# Modulation and FEC scheme for 400G/lane AUI-C2M

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# Background

- **400GPL Study Group Progress**.
  - Key objectives agreed upon in May Interim; 400G/lane AUI and CR reached consensus.
- **C2M Challenges & Opportunities**
  - AUI-C2M is critical for supporting front-panel pluggables.
  - Channel bandwidth limits are the primary bottleneck for electrical links.
- **Passive Channel Advances**
  - Great progress in passive component/connector bandwidth.
  - OIF data shows multiple measured/simulated channels with **>100 GHz bandwidth**, supporting both PAM4 and PAM6.
- **400G/lane PAM4 optics is setting the context for C2M modulation evaluations.**

# Introduction

- We provided simulated NPC channel in he_e4ai_01_251023.pdf last year.
- This contribution focuses on C2M channels with simulated **AND** measured data.
- We've considered three flavors shown below.


- PCB based, 8" to 10" PCB length
- Up to 32dB for 200G/lane
- 32dB is a good starting point.


- NPC – near-package copper
- Cable based, 250-350mm reach.
- Includes 1-3" PCB and at least two vias.


- CPC – co-packaged copper
- Cable based, 250-350mm reach.

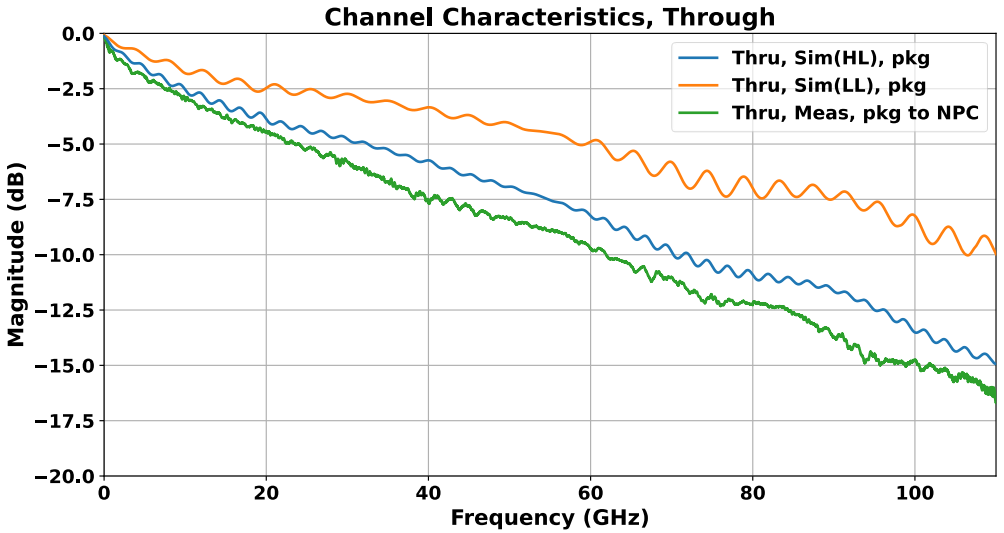
Lower loss or longer reach

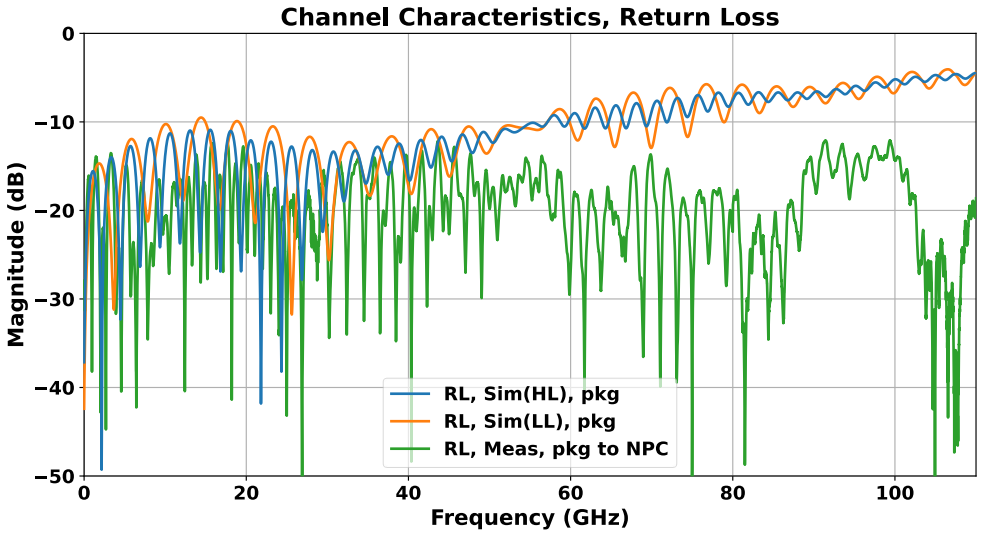
*Due to limited time we do not have data for CPC yet. Channel should be better than NPC.

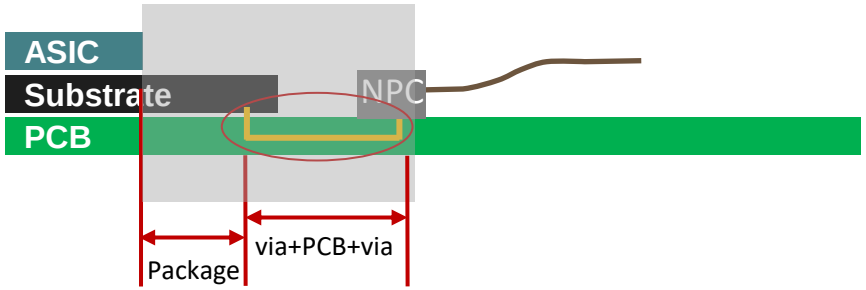
# Essential components to build a C2M channel

- **Package** – assuming we are continuing with a die-to-die model
- **Vias and PCB** - for PCB and NPC based C2M
- **NPC and CPC connectors**
- **Cables** – for cabled C2M
- **Front panel IO connector –** Module connector
- **Module PCB –** short trace of PCB in the module is considered

# Package model – simulation vs measured data

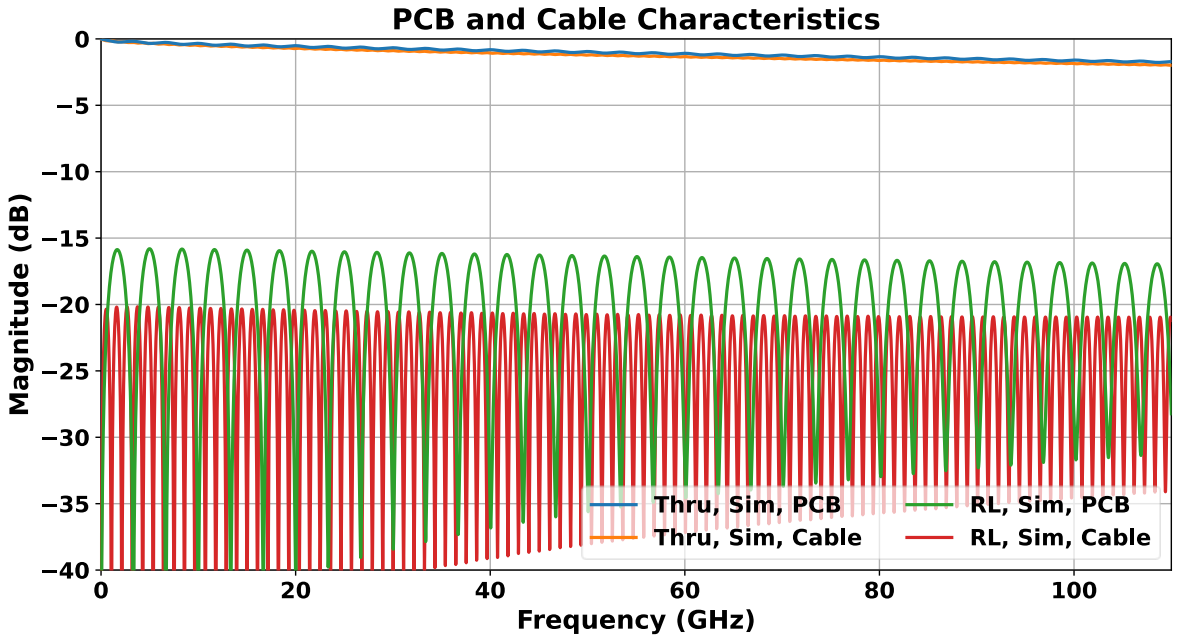


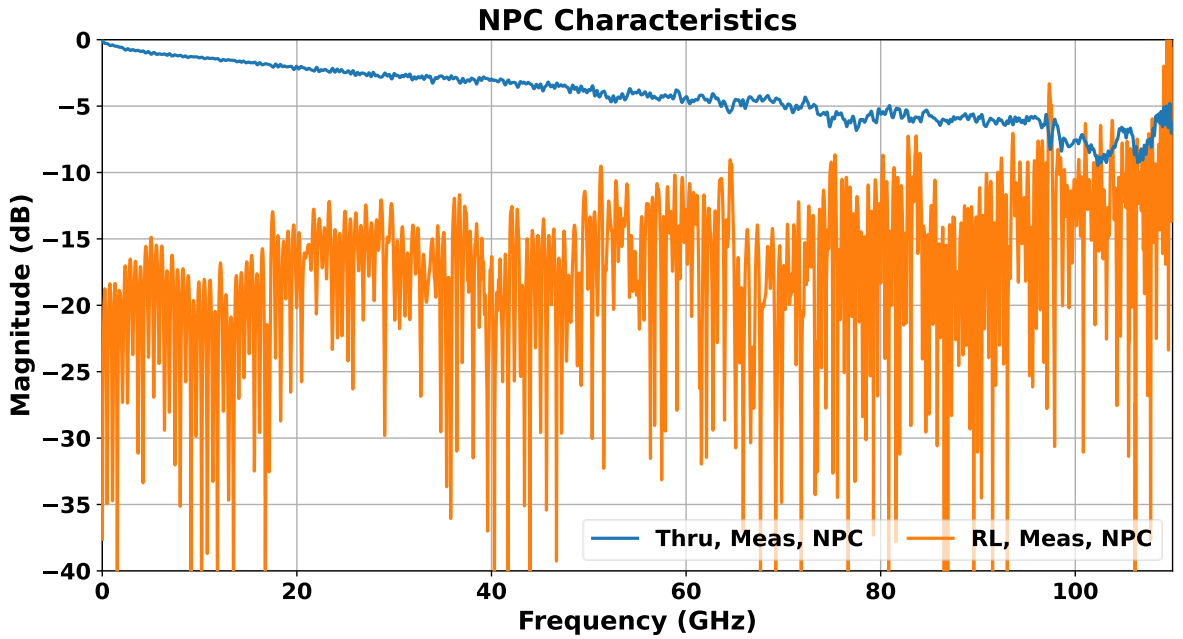

- Simulation ran with two package loss profiles, high loss (**HL**) and low loss (**LL**)
- Green lines are measured channel from package to NPC connector
  - Measured data is for the low-loss package
  - Measured data includes pkg + via + 1.5”PCB + via

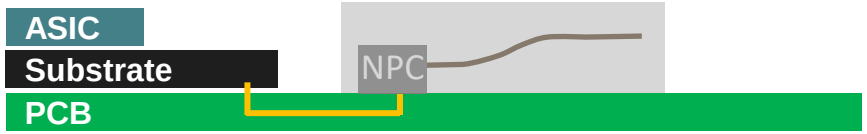
# PCB and raw cable – simulation model




- PCB traces and raw cable segments shown above are based on high-fidelity simulation models with proven correlation to measured data. We will use them when necessary.
  - PCB: 1 inch
  - Cable: 100mm 31AWG

# NPC with cable – measured data

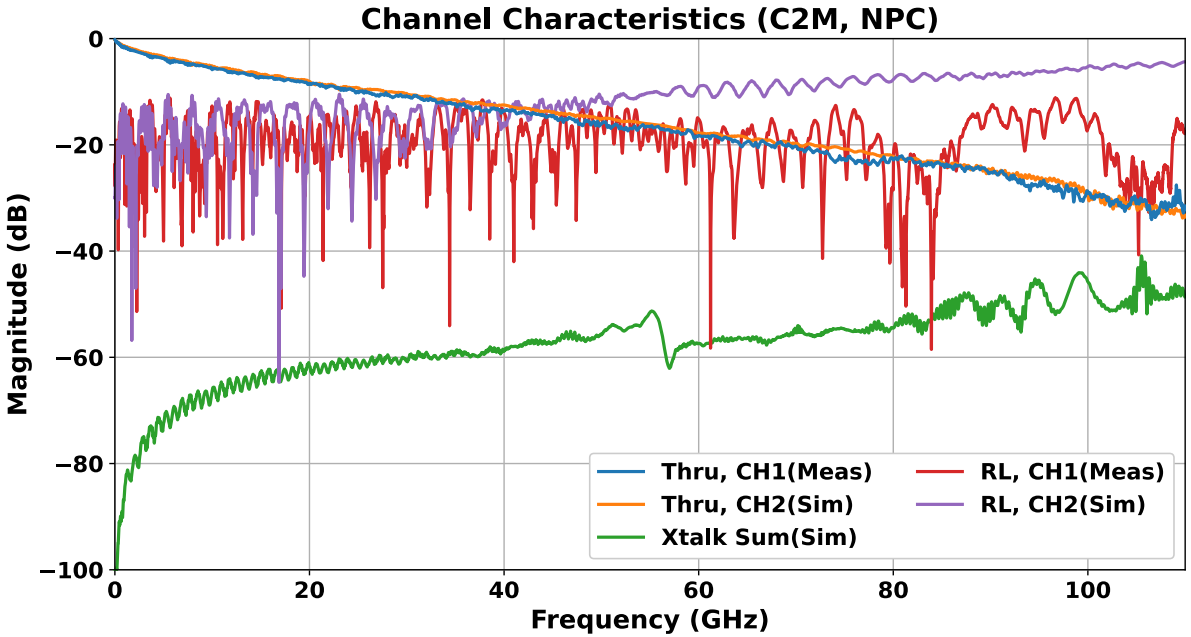



- Measured NPC with 150 mm cable
  - De-embedding issue beyond 100GHz.

# Constructed C2M channel with 2D IO connector – NPC based

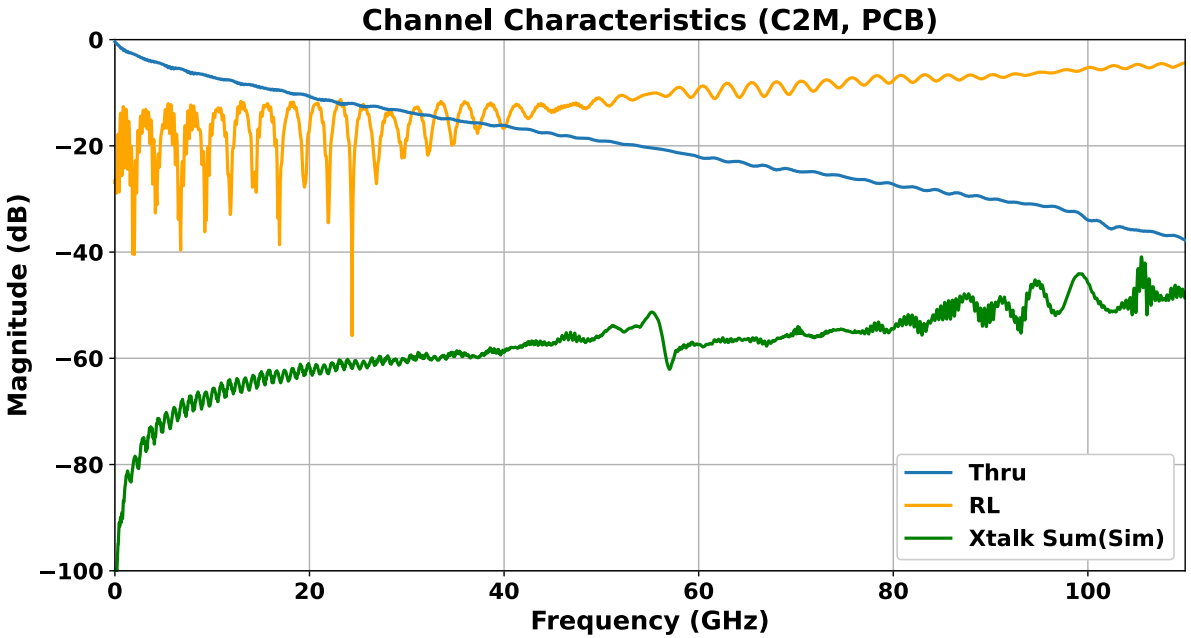
## (measured vs simulation)




- **CH1:** Measured NPC w/300mm cable, plus simulated 2D IO connector.
- **CH2:** Simulated NPC w/ 250mm cable, plus simulated 2D IO connector
- Simulated crosstalk.

*We would like to acknowledge Toshiyasu Ito affiliated with Yamaichi to provide the 2D IO connector files.

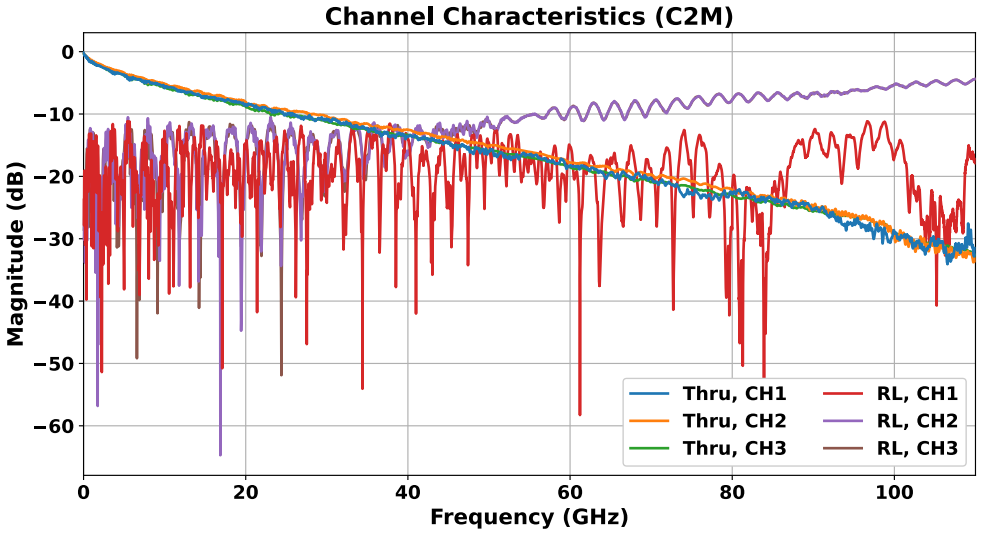
# Constructed C2M channel with 2D IO connector – PCB based (simulation)

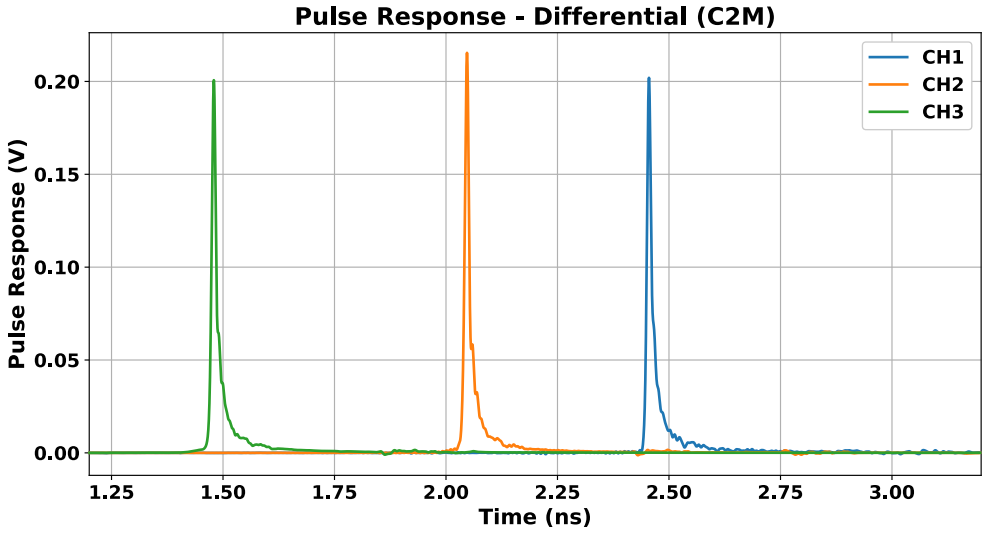



- **CH3:** Simulated, NPC w/ 9” PCB, plus 2D IO connector
- Simulated crosstalk.

This is an on-going effort and we will provide updates along the way.

# Summary of C2M channels




| | PKG | via | PCB | via | NPC | Cable | 2D IO Conn. | PCB | IL @ 106.25GHz |
|---|---|---|---|---|---|---|---|---|---|
| CH1 (NPC, measured) | Measured | | | | Measured 300mm | | Sim. | Sim | 31.6 dB |
| CH2 (NPC, simulated) | Sim. HL | Sim. | Sim. 2” | Sim | Sim | Sim 250mm | Sim. | Sim | 32.1 dB |

| | PKG | via | PCB | via | 2D IO Conn. | PCB | IL @ 106.25GHz |
|---|---|---|---|---|---|---|---|
| CH3 (PCB, simulated) | Sim. HL | Sim. | Sim. 9” | Sim. | Sim. | Sim. 1.5inch | 36 dB |

# Simulation results with PAM4 and PAM6 modulations

| | | PAM4 | PAM6 | PAM6, HD | PAM6, SD |
|---|---|---|---|---|---|
| CH1 | Data rate | 425Gbps | 425Gbps | 438.3Gbps | 437.9Gbps |
| | Inner FEC | / | / | (660, 640), SP4 | (340, 330), SP2 |
| | Insertion Loss | 31.2dB | 23.8dB | 24.5dB | 24.3dB |
| | ICN@bump, mV | 1.08 | 0.78 | 0.82 | 0.81 |
| | Alpha | 0.72 | 0.35 | 0.38 | 0.36 |
| | Precoding | OFF | OFF | OFF | OFF |
| | BER (w/MLSE) | **2.01e-8** | 7.30e-7 | 8.36e-6 | 1.56e-5 |
| | BER (after iFEC) | / | / | **<7e-9** | **<7e-9** |

| | | PAM4 | PAM6 | PAM6, HD | PAM6, SD |
|---|---|---|---|---|---|
| CH2 | Data rate | 425Gbps | 425Gbps | 438.3Gbps | 437.9Gbps |
| | Inner FEC | / | / | (660, 640), SP4 | (340, 330), SP2 |
| | Insertion Loss | 29.9dB | 23.3dB | 24.0dB | 24.1dB |
| | ICN@bump, mV | 1.08 | 0.78 | 0.82 | 0.81 |
| | Alpha | 0.65 | 0.35 | 0.42 | 0.36 |
| | Precoding | OFF | OFF | OFF | OFF |
| | BER (w/MLSE) | **<8e-9** | 2.49e-7 | 1.22e-6 | 6.46e-7 |
| | BER (after iFEC) | / | / | **<7e-9** | **<6e-9** |

# Simulation results with PAM4 and PAM6 modulations

| | | PAM4 | PAM6 | PAM6, HD | PAM6, SD |
|---|---|---|---|---|---|
| CH3 | Data rate | 425Gbps | 425Gbps | 438.3Gbps | 437.9Gbps |
| | Inner FEC | / | / | (660, 640), SP4 | (340, 330), SP2 |
| | Insertion Loss | 31.2dB | 24.4dB | 24.5dB | 24.4dB |
| | ICN@bump, mV | 1.08 | 0.78 | 0.82 | 0.81 |
| | Alpha | 0.65 | 0.32 | 0.30 | 0.28 |
| | Precoding | OFF | OFF | OFF | OFF |
| | BER (w/MLSE) | **<8e-9** | 5.33e-8 | 5.34e-8 | 1.60e-7 |
| | BER (after iFEC) | / | / | **<7e-9** | **<6e-9** |

# Summary

- We have seen amazing progress in passive components for the past year.
  - The "110 GHz+ Club" has expanded rapidly—multiple vendor channels show clean response with resonances pushed **past 120 GHz**.
- End-to-End PAM4 Synergy
  - Optics are locking in PAM4: matching the C2M interface eliminates gearbox power/latency
  - Seamlessly enables CPO/NPO architectures.
- Bandwidth is key, but time-to-market is not only about bandwidth.
  - Test & Measurement for PAM4 is mature—developing brand-new test methodologies for alternative modulations is a far bigger schedule risk than pushing channel bandwidth.
  - The RS(544,514) FEC and BLER test methodology…
- **We propose PAM4 as the baseline modulation for 400G/lane AUI-C2M.**

# Thank you!