Complexity Comparison of Asymmetric PHYs

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Outline

- IEEE 802.3dm is to specify an efficient PHY to support asymmetric throughput
- Will present an overview of a number of asymmetric schemes and a comparison of their trade-offs
- Background material
  - https://www.ieee802.org/3/B10GAUTO/public/jan20/sedarat_3B10G_01_0120.pdf
  - https://www.ieee802.org/3/ISAAC/public/091423/sedarat_isaac_202309.pdf
  - https://www.ieee802.org/3/dm/public/0524 /sedarat_3dm_01_202405.pdf

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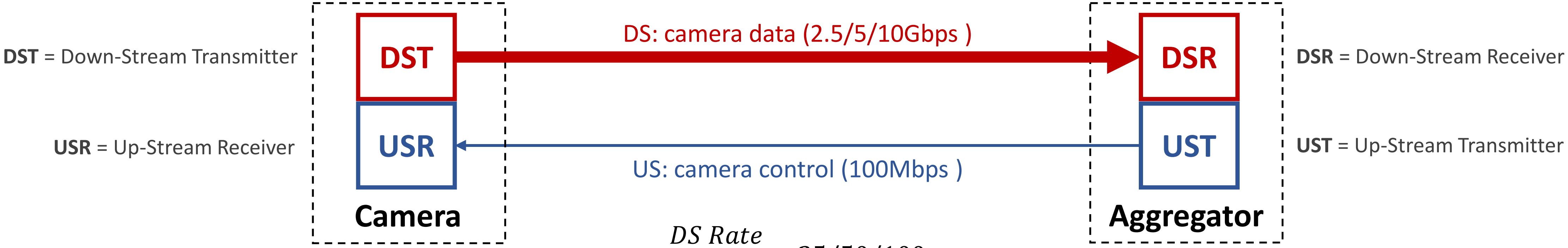
Asymmetric Camera Link

- High volume of video data flows down-stream (**DS**) from the PHY in the camera to the PHY in the aggregator

- Low volume of control information is transmitted up-stream (**US**) from the aggregator to the camera



$$\frac{DS\ Rate}{US\ Rate} = 25/50/100$$

Asymmetry and PHY Complexity

Asymmetry in data rates may offer opportunities to lower the complexity of the communication system resulting in

- Lower power consumption
- Lower PHY complexity: silicon area, relative cost
- Lower overall system cost
    - Lower complexity of cooling system
    - Simpler power delivery system
    - Easier integration with other components (*e.g.* imager)

- **802.3ch with EEE can achieve most of these goals**

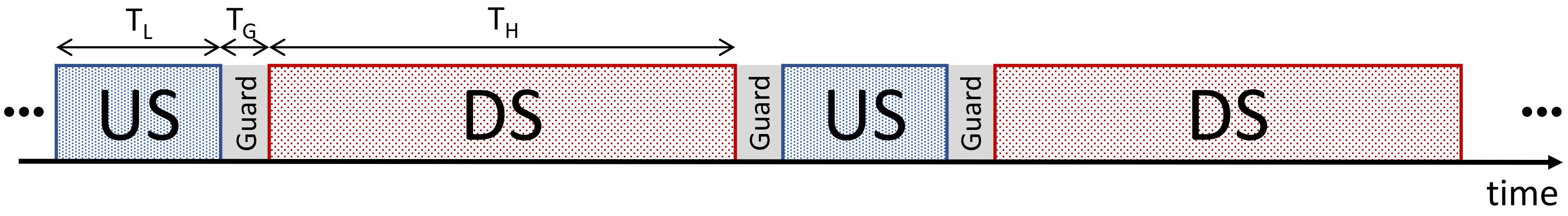
Asymmetric PHY Alternatives

This presentation focuses on asymmetric methods beyond EEE

- Time-domain duplexing (TDD)
- Frequency-domain multiplexing (FDM)
- Code multiplexing (CM)

Time-Domain Duplexing (TDD)

- Link-partners transmit over nonoverlapping periodic timeslots



- When the local transmitter is ON the remote transmitter is OFF eliminating echo into remote receiver (and vice versa)

- Guard bands, where both transmitters are off, needed at transition between US and DS to eliminate echo from far-end reflection points

TDD Inefficiencies

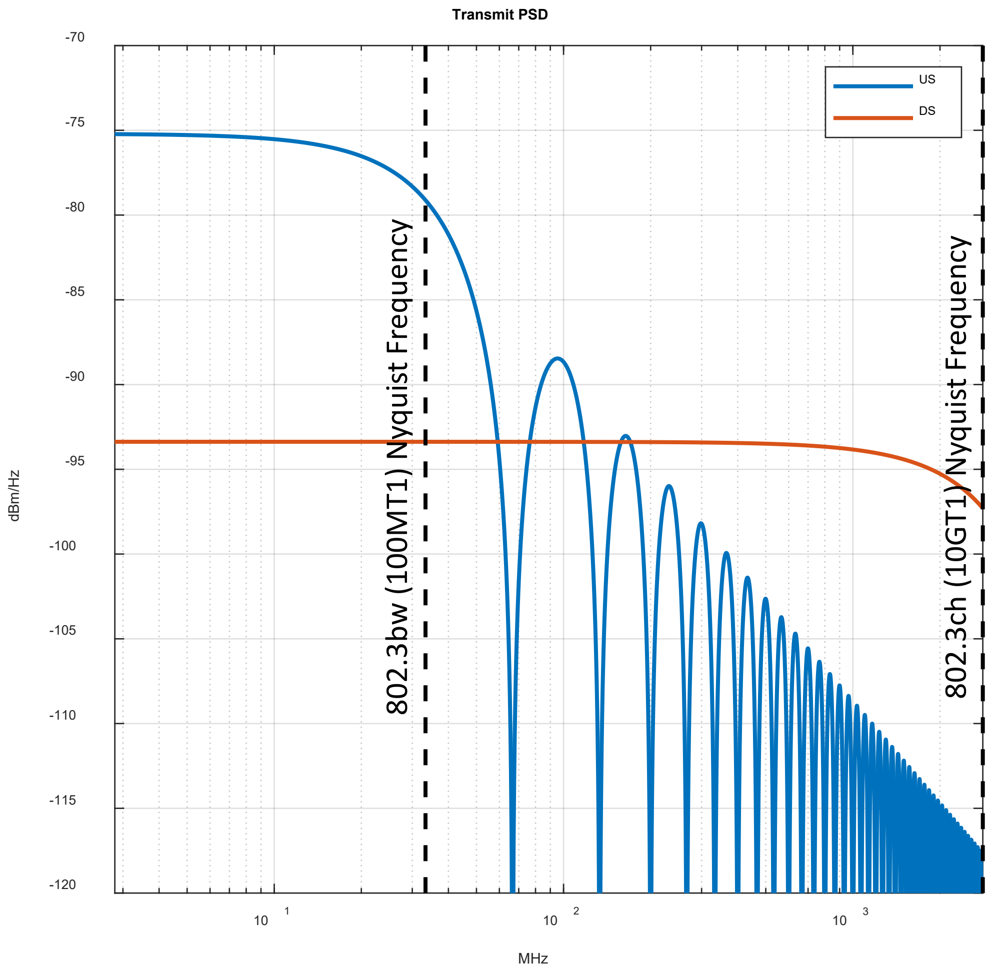
- US data is transmitted over very short time-windows demanding extremely high US symbol rate
  - ➔ Very complex equalization, AFE, and EMI in US receiver
- US transmitter is inactive for very long time-windows
  - ➔ Long latency in US direction
- The US receiver needs deep FIFOs to adapt the much higher incoming symbol to much lower rate outgoing data
- There are gaps in DS transmission, demanding higher symbol rate
  - ➔ More complex equalization, AFE, and EMI in DS receiver
- The TDD transmitters are turned on and off periodically
  - ➔ Fluctuations in crosstalk and power consumption

Frequency-Domain Multiplexing (FDM)

- Both DS and US nodes transmit at the same time

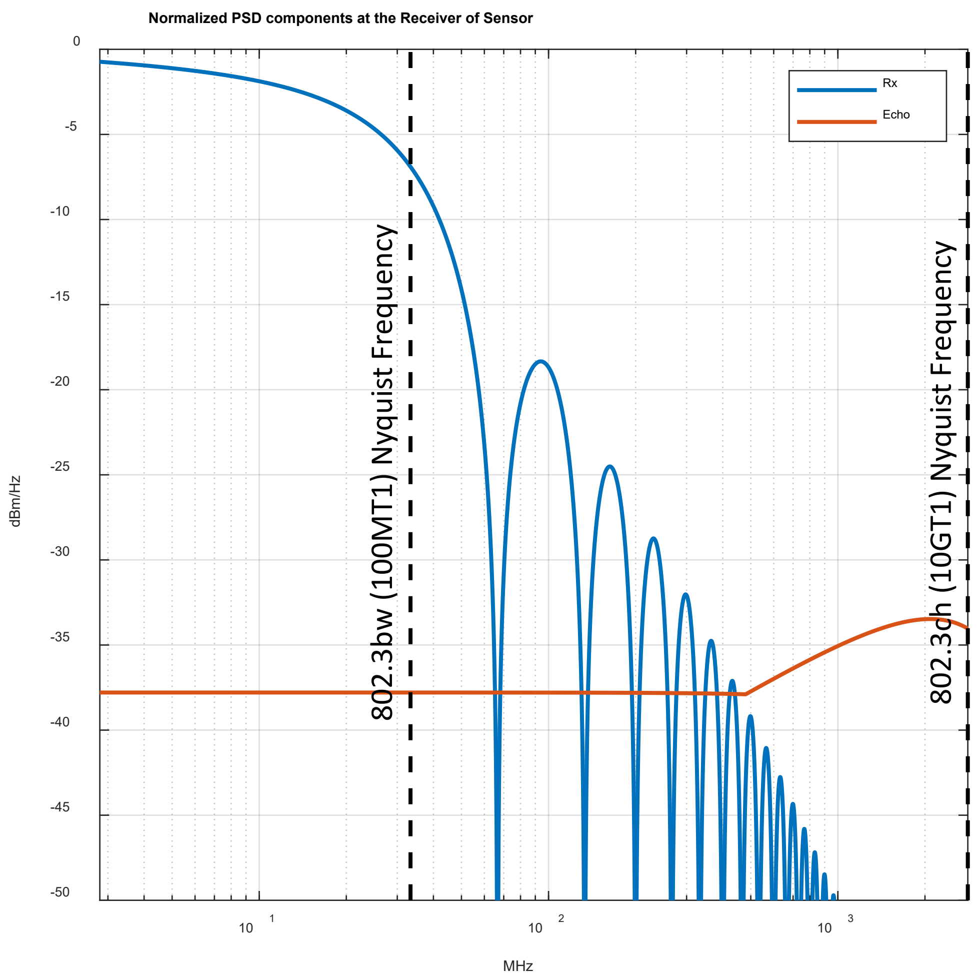
- Symbol rate scales with data rate
  - High symbol rate in DS direction
  - Low symbol rate in US direction
  - ➔ Limited overlap in frequency domain

- Complexity of the receiver scales with the supporting data rate
  - ➔ Very low complexity US receiver



FDM – Echo in US Receiver

- The sensor PHY transmits at higher baud rate and receives at low rate
- Echo power is mostly at high frequency while the receive signal from link-partner is low frequency
- The receiver anti-aliasing filter blocks most of the high-frequency echo
- Signal-to-Echo Ratio = 35 dB
  - echo cancellation is <u>not</u> needed!



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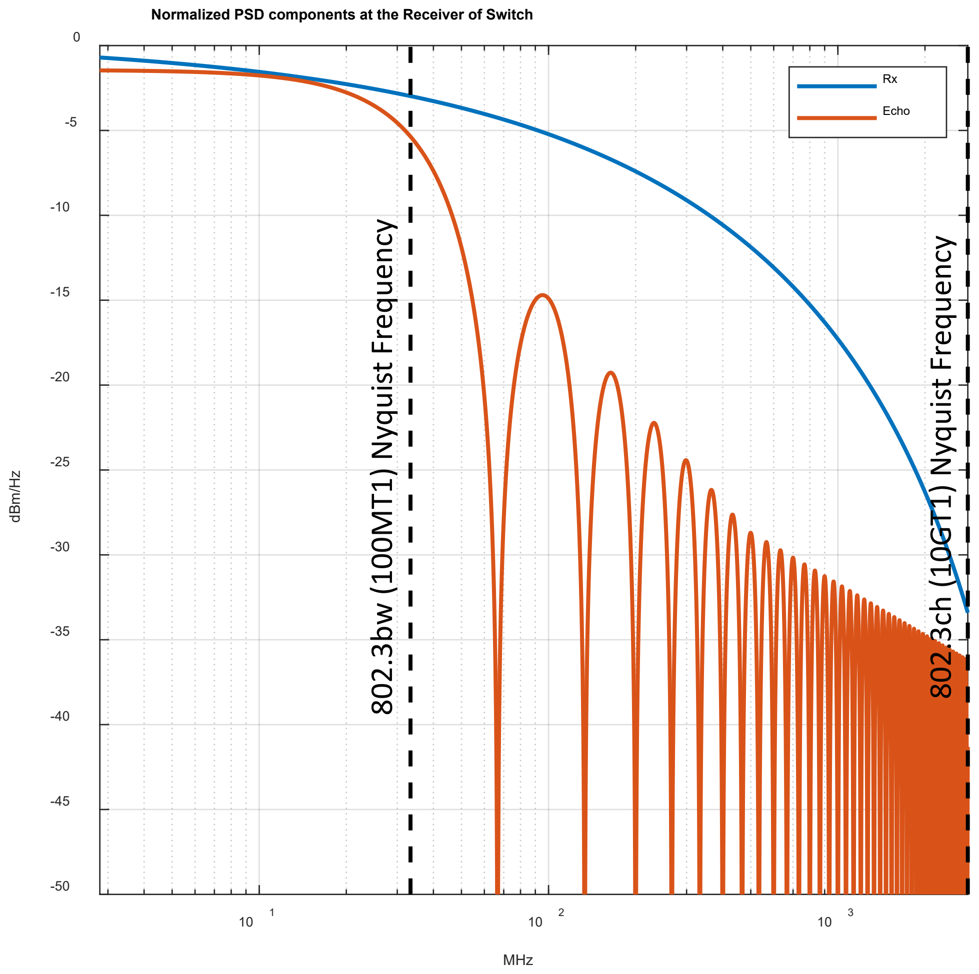
FDM – Echo in DS Receiver

- The PHY in aggregator transmits at low rate and receives at high rate
- Transmit signal is mostly low frequency resulting in small echo power covering a fraction of the receiver bandwidth
  - Partial echo cancellation may be needed
  - Polyphase implementation reduces the complexity by the ratio of DS/US data rates



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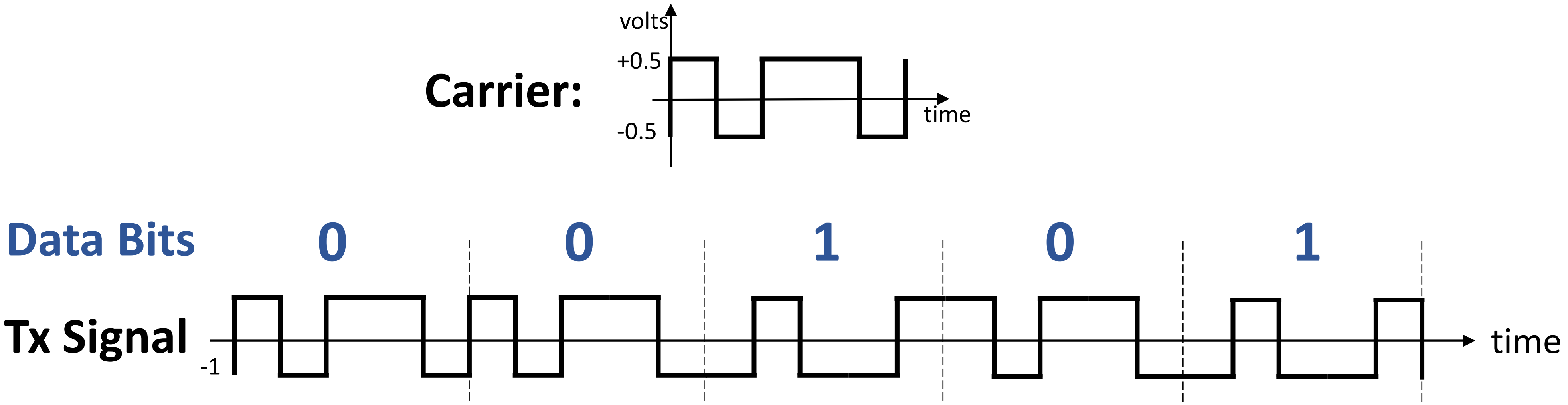
FDM – Trade-offs

- Power consumption matches the inherent complexity associated with the supporting data rate
- The upstream transmitter and receiver are both very simple
  - Very low complexity for equalization, AFE and EMC
  - No need for echo cancellation
- Small latency with no need for FIFOs
- The learnings and the specifications from previous 802.3 task forces may be leveraged to expedite the standardization process
- The downstream receiver needs partial echo cancellation with simplicity of a polyphase implementation

- Lower signaling bandwidth may create difficulties in DC decoupling components for power delivery in US receiver

Code Multiplexing (CM)

- Low-frequency upstream data bits modulate high-frequency pseudo-random carrier before launched on the cable



- A matched filtering scheme may be used to correlate across carrier subsymbols and average out noise, resulting in SNR gain

CM – Examples

USR=100 Mbps and DSR=10G (802.3ch)

- Baseband: 802.3ch PCS + PAM2 + 112.5 Msps
  - CM with spreading factor of 25

    ⇒ **SNR Gain** ≈ 7 (PAM2) + 3 (ISI + Noise) + 14 (CM) = <u>24 dB</u>
  - CM with spreading factor of 10

    ⇒ **SNR Gain** ≈ 7 (PAM2) + 5 (ISI + Noise) + 10 (CM) = <u>22 dB</u>

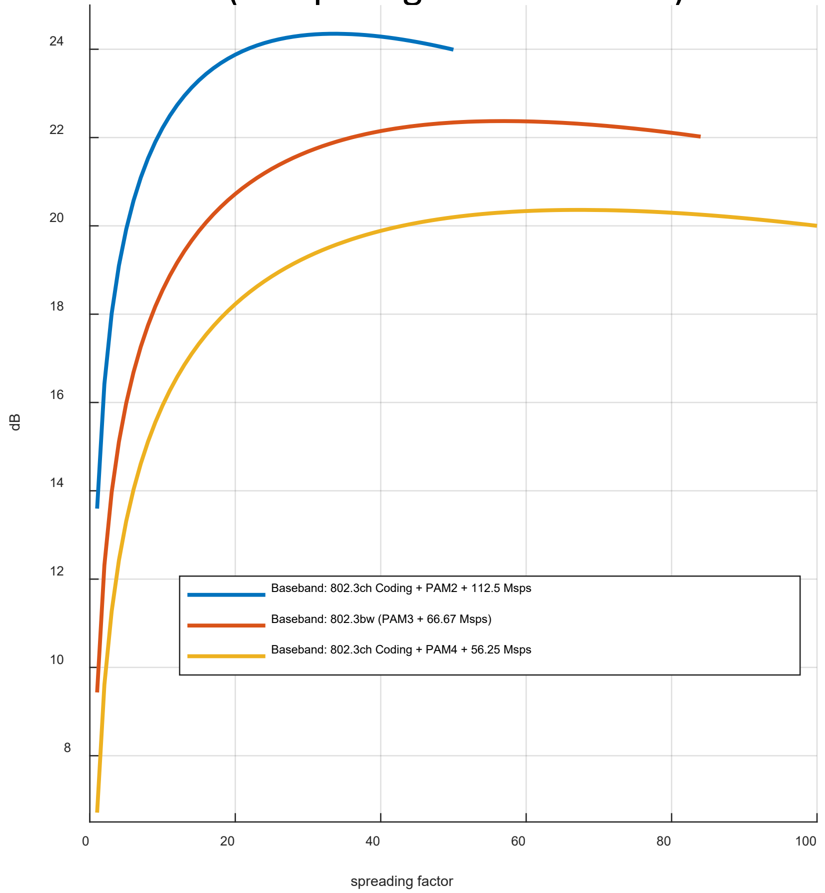
- Baseband: 802.3ch with 56.25 Msps
  - CM with spreading factor of 50

    ⇒ **SNR Gain** ≈ 3 (ISI + Noise) + 17 (CM) = <u>20 dB</u>
  - CM with spreading factor of 10

    ⇒ SNR Gain ≈ 6 (ISI + Noise) + 10 (CM) = <u>16 dB</u>

SNR Gain in US Reliever

(comparing to DS receiver)



Code Multiplexing – Trade-offs

- 👍 Very simple upstream receiver (similar to Alert detector)
  - 👍 Minimal equalization, echo cancellation, and simpler analog components
- 👍 Spreading factor is an effective tuning knob to trade-off various complexities of the receiver
- 👍 Small and predictable latency, no need for FIFOs
- 👍 The learnings and the specifications from previous 802.3 task forces may be leveraged to define the baseband system
- 👍 Downstream receiver requires a simple polyphase echo canceller

- 👎 While the required dynamic range of AFE in the upstream transceiver is very low, the sampling analog-digital conversion rate remains high

Comparison

Receiver Function		TDD	FDD	CM
Echo Canceller		+	+	+
Equalization		-	+	+
EMI		-	+	+
AFE	Dynamic Range	-	+	+
	Sampling Rate	-	+	o
PLL	Frequency	-	+	o
	Jitter Tolerance	-	+	+
Latency & FIFO		-	+	+
Power Delivery		+	-	+
Power and Crosstalk Fluctuations		-	+	+

Summary

- EEE is a reasonable candidate to support asymmetry
- Time-domain duplexing eliminates the need for echo cancellation but increases the complexity of equalization, AFE, EMI, and PLL. It also comes with long latency and big FIFOs.
- Frequency duplexing is a very reasonable choice for asymmetry
  - minimal (or no) equalization, echo cancellation, and simple AFE/PLL
- Code multiplexing offers a tunable scheme to trade-off signaling bandwidth for SNR gain with minimal receiver complexity
  - minimal (or no) equalization, echo cancellation, and simple AFE/PLL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