T10/05-219r0

Survey of High-Speed Serial Technologies

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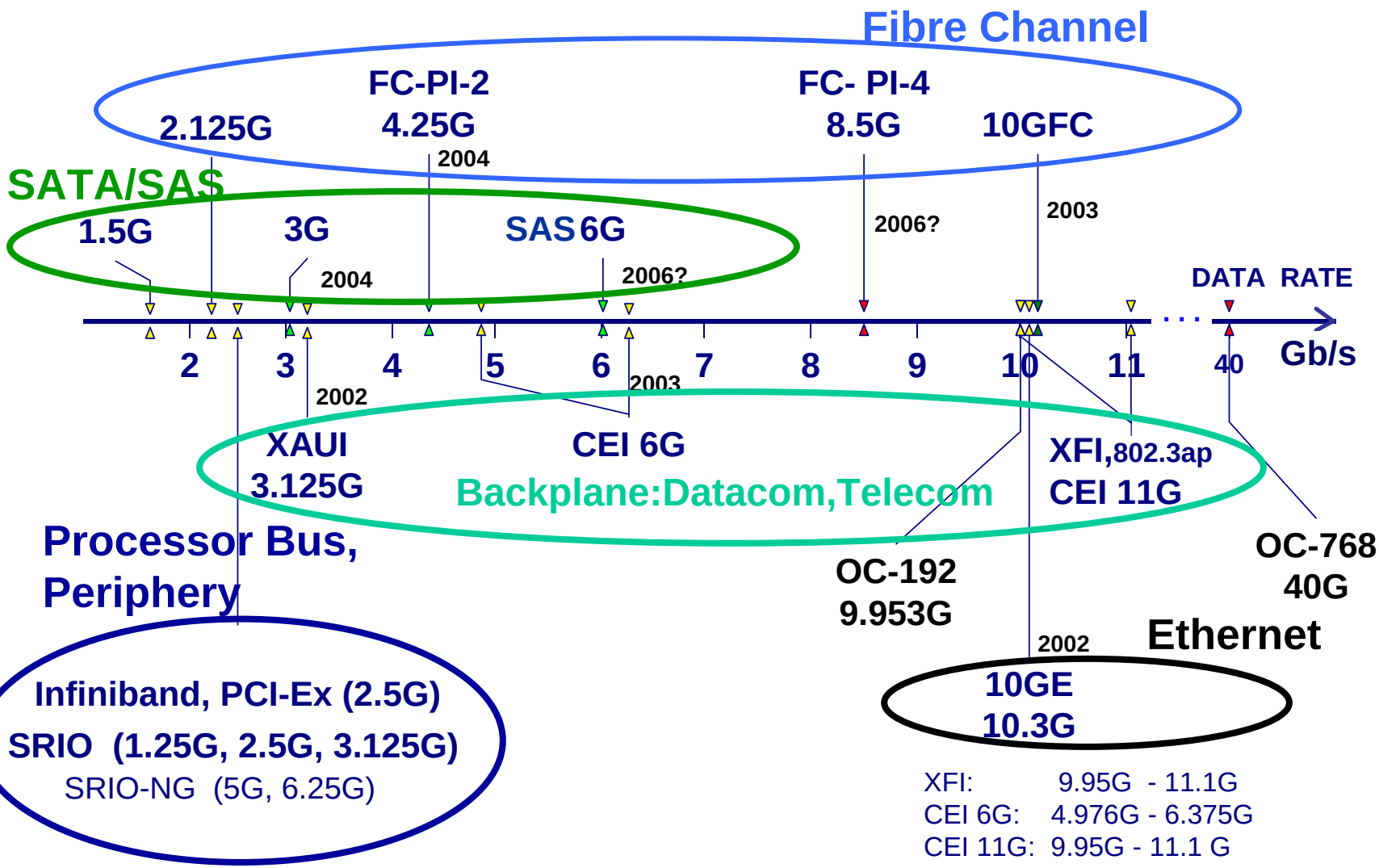
Outline

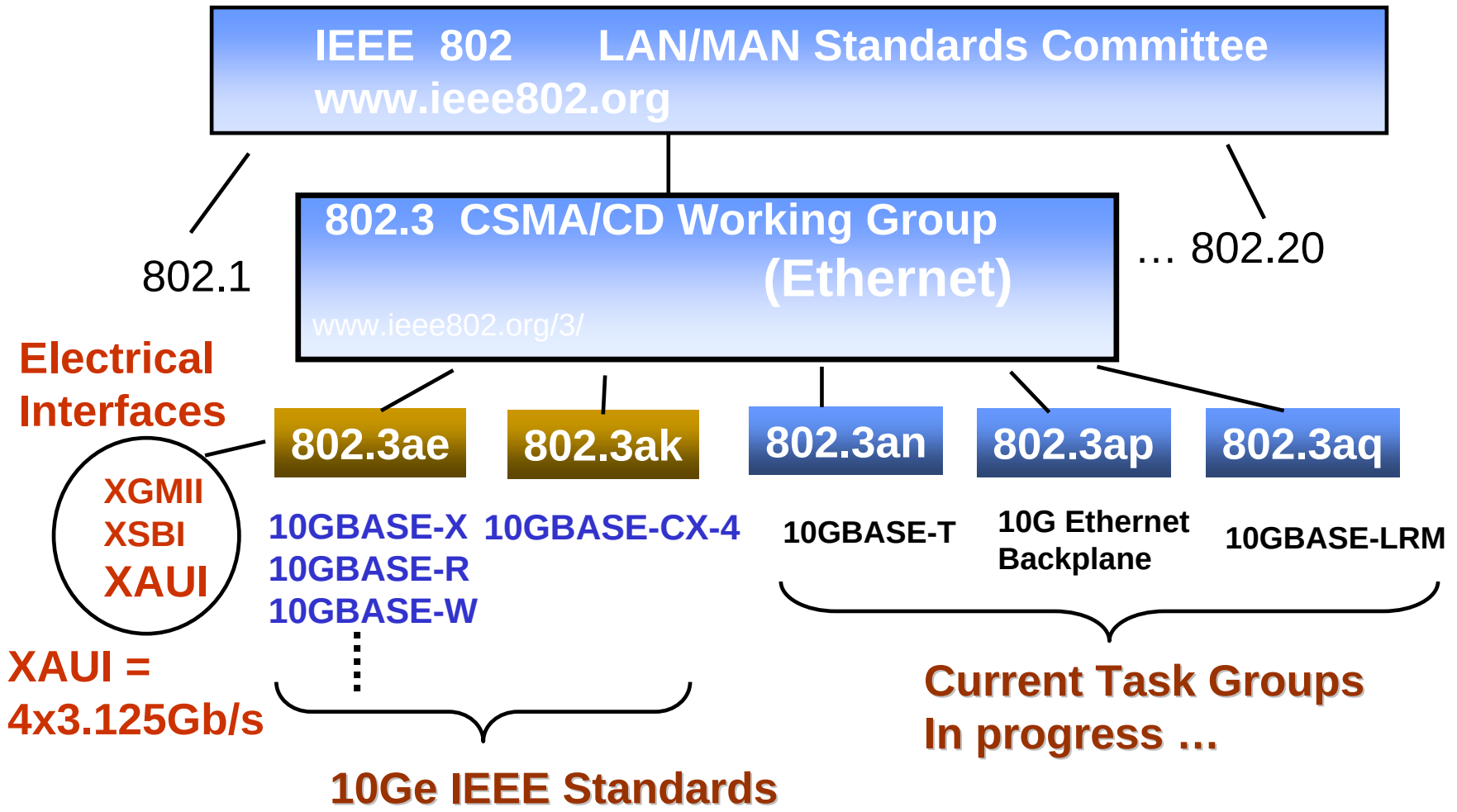
- Multi-Gigabit Standard Space
- Milestones
  - XAUI
  - XFI
  - OIF CEI
- Transceiver Equalization at 6Gb/s
  - Basic Techniques and Terminology
  - Industry 6Gb/s state-of-the-art ICs and trends
- New Frontiers

Multi-Gigabit Standards Space



XFI: 9.95G - 11.1G
CEI 6G: 4.976G - 6.375G
CEI 11G: 9.95G - 11.1 G

IEEE 802.3 FrameWork

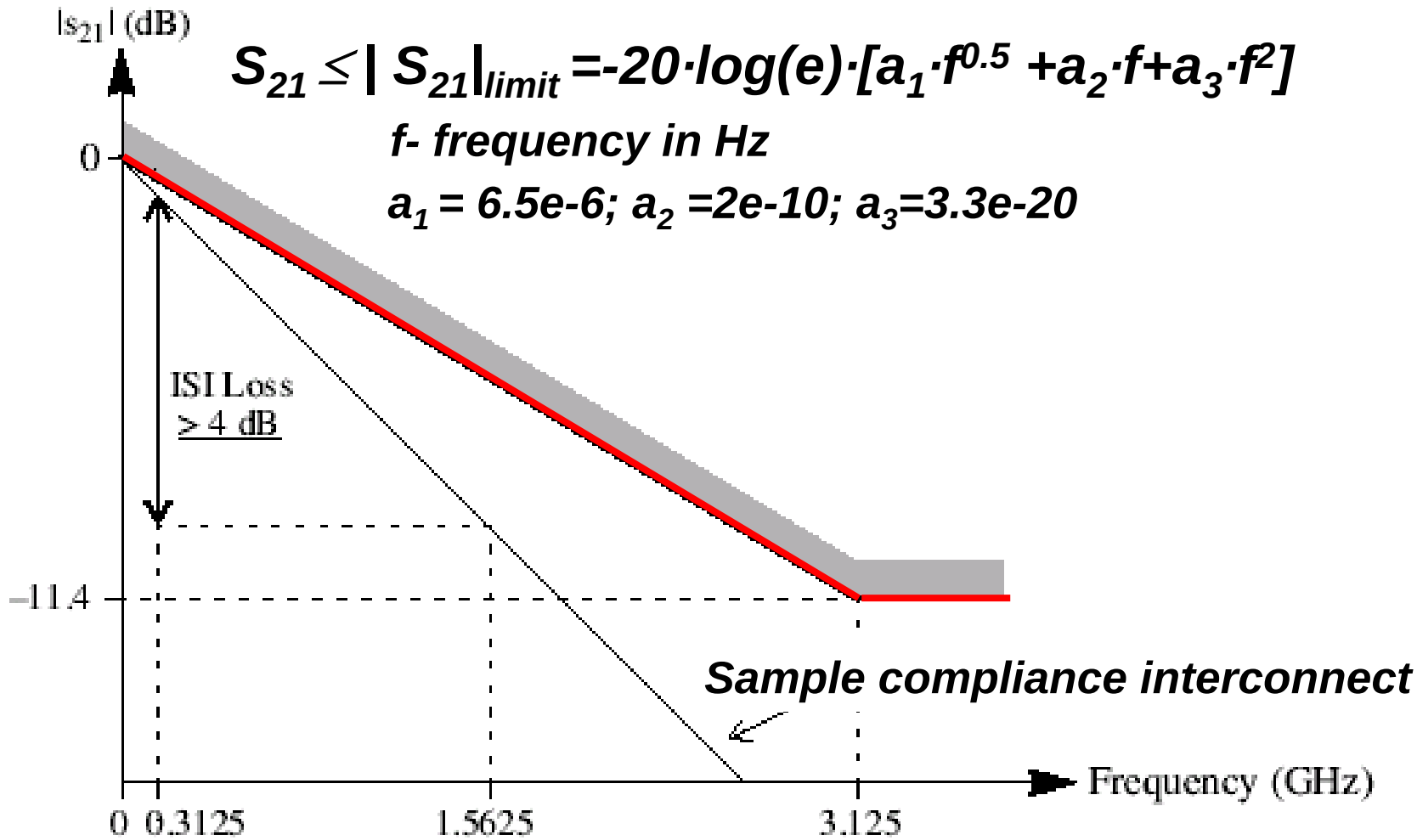


Industry sponsored IEEE std download: http://standards.ieee.org/getieee802/

XAUI-like Electrical Interfaces

- XAUI was the first 3.125Gb/s industry standard
  - Channel ISI is limited to 4-6 dB, two connectors
  - The Rx eye is open
  - Moderate reflections and frequency dispersion
    - Single-pole equalization is sufficient
      - 2-tap FIR in Tx (pre-emphases)
      - FFE in Rx (if no equalizer in Tx)
      - Or both for cables
  - 8b/10b, CJPAT - testing
- Due to interoperability success XAUI has influenced many other electrical standards

XAUI - Compliant Interconnect



$S_{21} \leq |S_{21}|_{limit} = -20 \cdot \log(e) \cdot [a_1 \cdot f^{0.5} + a_2 \cdot f + a_3 \cdot f^2]$

f- frequency in Hz

$a_1 = 6.5e\text{-}6;\ a_2 = 2e\text{-}10;\ a_3 = 3.3e\text{-}20$

Sample compliance interconnect

- **The S21 phase and S12,S11,S22 are not specified. Potentially could lead to interoperability problems**

The XFI “Ziffy”

“The XFI “Ziffy” is the high speed serial electrical interface for XFP modules with a nominal baud rate of 9.95-11.1 Gb/s. XFI connects a serial 9.95-11.1 Gb/s SerDes to a module over 300mm of improved FR4[1] material or up to 200mm of standard FR4 with one connector. The electrical interface is based on high speed low voltage AC coupled logic with a nominal differential impedance of 100 Ω. The XFP module could be an Electrical-to-Optical or an Electrical-to-Electrical device.

The XFP modules and the host system are hot-pluggable. The module or the host system shall not be damaged by unexpected insertion or removal of the module”

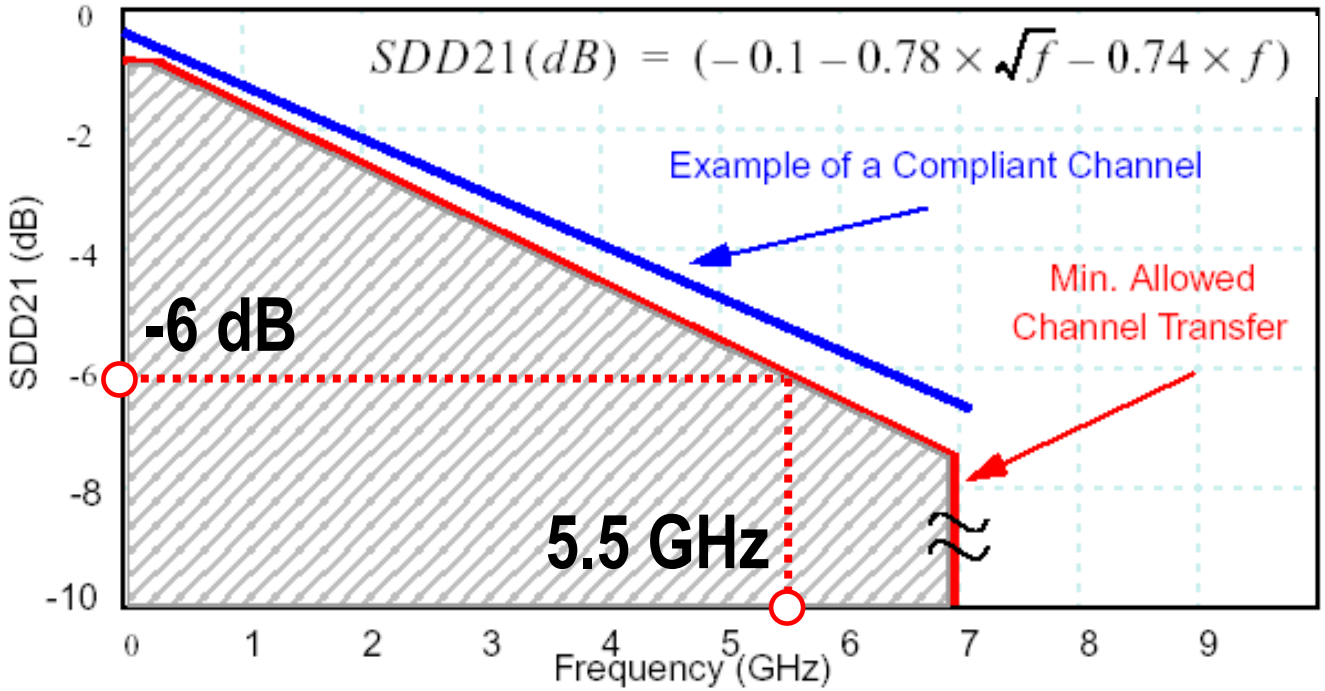
1. Standard FR4 has a typical loss tangent of 0.022, where improved FR4 such as Nelco 4000-13 has a typical loss tangent of 0.016.

Source: XFP MSA, Rev.4,2004

XFI Impact

- XFI had become de facto next milestone in H/S interfaces at 10Gb/s
  - Data protocol agnostic
  - Was also adapted by Fiber Channel and OIF 11G SR
- Requires Rx FFE, no Tx equalization is allowed
  - Reduced EMI
- Specifies advanced set of differential S-parameters to control primary and secondary reflections
- Interoperability testing with the test boards

XFI Compliant Channel



- **Includes XFP connector (0.5dB at 5.5GHz)**
- **Total channel loss budget 9.6 dB including crosstalk and reflections**

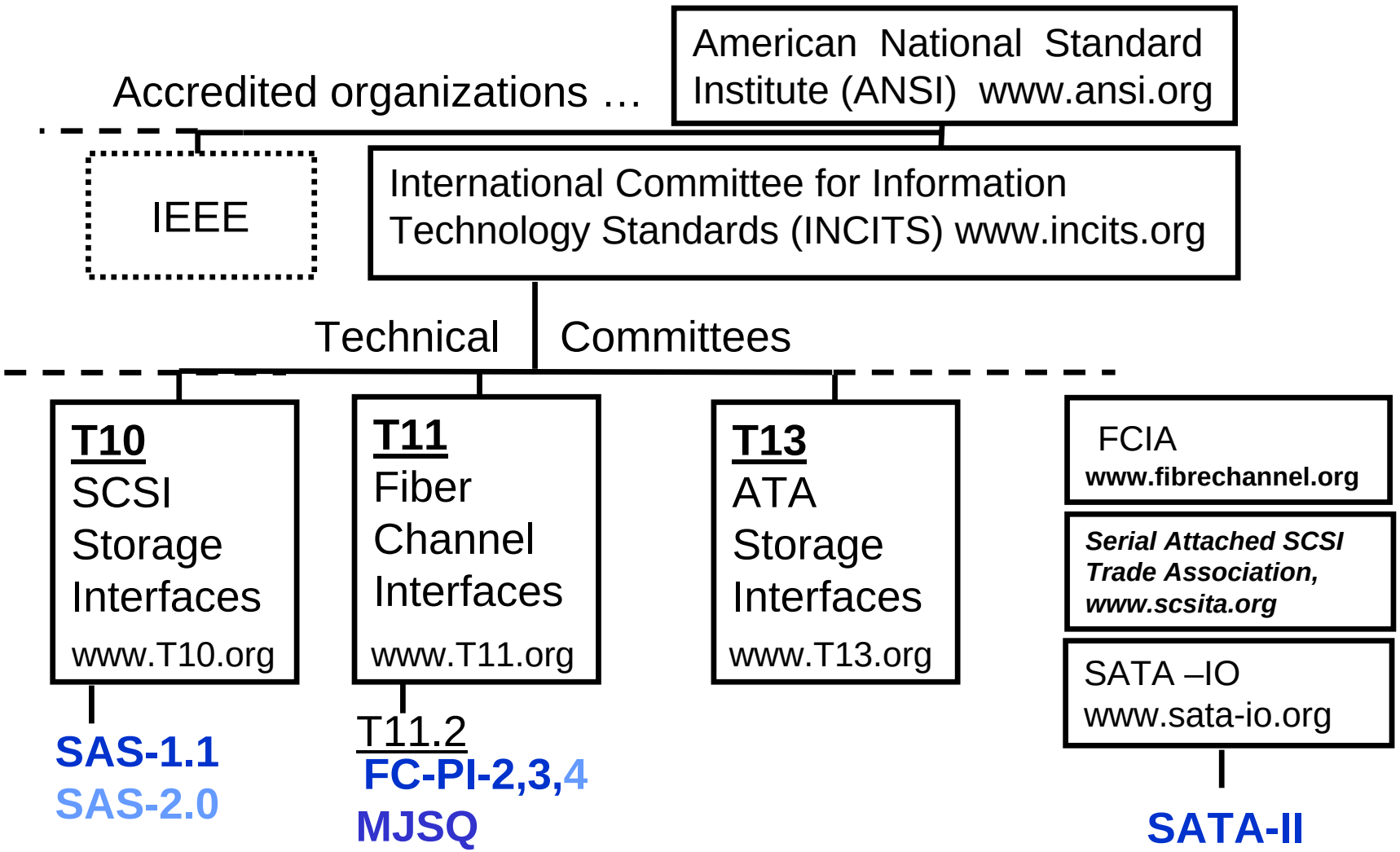
Source XFP MSA

Optical Internetworking Forum (OIF)

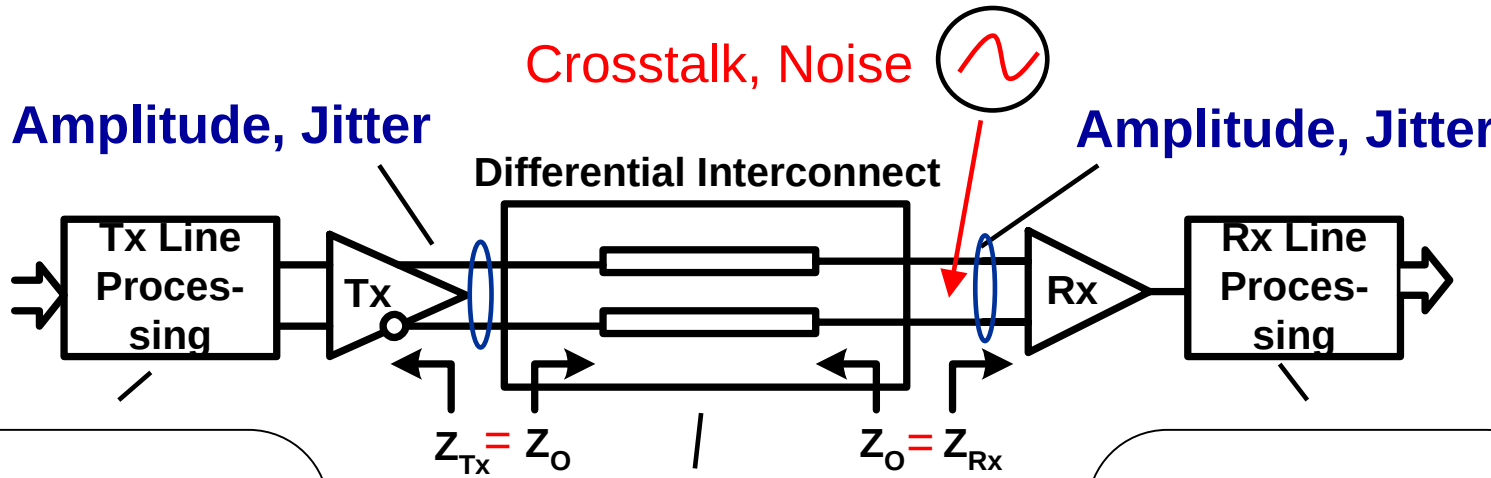
- Electrical Interfaces for OC-192, OC768
- CEI 6G SR, LR (over legacy backplanes)
- CEI 11G

- **A milestone in 6Gb/s interconnects and in advanced equalization techniques for interfaces with BER < 10^{-15}**
- **Has the most comprehensive up to date multi-gigabit range serial electrical interface specification with Common Electrical Interfaces (CEI) *"Jitter and Interoperability Methodology***
- **Will be covered in separate presentations**

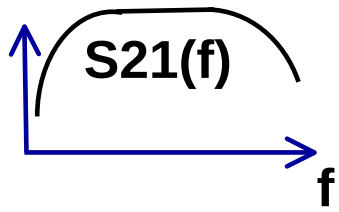
Storage Area Standards Framework



Generic View on Serial Electrical Interface



- ✧ Line Coding (i.e. 8b10b, 64b66b, …), Serializer
- ✧ Modulation (i.e. NRZ, PAM4, …
- ✧ Equalization
- ✧ FEC



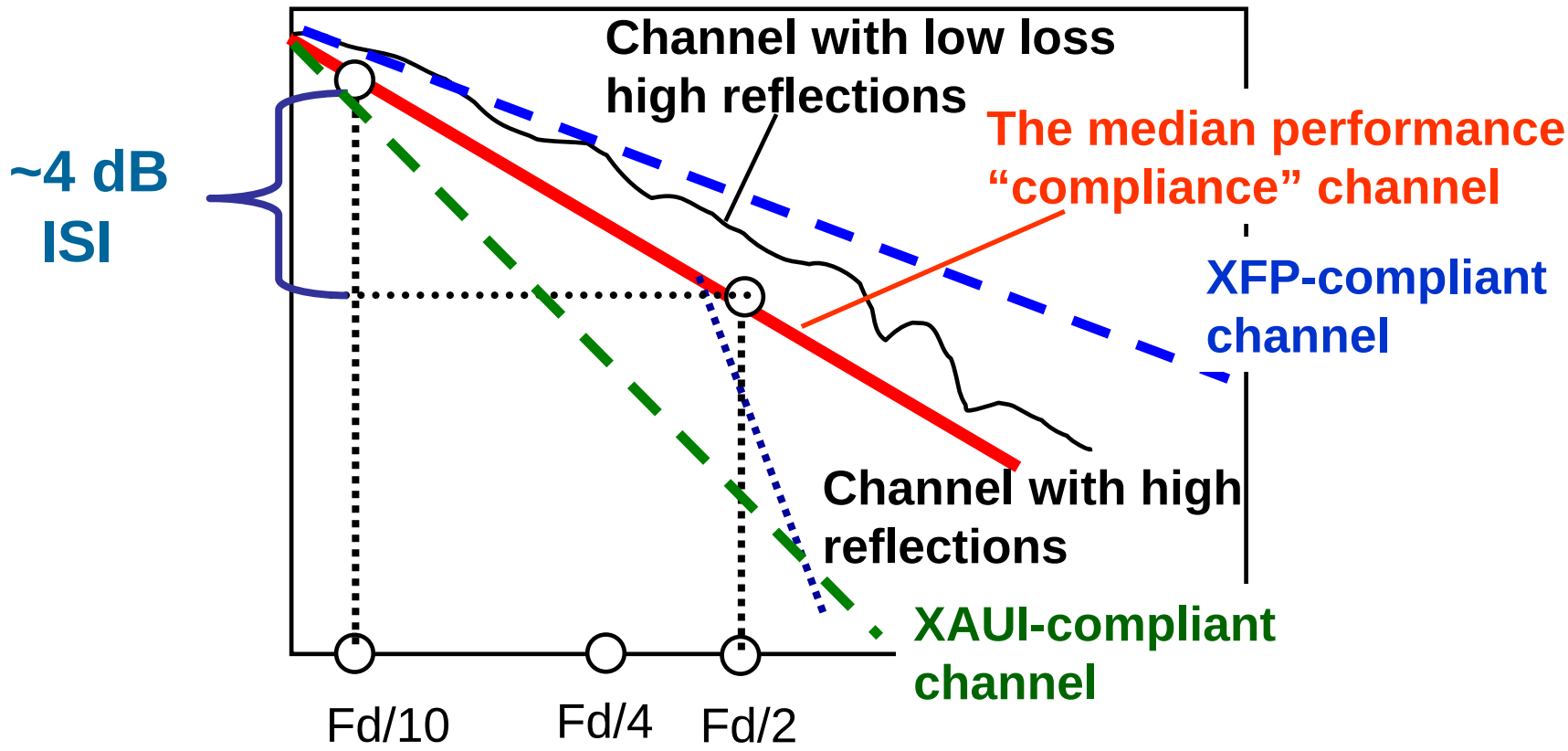
- ✧ Insertion Loss
- ✧ Return Loss
- ✧ Crosstalk
- ✧ Mixed-Mode S-parameters

- ✧ Equalization, Data Recovery
- ✧ Clock Recovery
- ✧ Line Decoding, Deserialzer
- ✧ FEC

What Matters in Interconnects ?

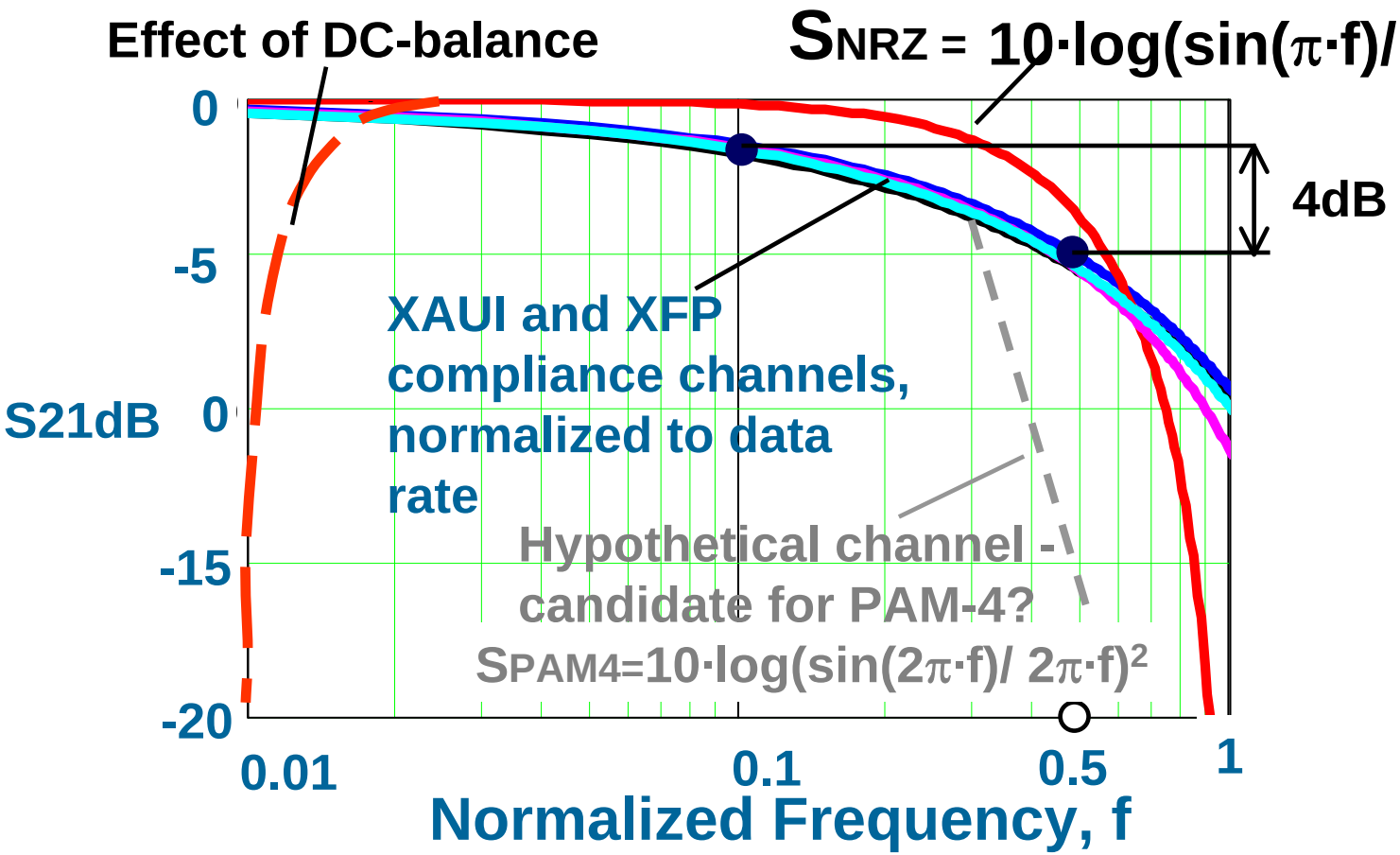
- **Characteristic impedance**
  - **Differential, Zdif = 100 Ohm (+/- 10% typical)**
  - **Common mode, Zcm= 25-40 Ohm**
- **The differential transfer function S21(jω)**
  - **|S21(jω)| - insertion loss vs. frequency (compliance channel limits acceptable loss in the interconnect)**
- **Crosstalk with adjacent channels**
- **What matters but, not usually specified?**
  - **Arg(S21(jω)) - phase vs. frequency response, or delay DELAY(ω) = Arg(S21(jω))/ω (must be constant over frequency). "Group delay" is not this same parameter !**
- **Recent standard developments use S-parameters matrix describing interconnect as a "black box" including adjacent channel interconnect**

PCB Compliance Channel,|S21|



- **Compliance channel is a useful tool, however may not always guarantee interoperability without knowledge of the full S-parameters matrix**

NRZ Spectrum and Compliance Channel

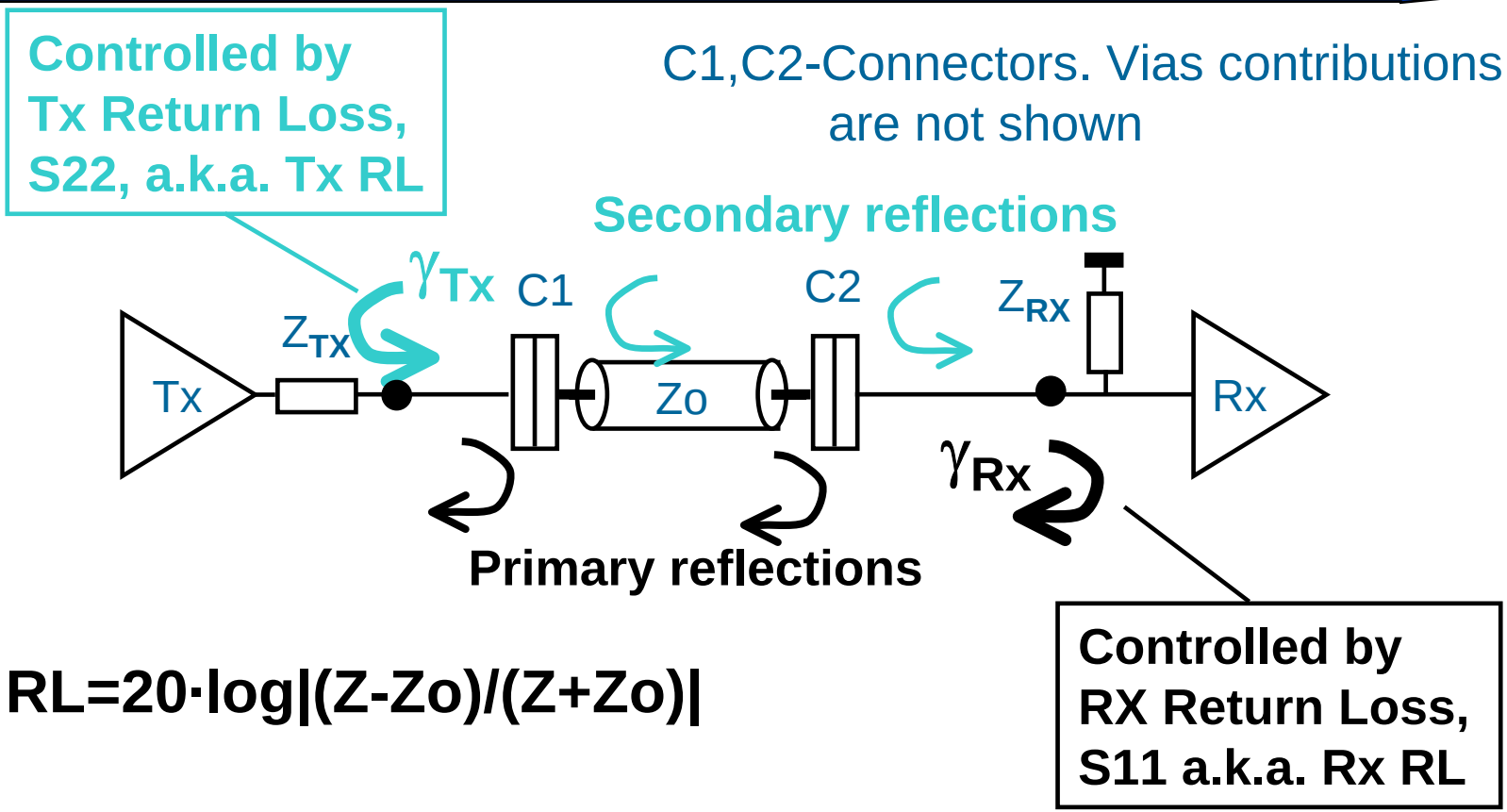


- Compliance channel in many standards fits NRZ power spectrum roll-off after single-pole equalization

Multi-Level Spectral Efficiency

- PAM-4 (4-levels)
  - Theoretically, could almost double the throughput
    - In practice, is less favorable as compared to NRZ with advanced channel equalization
  - Not used by current standards
- Duo-binary (3-levels)
  - Theoretically, has an intermediate efficiency between NRZ and PAM-4
    - Employed in Hard Drives Channels
    - Was under consideration at 802.3ap
- All multi-level signaling changes RX detection scheme from zero-crossing (NRZ) to an absolute level detection, thus requiring Tx adaptation

Return Loss and Signal Reflections



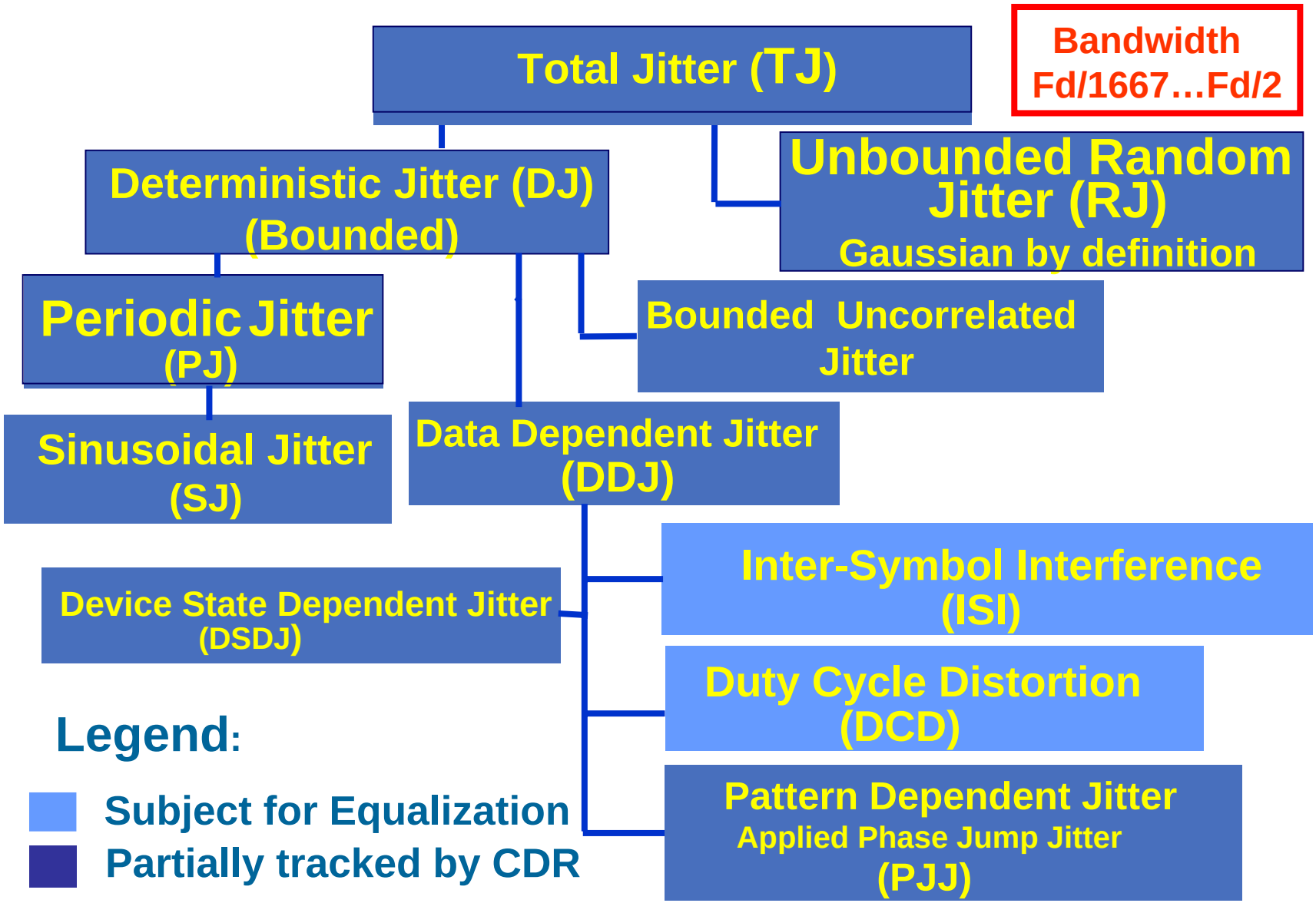
RL=20·log|(Z-Zo)/(Z+Zo)|

- **Return loss impact depends on channel attenuation and reflections from neighboring discontinuity**
- **Maximum ISI jitter is for the worst mismatch and minimum loss in the channel**

Jitter Methodologies

- **Fiber Channel Methodology for Jitter and Signal Quality Specification – MJSQ (MJS-1999, MJSQ, rev14 -2004)**
  - **Deals with the "Open Eye" interfaces**
  - **Originally was developed to serve FC specifications, however has become an industry wide methodology**
  - **Defines jitter components, Tx,Rx measurement methods**
- **Statistical Eye (OIF)**
  - **Was mainly developed to target "Closed Eye" interfaces with BER requirement <10^{-15}-10^{-18}. Based on analytical BER simulation technique ("StatEye") with 5-tap ideal DFE to open the eye and S-parameters to represent the "channel"**
  - **StatEye.org is a non-profit open source forum. Operates under the open source license agreement. *www.StatEye.org***

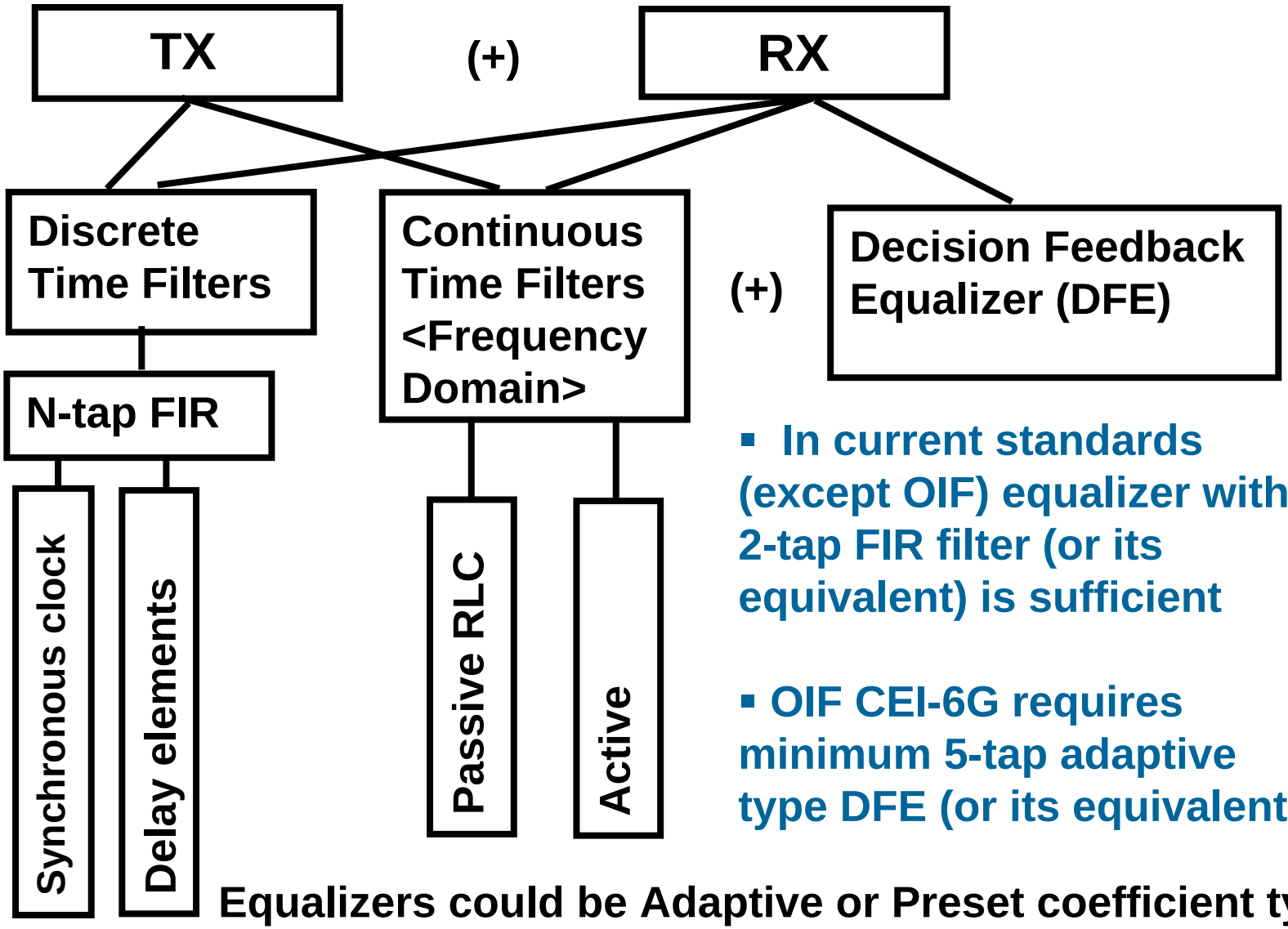
Jitter Components



The Interconnect Channel Equalization

- The interconnect channel equalization aims to reduce impact of channel induced ISI – a generally known and well defined problem in *Digital Communications*
- Current standards are based on NRZ signaling technique – the poorest in spectral efficiency. Equalization helps to substantially improve NRZ signaling quality
- Most backplane standards do allow, but do not budget Rx for equalization (except OIF)
- Equalization can be implemented in either the Tx or Rx, or simultaneously in both
  - Tx equalization (i.e. pre-emphasis)
  - Rx equalization (i.e. decision feedback equalizer,DFE)

Equalization Methods



- In current standards (except OIF) equalizer with 2-tap FIR filter (or its equivalent) is sufficient
- OIF CEI-6G requires minimum 5-tap adaptive type DFE (or its equivalent)

Equalizers could be Adaptive or Preset coefficient type

Tx Equalization Terminology

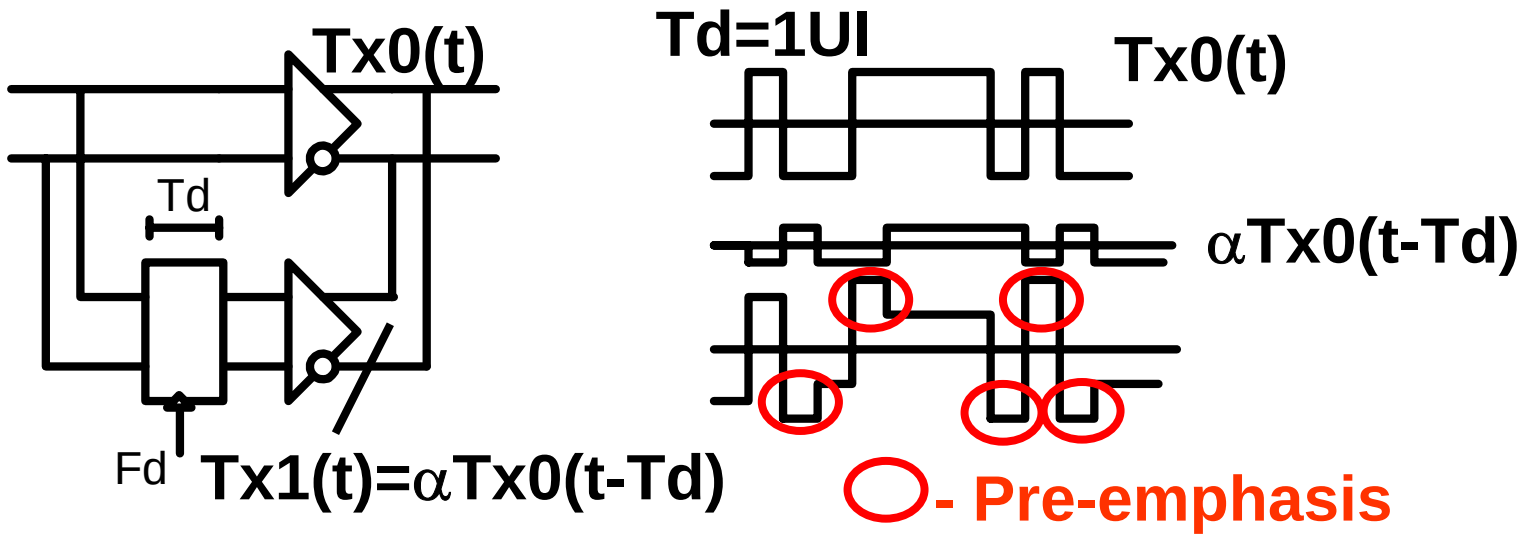
Tx “pre-emphasis” (signal emphasis before the channel)

=“transmit emphasis”

=“de-emphasis” (a way to implement emphasis in a Tx circuit, when the maximum amplitude is reduced)

= “single-pole post tap” (equalizer filter type)

= “2 tap FIR” (equalizer filter type)



The FIR Filter

- The "FIR" means "Finite Impulse Response".
- The impulse response is "finite" because there is no feedback in the filter: only delayed inputs are taken to construct the filter output
- In opposite to“IIR” (Infinite IR), where filter output is used to construct filter response and it may become infinite
- The "impulse response" of a FIR filter is actually just the set of FIR coefficients
- Important feature of FIR is a linear phase response
- Transversal Filter - another name for a FIR filter implementation

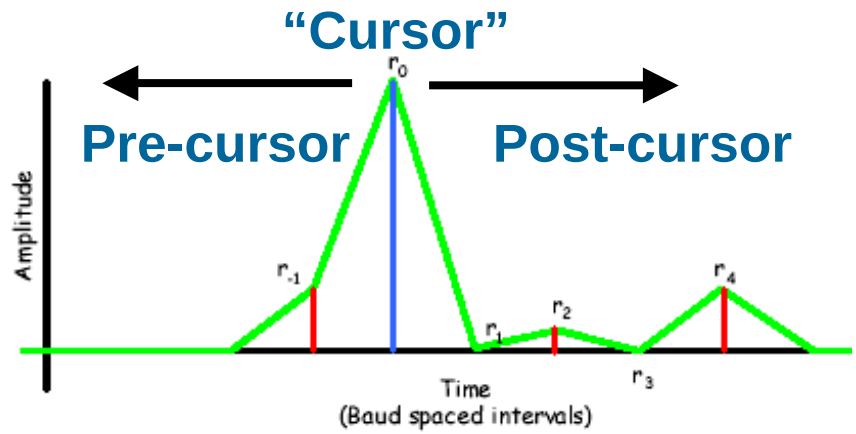
Rx-equalization

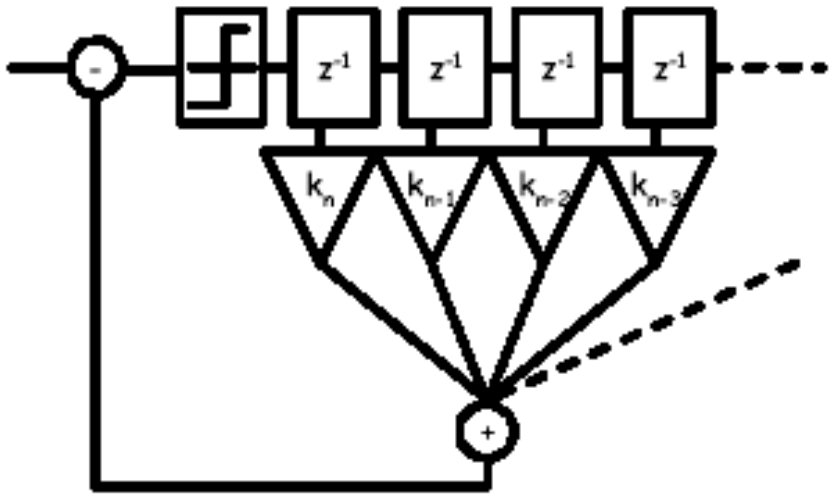
- A simple equalizer is an amplifier with boosted high frequency gain at Fd/2
  - Useful, if signal comes from not-equalized Tx or, if working in conjunction with Tx equalization
  - Subject for SNR degradation
- A Feed Forward Equalizer (FFE) equalizer uses a parallel combination of “flat gain” amplifier and “boost amplifier”
  - In FFE equalizer with adaptation the gain is varied, based on the measured power in the frequency band of interest
- An FFE type equalizer some times is used in front of DFE and/or clock recovery path to “pre-open” the eye

Step, Pulse and Impulse Responses

- *Step response* – is a system response on a step function 1(t)
- *Impulse response* - is a system response on δ-function, that is a derivative of the step response
  - TDR is based on impulse response
  - Impulse response is an IFFT of S21(f)
- *Pulse response* – is a system response on a pulse width equal to a bode interval
- All parameters are interrelated according to linear system theory

Decision Feedback Equalizer (DFE)





- DFE is a nonlinear type equalizer for post-cursor ISI only

Pros:

- DFE has an advantage in high crosstalk environment
  - DFE does not amplify crosstalk noise
- DFE may efficiently cancel reflections
  - Subject to a number of taps

Cons:

- Probability of error propagation
  - may be low with typical DFE settings

Graphics is from CEI-02.0

6Gb/s Backplane Transceivers

Company	Data Rate Gb/s	Tx	Rx	Channel Loss at Nyquist Frequency	Comments
Agere	3-6.25	PAM-4/NRZ	PAM-4/NRZ	Legacy backpl	Macrocell
IBM	4.9-6.4	4-tap FIR	Peak+5-tap DFE	32 dB 25 dB (DFE)	Core IP
LSI Logic	4.8-6.4	2-tap FIR	4-tap DFE	40'' FR4	Core IP
PMC-Sierra	4.9-6.4	2-tap FIR	10-tap DFE	25dB	Device
Synopsis	0.6-9.6	3-tap FIR	1-tap DFE	36'' BER=10^{-12}	Core IP
Texas Instruments	3.5-6.25	4-tap FIR	4-tap DFE	30'' FR4	Device
Vitesse	5-Gb/s	3-tap FIR	FFE +3-tap DFE	9.9dB	Device

Source:ISSCC'05, CICC'04, www.agere.com

6Gb/s Transceivers Trends

- More aggressive bandwidth utilization in existing infrastructure
  - Tx pre-emphases (2-tap) → multi-tap Tx FIR
    - Improved pre – and post -cursor (due to convolution with the channel response). May help to reduce number of DFE taps
    - Preset or adaptable FIR Tx (if up-channel is permitted by requirements)
  - FFE Rx → Rx DFE
    - DFE tackles ISI without amplifying noise
      - » Adaptable DFE has been widely proven
    - Preceding FFE may be a subject for consideration
      - » Noise impact

New Developments Beyond 6G

IEEE 802.3ap

- **10G Ethernet Backplane**

11Gb/s + over 1 m backplane, BER < 10^{-12}

- **Ethernet protocol (duplex link) opens a way for adaptable Tx equalizer and multi-level (PAM-4, Duo-binary) signaling techniques**

FC-PI-4

- **8.5 GB/s Fibre Channel Physical interfaces**