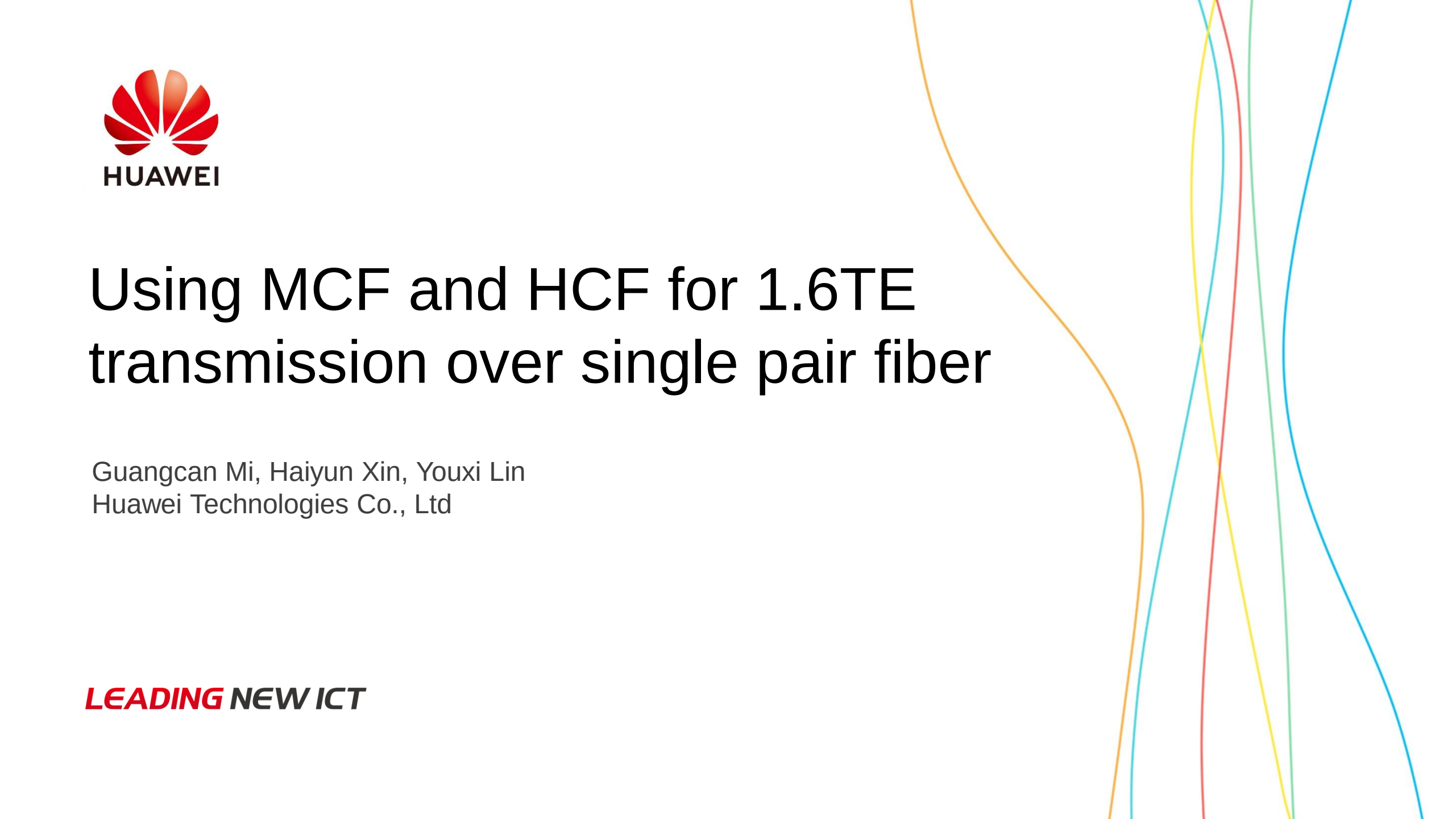

Using MCF and HCF for 1.6TE transmission over single pair fiber

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LEADING NEW ICT

Introduction

- Standardization of 400G signaling has been the recent focus in the Ethernet industry, which starts with the fundamental building blocks, i.e. 400G electrical signaling and 400G optical signaling.
- Need and use case of single pair fiber link was reviewed, pointing its key market driver to be, again, the AI driven data center.
- We present preliminary study on optical interconnect over hollow-core fiber (HCF) link using 400G signaling, to show that new fiber technologies adds a new dimension to the solution space of optical interconnect.

Single pair IMDD link: where and why

Telecom

- Transition from 5G to 6G is expecting another wave of network upgrade
- Carrier backhaul network with limited fiber resources. FR/LR/ER optics for p2p transmission of x00G Ehternet
- Multiple ethernet generations

Data Centers in China

- Multi-floor DC buildings
- Server to TOR with DAC
- TOR to leaf with SR optics
- Leaf to spine with FR optics.
- Multiple connectors in between
- Multiple ethernet generations

AI Infra - New Scenario

- Hidden cost in Structured Cabling and Fiber cable bundles
- Relatively large volume: cost sensitive
- Full capacity/port deployment of switch box: power sensitive
- Typically new Infra with new cabling system: new technology welcomed.

Later upgrade and adoption of new rates with mature PHY components, and enjoys the benefit of lower cost.

★ Drives tech. innovation and first deployment of new rates

Core value unchanged: Cost effective, power efficient, and Capex/Opex

Deeper into the requirement of AI infra

Multi-Giga Watt Data Center projected in all relevant market

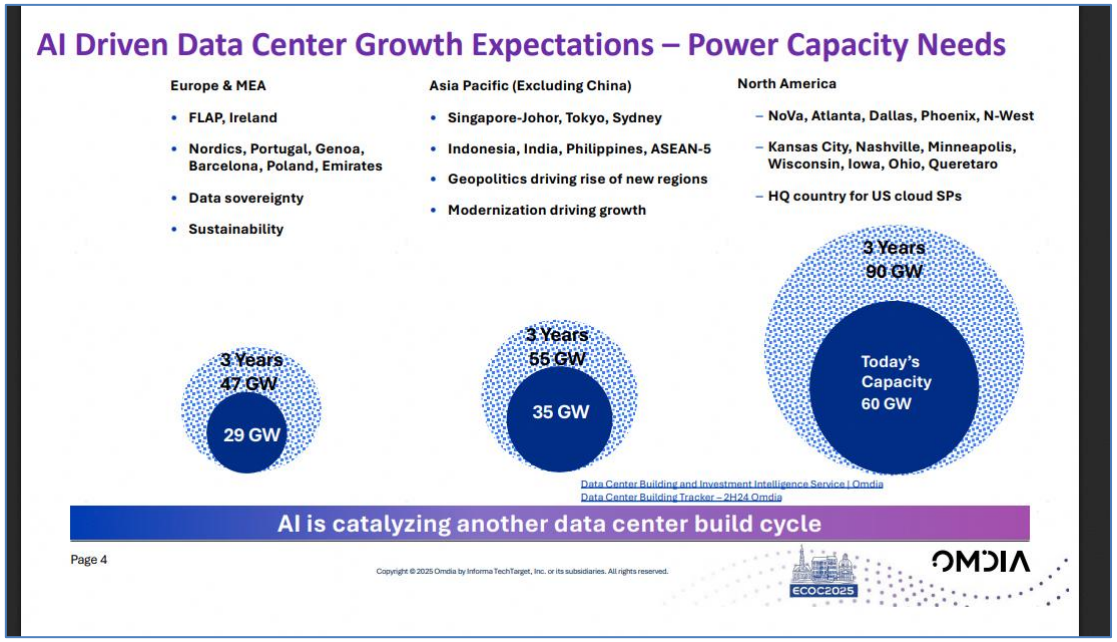
- Large number of ASICs, and huge pressure on power supply
- Translates to bigger landscape/domain of the intra-data data center network

Interconnect outside of the rack and row

- Minimum 2km reach is needed fulfilling the required landscape
  - Fiber resource and cabling is contributing importantly to Capex and networking design.
  - End-user perspective that was shared in mi_e4ai_01_260219 indicated clear need for 2km single pair link, as well as the willing ness to use new fiber tech.
- Multiple connectors via ODF to go outside of the room, the floor and the building → LC style provides advantages in terms of cost, dimension/layout and serviceability compared to MPO style.

As a result

- x00GBASE-FR4 optics has been extensively used in AI driven data centers for interconnect beyond the row, and are expected to continue its role in 400G signaling generation.



https://www.ieee802.org/3/ad_hoc/E4AI/public/25_1023/huff_e4ai_01a_251023.pdf

Challenge in keeping up with the 2x rate growth

Investigation of WDM optics for 2km reach has been shared in kuschnerov_e4ai_01_251023 and johnson_e4ai_01a_250227, both pointed out technical challenges in closing the link, with current estimation of component performance and fiber link characteristic .

Potential solution space

- Wavelength grid
- Component innovation: chirp tuning, more complex DSP algorithm, strong FEC
- SMF fiber characteristic

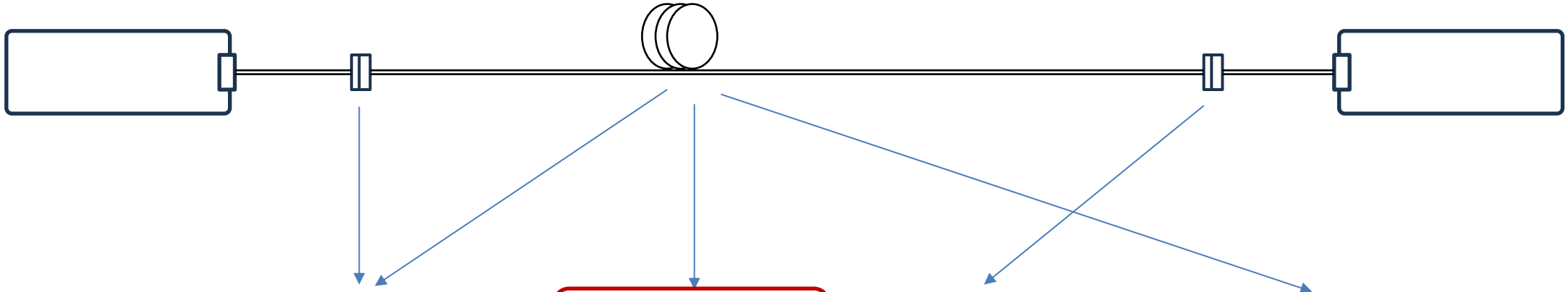
The core market driver, AI Infra, uses new installment of cabling system provides the freedom of engineering the fiber link with new technologies.

New Fiber technologies: MCF and HCF

- Benefits of MCF has been discussed in yu_e4ai_01_250327 , suggested 3km transmission feasibility at 400Gbps.
- HCF, opens up the design space of characteristics such as CD/PMD by engineering the fiber modal structure.

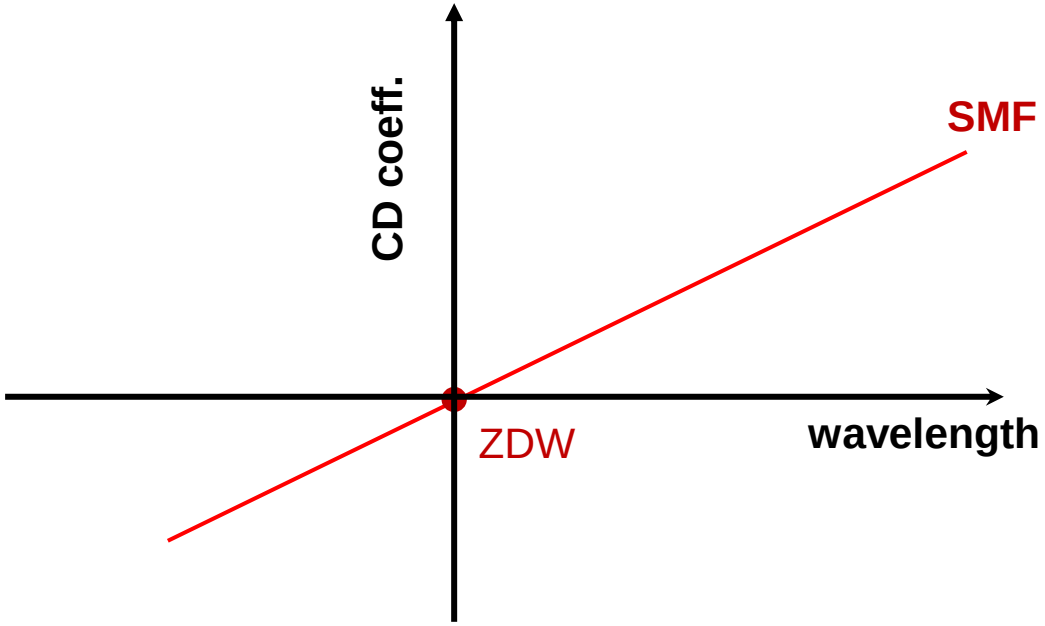
How much longer reach could engineering (fiber) help achieve?

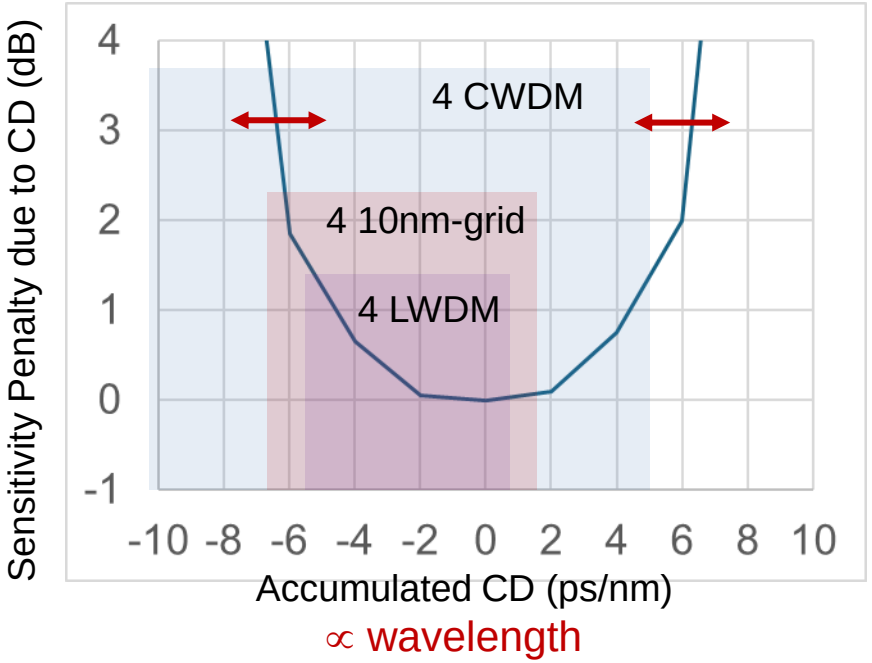
Link Budget Breakdown of various fiber link



Power Budget =	IL		CD Penalty	MPI Penalty	DGD Penalty	New Attributes
	Fiber loss	Connector/ Splice	ZDW+Slope	Connector and return loss		
SMF	Mitigation possible		Updated in 802.3dj	Updated in 802.3dj	Updated in 802.3dj	
MCF	similar	+	Similar	Need investigation	Similar	Xtalk
HCF	–	+	Engineered	Need investigation	Engineered	

The painful CD effect

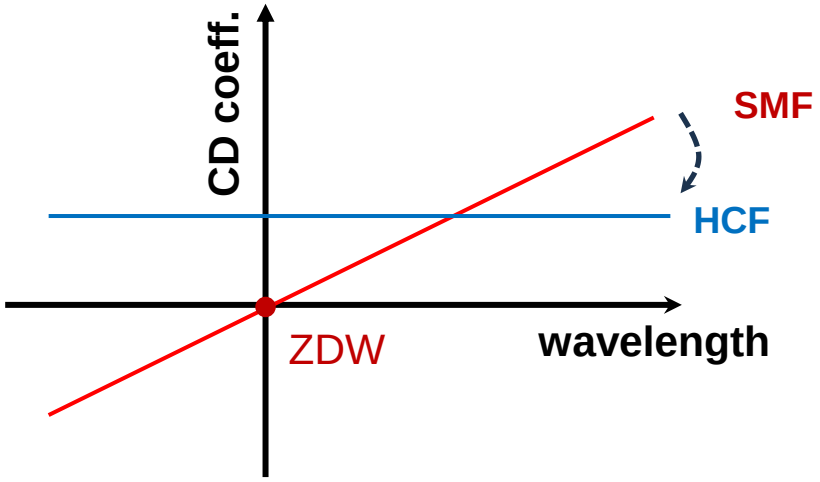


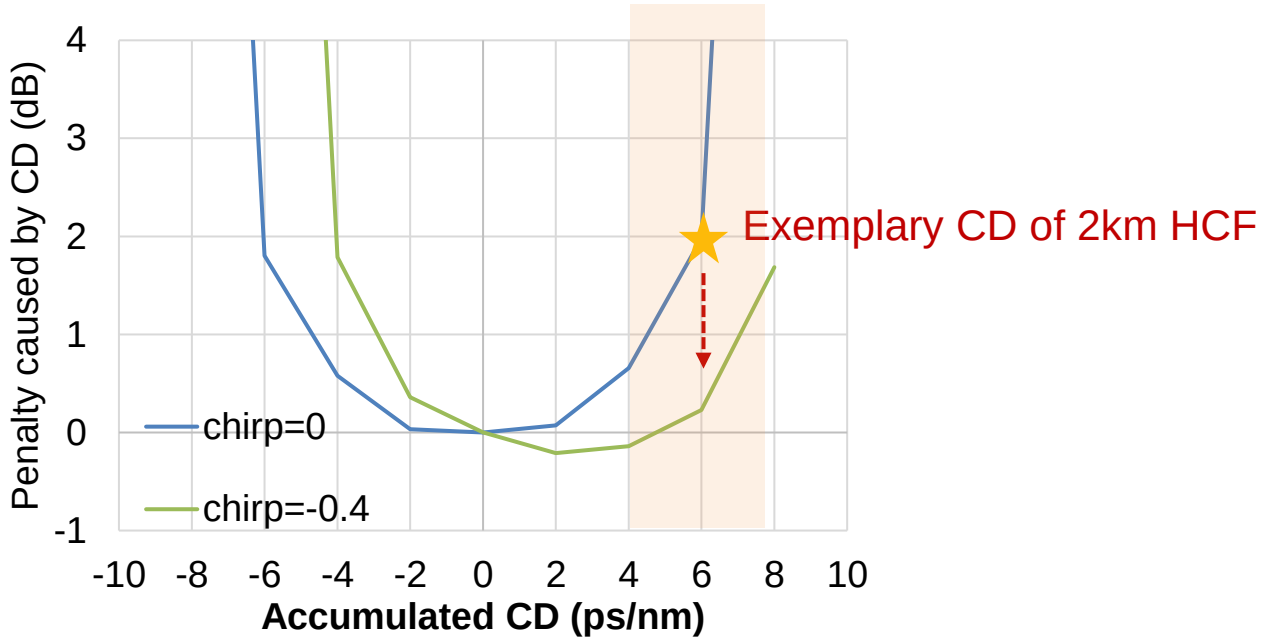


Assuming 4.85e-3 pre FEC BER under AWGN

- CD penalty varies with wavelength, with a bath-tub shape.
- Modulator chirp essentially adds/compensates the effective CD, therefore adding uniform chirp to all channels is only re-allocating the burden.

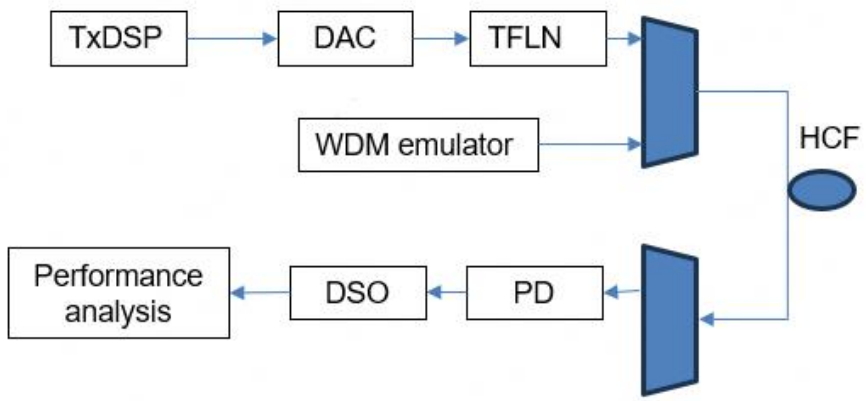
HCF provides engineered CD characteristic

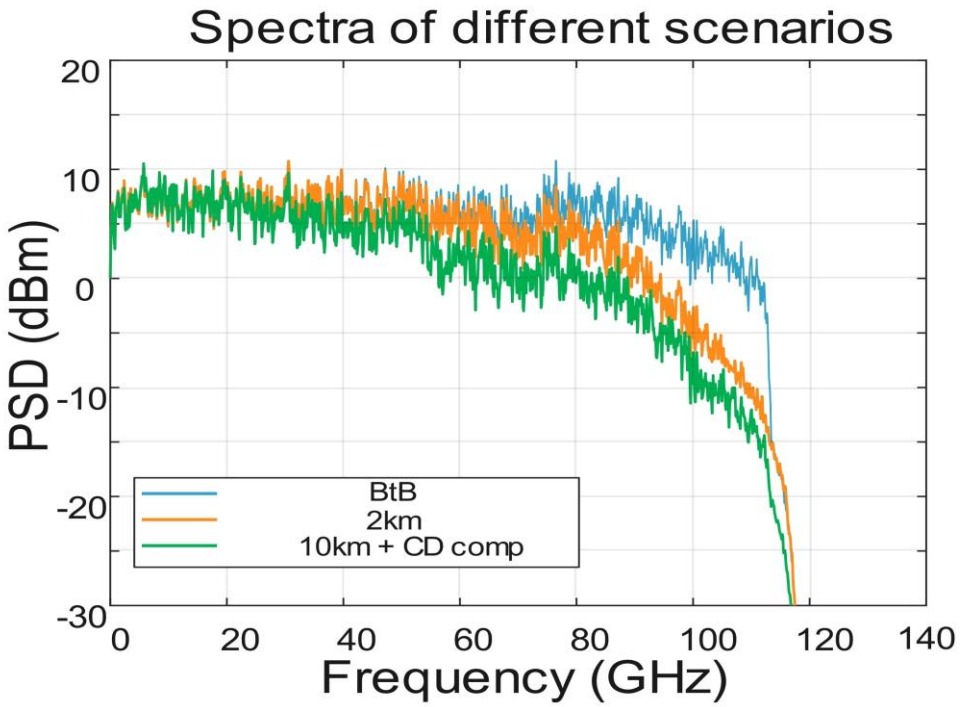


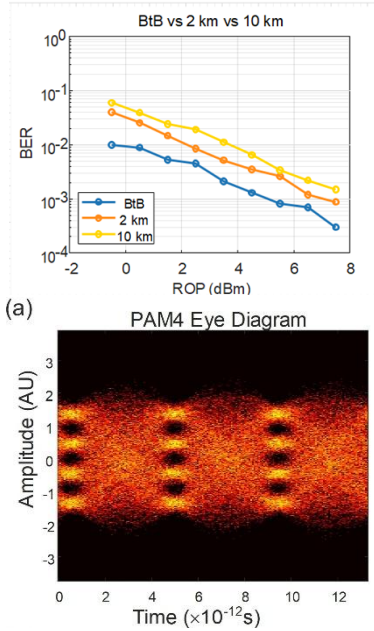


- In HCF, CD is independent with λ, easy to predict and compensate.
- Dispersion compensation module is a mature deployed product in Telecom industry. Integration of CD compensation component into a SiPh chip is also possible.
- Chirp of a Mach-Zehnder modulator is tunable with appropriate design.
- HCF + CD compensation can potentially push IMDD single pair fiber link to even longer reach than 2km by eliminating the CD effect.

Experimental demo of using HCF + CD compensation for longer reach of IMDD link







- **Key hollow core fiber parameters**:
- 8λ×225GBaud PAM4 in Cband
- 2dB end-to-end loss
- Chromatic dispersion: ~ 2.4 ps/(nm·km)
- PMD: <0.5 ps/$\sqrt{km}$

- **2km case**: bandwidth limitation is mainly caused by CD
- **10km case**: CD is fully compensated, the degradation of PSD was mainly caused by PMD
- No beating noise indicates **no FWM**

Summary

- Optical link over single pair of fibers serves an important role in intra-DC networks for AI infrastructures. x00GBASE-FR4 type of optical interface has been the preferred solution so far, which implies the need of IMDD optics over single pair of fiber will come along as the transition to 400G signaling based network, i.e. 1.6TE-FR4 types.
- New fiber technologies provide freedom of engineering the optical channel characteristics, thus relaxing the power budget and extending the reach of WDM IMDD optics at 400Gb/s era.
- Our preliminary study showed that HCF could effectively mitigate a key impairment of fiber link, i.e. chromatic dispersion, opening up the possibility of reaching beyond 2km using 400G-signaling optics.
- A new paradigm of Ethernet optical PMD is down the path as we starts to consider fiber link beyond current SMF, further study on the fiber link model is required and on-going.

THANK YOU

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