad j = 1, 2, \ldots, N_{\max}$$

From here we have the Connector Transfer Matrix to take into account mode mixing

Connector degradations

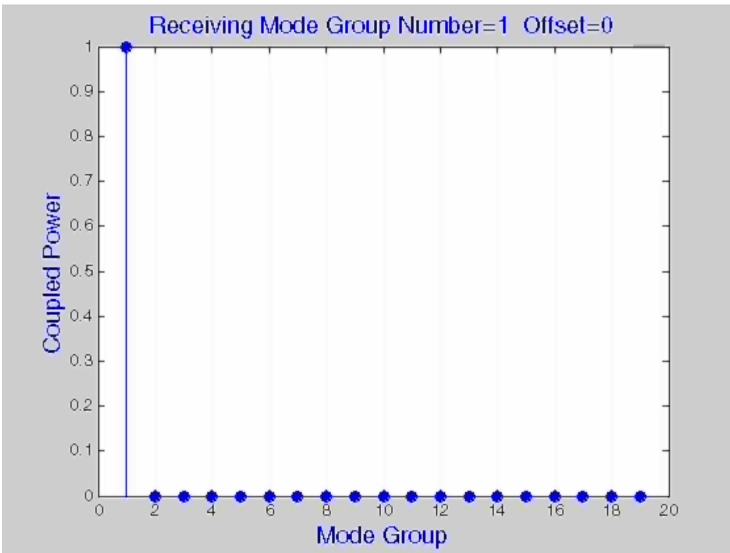
Connector offset introduces mode mixing, attenuation
Connector model uses connector transfer matrix C_{PMN} – calculated using overlap integral:

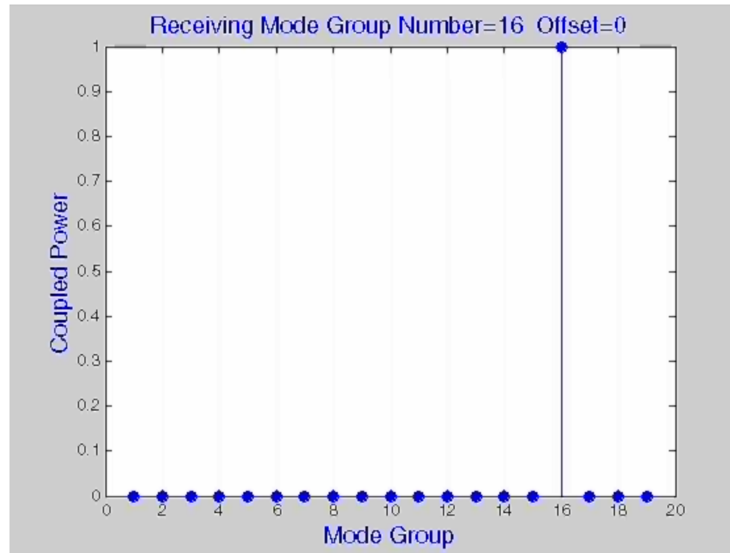
$$\mathbf{MPD}_2 = \mathbf{MPD}_1 \times \mathbf{C}_{PMN}$$

$\mathbf{C}_{PMN}$ is diagonal matrix for perfect alignment, MPD does not change

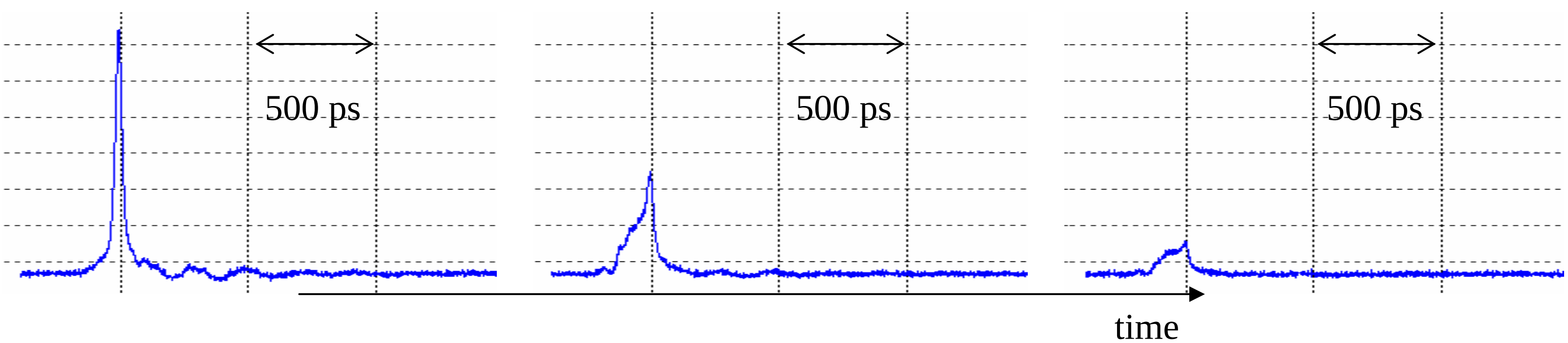
Effect of Laser Offset on Modal Power Distributions (MPD's) & Fiber Transfer Function

Computed MPD's





no offset   10 µm   20 µm



Measured pulses at fiber output

Receiver Model

- Receiver separated into linear part and post-amplifier
- Model stops at the (internal) analog output of the receiver (needed for equalization) – introduce TP3.5
- Two linear models:
  - A filter with variable low frequency cutoff, 3dB bandwidth and filter order,
  - a typical transimpedance amplifier found in textbooks (Miller, OFC II)

$$H_{rec}\left(f\right)=\frac{R_F h\left(f\right)}{1+\frac{1+j2\pi fC_T R_F}{A\left(f\right)}} \qquad A\left(f\right)=\frac{\left(g_m+j2\pi fC_{gd}\right)R_L}{1+j2\pi f\left(C_{gd}+C_{gdl}+C_{gdb}\right)R_L}$$

h(f) – post-amp transfer function

Laser Models

- Linear Model – filter based, with filter type and order user defined
- Rate Equation model: laser modeled using the standard single mode rate equations:

$$\frac{dN}{dt} = \frac{I}{q} - \left(A + Bn + Cn^2\right)N - \Gamma\nu_g a\left(N - N_0\right)P\left(1 - \varepsilon P\right)$$

$$\frac{dP}{dt} = \left(\Gamma\nu_g a\left(N - N_0\right)P\left(1 - \varepsilon P\right) - \nu_g\left(\alpha_m + \alpha_{\text{int}}\right)\right) + \beta_{sp}^2 N^2 V$$

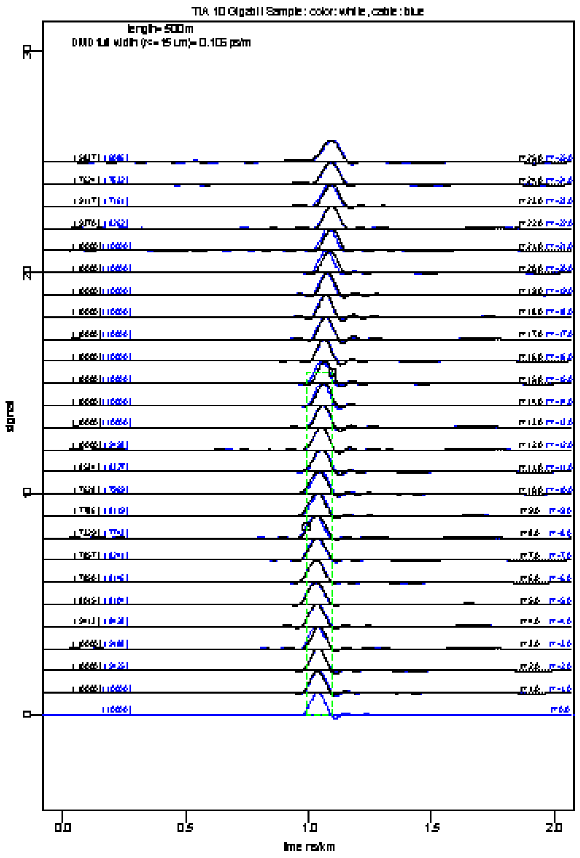
- Accurate analysis that fits the needs of optical links:
  - Transmitter turn-on jitter and signal duty cycle distortion
  - Transient effects (relaxation oscillations)
  - Pattern dependent waveforms effects
- Extension to multimode rate equations straightforward
- Laser noise can be easily added

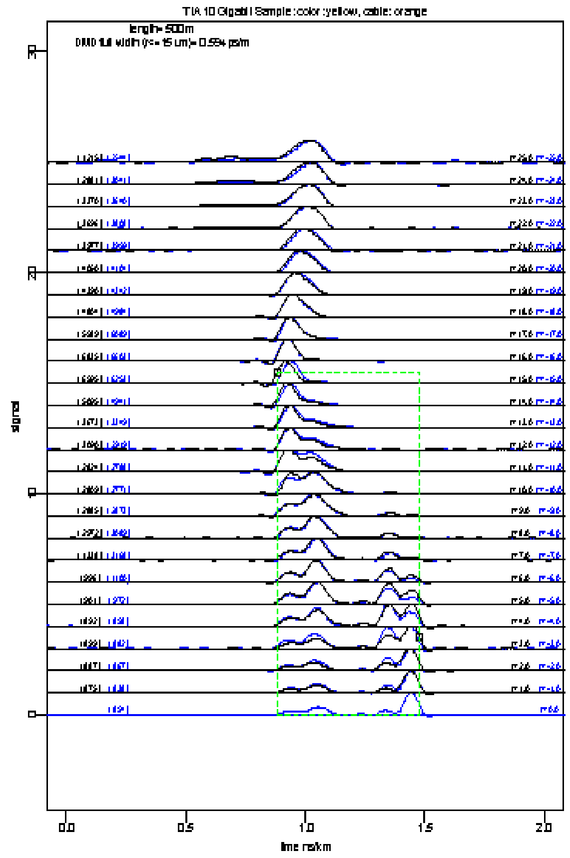
Extension to Legacy Fiber @1300nm

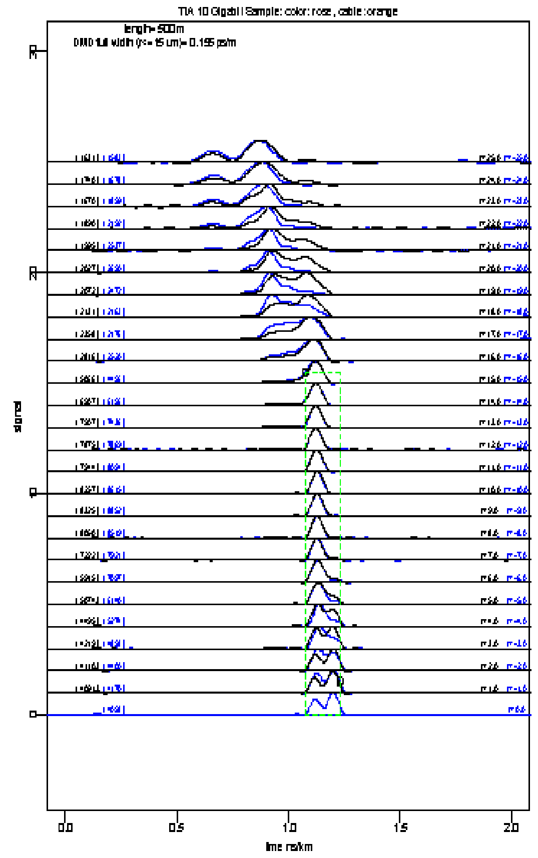
- Model is applicable to all multimode fibers
- Need a distribution for fiber DMD to estimate link yield
  - ✓ Perform DMD measurements on various round robin fibers
  - ✓ Scale the existing delay set to 1300nm as in ref (2) for simulations
  - – Get DMD distributions from fiber manufacturers
- What launch conditions are permissible?
  - – Center or offset launch?
  - – OFL, ROFL, encircled flux limited?
  - – MMF only or both SMF/MMF compatible launch?
  - – Laser Type – DFB, VCSEL, FP?
- May need to consider higher limit for maximum DMD in simulations than currently proposed (e.g. > 2 ns/km)
  - – But Legacy fiber installations after 1997 Gigabit Ethernet adoption greatly outnumber earlier legacy installed fiber
  - – legacy fiber installed after 1997/98 is supposed to be better (DMD awareness after Gigabit Ethernet investigations)

Typical measured fiber DMD profiles

DMD Measured using single mode fiber (4.5μm) launch





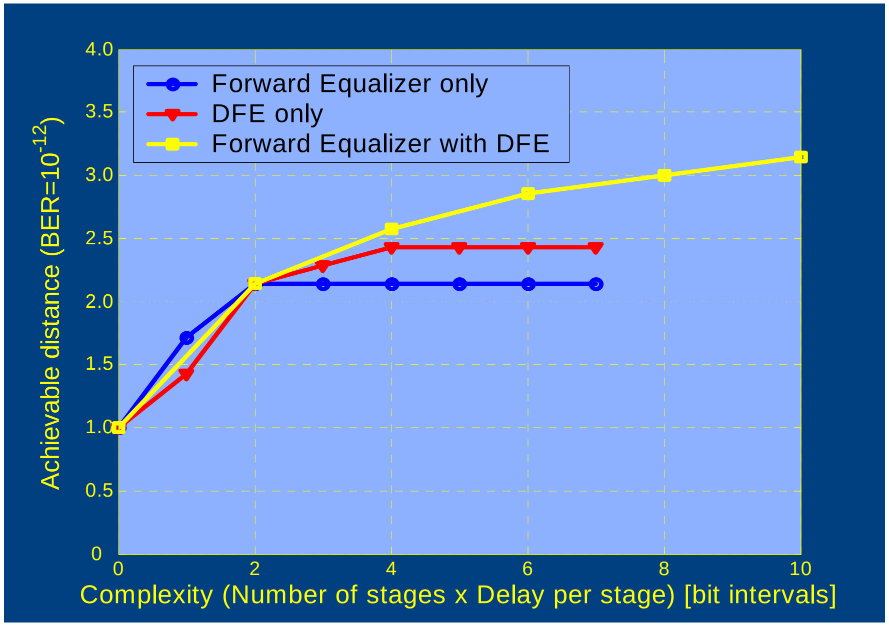


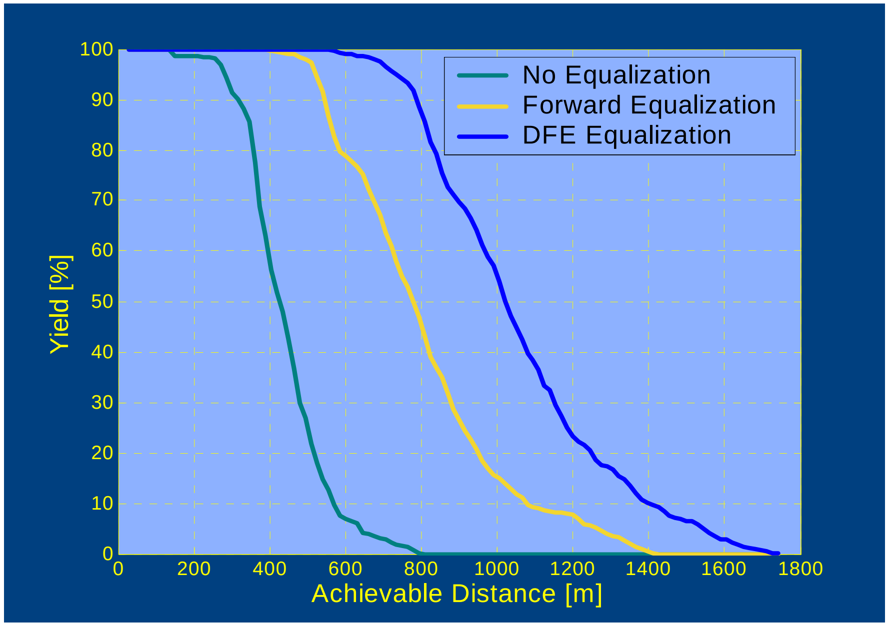
Use of the MMF Link Model in the Design of Equalizer Chip

(results presented at OFC2003, ref. 5)

Equalizer Design

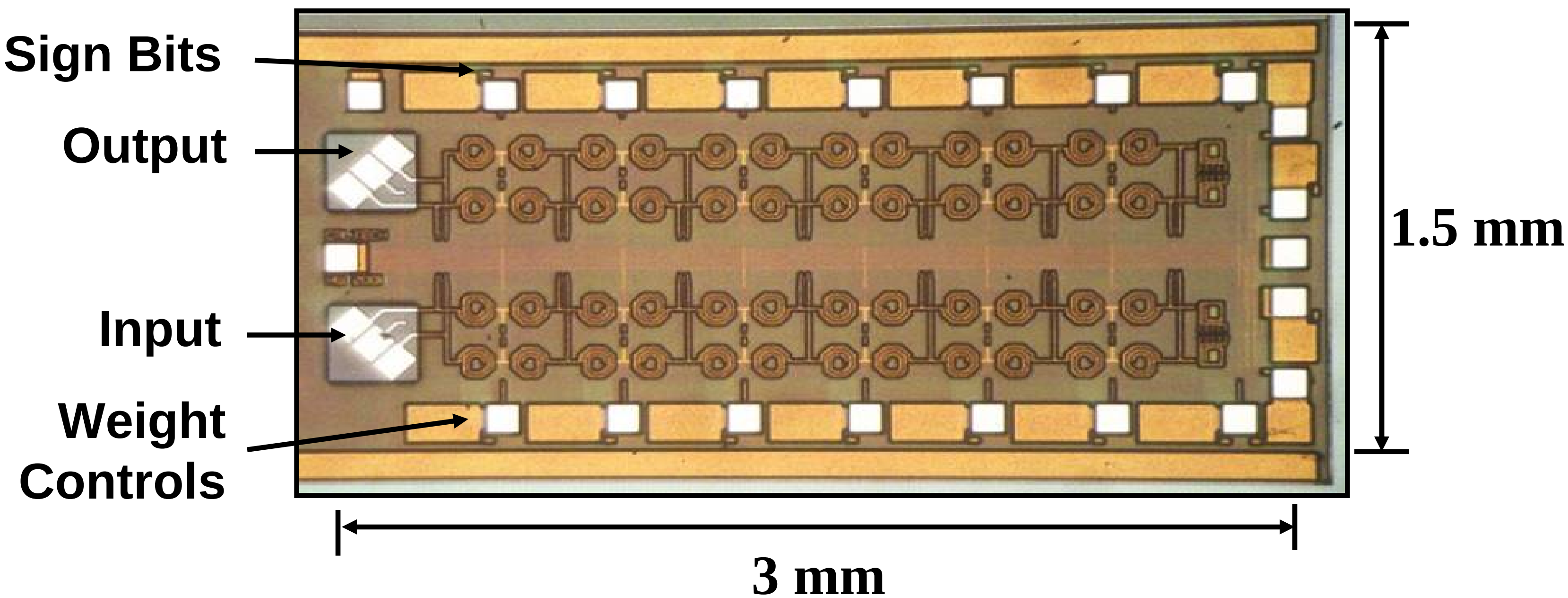
- Simulations based on measurements on 1500 MMF links
  - 6 transmitters, 12 fibers and 21 launch conditions
- MMF Link Model integrated with equalizer models
- Equalizer complexity compared for DFE, FFE, FFE w DFE
- Yield comparison for FFE, DFE and No equalization





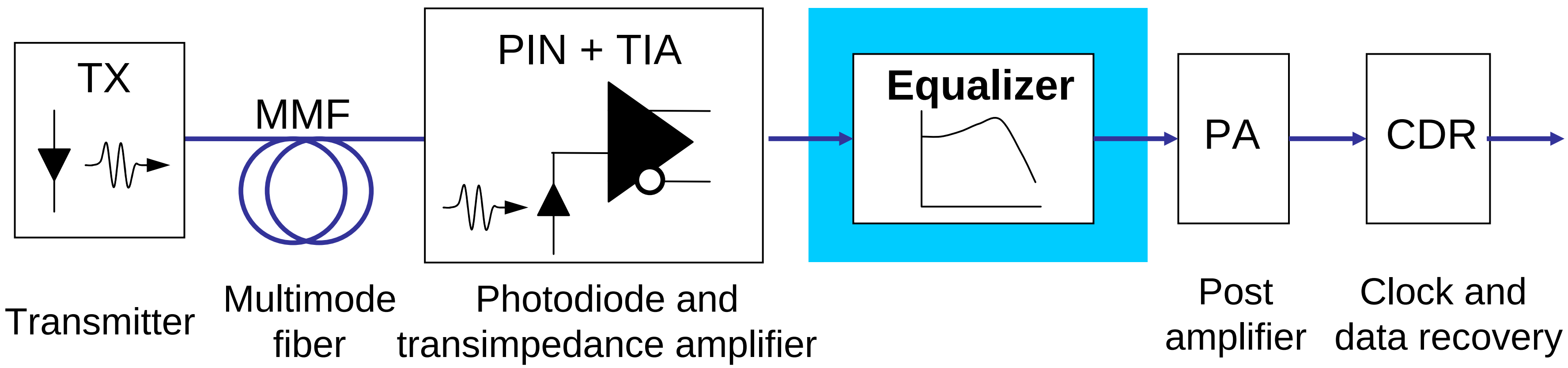
Similar studies underway for 1300nm legacy fiber

7-Tap 10Gb/s Transversal Filter



- IBM SiGe BiCMOS 7HP process (f_T=120 GHz)
- Tilted input and output SGS pads for probing

Link Equalization Test



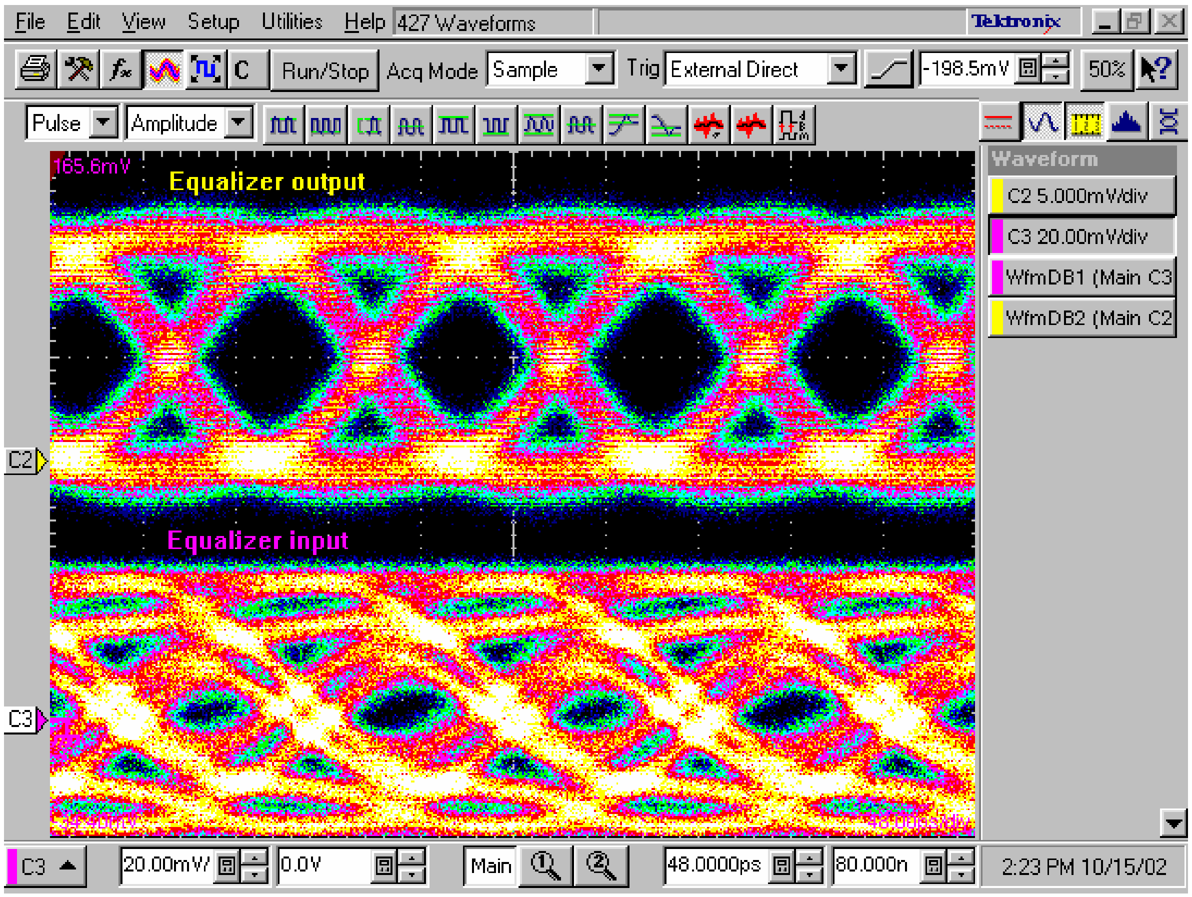
- 2^{31}-1 PRBS pattern, 10Gb/s
- 850nm VCSEL transmitter, direct modulation
- 800m long 50µm Next Generation MMF

10 Gb/s, 800m MMF Link Equalization

- ISI reduced from 11 to 2.2 dB, DJ from 60 to 21 ps

After equalization: BER < 10^{-12}

Before equalization: BER ≈ 10^{-5}



2^{31}-1 PRBS pattern, Power dissipation 40 mW

Conclusion

- Matlab based MMF Link model allows accurate link simulations
- Data sets from previous TIA work can be used in simulation of legacy MMF
  - existing delays can be scaled
- MMF Link Model was integrated with equalizer models, link yield calculated and used in chip design

References

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MMF Terminology

- *mode group* - group of fiber modes that propagate with approximately the same speed
  - 19 mode groups in 50 μm core fiber (180 modes)
  - 23 mode groups at 850nm in 62 μm core fiber, 18 mode groups at 1300 nm
- *mode power distribution (MPD)* - distribution of input optical power among the fiber modes at fiber input
- *differential mode delay (DMD)* - propagation delay difference between mode groups, result of intermodal disprersion
- *differential mode attenuation (DMA)* - attenuation difference between mode groups
- *fiber modal bandwidth* - the frequency at which the fiber TF drops 3 dB optical (takes into account only intermodal effects)
- *effective modal bandwidth (EMB)* - the bandwidth of the fiber when the source is modulated (it can only be calculated)
- *effective bandwidth* – the bandwidth of the fiber including the chromatic dispersion