10 Gb/s MULTIMODE FIBER TRANSMISSIONS OVER ANY (LOSS-LIMTIED) DISTANCES USING ADAPTIVE EQUALIZATION TECHNIQUES

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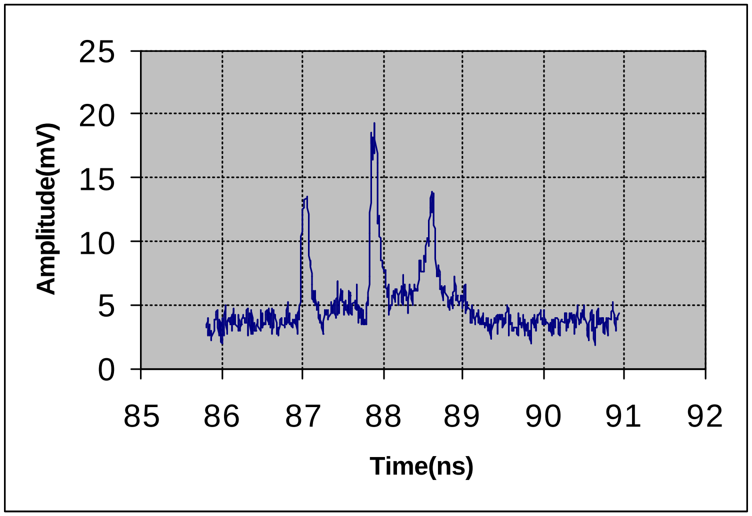
10 Gb/s Ethernets

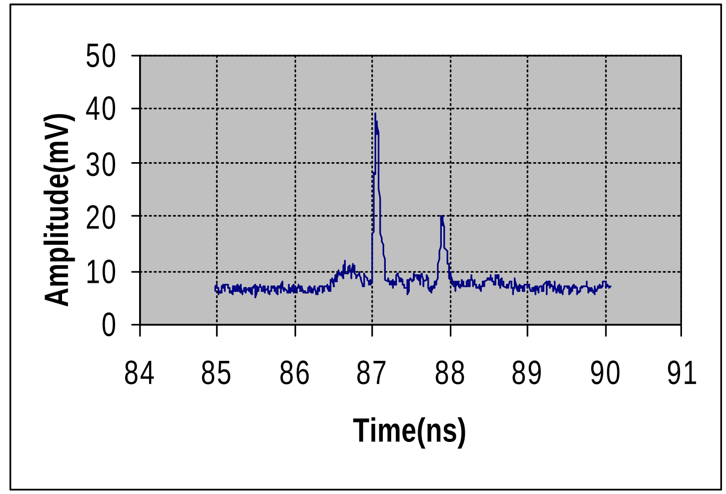
- The speed of Ethernets increases nearly 10 times for every 3 years It is 1Gb/s now and in the next 1-2 years, it will be focused on the 10Gb/s (meet with SONET)

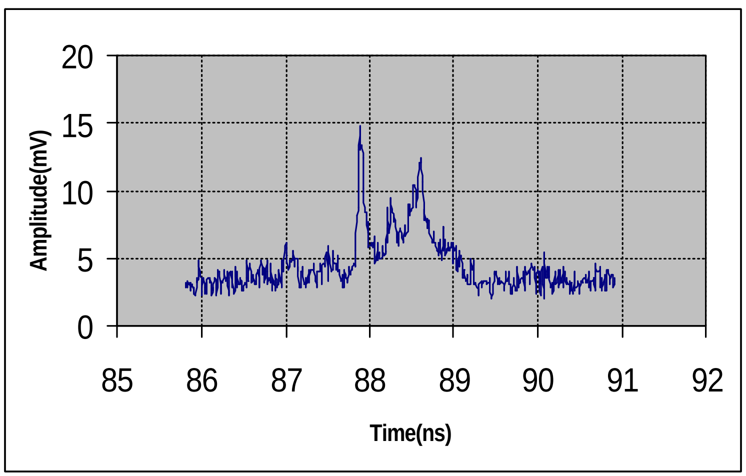
- Among the 5 objectives of 10Gb/s GE in the standards meeting (**1.** 100 m installed multimode fiber, **2.** 300m on new multimode fiber, **3.** 2 km on single mode fiber, **4.** 10 km on single mode fiber, and **5.** 40 km single mode fibers) the only one without solution is about the already installed multimode fibers (MMFs).

- The main source of bit errors in a MMF transmission system is the inter-symbol interference (ISI) caused by the differential mode dispersion (DMD) generated multi-path effects

Multipath Delay Bin Outputs





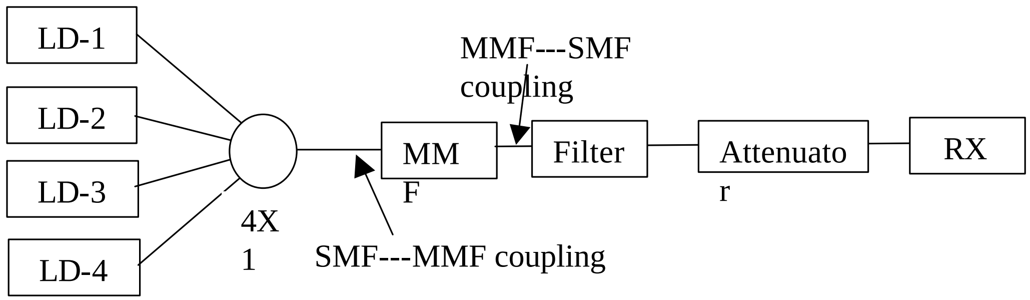


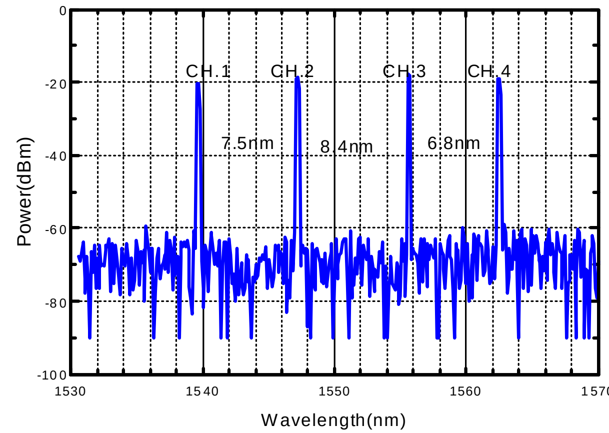
A single pulse is transmitted through a 1.5 km long MMF at different launching offsets using a 1.55 um gain switched DFB laser. The fundamental mode is at around the time 87 ns. Other higher order modes are followed.

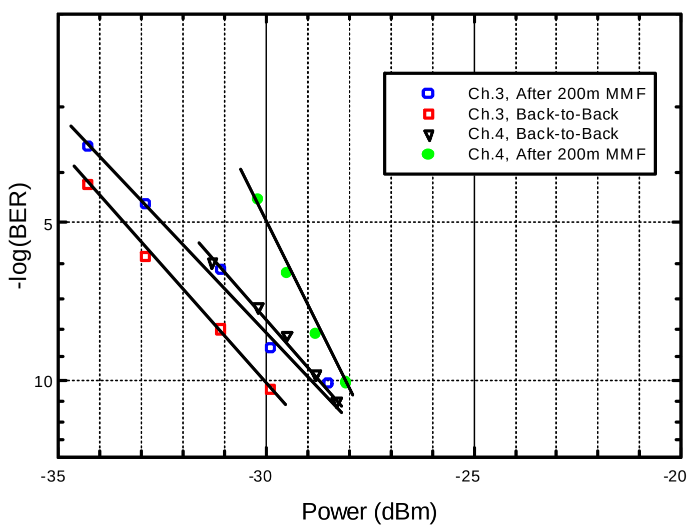
Approaches to Resolve The Multi-Path/ISI Problems

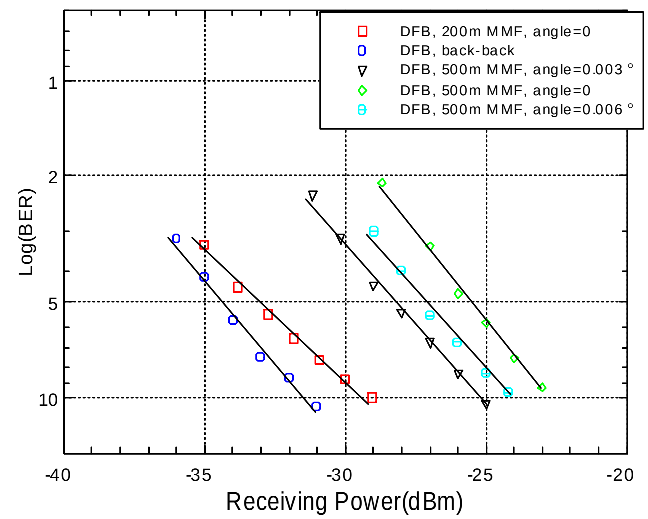
- ❑Multi-fiber parallel transmissions 10x 1Gb/s.
- ❑Multi-Wavelength WDM approaches 4x2.5 Gb/s or 2x5 Gb/s.
- ❑Multi-level modulation approaches.
- ❑Subcarrier modulation approaches.
- ❑Single channel equalization approaches.

Examples (WDM Approaches)

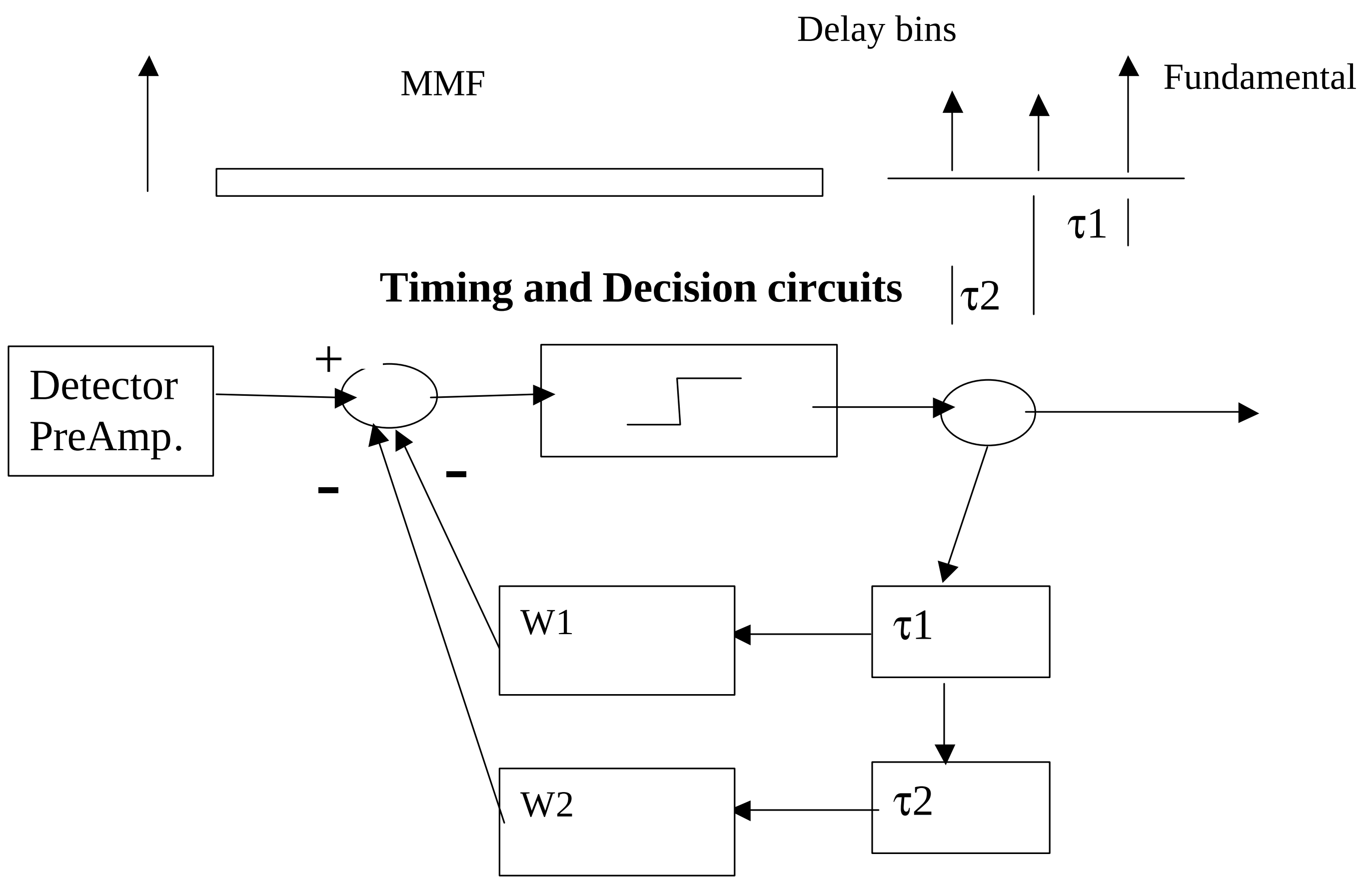




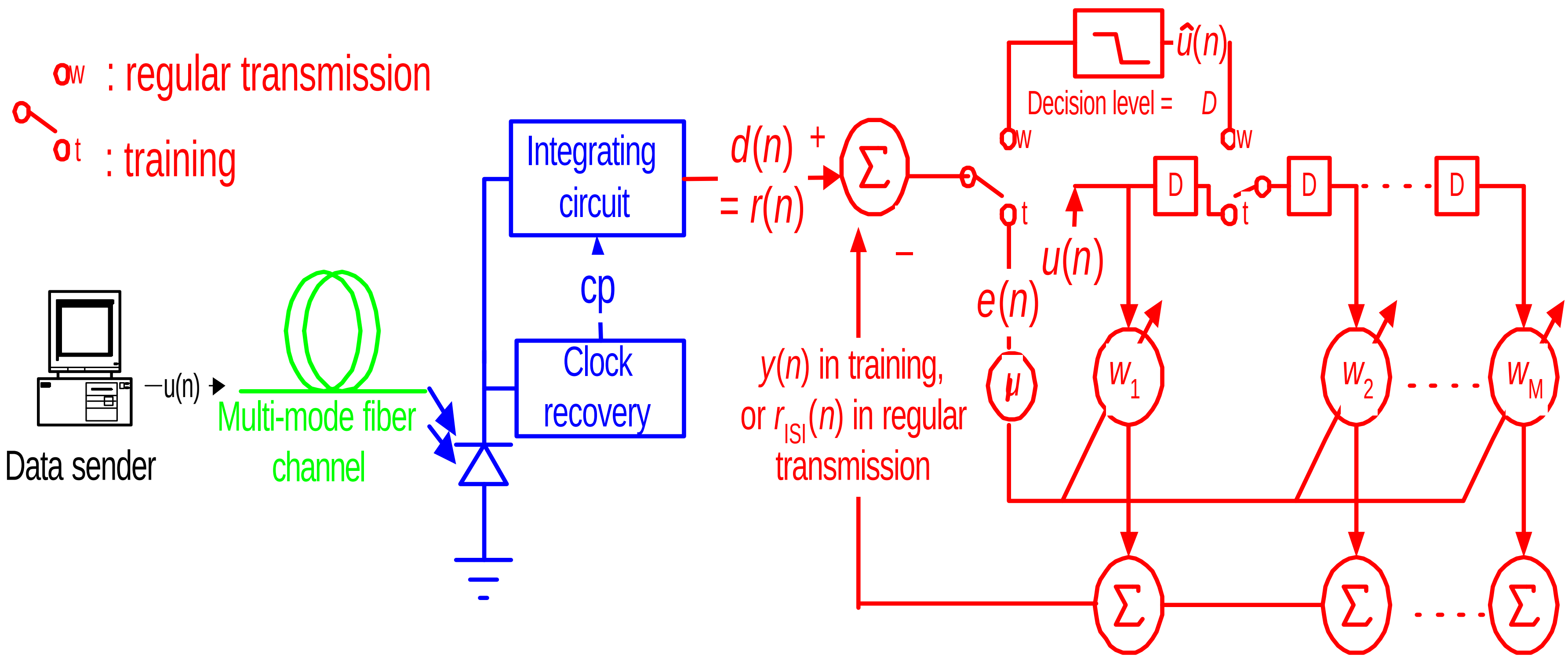




Equalization Principle



Equalization Architecture



Transmission Stages of the Adaptive Equalizer

- **Training Periods**
  - — A training data stream is transmitted
  - — A replica of the training data is stored at the receiver end as the input vector $\mathbf{u}(n)$ of the adaptive equalizer
  - — Desired value d(n) is the detected signal $r(n)$ before decision
  - — Weight $\mathbf{w}(n)$ is updated adaptively (LMS) to approach the impulse response $h(t)$ of the MMF transmission channel
- **Regular transmissions**
  - —The equalizer works with the fixed weights $\mathbf{w}^*(n_T)$

$$r_{ISI}(n) = \mathbf{w}'^{*T}(n_T)\hat{\mathbf{u}}(n\text{-}1)$$

$$\hat{u}(n) = \begin{cases} 1, & \text{if } [r(n) - r_{ISI}(n)] > D \\ 0, & \text{if } [r(n) - r_{ISI}(n)] < D \end{cases}$$

Nature of the MMF channel

- **Impulse response of the MMF channel**

$$h(t) = \sum_{k=0}^{N} A_k d(t + t_k)$$

- **Impulse response of the inverse system**

$$h'(t) = F^{-1}\left\{\left(\sum_{k=0}^{N} A_k e^{j2pft_k}\right)^{-1}\right\}$$

- **Length of filter approaches *h*(*t*)**

$$M_{\min} = \lceil (t_{\max} - t_{\min}) / \mathrm{T} \rceil$$

The filter approaching h(t) is much shorter than the one approaching h'(t)

Statistics of the Input Tap Vector

- **Correlation matrix (R** = E{**u**(n)**u**^{T}(n)})

$$\mathbf{R} = \begin{bmatrix} p & p^2 \cdots & p^2 \\ p^2 & p \ddots & \vdots \\ \vdots & & p^2 \\ p^2 \cdots & p^2 & p \end{bmatrix}_{M \times M}$$

Assuming i.i.d. input samples $u(n)$

- **Condition number of the matrix (*c*(R))**

$$c(\mathbf{R}) = \frac{1 + (M-1)p}{1-p}$$

Conditioning of R becomes worse as M increases

Performance of the LMS Algorithm

- **Maximum step size m_{max} for LMS to converge**

$$m_{\max} = \frac{2}{Mp}$$

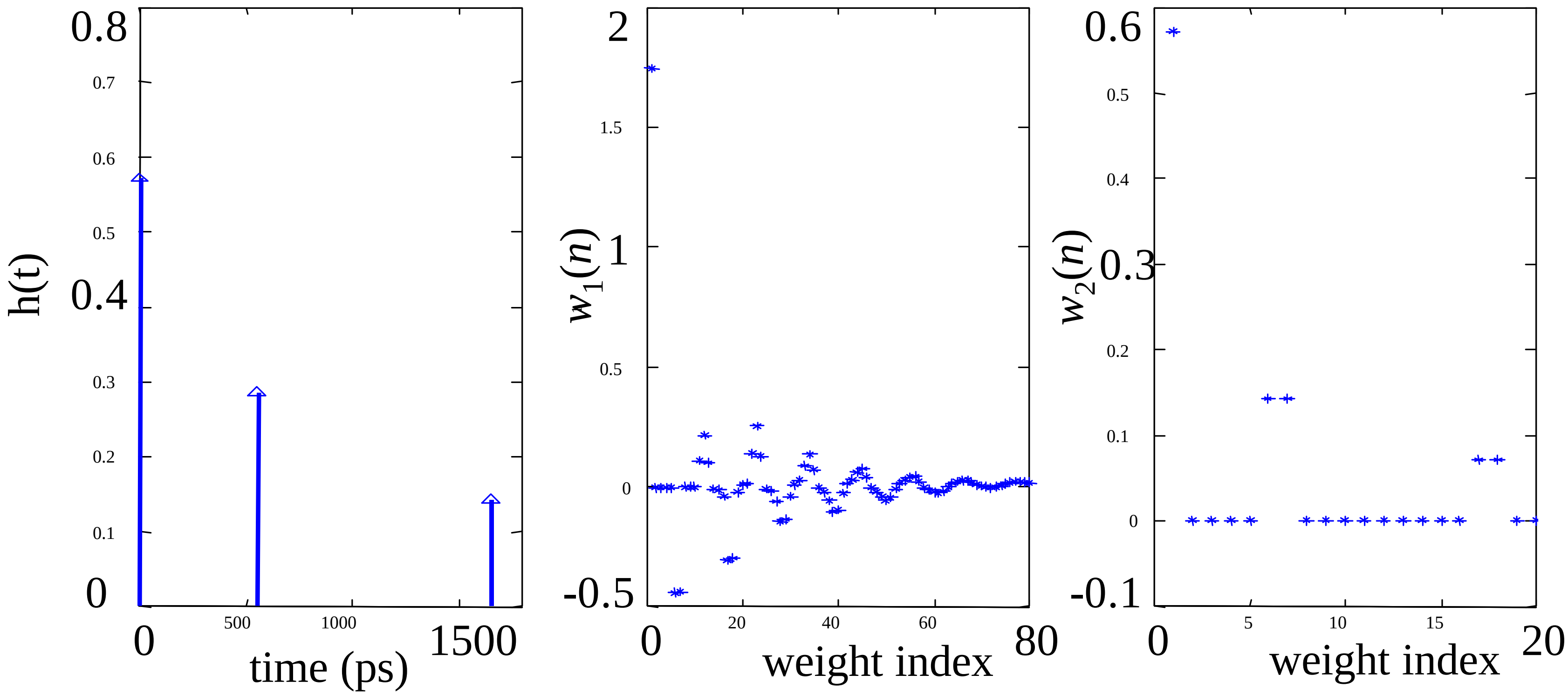
- **m_{max} becomes smaller and c(R) bigger as M increases**

  Slowing down the convergence of the LMS algorithm

- **M_{min} is proportional to the transmission distance z**

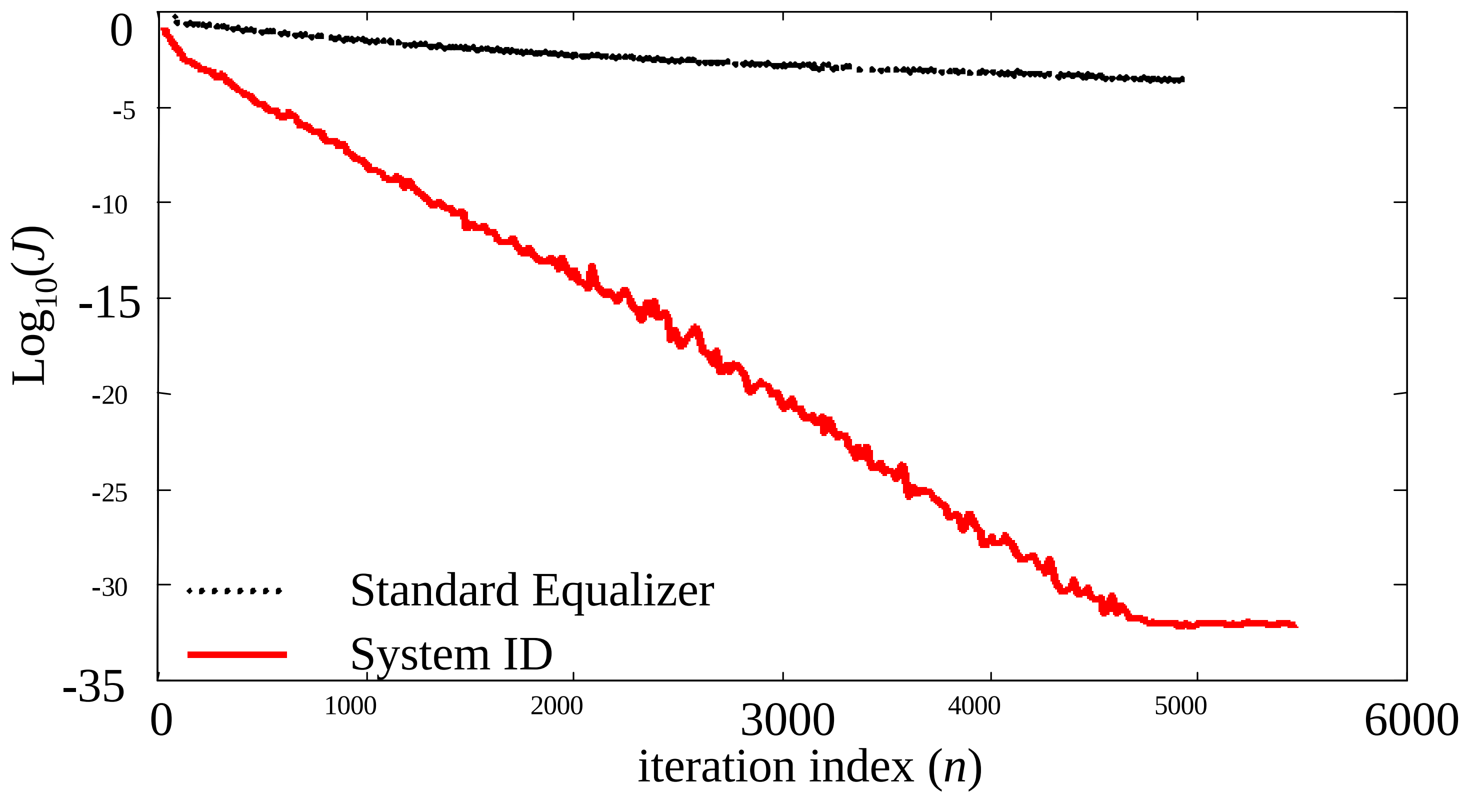
Longer distance between communication hosts requires more iterations for LMS algorithm to converge

Simulation Results: Comparison of Converged Filter weights



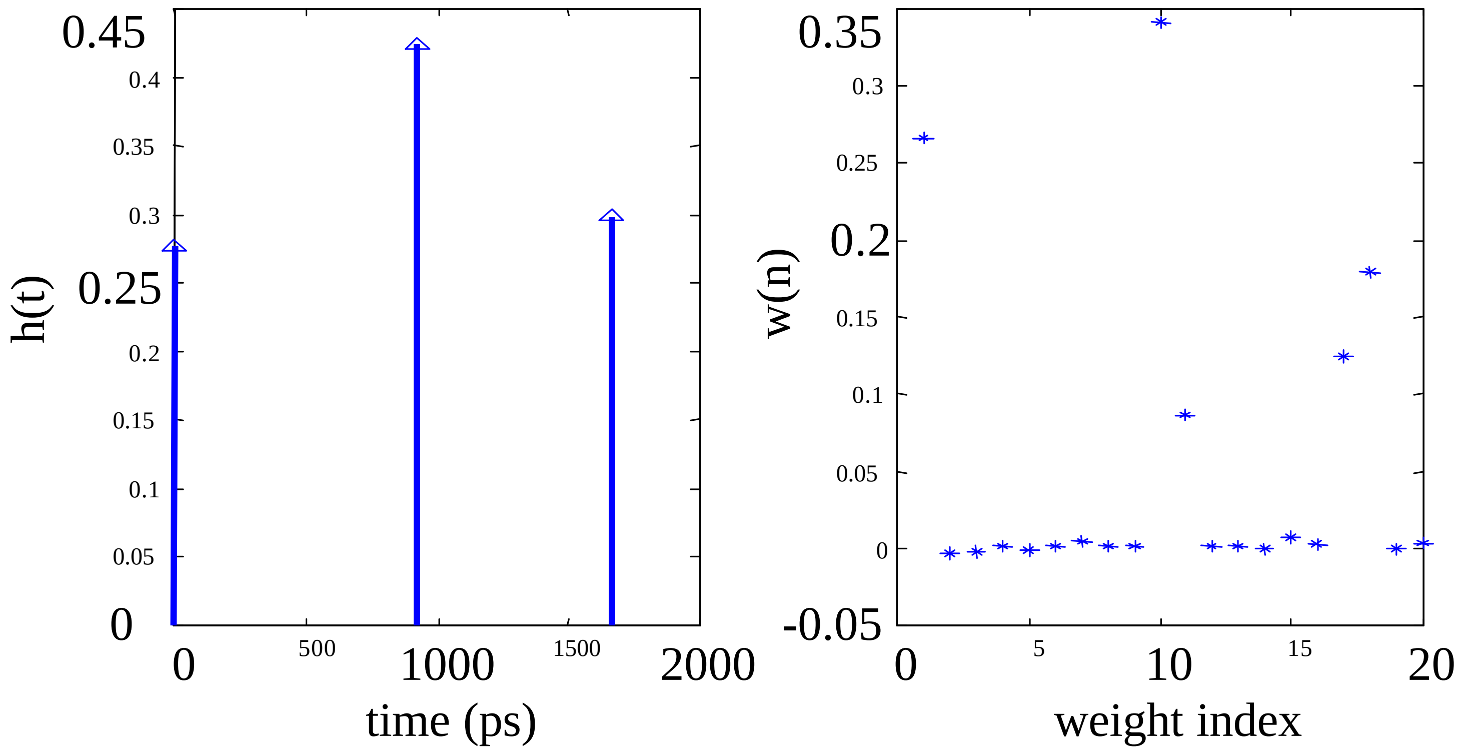
w_2 has a simpler structure than w_1 and can be represented by a few nonzero coefficients

Simulation Results: Comparison of Learning Curves



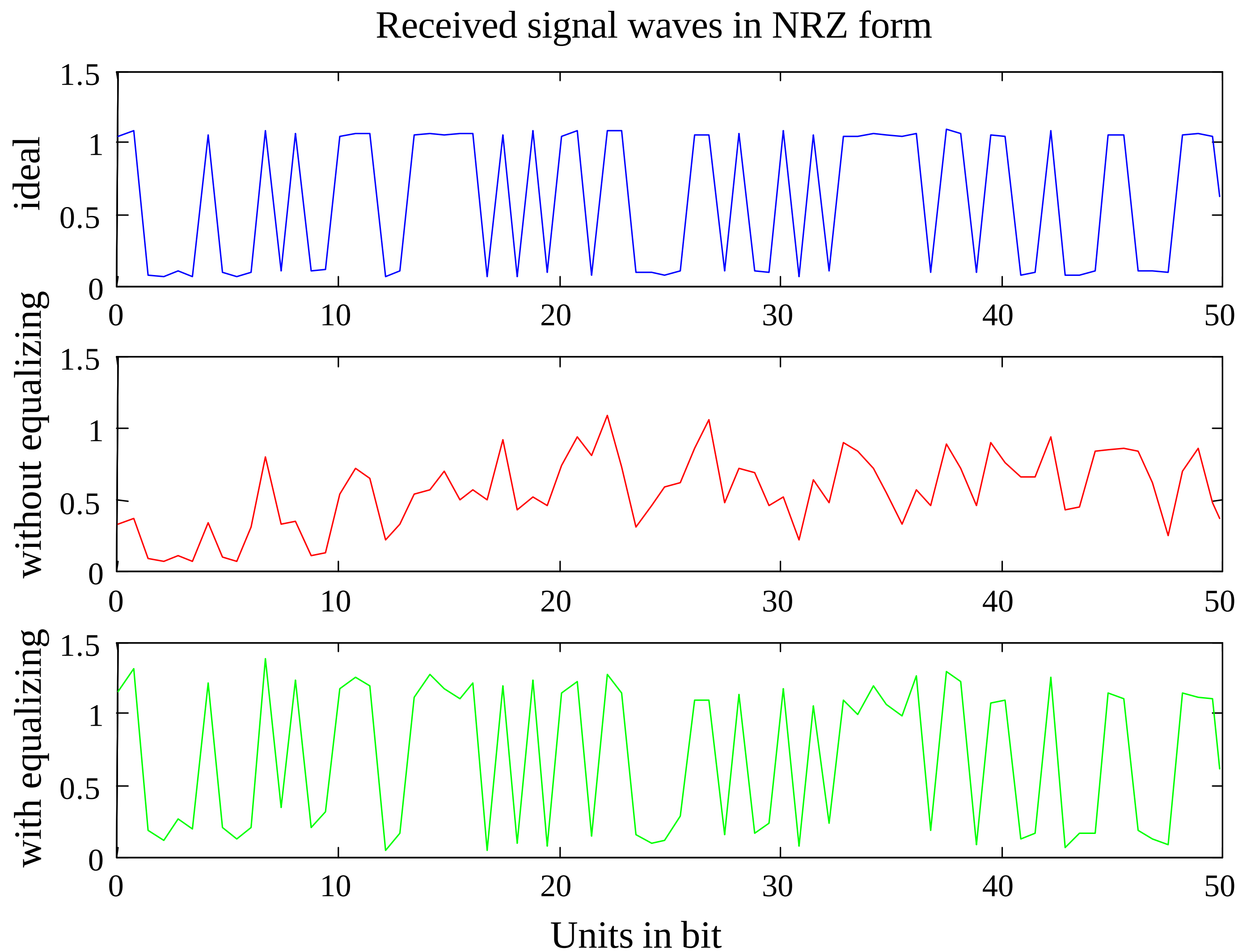
System ID based approach converges much faster

Simulation Results (I): Performance of the Proposed Equalization approach

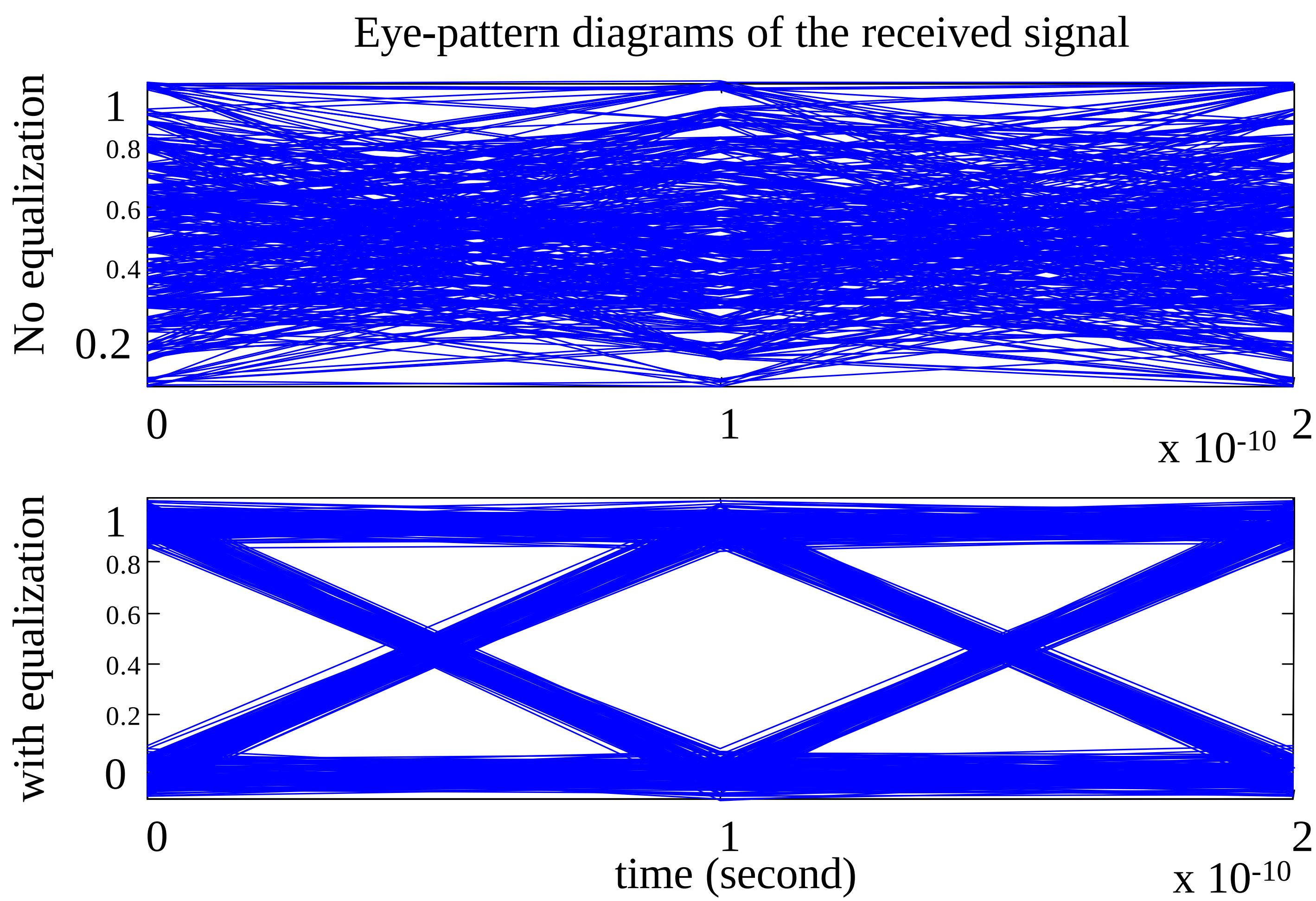


Impulse response of the MMF channel and the converged filter weights

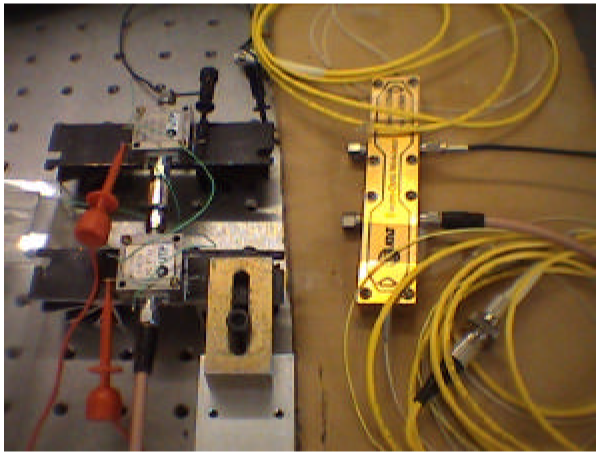
Simulation Results (II): Performance of the Proposed Equalization approach



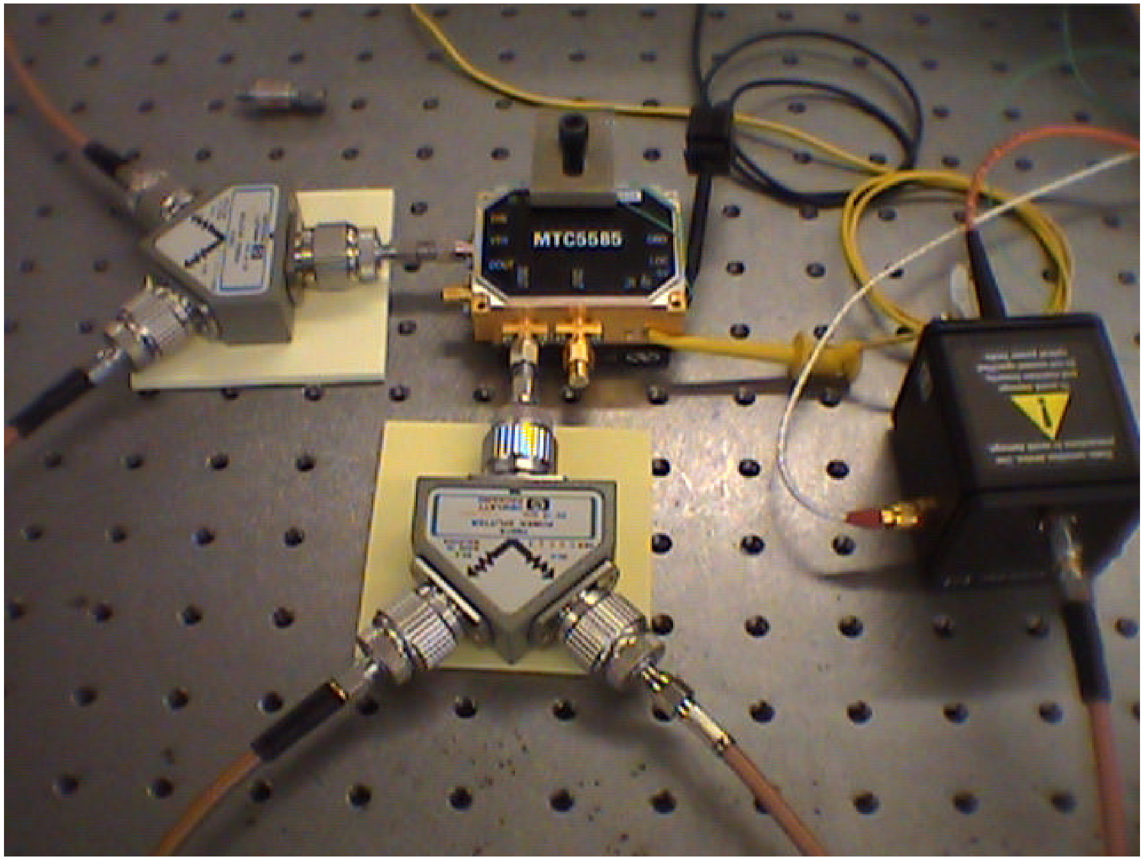
Simulation Results (III): Performance of the Proposed Equalization approach



Experimental Setup



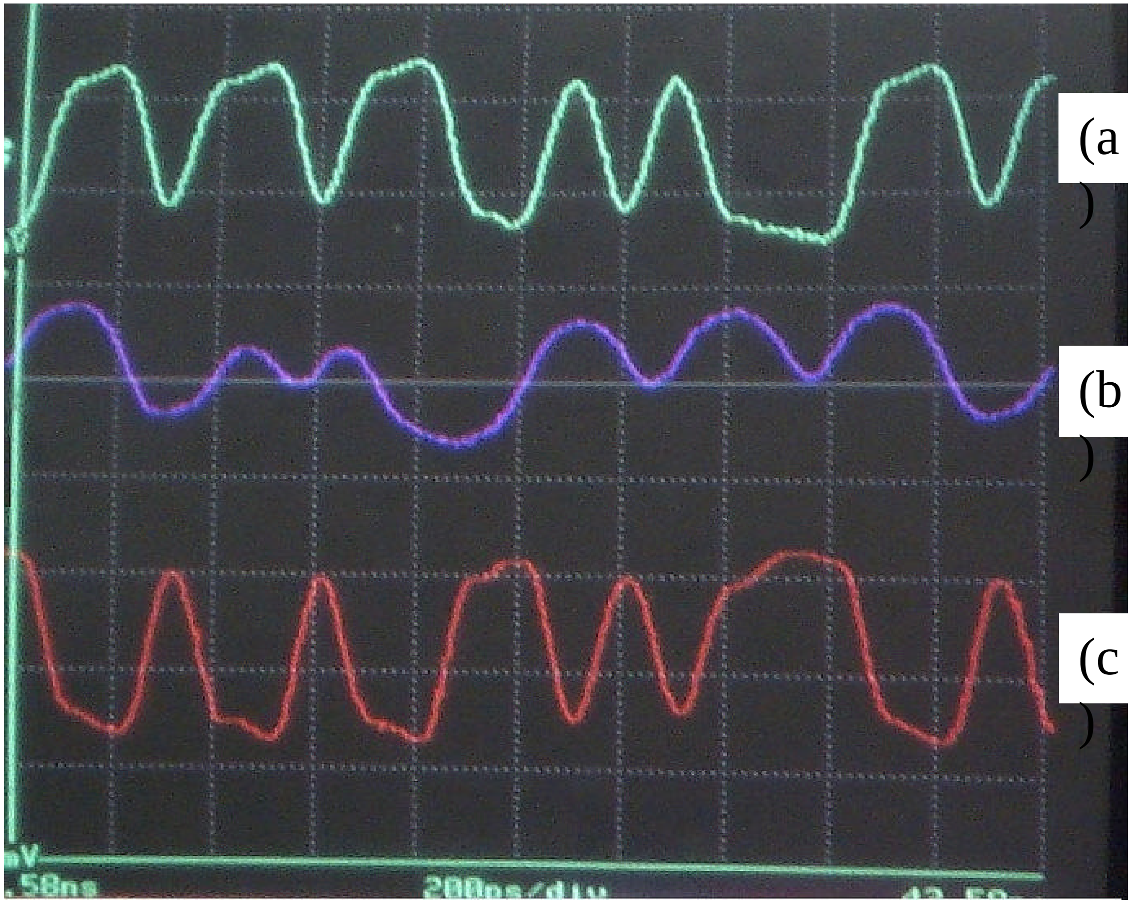
Transmitter



Receiver and Part of the Equalizer

Equalizer is composed of Multilink Decision Ckt., Delay lines, Amplifiers (providing phase reversal).

Experimental Results



Since the delay path (cables) are long, we send fixed data pattern and use signals in the current frame to cancel multipath copies in the next frame.

a. Transmitted Pattern, **b**. Before equalization, **c**. After equalization

Conclusions (I)

❑We have demonstrated using adaptive equalization techniques to overcome the signal degradation caused by differential modal dispersion in a conventional multimode fiber.

❑With this technique, we can not only obtain MMF-based 10 Gb/s GEs but also upgrade all the already installed MMFs (OC-3 backbones) to higher-speed pipes at nearly any (loss limited) lengths.

Conclusions (II)

- **The good news**: The modal diffusion constant in MMF is small and once the initialization process is done no more adaptive processes are required in later transmission. No matter how we change the fiber temperature and stress if the launching condition is not changed, the excited modes will be very stable in the MMF. Ethernet protocol can be boosted after the initialization without any modification to accommodate the adaptive process, since there is no more "adaptive equalization“