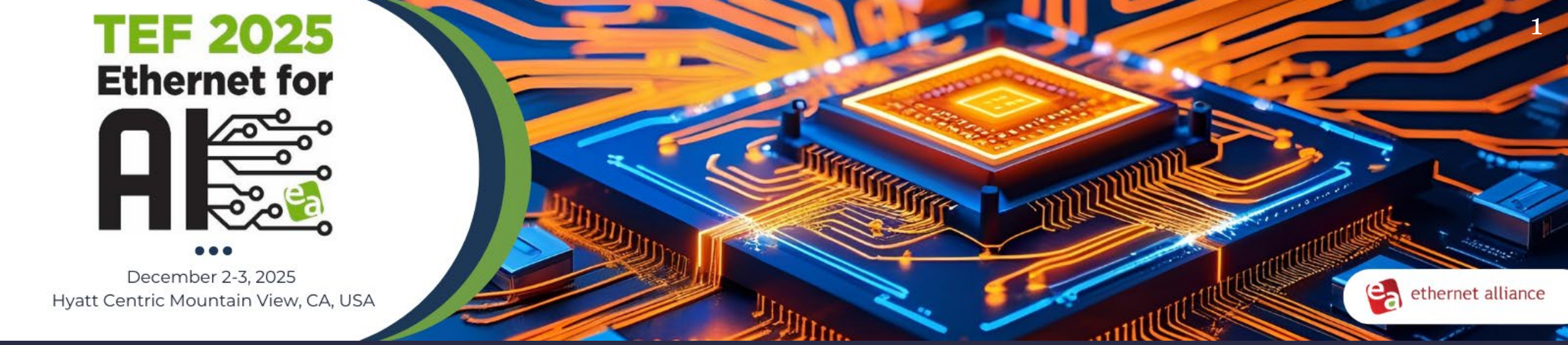

Defining 400 Gbps per Lane Electrical and Optical Signaling for Ethernet

Kent Lusted, Distinguished Architect, Synopsys
[Champion for IEEE 802.3 Mar 2026 CFI – 400Gbps Signaling Ethernet Project]

Mark Nowell, Fellow, Cisco

December 2-3, 2025

This presentation has been developed within the Ethernet Alliance, and is intended to educate and promote the exchange of information. Opinions expressed during this presentation are the views of the presenters, and should not be considered the views or positions of the Ethernet Alliance

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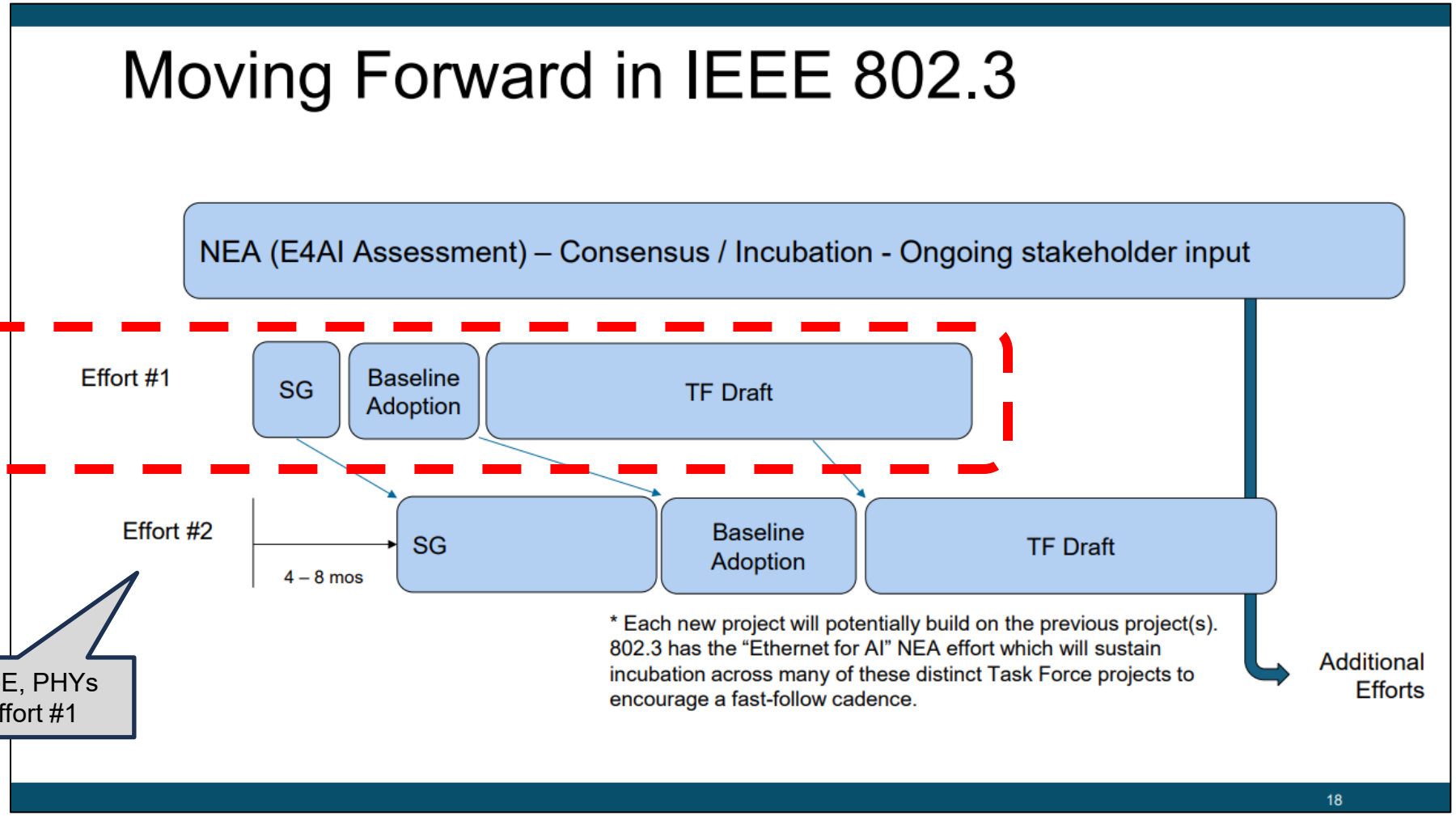
The Effort(s)
Interconnect Implications
Getting Started Now

Two Efforts Forming In the Pipeline

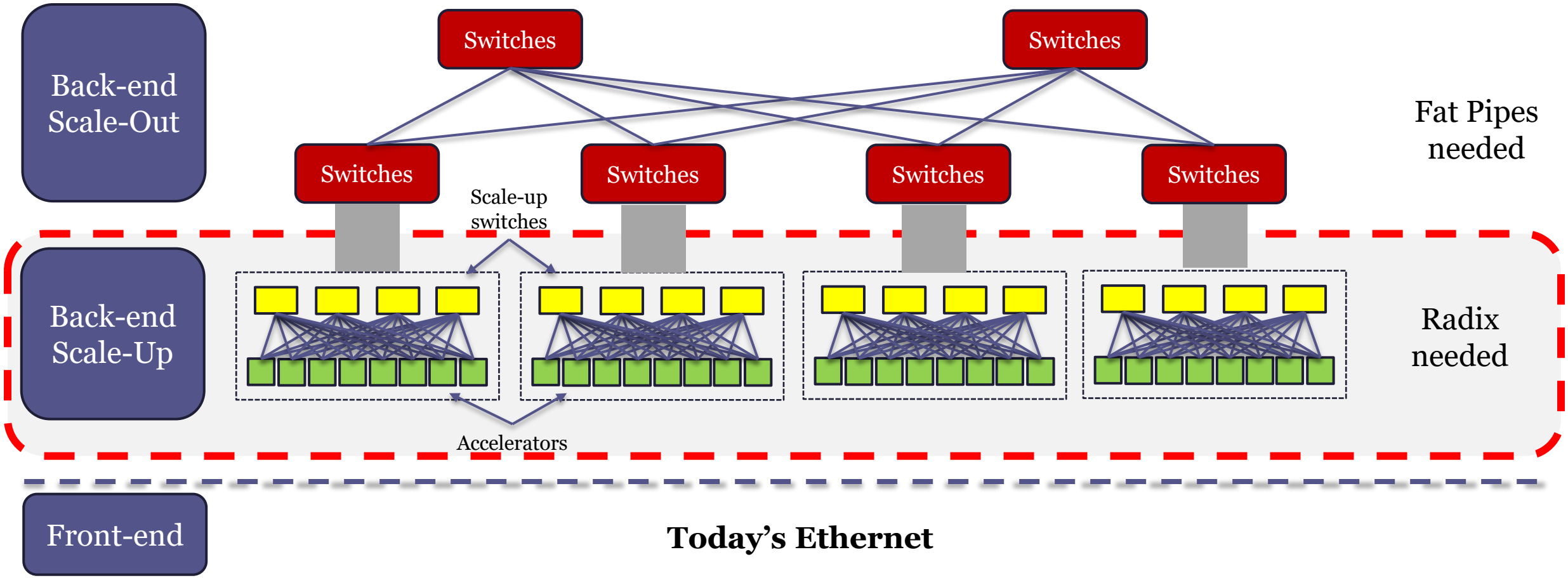


https://www.ieee802.org/3/ad_hoc/E4AI/public/25_0819/dambrosia_e4ai_01_250819.pdf

Looking Forward and Moving **Fast**

- AI Back-end “scale-up” networks are driving higher signaling rates first
  - Followed by scale-out
  - Then front-end networks
- Scale-up = high radix (flat network, lots of x1/x2 links)
- Copper is known for low cost & power and high reliability, but the reach is shrinking
- Optics have a growing footprint in scale-up (and scale-out)
  - Co-packed optics (CPO) are increasingly important

AI Datacenter Network Hierarchy



Today's Ethernet

TEF 2025 Ethernet for AI

Based on AI Datacenters and their Diverse Network Requirements, Ram Huggahalli (Microsoft), Ethernet Alliance TEF 2024, Oct 2024.

The Effort(s)
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Copper Interconnect at 400 Gbps/lane

- Reach limitations of passive copper emphasizes the need for active solutions
  - Passive:
    - Well known and well-established methodologies
  - AEC:
    - Comparable to a pluggable optical transceiver
  - ACC:
    - Not well specified across industry

Type	IC	Reach	Power
Passive	None	~1m	
Active Electrical Cable (AEC)	Retimer		
Active Copper Cable (ACC)	Redriver		

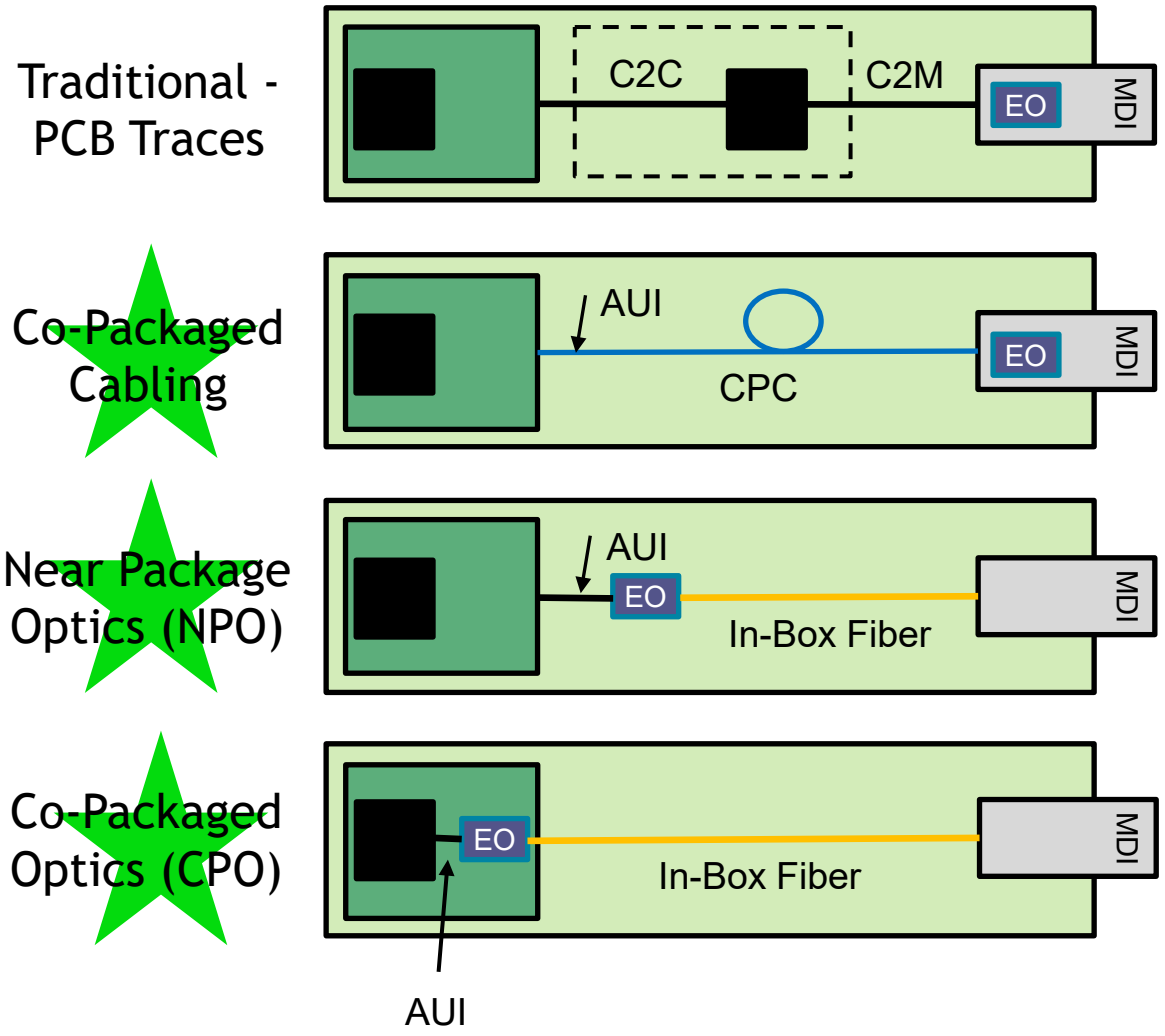
Passive Cable

Active Electrical Cable (AEC)

Active Copper Cable (ACC)

C2M Hosts for 400 G/lane

- Broader mix of host implementations than previous rates
  - PCB traces to front panel pluggable (FPP)
  - Co-packaged cables to FPP
  - Near-Package Optics (NPO)
  - Co-Packaged Optics (CPO)
- Electrical and optical integration becomes critical for achieving performance and reach targets



Electrical Interfaces: PAM4 or Not?

- Electrical modulation choice is highly dependent on the channel response:
  - Package, host traces or CPC assembly, front panel or CPO/NPO connector, cable assembly or backplane, etc.
- Every individual element in the channel has a dramatic effect on the overall end-to-end link performance
- There is no extra margin ☹ – “pennies in the sofa”

Key Questions for Electrical PAM-4/6/8

- **System Design:** How many 400 G/lane ports and what mix (copper vs. optics) of them will be in a switch, NIC, accelerator/xPU?
  - Will there be a change in the base assumptions of how to build a system?
- **Industry Readiness:** Will new electrical connectors and media meet performance targets at scale?
- **Modulation Alignment:** How critical is common coding for electrical and optical interfaces?
  - Are linear solutions (pluggable/co-packaged) viable at 400G/lane, and when?
- **Validation Tools:** Are test & measurement solutions prepared for PAM-4/6/8 at scale?

Optical Interfaces: Is There a Quick Start?

- Strong assumption regarding optical modulation
  - PAM4 modulation is the leading candidate
- Can existing building blocks (FEC) be assumed?
- High-radix use case assumes both CPO & pluggable implementations
- SMF is a benign channel for single-lane
  - 500m reach seems useful. Any power/cost/yield advantage to defining shorter (or longer)?
- Link methodologies (e.g. test methodologies) need early focus

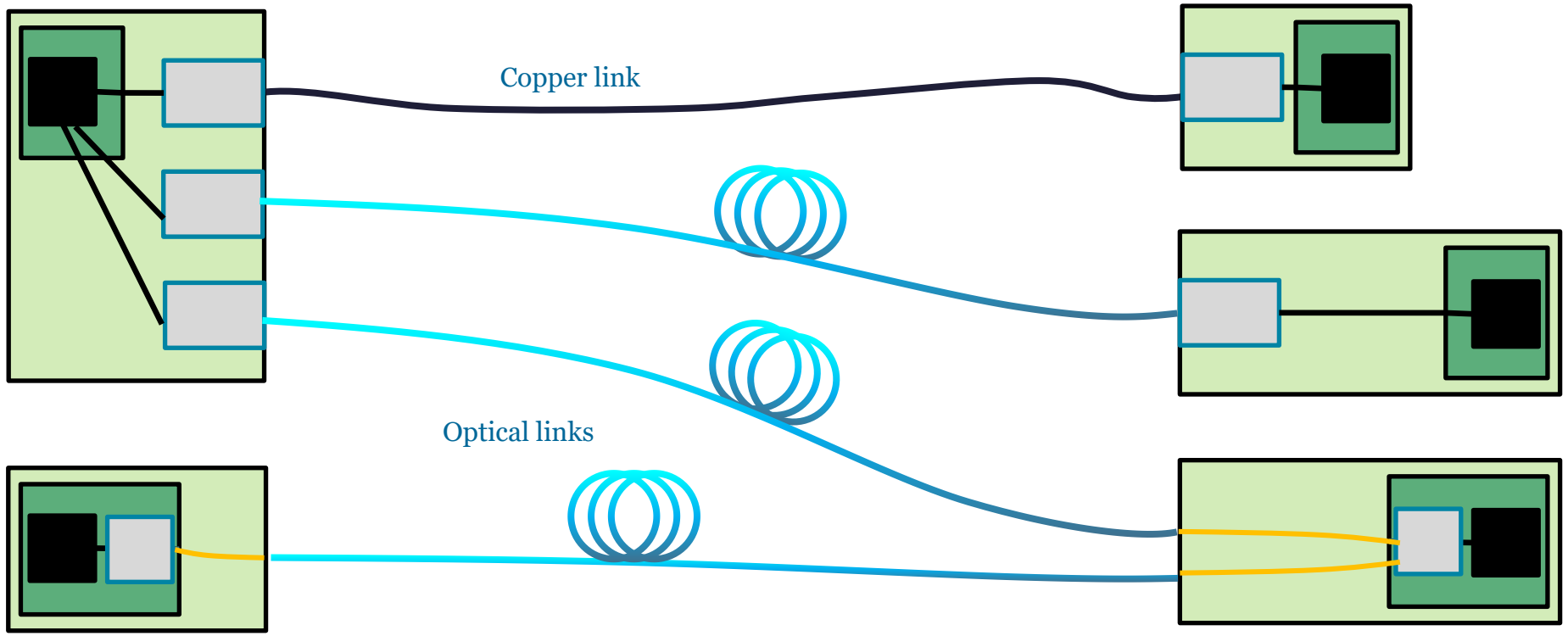
Key Questions for Optical

- **System Design:** Does CPO (in addition to pluggable) bring any new considerations? Interop needs to be independent.
- **Industry Readiness:** Will any new technologies or media meet industry ability to scale? The ecosystem matters.
- **Modulation Alignment:** How critical is common coding for electrical and optical interfaces?
  - Are linear solutions (pluggable/co-packaged) viable at 400G/lane, and when?
- **Validation Tools:** Are test & measurement solutions prepared for 400G optical?

FEC/PCS: Intersection of Electrical and Optical

- Historically, there was modulation commonality of optics and electrical
  - E.g. NRZ-to-NRZ, PAM4-to-PAM4
  - Enabled linear/un-retimed optical solutions
- Historically, the copper interconnect determined the FEC code
  - Copper required burst-tolerant FEC codes, e.g. RS(544, 514)
  - Optics used the same or added an inner FEC code, e.g. Hamming(128,120)
- Is RS(544) sufficient for 400G/lane, or should we proactively consider a clean sheet FEC approach?
- Does the existing FEC/PCS scale well for high-radix uses cases at the new signaling rate?
  - What about the latency for single-lane and two-lane cases?

Seamless Interoperability: An Ethernet Expectation



- Both copper and optical connections are essential for hosts
- Pluggable and CPO optics must work together cohesively

The Effort(s)
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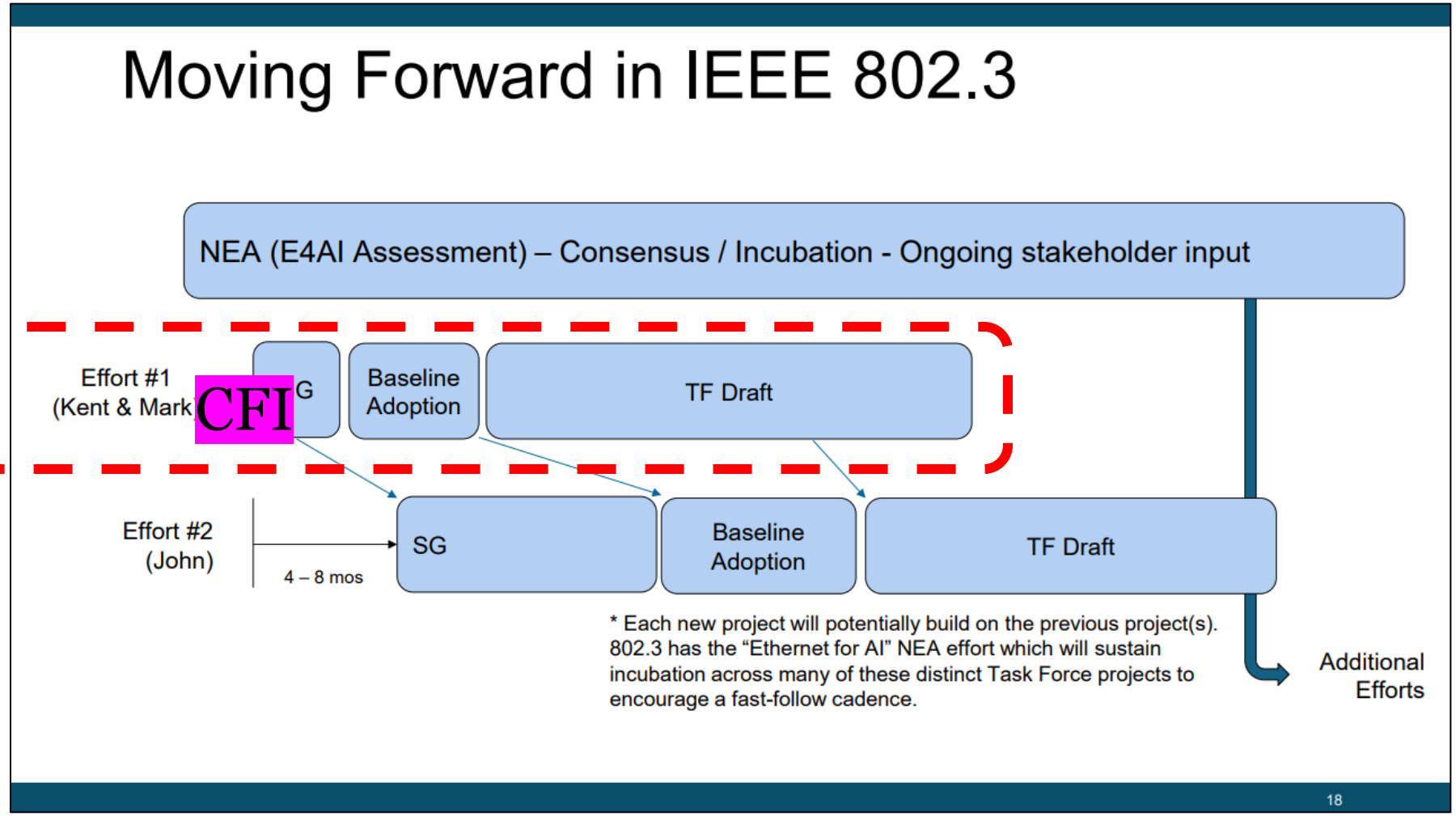
Fast and Nimble!

Critical First Step Towards 400G/lane Standard



https://www.ieee802.org/3/ad_hoc/E4AI/public/25_0819/dambrosia_e4ai_01_250819.pdf

Anticipated 400G/lane Signaling Project Objectives

- Usual Foundational
  - Full Duplex, Ethernet frame format & size, FLR, etc.
- Existing Ethernet rates
  - 400GbE (x1), 800GbE (x2), 1.6TbE (x4)
- New 400 Gb/s per lane PHYs & Interfaces:
  - Copper cable and backplane - reach TBD (passive plus active)
  - Optical single-lane SMF (PSM) - reach <= 500m
  - Electrical C2M and C2C interfaces

Summary

- The Ethernet community must *quickly* respond to support the AI network time-to-market requirements and use cases
  - Make decisions (modulation, FEC, host type, etc.), refine as necessary
- 400G/lane technology will tightly integrate electrical, optical, and FEC/PCS domains.
  - Both copper and optical connections are essential for hosts
  - Pluggable and CPO optics must work together cohesively
  - The ecosystem matters
- March 2026 CFI for 400 G/lane signaling
  - Initial focus is 400G/lane copper and short-reach optical PHYs based on existing MAC rates

Thanks!