10 Gb/s Ethernet on FDDI-grade MM Fiber Tutorial

Agenda

- Broad Market Potential: Bruce Tolley, Cisco
- Distinct Identity: Ed Cornejo, Opnext
- Economic Feasibility: Ed Cornejo
- Technical Feasibility: John Jaeger, Big Bear Networks
- SG Objectives: John Ewen, JDSU
- Tutorial Summary
- Q & A

posted to 802.3 web site
– www.ieee802.org/3/tutorial/index.html

Introduction

- Support for installed FDDI grade MM fiber means that we have broad market potential. Increasing density of 10GBASE- solutions is key to lowering cost to end users
- Distinct identity: one problem - one solution
  – Need a serial solution to support installed FDDI-grade fiber. Serial interface enables not just lower power and lower cost but also higher-density system solutions.
- Technical feasibility: We have at least three approaches to solving the problem
- Economic feasibility: costs are expected to be comparable to or less than 10GBASE-LR
- Compatibility. This project will just be a PMD/PHY

Broad Market Potential of 10 Gb/s Ethernet on FDDI-grade MM Fiber

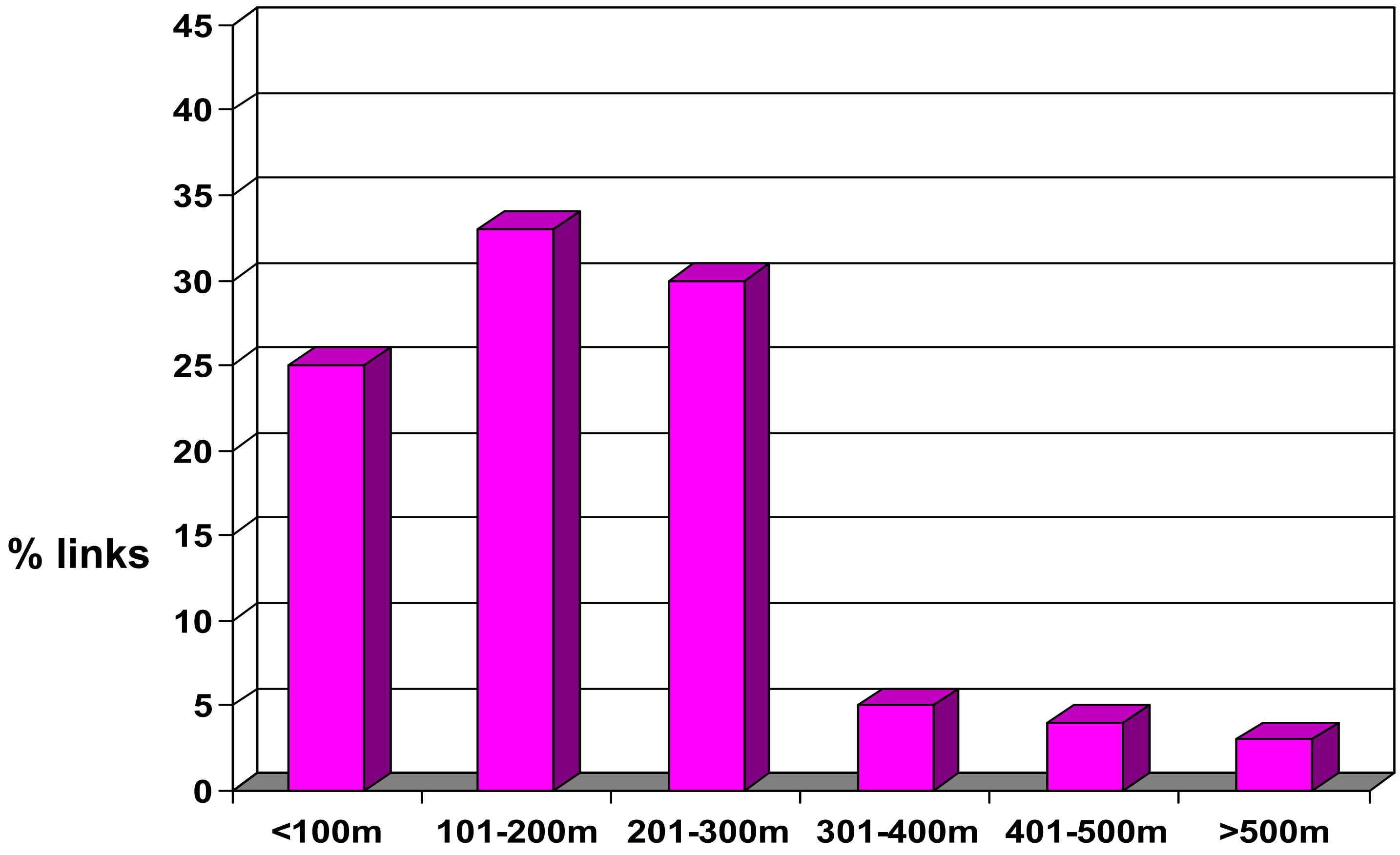
Mike Bennett, Alan Flatman, Bruce Tolley

Why 10GbE on Legacy MMF is Important

- Today: 80 to 90% of 1000BASE-X pluggables are –SX for MMF
- Fact: Enterprise customers reluctant to pull new fiber to deploy 10 GbE
  - MMF is the installed fiber base in vertical risers
- Post 2001 IT budgets are static or declining for Enterprise customers
- Near Future: $400 to $600 M of total addressable market revenue opportunity is at stake
- 10GBASE- on MM fiber is aimed specifically to extend core business of enterprise Ethernet switching
  - 175 million ports Ethernet switch ports to ship in 2004 worth $12.2B
- Killer application: aggregation of 10/100/1000
  - 24 million GbE ports to ship this year

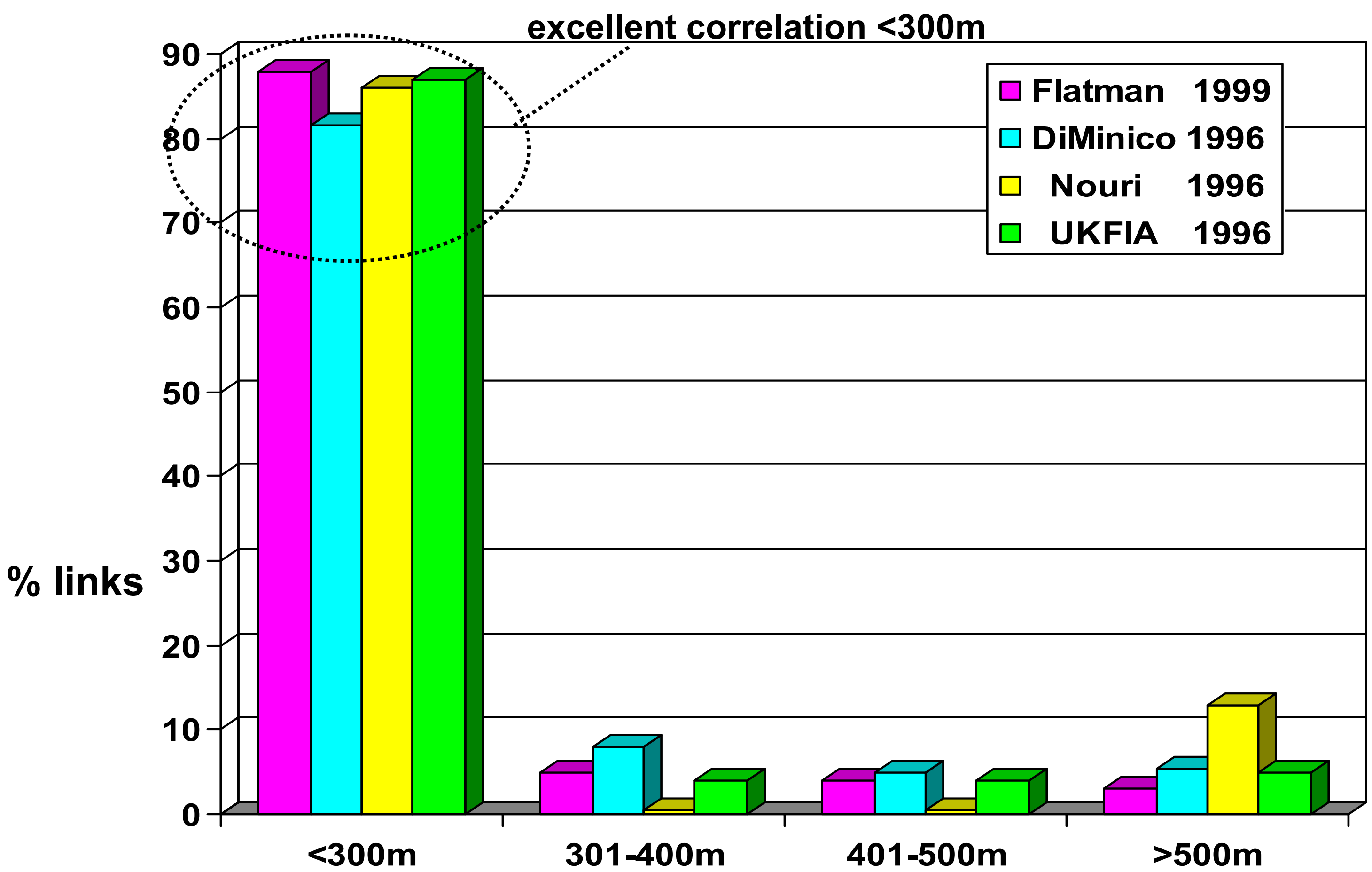
Source of CY2004 revenue and port shipments: Dell'Oro Group

Optical Fibre Installed Length Distribution in Building Backbones



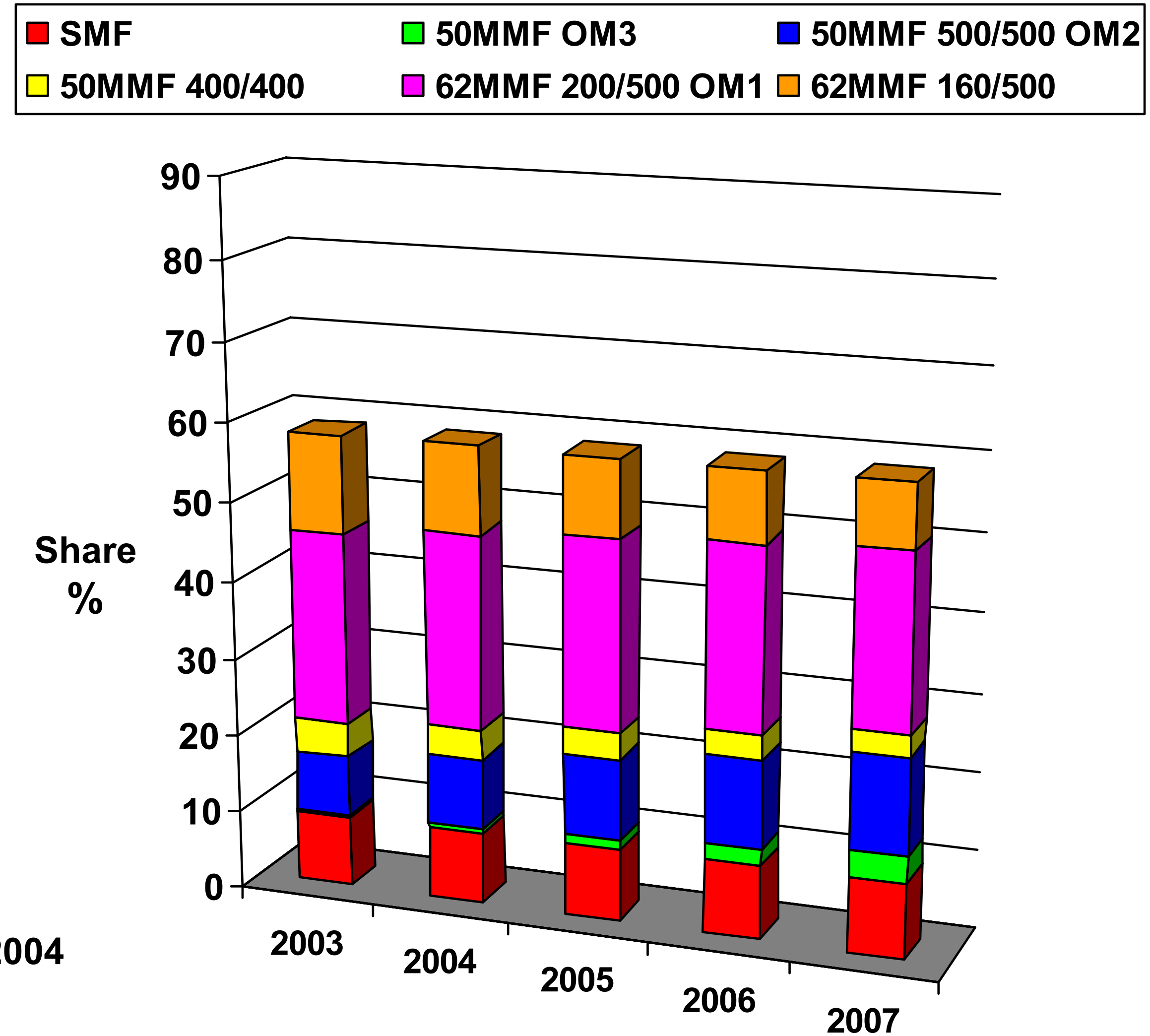
Source: Flatman 1999

Optical Fibre Installed Length Distribution in Building Backbones



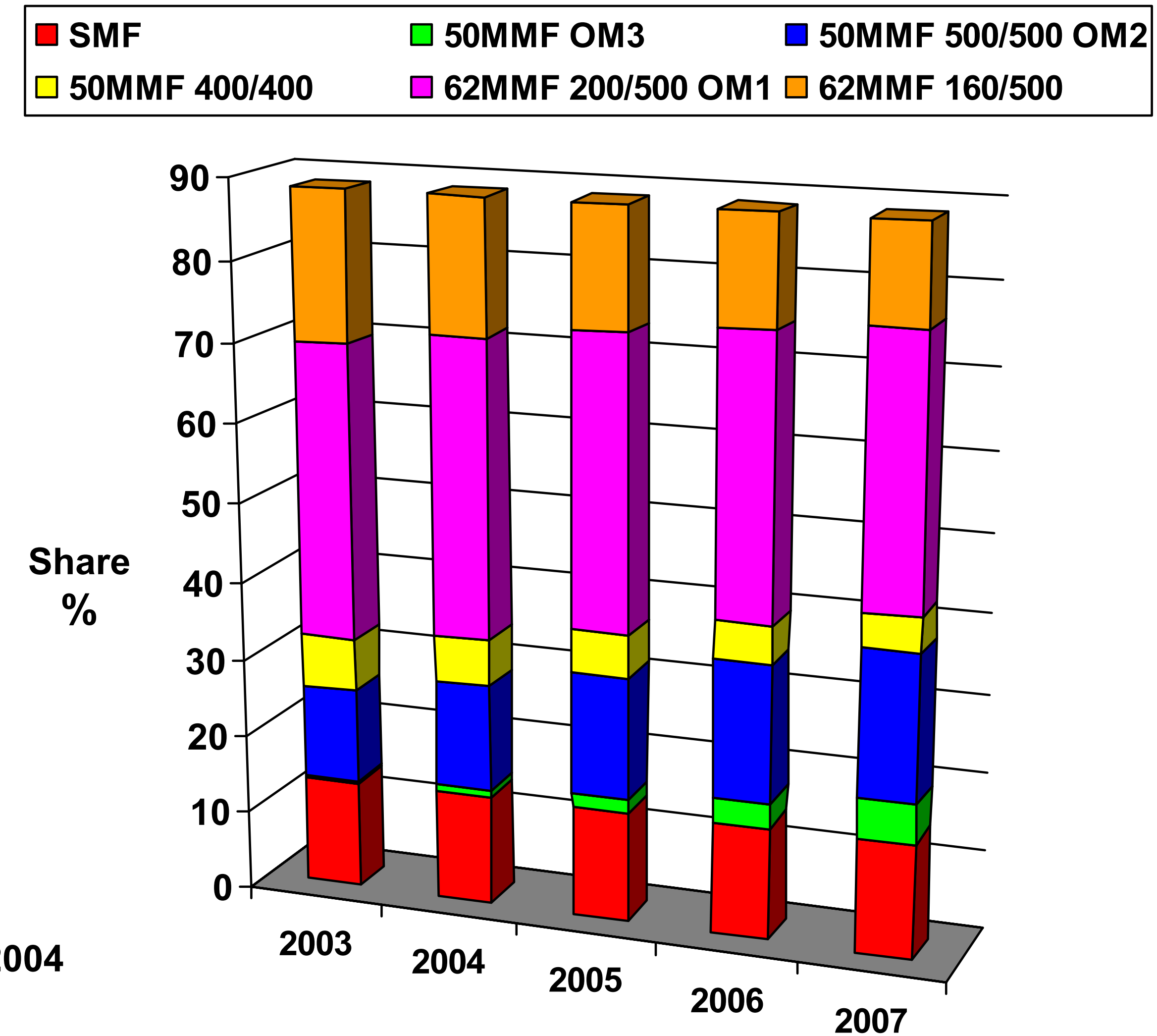
Source: Flatman 2004

Share of Building Backbone Links up to 200m in Worldwide Installed Base



Source: Flatman 2004

Share of Building Backbone Links up to 300m in Worldwide Installed Base

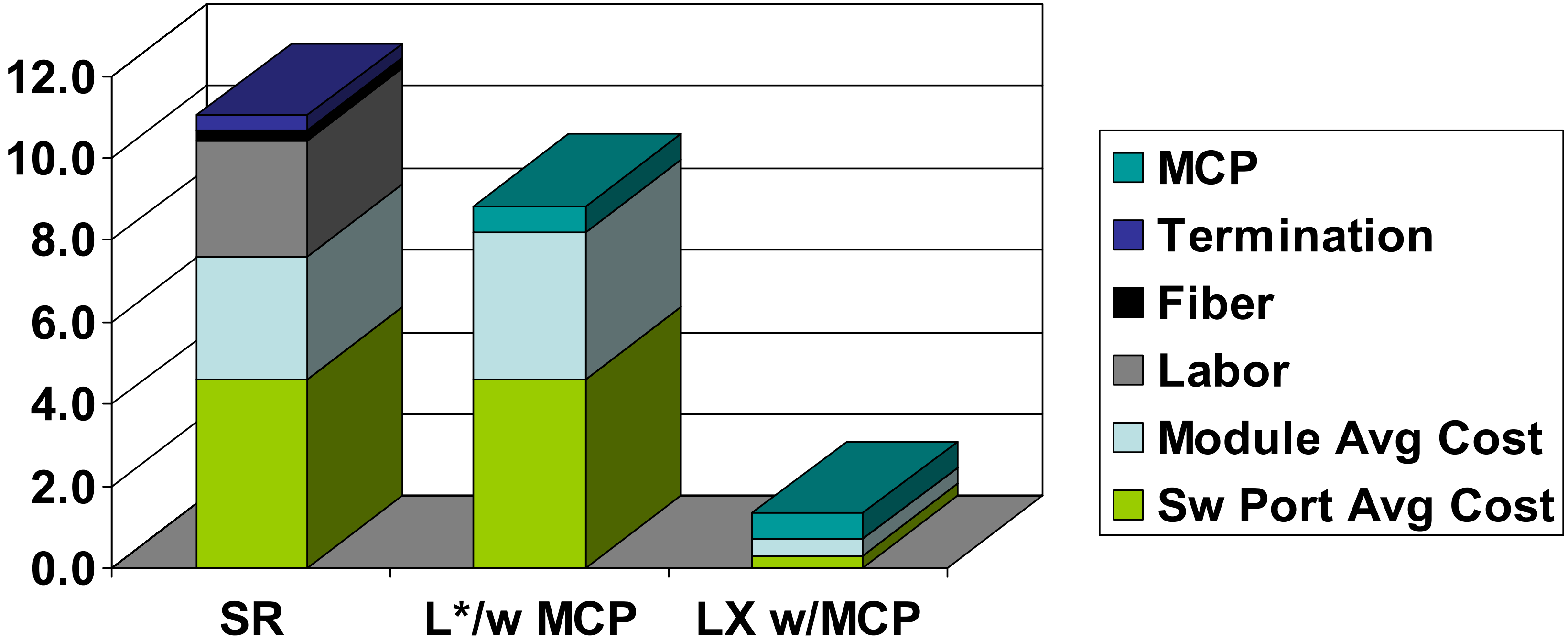


Source: Flatman 2004

Balanced Costs

- 1000BASE-SX and –LX support installed fiber. Costs balanced between new PMDs and network equipment
  - New adapters were required for GbE
  - Almost all 1000BASE-X optical PMDs are sold as pluggables, GBICs or SFPs
- 10GBASE-L* expected to have the same balanced cost characteristics as –SX and –LX
  - Will use same NICs and host bus adapter technology as 10GBASE-LR and -SR

Comparative Costs: Switch-to-Switch Duplex Link on MM Fiber



1.0 Index Value = Avg Cost to OEM of 10GBASE-LR X2/XENPAK module CY2005

L* assumed to be 90% of LR module. SR 75%. All costs for MCP, termination, etc. are end user costs

Fiber installation cost est. for 150 meters. Labor costs vary not only by building but also by region and geography

Sources: Dell'Oro Group , Industry sources, LBL Labs, Cisco Systems

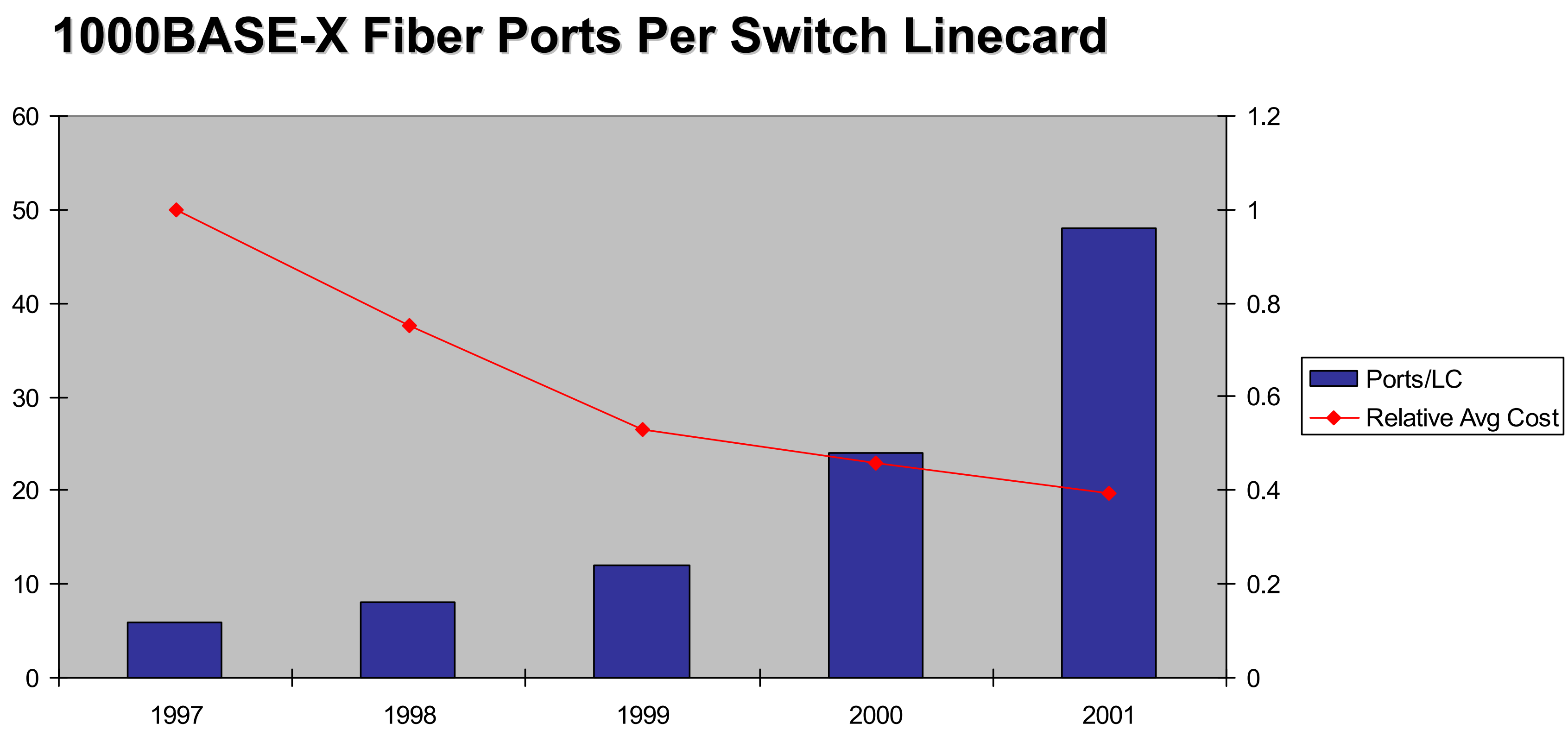
Case for 10G MMF

- IT budgets are flat or declining
  - Need low cost choices for optical 10 GbE
- Specifying a MMF solution that will operate on 300m of FDDI grade fiber will enable end users to save money on infrastructure
  - 51% of installed 3,048 MMF fibers* at Lawrence Berkeley Livermore NL fall into FDDI grade category
  - This equates to 13% of the annual LBL net budget if this infrastructure had to be replaced
  - *NOTE: Includes 160 MHz*Km and 200 MHz*Km (@850nm), 1,620 of these are less than or equal to 300 m long

10 GbE Enterprise, In Building Applications

- Now
  - Switch-to-switch
  - Core
  - Switch aggregation (aggregating multiple GbEs into 10 GbE uplinks)
  - Grid computing
- Tomorrow
  - Switch-to-server

Serial Interfaces Enable Density and Lower Cost per Port For Switch Line Cards



Source: Fiber port LC density: Cisco Systems, Sw Port Relative Avg Cost : DellOro Group. Index 1.0 = 1997 Avg Cost

Multiple Suppliers

- Over 65 representatives from module companies and IC companies are attending the SG meetings

Broad Market Potential Conclusions

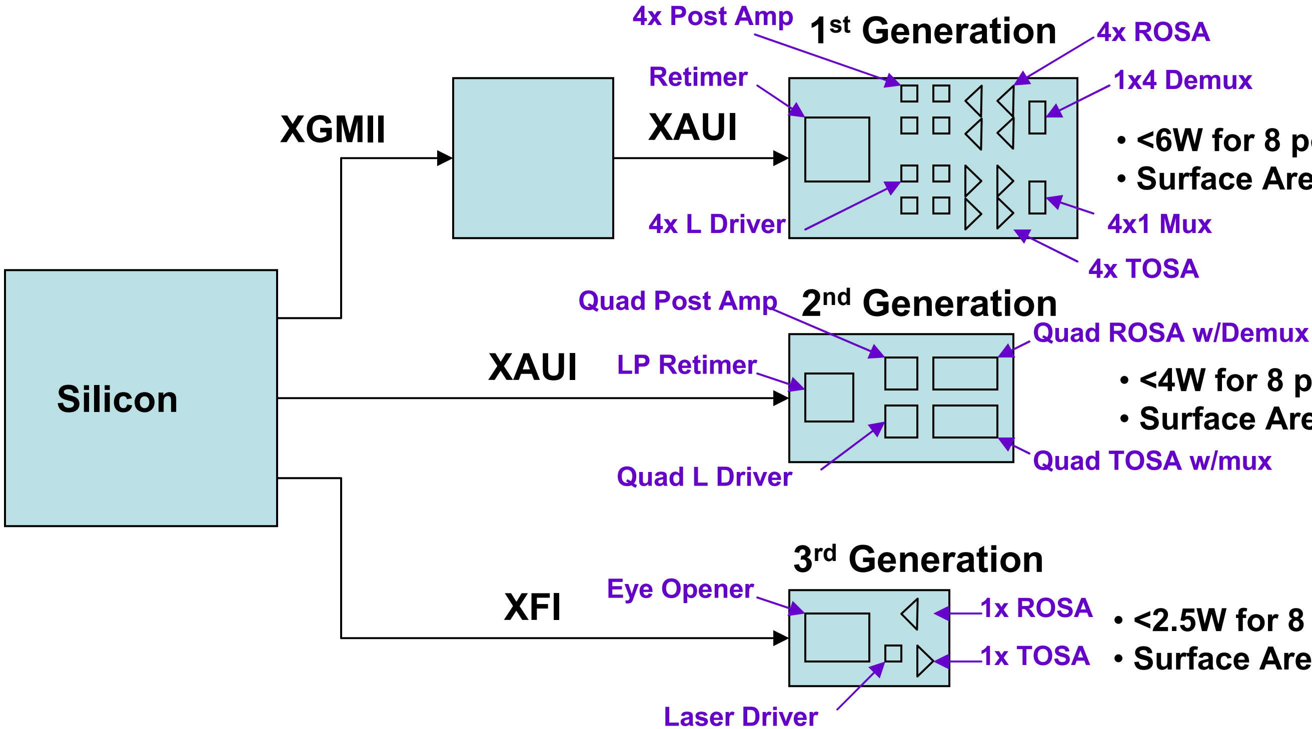
- Large addressable market,broad set of applications, multiple customers
- Balanced costs
- Multiple suppliers

Distinct Identity and Economic Feasibility

Ed Cornejo (OpNext)
David Cunningham, Mike Lawton (Agilent)
Norm Swenson (ClariPhy)

Problem of Supporting Legacy MMF in the Future

Power Dissipation and Space for Sub-Components are Major Problems as we Migrate towards 3rd Generation Modules



1st Generation:
- <6W for 8 port density
- Surface Area: 14176 sq mm

2nd Generation:
- <4W for 8 port density (33%↓)
- Surface Area: 8594 sq mm (40%↓)

3rd Generation:
- <2.5W for 8 port density (58%↓)
- Surface Area: 4372 sq mm (70%↓)

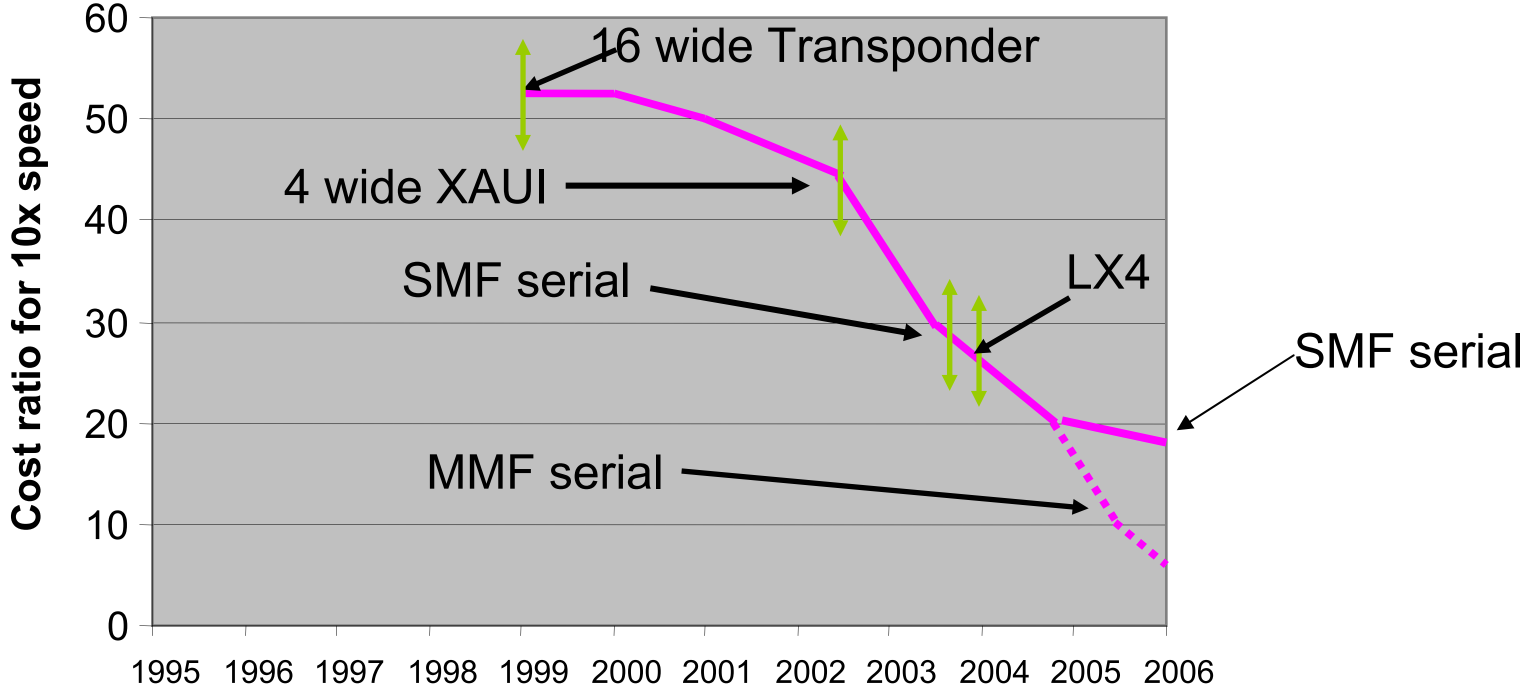
Distinct Identity

- The proposed 10 Gbps PHY:
  - Targets a small serial form factor
  - Enables distance of at least 220m on legacy FDDI-grade installed fiber with a serial solution
  - Introduces new technology that solves current needs and promotes future capabilities
    - 10 Gbps serial on legacy fiber
    - Longer distance and/or higher speeds (future) on OM-3

Distinct Identity (Cont'd)

- The existing 10 Gbps PHYs do not achieve both:
  - Distances exceeding 220m over legacy FDDI-grade fiber, and
  - Small serial form factor realization
- Limitations of existing PHYs:
  - 10GBASE-LR requires single-mode fiber
  - 10GBASE-SR requires laser-optimized multimode fiber
  - 10GBASE-LX4 is a parallel four-wavelength technology requiring non-serial form factor

802.3aq Economic Feasibility



- The progression from 16w to 4w to serial/LX4 is improving economic feasibility
- Increased focus on serial solutions will produce economies of scale
- Reduction in “cost of test” is important

Economic Feasibility

- 10GBASE-LR devices provide a benchmark for economic comparison
- Proposed solutions use comparable or cheaper components than 10GBASE-LR, with the addition of either
  - an integrated circuit (Receive EDC, PAM-4+EDC), or
  - constrained launch conditions + optical mode filter (Optical Mode Filtering)
- The high volumes of serial solutions are expected to enable cost reduction through economies of scale
- The continued use of installed infrastructure favorably impacts total cost of ownership for end user

Economic Feasibility Summary

- Economic feasibility is fairly well understood
- At some point in time, serial interface based modules will be used, and we need a technology that enables these modules to support legacy MMF to at least 220m
- Power and space constraints become more and more severe as we move to these serial interface based modules

Technical Feasibility

Sudeep Bhoja , Pete Hallemeier, Norm Swenson

Technical Problem Statement

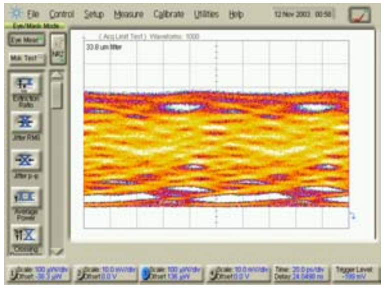
- ‘Conventional’ serial 10G transmission on installed base fiber exhibits differential mode delay (DMD) of the transmitted signal
  - Specifying a **serial** solution is important to meeting the 5 criteria
- This modal dispersion leads to complex multi-path impulse responses resulting in ISI
  - The impulse responses can vary with time due to cable movement, temperature change, or other effects that result in a change of the optical power split across the mode groups
- Major Technical work items:
  1) Channel Definition, Characterization & Model
     - Provide a frame work for a channel model(s) to benchmark solutions
  2) Compliance / Conformance Test
     - Define a standardized test approach to provide a uniform compliance procedure to ensure link interoperability
  3) Selection of a PHY / PMD solution
     - The detailed specification of a PHY is a work item for the Task Force

Technical Feasibility Summary

- Over 25 technical presentations reviewed in Vancouver meeting beginning to address the array of technical items such as:
  - MMF channel model & channel behavior
  - Link compliance approaches & PHY solution evaluation proposals
  - Technical approaches for the MMF PHY
    1. Optical Mode Filtering
    2. Receive Equalization (EDC – electronic dispersion compensation)
    3. PAM-4 w/ Receive Equalization
- Excellent progress made on all fronts
  - Continued progress will be made at this meeting (over 20 add'l presentations)
  - The study group has confidence that a solution is obtainable that will meet the stated objectives

Optical Mode Filtering Approach (1)

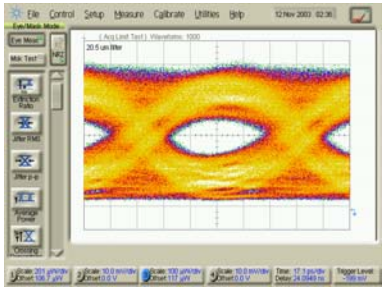
1. The ISI caused by DMD attributable to poor index profile limits link distance



DMD Limited Eye

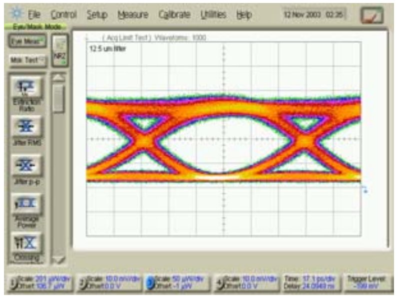
2. An output optical filter can be used to recover the desired set of the modes to reduce ISI in the received signal

   <u>However</u>, if Mode Selective Loss is present, <u>MODAL NOISE will be present</u> and must be compensated



Mode Filtered Receive Eye with Modal Noise

3. Modal Noise can be compensated with proper Tx design and enables 300m transmission



Mode Filtered Receive Eye with Modal Noise Compensated

Optical Mode Filtering Approach (2)

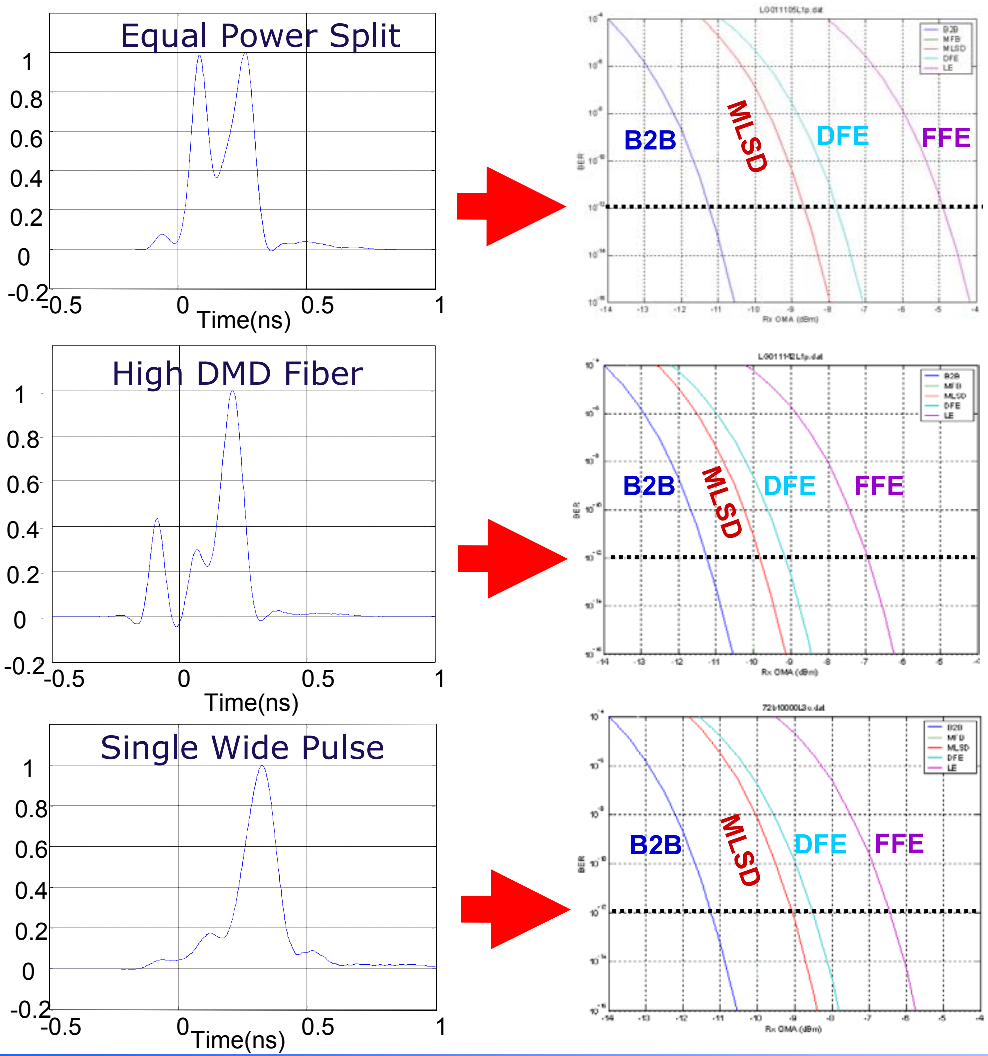
- An optical DMD compensation method overcoming modal noise has been demonstrated
- Preliminary testing looks very good on 12/96 TIA Fiber Spool
  - 'FO2.2 12-96 BW MODAL Launch Test Cable' June '97

TIA Fiber Number	DetailedFiber Description	Modal BW	Link Length	Number of Connector Junctions in Link	Tx Launch	Rx B-B Sensitivity (1E-12)	Rx Receive power MM detector	Rx Receive Power at Rx	Temporal Variation at Output of Modal Filter	Link Margin (Inserted Attenuation for Link Failure at BER 1E-12)
					dBm	dBm	dBm	dBm	dB	dB
1	1/orange	0.6223	300m	2	-3	-17	-3.61	-5.4	0.80	**13.0**
2	1/green	0.347	300m	2	-3	-17	-3.33	-6.3	1.40	**12.0**
3	1/blue	0.6803	300m	2	-3	-17	-3.5	-5	0.80	**12.5**
4	2/orange	0.3153	300m	2	-3	-17	-3.35	-5.1	1.00	**12.7**
5	2/green	0.337	300m	2	-3	-17	-4.19	-6.73	1.80	**12.5**
6	2/blue	0.4963	300m	2	-3	-17	-3.7	-5.9	1.30	**12.5**
7	3/aqua	0.2837	300m	2	-3	-17	-3.76	-5	0.40	**13.6**
8	3/blue	0.2332	300m	2	-3	-17	-3.5	-5.22	0.60	**13.0**
9	3/violet	N/A	300m	2	-3	-17	-3.38	-5.69	1.50	**13.0**
10	4/orange	0.4558	300m	2	-3	-17	-3.4	-5.7	1.40	**12.5**
11	4/green	0.555	300m	2	-3	-17	-3.4	-6.4	0.50	**13.0**
12	4/blue	N/A	300m	2	-3	-17	-3.3	-6.1	1.20	**13.0**
13	5/orange	0.70395	300m	2	-3	-17	-3.35	-5.4	2.00	**11.0**
14	5/green	0.8175	300m	2	-3	-17	-4.2	-6.5	2.50	**7.0**
15	5/blue	0.7367	300m	2	-3	-17	-3.5	-5.33	1.70	**11.0**

EDC Overview

- Variety of Modulation formats/EQ architectures could possibly be deployed, depending on the final channel constraints & allocated budget
  - NRZ & PAM-4 modulation schemes have been proposed.
  - Architectures include the well-understood Feed-forward Equalizer (FFE) and Decision Feedback Equalizer (DFE)
  - Maximum Likelihood Sequence Detection – a near-optimal approach, but more challenging to implement at these high speeds
  - Performance metrics to compare different EDC solutions were examined
- Blind (or decision-directed) LMS adaptation can provide sufficient performance; therefore training sequences are likely not needed
  - Adaptive EDC can track time varying MMF channels; data requested from channel effort to quantify residual penalty
- EDC dispersion and implementation penalties can be accommodated in a 10GBASE-LR "like" power budget

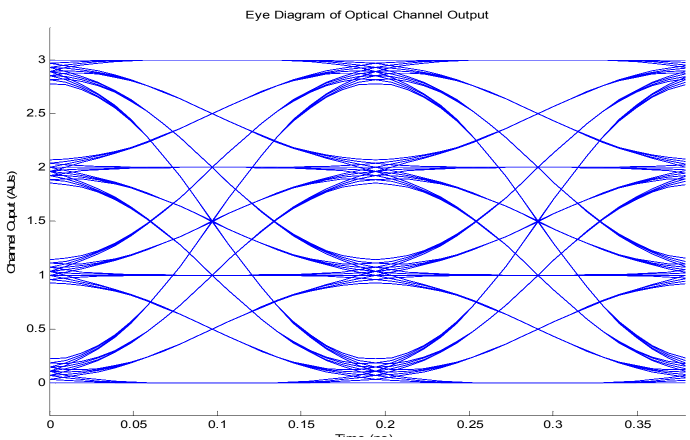
Receive Equalization

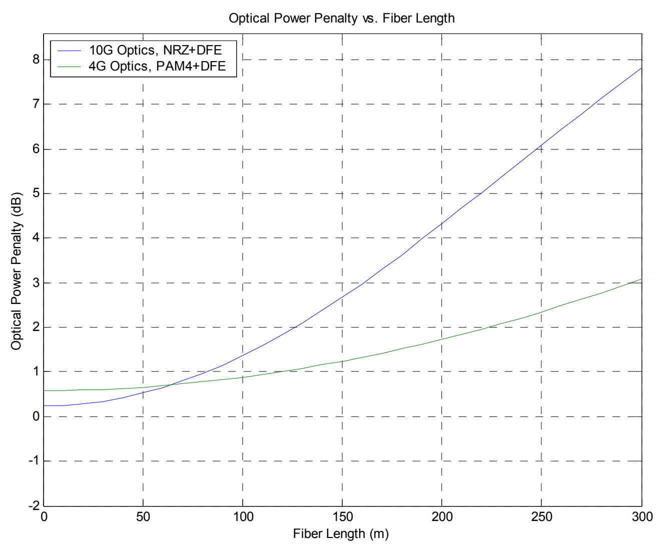


- Measured impulses from the 802.3z National Lab set
  - Bandwidth of ~500 MHz·Km
- 3 fibers were chosen as representative "worst case" candidates
  1. Equal power split which causes notch in spectrum
  2. High DMD fiber & marginal modal bandwidth
  3. Single wide pulse with monotonic frequency roll-off
- 3 EDC architectures simulated - BER vs. Rx OMA plotted
  - Linear (FFE):
    - Dispersion Penalty*: 4.4–6.4 dB
  - Decision Feedback (DFE):
    - Dispersion Penalty*: 2.1–3.5 dB
  - Maximum Likelihood Sequence Detection (MLSD):
    - Dispersion Penalty*: 1.5–2.7 dB

(* vs. unequalized B2B case)

PAM-4 with Receive Equalization





- Used a Gaussian fiber model, modal BW = 500 MHz·km
- Transmit 4 levels instead of 2
- Two cases examined for comparison:
  - 1. NRZ, 10G optics
  - 2. PAM4, 4G optics
  - Both use ideal DFE
- Additional (> 4.5 dB) power budget provided by PAM4 at 300m can be used to:
  - Operate over worse fiber
  - Relax launch requirements
  - Lower Tx power
- Issues for further study
  - Laser linearity
  - RIN
  - Modal noise

Technical Feasibility – Next Steps

- The study group has concluded that several approaches have demonstrated sufficient technical feasibility to achieve the stated objectives
  - (Ref.: cunningham_1_0104.pdf, pepeljugoski_1_0104.pdf, penty_2_0104.pdf, bhoja_2_0104,…)
    - ⇨ *At least 220m on installed 500MHz·km multimode fiber*
- The group has received additional presentations for this meeting to advance all the major technical items to the next level
- One of the key next step items is to examine in detail how the various PHY proposals meet the stated objectives and are in-line with the 5 criteria
  - This down selection process will be accomplished within the task force

Objectives

John Ewen

SG Objectives (adopted 1/14/04)

- Use the existing 10GBASE-R PCS
- Support a BER of better than or equal to 10^{-12}
- Support fiber media selected from IEC 60793-2-10: 2003
  - 62.5μm
    - 160/500 MHz-km (A1b, 60793-2-10: 2003)
    - 200/500 MHz-km (A1b, 60793-2-10: 2003)
  - 50μm
    - 500/500 MHz-km (A1a.1, 60793-2-10: 2003)
    - 400/400 MHz-km (A1a.1, 60793-2-10: 2003)
    - 1500/500 MHz-km (A1a.2, 60793-2-10: 2003)
- Provide a Physical Layer specification which supports link distances of:
  - At least 220m on installed 500MHz·km multimode fiber
  - At least 300m on multimode fiber

Fiber Media Objective

- The issue: defining "FDDI-grade" multimode fiber
  - ISO/IEC 11801:2002 contains no specific reference for 160/500 MHz·km fiber!
    - This is an important fiber for "FDDI-grade" installed fiber
  - TIA 568 B.3 specifies 160/500 MHz·km MMF, but require reference to international standard
- IEC 60793-2-10: 2003
  - IEC 60793 maps out broad ranges of modal bandwidth
  - 60793-2 is the reference for several 802.3 PMD's
    - E.g. 10GBASE-LR and 10GBASE-LX4
    - The PMD's explicitly list the OFL bandwidths for the referenced fiber types
- Follow 802.3ae methodology in specifying the fiber
  - However wavelength, launch conditions, distance, etc. still TBD

802.3ae: Fiber Media

- **802.3ae methodology (Clause 52):**
  - Refer to IEC60793-2
  - Define specific modal bandwidth as required (e.g. Table 52-25)
  - Define reach for each modal bandwidth supported (e.g. Table 52-6)

52.14.1 Optical fiber and cable

*The fiber optic cable shall meet the requirements of **IEC 60793-2** and the requirements of Table 52–25 where they differ for fiber types **A1a** (50/125 µm multimode), **A1b** (62.5/125 µm multimode), B1.1 (dispersion un-shifted single mode), or B1.3 (low water peak single mode).*

Table 52–6—10GBASE-S operating range for each optical fiber type

Fiber type	Minimum modal bandwidth @ 850 nm (MHz•km)	Operating range (meters)
62.5 µm MMF	160	2 to 26
	200	2 to 33
50 µm MMF	400	2 to 66
	500	2 to 82
	2000	2 to 300

Reach Objective (1/3)

- Low cost is recognized as an important part of the 5 criteria
  - 1000BASE-SX is the most successful 1Gb/s fiber PMD
    - Only specified to 220m but provides compelling cost/performance
    - 1000BASE-LX offers solution for longer distances
  - New PHY should offer similarly compelling cost/performance
    - 10GBASE-LX4 offers solution for longer distances
- The appropriate complexity performance tradeoff enables the economic feasibility sweet spot.

GbE Operating Ranges

	62.5 MMF	50 MMF
SX	220 m	550 m
LX	550 m	550 m

10GbE Operating Ranges

	62.5 MMF	50 MMF
LX4	300 m	300 m
LXEZ	220 m	220 m

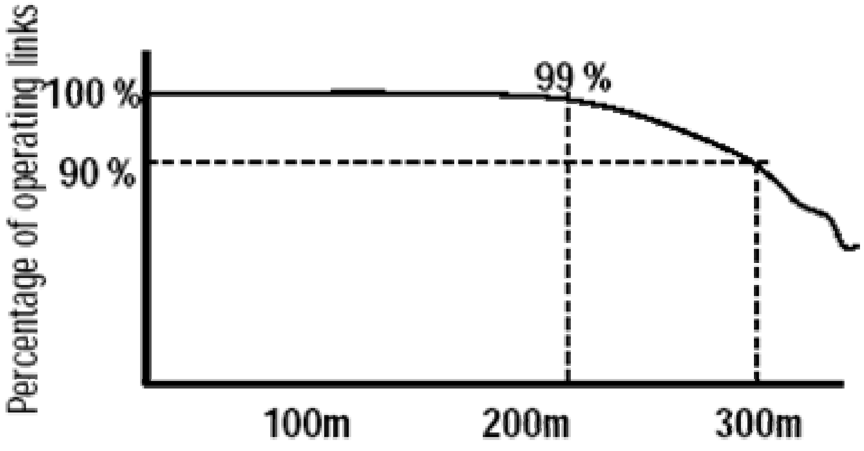
Reach Objective (2/3)

Provide a Physical Layer specification which supports link distances of:

⇨ *At least 220m on installed 500MHz.km multimode fiber*

- 2x – 3x distance improvement with ≥99% yield and reasonable complexity for FDDI-grade MMF
  (e.g. cunningham_1_0104.pdf, pepeljugoski_1_0104.pdf, penty_2_0104.pdf, bhoja_2_0104.pdf)

- From cunningham_1_0104.pdf:



<u>Advantages of this approach include:</u>

- Practical power penalties (3 – 5 dB)
- Wide implementation space
- Shorter standardization time

Reach Objective (3/3)

Provide a Physical Layer specification which supports link distances of:

⇨ *At least 300m on multimode fiber*

- Stretch goal for SG
  - 300m may be possible using more advanced equalization, modulation or optical techniques (e.g. bhoja_1_0104.pdf, voois_1_0104.pdf, hallemeier_2_0104.pdf)
- Maintain "reach compatibility" with existing 10Gb/s PMDs
  - Existing 10GBASE-SR achieves 300m on OM3 fiber
  - New PMD should support at least 300m on this fiber
- OM3 engineered for better DMD performance
  - May support longer distances than FDDI-grade MMF
  - Further investigation required to determine performance at 1310nm

Tutorial Summary

- Distinct identity: one problem-one solution
  - We need a serial solution to support installed FDDI-grade fiber. Serial interface enables higher density, lower power, lower cost
- Technical feasibility: We have at least three approaches to solving the problem
- Broad market potential - demonstrated
- Economic feasibility: costs are expected to be comparable to or less than 10GBASE-LR
- Compatibility: Yes

Q & A