A Dual-Duplex PAM4 100Gbps PHY Analysis

Ramin Farjadrad
Frank McCarthy
IEEE 802.3ck Task Force Meeting
September 2018, Spokane
Supporters

• Jon Lewis (DELL)
• George Zimmerman (CME)
100Gbps Over 2m+ Passive Copper Cables

• The committee has mostly focused on technical feasibilities of Chip-to-Module & Chip-to-Chip solutions

• One of the key 8032.3ck objectives still remains to define single-lane 100 Gb/s PHY for operation over passive copper cables with lengths up to at least 2m

• 53Gbaud PAM4 signaling has not provided a reliable solution (with a practical SNR margin) over any of the proposed copper cable channels with at least 2m length
  – To further complicate the matter, to cover majority of existing applications of passive copper cables, we need at least ~2.5m reach

• Should the committee consider alternative signaling schemes that can provide a practical solution for the passive copper cable objective as well?
Common Data Center Cabling Installation Topologies

Common installation topologies presented in  goergen_100GEL_01_0318  (Cisco)
Selected Passive Copper Cable Channel Topology

- Channel model used is the proposed topology in mellitz_100GEL_adhoc_01_021218:
  - 2.5m of 28-AWG Cable + 2 x 0.3m 34-AWG Cable → Total Cable Length = 3.1m
- Worst-Case (WC) and Best-Case (BC) line card break-out considered
  - Total of 32 S-parameters per case with all mutual crosstalk sources (NEXT & FEXT) included
Thru & Crosstalk Channels in Single-Duplex Mode

Single Duplex (SD): Simultaneous transmit & receive over separate physical channels

Receive signal runs over separate cable bundle from transmit, therefore NEXT magnitude will be negligible

mellitz_3ck_02_0518
Selected Channel Frequency Transfers
Fails to meet minimum 3dB SNR margin with
- 32-tap FFE + 1-tap DFE

Case 1: 12mm package trace
Case 2: 30mm package trace
53Gbaud PAM4-SD Vertical Eye Opening Results for 2.5m BC

Case 1: 12mm package trace
(12mm for both Rx & Tx package)

Case 2: 30mm package trace
(30mm for both Rx & Tx package)
53Gbaud PAM4-SD SNR Results for 2.5m BC Channel

- Comes barely close to the required 3dB SNR margin with
  - 64-tap FFE + 32-tap DFE
  - Definitely not a practical solution!
53Gbaud PAM4-SD SNR Results for 2.0m BC Channel

- Fails to meet minimum 3dB SNR margin at 2.0m cable as well with
  - 32-tap FFE + 1-tap DFE
53Gbaud PAM4-SD Vertical Eye Opening Results 2.0m for BC

Case 1: 12mm package trace (12mm for both Rx & Tx package)

Case 2: 30mm package trace (30mm for both Rx & Tx package)
53Gbaud PAM4-SD SNR Results for 2.0m BC Channel

- Barely passes the required 3dB SNR margin using excessively long filters:
  - 64-tap FFE + 32-tap DFE
  - Definitely not a practical solution either
A dual-duplex transceiver is exposed to two additional signal impairments:
- Echo: reflection signals from its own transmitter
- sNext: self near-end xtalk signals from transmitters in the same bundle

Depending on the magnitude of these extra impairments, we may have to cancel them or accept their SNR degradation.
- In the selected channel (at MDI input)
  - Signal/Echo=\sim10\text{dB}
    - \Rightarrow\text{Echo canceller are necessary}
  - Signal/Xtalk=30-40\text{dB}
    - \Rightarrow\text{Evaluate if Xtalk cancellers are necessary}

Dual Duplex (DD): Simultaneous transmit and receive over same physical channel
sNEXT Power-Sum in Dual Duplex Mode

- Compare the 100Gbps SNR performance of 26.5Gbaud DD (with sNEXT impairment) versus the SNR performance of 53Gbaud SD over the BC channel using the COM tool.
26.5Gbaud PAM4-DD SNR for 2.5m BC Channel + sNEXT

- Passes by more than 6dB SNR margin
  - Needs only 16-tap FFE + 1-tap DFE

- Case 1: 12mm package trace
- Case 2: 30mm package trace
26.5Gbaud PAM4-DD Vertical Eye Opening for 2.5m BC + sNEXT

- 26.5Gbaud DD signaling shows more than 10x larger vertical eye opening versus 53Gbaad SD mode even after adding sNEXT impairment

**Case 1:** 12mm package trace (12mm for both Rx & Tx package)

**Case 2:** 30mm package trace (30mm for both Rx & Tx package)
Echo Impairment for 26.5Gbaud PAM4-DD Mode (2.5m)

- The dominant reflections happen at the connectors, while there is very minimal echo power along the cable length itself.
- Echo cancellation at connector locations removes majority of the echo power.
To achieve DER<1E-4, the total link SNR including all impairments must be >18.5dB

Separate Rover Echo Canceller segments can be independently moved to cancel each major discontinuity in the RL channel

A total of four 8-tap Rover Echo Cancellers is shown to considerably improve the Signal/Echo (S/E) ratio for Mellitz 2.5m channel:

- No Echo Canceller → S/E=~10dB
- 4 Echo Cancellers → S/E=~45dB
- S/E=~45dB is significantly below the required SNR=18.5dB to degrade the link performance
26.5Gbaud DD SNR with Different FFE/Echo Filters Over 2.5m BC Channel

- All cases use 1-tap DFE
- SNR performance curves are for different FFE lengths and increasing # of active 8-tap Echo canceller segments
- As shown by COM tool, 16-tap FFE provides 6dB SNR margin
- 12-tap FFE has +1dB margin to the required 3dB SNR margin
- These SNR curves further prove that after 4th 8-tap Echo Canceller segment, there is hardly any more SNR improvement.
- 53Gbaud SD SNR, even with 32-tap FFE, has -2dB to the required 3dB margin
All cases use 1-tap DFE

Even over WC channel with extra 10dB sNEXT, 26.5Gbaud DD link can provide enough SNR margin with 16 to 24 taps (e.g. 20 taps) FFE and same size Echo filter

53Gbaud SD link ends up with completely negative SNR margin over this WC channel even with much more complex FFE/DFE
100Gbps AFE/Clocking Power for 2.5m Passive DAC

2x AFE at 26.5Gbaud PAM4 for 100Gbps Passive DAC DD PHY

- 7-bit ADCs = 200mW
  - 2x ADC = 2 x 100mW
- PGAs & CTLEs = 70mW
  - 2x PGE/CTLE = 2 x 35mW
- 6-bit DACs = 70mW
  - 2x DAC = 2 x 35mW
- PreDrivers/Drivers = 90mW
  - 2x PreDriver/Driver (1V_{pp}) = 2 x 45mW
- Hybrid Echo Canceller = 80mW
  - 2x Hybrid Echo Canceller = 2 x 40mW

→ 100Gbps DD-PHY AFE (2.5m) = ~510mW*

*Clocking/CDR power not included, as it is very similar for 100Gbps DD and SD PHY

farjadrad_100GEL_01a_0318 → Power (100G SD AFE) = Power (100G DD AFE) + ~100mW
100Gbps DSP Power for 2.5m Passive DAC

2x DSP at 26.5Gbaud PAM4 for a 100Gbps Transceiver

- **Assumptions:**
  - FIR Power: $0.04\text{mW/tap/}G\text{baud/}\text{data}_{\text{res}}$
  - Crosstalk: (Mellitz 2.5m)
    - $3\ s\text{NEXT} + 3\ F\text{EXT} + 4\ a\text{NEXT}$
  - Equalization:
    - 1-Tap DFE
    - 12-Tap FFE
  - Echo Cancellation
    - Four 8-Tap Canceller Segments

- **DSP Power Calculations:**
  - **DFE Power = 20mW**
    - 1-Tap DFE = 10mW → Total DFE = 2 x 10mW = 20mW
  - **FFE Power = 180mW**
    - 12 Taps → $0.04\times12\text{tap}\times7\text{bit}\times26.5\text{Gbaud} = \sim 90\text{mW}$
    - Two Channels → Total FFE = 2 x 120mW = 180mW
  - **Echo Canceller power = 132mW**
    - 4 x 8 Taps → $0.04\times32\text{tap}\times2\text{bit}\times26.5\text{Gbaud} = \sim 66\text{mW}$
    - Two Channels → Total Echo = 2 x 66mW = 132mW

→ **100Gbps DD DSP Power = \sim 332mW**

- **Power (100Gbps SD-PHY DSP) = Power (32-tap FFE @53Gbaud) = \sim 480mW**
  → Even at \sim 150mW higher DSP power, 100G SD fails to meet the SNR margin for 2.0m BC channel!

* Assuming BC channel & 7nm process node
A DD-PHY Can Support Both DD & SD Operation Modes

- 2.0m+ Passive Cable → 26.5Gbaud Dual-Duplex mode on both sides of cable
A DD-PHY Can Support Both DD & SD Operation Modes

- Chip-Module/AUI \( \rightarrow \) Switch ASIC PHY to 53Gbaud Single-Duplex mode and Module PHY stays as a VSR 53Gbaud Single-Duplex PHY
Selected Chip-Module/AUI Channel (8” PCB)

- Channel model used is the proposed channel in lim_3ck_01b_0718
  - VSR channel with IL=16dB @26.5GHz
Echo Impairment for 26.5Gbaud PAM4-DD Mode (8” PCB)

- To achieve DER<1E-6, the total link SNR including all impairments must be >20.6dB
- A total of three 6-tap* Rover Echo Cancellers considerably improve the Signal/Echo (S/E) ratio for Lin 16dB VSR channel:
  - No Echo Canceller → S/E=~11dB
  - 3x Echo Cancellers → S/E=~32dB
- S/E= 32dB is significantly below the required SNR=20.6dB to degrade the link performance

*Each 6-tap canceller covers 20mm of channel
100Gbps AFE/Clocking Power for 16dB@26.5GHz VSR Channel*

2x AFE at 26.5Gbaud PAM4 for 100Gbps VSR DD PHY

- **PAM4 Slicers = 30mW**
  - 2x Slicers = 2 x 15mW

- **CTLEs = 40mW**
  - 2x CTLE = 2 x 20mW

- **PAM4 Drivers = 60mW**
  - 2x PAM4 Driver (0.8V_{pp}) = 2 x 30mW

- **Hybrid Echo Canceller = 50mW**
  - 2x Hybrid Echo Canceller = 2 x 25mW

⇒ 100Gbps DD AFE (VSR) = ~180mW

* VSR 16dB channel as presented in → lim_3ck_01b_0718
100Gbps DSP Power for 16dB@26.5GHz VSR Channel*

2x DSP at 26.5Gbaud PAM4 for 100Gbps VSR DD-PHY

**Assumptions:**
- FIR Power: 0.04mW/tap/Gbaud/data_res
- Crosstalk:
  - 3 FEXT+4 aNEXT & 3 sNEXT (Mellitz)
- Equalization:
  - CTLE
  - 4-Tap FFE (Tx)
- Echo Cancellation
  - Two 8-Tap Canceller Segments

**DSP Power Calculations:**
- **FFE Power** = ~16mW
  - 4 Taps → 0.04*12tap*2bit*26.5Gbaud=~8mW
  - Two Channels → Total FFE=2 x 8mW=~16mW
- **Echo Canceller power** = ~72mW
  - 3 x 6 Taps → 0.04*18tap*2bit*26.5Gbaud=~38mW
  - Two Channels → Total Echo= 2 x 32mW=~72mW

**VSR DD-PHY Power (AFE + DSP) = ~270mW**

* VSR 16dB channel as presented in → [lim_3ck_01b_0718](#)
Conclusion

- A DD-PHY makes 100Gbps/Lane over 2.5m+ passive cables a practical reality
  - 26.5Gbaud PAM4 signaling is same as in 50GBASE-CR
    - Operates over existing 50G systems & eliminates the need for new costly channels
    - Same Mux/Demux Datapath and FEC/PCS as 50GBASE-CR2 can be used
  - Dual-duplex architecture does not lead to higher power than SD architecture
    - Echo canceller operates on 2-bit input data & needed at the connector locations
    - Equalizer + Echo Canceller power in DD-PHY < Equalizer power in SD-PHY
  - A DD-PHY can be configured to provide both modes of DD and SD
    - DD (@26.5Gbaud) for Chip-Chip over 2m+ Passive Cables
    - SD (@53Gbaud) for VSR Chip-Module over 8” PCB
- A VSR DD-PHY can also deliver 100Gbps over at least ~8” PCB at < 400mW
  - VSR DD-PHY Power (AFE+DSP) = ~270mW
Thank you.