The 10 Gb Ethernet Link Analysis for Single Mode Lasers - Issues and Paths to Solutions

David Dolfi
Hewlett-Packard Laboratories
3500 Deer Creek Road
Palo Alto, CA 94304
Phone: 650-857-3764
email: dolfi@hpl.hp.com

Acknowledgements:
Lisa Buckman
Jonathan Lacey

HEWLETT PACKARD

OPTICAL COMMUNICATIONS & MEASUREMENTS DEPARTMENT (OCMD)

COMMUNICATIONS & OPTICS RESEARCH LABORATORY (CORL)

Outline -

*** Approaches to Link Modeling -**

Numerical Link Simulation Model

GbE Spreadsheet Model

*** Spreadsheet Model and DFB lasers -**

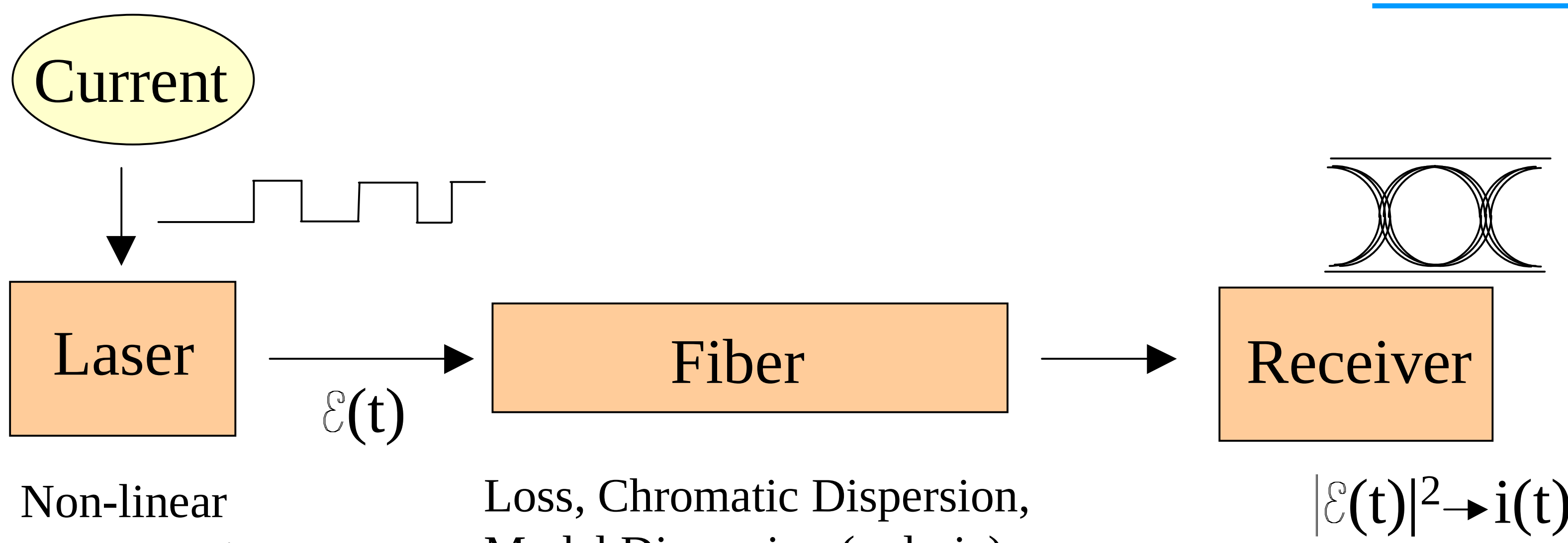
a. Narrow linewidth (single-mode) lasers

- ISI Penalty (mainly Chromatic Dispersion)
- Chirp

b. Two-mode lasers

- Mode Partition Noise Penalty
- ISI Penalty

Link Simulation Model:



Non-linear
Rate equation
model

Loss, Chromatic Dispersion,
Modal Dispersion (polariz),
non-linear effects

"First Principles" Approach

Models laser response in detail (ex: pattern dependent jitter)

Models coherent effects (chirp, etc)

Link Simulation Model - Drawbacks

* Laser model is usually single mode
→ effects of multiple modes are typically added in an ad hoc fashion

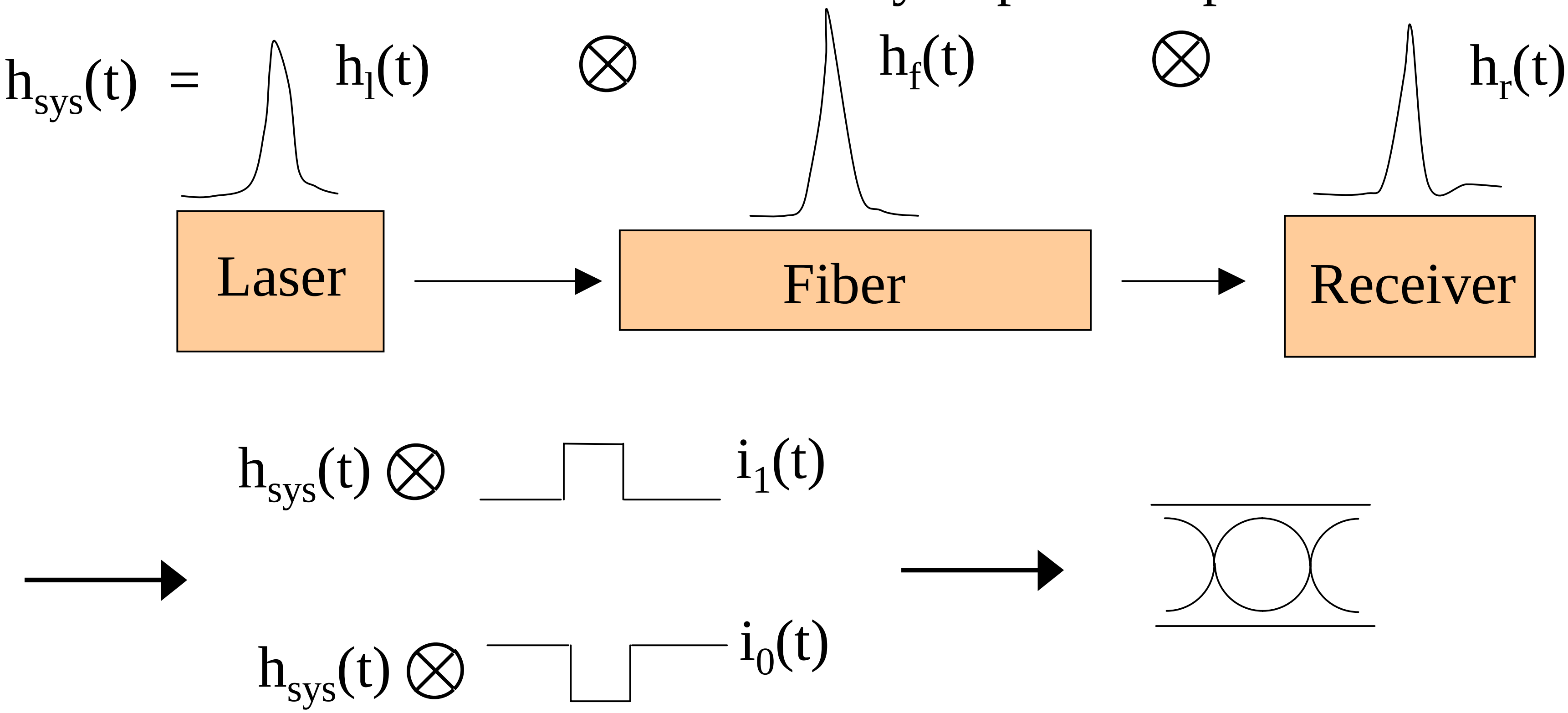
* Difficult to include "everything" from first principles

* Different sources of power penalty not easy to sort out

* Rate equation based laser models not typically suitable for spreadsheet evaluation

Gb Ethernet Link Model:

Laser, fiber, and receiver are modeled as
a linear system with respect to the drive current
with a net Gaussian intensity impulse response



Gb Ethernet Link Model: +'s and -'s

* Very easy to calculate in spreadsheet format
* Different power penalties are treated separately
→ easier to see their individual effect
* Noise related penalties can be simply added on

* (Laser+fiber+receiver) is NOT really a linear system with respect to drive current
- laser output shape depends on current amplitude
- fiber chromatic dispersion can depend on drive current (through laser linewidth)

* Model deals with light intensity (not amplitude)
- does not deal with laser chirp or other phase dependent effects

* Coupling between different power penalties not accounted for

Gb Ethernet Model with Single mode Lasers (DFB's):

* Fiber impulse response calculation requires laser linewidth as an input parameter (for chromatic dispersion)
* For multimode lasers (large area, multimode VCSEL's, FP lasers) the intrinsic (cw) linewidth is very broad (~ nm). For DFB's it is very narrow (< GHz)

→ Laser output waveform under modulation has negligible effect on linewidth for multimode lasers, but can have large effect on linewidth of single mode, DFB lasers.

→ For single mode lasers, drive current will have non-negligible effect on linewidth/fiber chromatic dispersion; hence difficult to construct a current independent fiber impulse response.

GbEthernet Model with Single mode Lasers (DFB's):

Additional issues due to chirp:

* Chirp adds an additional non-negligible component to the linewidth of single mode lasers (DFB's)

→ Creates issues with fiber impulse response (see above)

* Depending on the relative sign of chirp and dispersion, a positive or *negative* chromatic dispersion penalty may result (principle behind dispersion compensation)

→ Cannot account for this effect if model only looks at intensity of light.

→ Not clear how to handle pulse width reduction in context of an intensity impulse response based model

Reconciling Model with these effects

Leverage on work done by Marcuse [1,2] on chromatic dispersion broadening of chirped, Gaussian pulses:

* Simple *analytic* expression for output/input pulse width
* Both intrinsic (cw) and transient contributions to linewidth taken into account
* Effect of chirp (both linear and quadratic) are taken into account
  - Main limitations - Assumes Gaussian input into fiber
    Simplistic chirp model (linear)

[1] Marcuse, D, Applied Opt **19**, 1653, 1980……
[2] Marcuse, D., Applied Opt **20**, 3573, 1981…….

Inserting Marcuse's Treatment into Model:

1. Assume laser intensity can be derived from the drive current through a laser impulse response (as in present model)
2. Use them to construct a corresponding chirped (Gaussian) amplitude and linewidth which is input into the fiber.
3. Use Marcuse's theory in spreadsheet to calculate the pulse width at the fiber output.

Have combined effect of drive current, laser, and fiber chromatic dispersion (including chirp)

4. Convolve this output intensity with other link elements (fiber modal dispersion, receiver)
5. Generate the eye opening function and calculate ISI Penalty

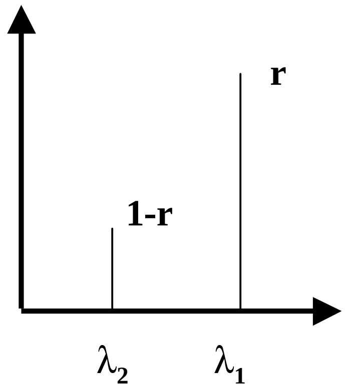
Testing this Approach (so far):

1. Looked at agreement with current Gb Ethernet model in limit of no chirp

2. Looked at relative ISI Penalty vs chirp in comparison to an in-house link simulation model in narrow linewidth limit for some individual cases.

A LOT more work needs to be done!!!

“Almost” single mode lasers (two-mode)



$\sigma_\lambda = (\lambda_1 - \lambda_2)$

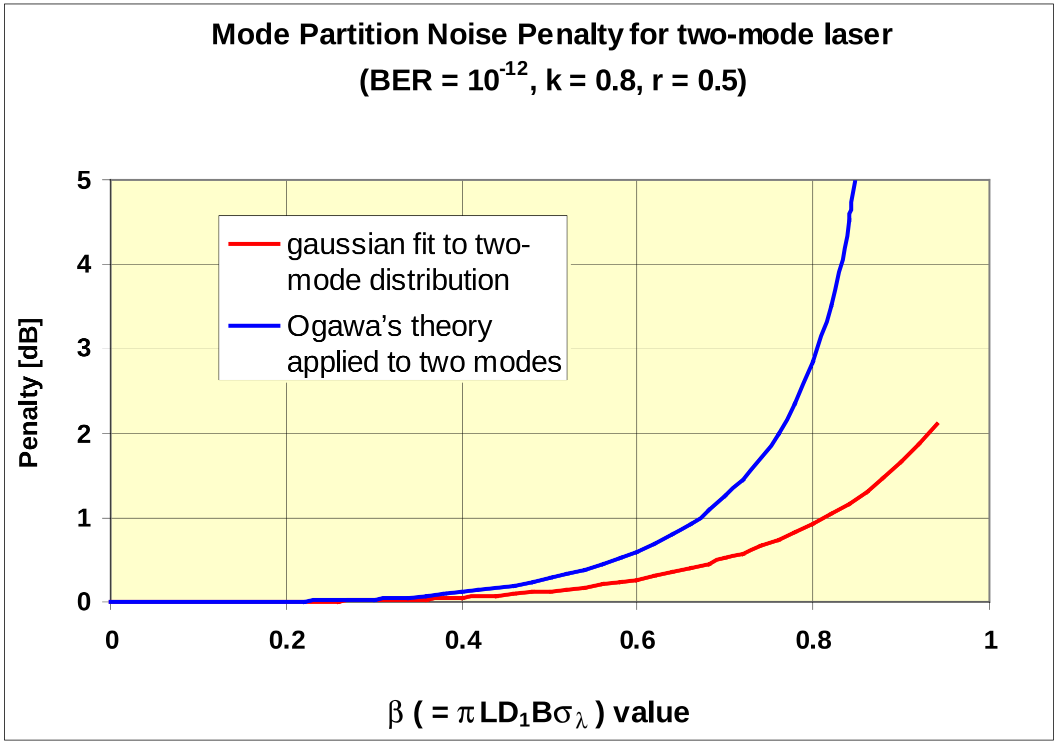
Presence of 2nd mode will affect ISI, Mode Partition Noise, and Eye Opening Penalties, due to different arrival times of signals from the two wavelengths.

ISI penalty - To the extent that the system impulse response approach is valid, can replace single Gaussian impulse response with two, having different arrival times and scaled by relative strengths of the two laser lines.

$$h_{sys}(t) \longrightarrow h_{sys,1}(t) + h_{sys,2}(t)$$

Mode partition Noise -

Mode Continuum approach used in present Gb Ethernet model not appropriate for two-mode lasers



Gaussian fit to two mode distribution: uses Gaussian with same mean and variance as the two-mode distribution

→ **Gaussian approximation underestimates the penalty**

→ Return to Ogawa's original theory and re-calculate for two discrete modes rather than mode continuum

Where in the 10 Gb Ethernet space might these factors be a concern?

Chirp in narrow linewidth lasers:

* Not significant for wide linewidth multimode lasers (FPs, large area VCSELs) - chirp has negligible effect on linewidth
* Not significant in multimode fiber links - Modal dispersion usually dominates over chromatic dispersion (NOTE - *may* be a factor with single mode VCSELs/improved BW multi-mode fiber, depending on amount of laser chirp)

For DFB based single mode links:

* At 1300 nm, could be a factor at the extremes (λ = 1.27 μ, link lengths 10+ km). Chirp could *lower* the chromatic dispersion penalty for conventional DFB lasers.
* At 1550 nm, will probably be a factor for 10+ km link lengths

Where in the 10 Gb Ethernet space might these factors be a concern? (con't)

Two-mode lasers:

Primary effect will be on Mode Partition Noise penalty for following sources @ 10+ GBd:

* Nominal Single mode VCSELs at 850/980 nm in combination with multimode fiber. (Short link lengths but large chromatic dispersion)
* Nominal Single mode DFBs at 1300 nm in combination with singlemode fiber (small chromatic dispersion but long link lengths)
* Nominal Single mode DFBs at 1550 nm in combination with single mode fiber (large chromatic dispersion AND long link lengths)

Summary -

<u>For narrow linewidth, chirped single mode lasers (DFB's):</u>

* Present Gb Ethernet model requires modification to properly calculate the chromatic dispersion penalty
* Marcuse's theory for chirped Gaussian pulse broadening in fiber may be applicable (needs further work)
* If not, link simulation model may be required for some cases

NOTE: If link simulations are required to address these issues, the results will be tabulated in such a way as to enable their insertion into a spreadsheet link model.

Summary (con't) -

For two-mode lasers:

* Primary effect is on Mode Partition Noise. Can be treated with Ogawa's original theory.

* System impulse response can be modified to include second mode.
  This can be applied to modify ISI, Eye Opening penalties.
  (Significance of second mode on these penalties may be negligible - need to check this)