Line modulation considerations for 2.5Gbps and 5/10Gbps Automotive Ethernet

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- Update of PAM-proposal
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Recap of status after Pittsburgh

- For 10Gbps PAM4-5 show as sweet spot regarding Salz margin for the baseline channel spec
- Implicitly the baseline channel spec was assumed to apply for 2.5Gbps too
- Salz margin for 2.5Gbps is sufficient for PAM2-8
- Interference tolerance perceived as much better for low PAM
  - Is this perception correct?
- Speed-grade modulation compatibility
  - 1Gbps versus 2.5Gbps
  - 2.5Gbps versus 5/10Gbps
  - Spectral content in GNSS bands

GNSS=Global Navigation Satelite Systems
(e.g. GPS, GLONASS, Galileo)

PAM5

- $b=\log_2(5)=2.322 \rightarrow 2\frac{1}{4} < b < 2\frac{1}{3}$
- Allows 9 bits mapped to 4 PAM5 symbols
  - 12.5% lower symbol rate than PAM4 to offset the coding overhead
  - Requires fairly complicated coding to realize this improvement
- Realizing true capacity requires large blocks
  - 9 bits in 4 symbols: 2.25
  - 23 bits in 10 symbols: 2.3
- Transmit 2-bits/symbol and use 5^{th} level for conditioning
  - Shape (analog) line signal properties & avoid killer packets
  - SNR margin assumes ~$2\frac{1}{3}$ bit/symbol, so causing an SNR penalty
  - Degrades interference tolerance
- Conceptually nice, but PAM4 is more efficient
  - May want to consider limiting runlength at higher level

Modulation compatibility

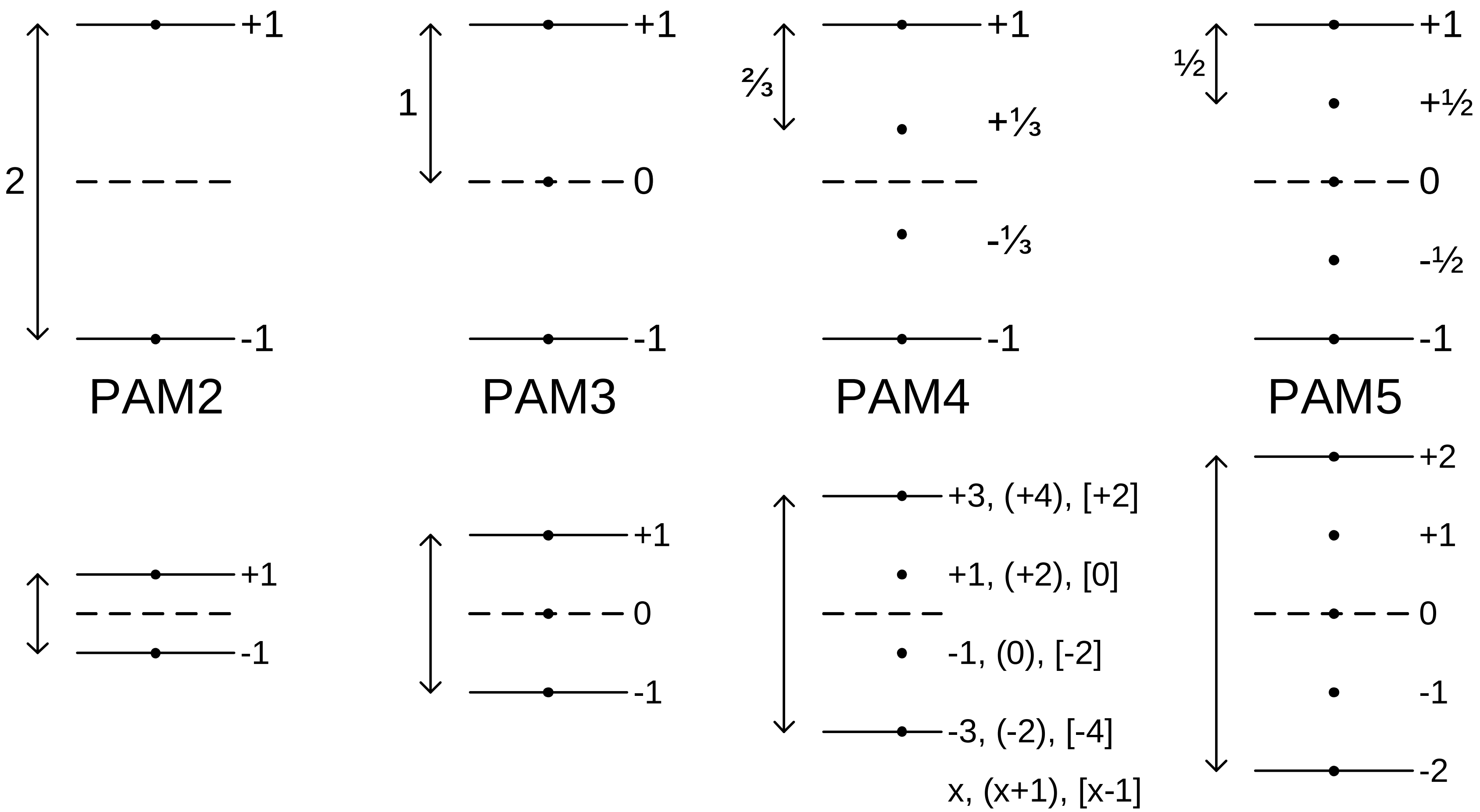
- Topic brought forward in Pittsburgh May meeting
  - Recent OEM poll suggests this is a relevant aspect
  - Priority choice seems to be dispersed
- This is not just about 2.5Gbps and 5/10Gbps as 100Mbps and 1Gbps standards already exist using PAM3
- Desirable to make 2.5Gbps compatible with 1Gbps
  - backward compatible
  - efficient multi-mode implementations (for switches)
- Desirable to make 2.5Gbps compatible with 5/10Gbps
  - forward compatible

Compatibility table

100M/1G	2.5G	5/10G	Compatible
PAM3	PAM3	PAM4	☺
PAM3	PAM4	PAM4	☺
PAM3	PAM2	PAM4	☹
PAM3	PAM8	PAM4	☹

- Choose for 2.5Gbps the same modulation scheme as for 1Gbps or the same as for 5/10Gbps, but not a third option

PAM options: reference levels



- PAM2-3-4-5: only power-of-two: multiplication by shift & add
- PAM6 and up: don’t have this property: require true multiply

Power: DSP impact

- Echo cancellation and DFE imply a lot of multiplications with symbol values
- Multiplication with zero and powers-of-two easy {0, ±1, (±2)}
  - PAM2, PAM3, PAM5
  - PAM4 with correction
- Multiplication with {±3, ±5, ±7} adds complexity
  - PAM6 (including Cross-32) or PAM8 (including DSQ-32)
- Lower baudrate requires fewer EQ/EC taps and relaxes timing
  - lower power
  - benefit of PAM3 over PAM2 (no multiplication downside)
  - benefit of PAM4 over PAM3 (small correction downside)
  - benefit of PAM8 is lost by multiplication downside
    + interference tolerance compromised

Summary of my current view

- PAM4 is the best option for 5/10Gbps
- Allow 2.5Gbps to have its own channel requirements
  - Lower quality cables
  - Longer cables
  - Maybe even UTP
- Ensure compatibility of 2.5Gbps with 1Gbps ànd 5/10Gbps
  - Modulation for 2.5Gbps should be PAM3 or PAM4
  - PHY supporting PAM3 ànd PAM4 is not extremely complex
- Conclusion:

  PAM4 might be the best choice for 2.5Gbps too

SNR margin

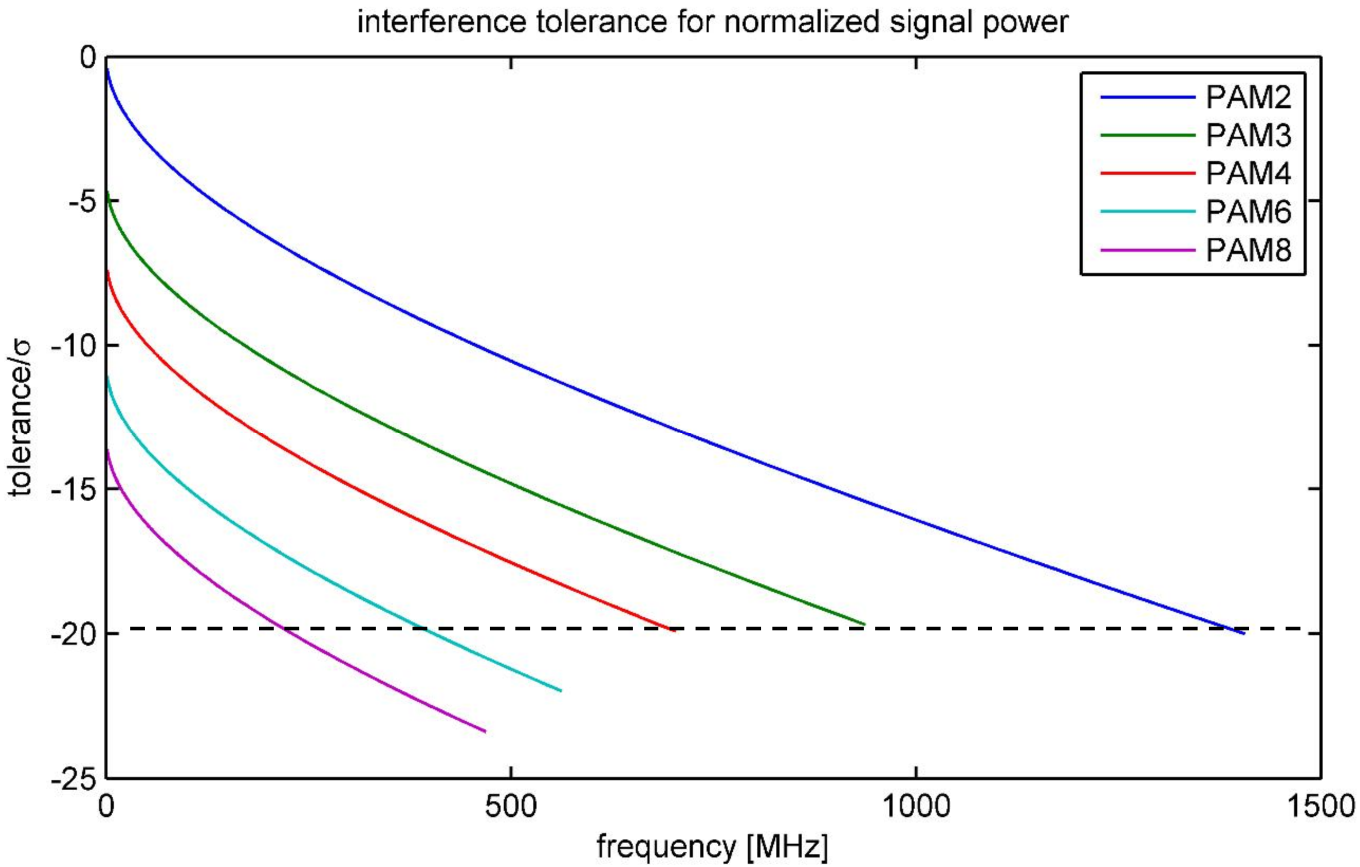
- For 10Gbps
  - PAM4 or PAM5 are optimal
- For 2.5Gbps
  - SNR margin is almost flat for PAM2-3-4-5 and much better than necessary for reliable reception
  - SNR margin it therefore not the most useful selection criterion here
- Dependent on noise floor assumption

	PAM2	PAM3	PAM4	PAM5	PAM6	PAM8
2.5Gbps (1Vpp)	35.5	35.0	34.3	33.3	32.2	30.2
2.5Gbps (σ-norm)	35.5	38.5	39.4	39.3	38.8	37.5
10Gbps -1Vpp)	14.3	18.5	19.3	19.1	18.6	17.5
10Gbps (σ-norm)	14.3	22.0	24.4	25.1	25.2	24.8

Interference tolerance

- It's about margin at the RX side, not so much about signal level spacing at the TX side
  - Vpp/(N-1)
- Channel IL is equalized in the RX, but as a consequence interference will be amplified
  - Lower channel loss is better
- For high frequency IC-package loss worsens the result
  - the signal faces this twice and the interference only once
- Interference typically has a high-pass characteristic
  - low-frequency tolerance matters less than high-frequency tolerance
  - due to coupling behavior in combination with terminated lines

Interference tolerance: 2.5Gbps



- Worst sensitivity almost equal for PAM2-3-4
- PAM6-8 compromise interference tolerance
- High-pass effect not included yet

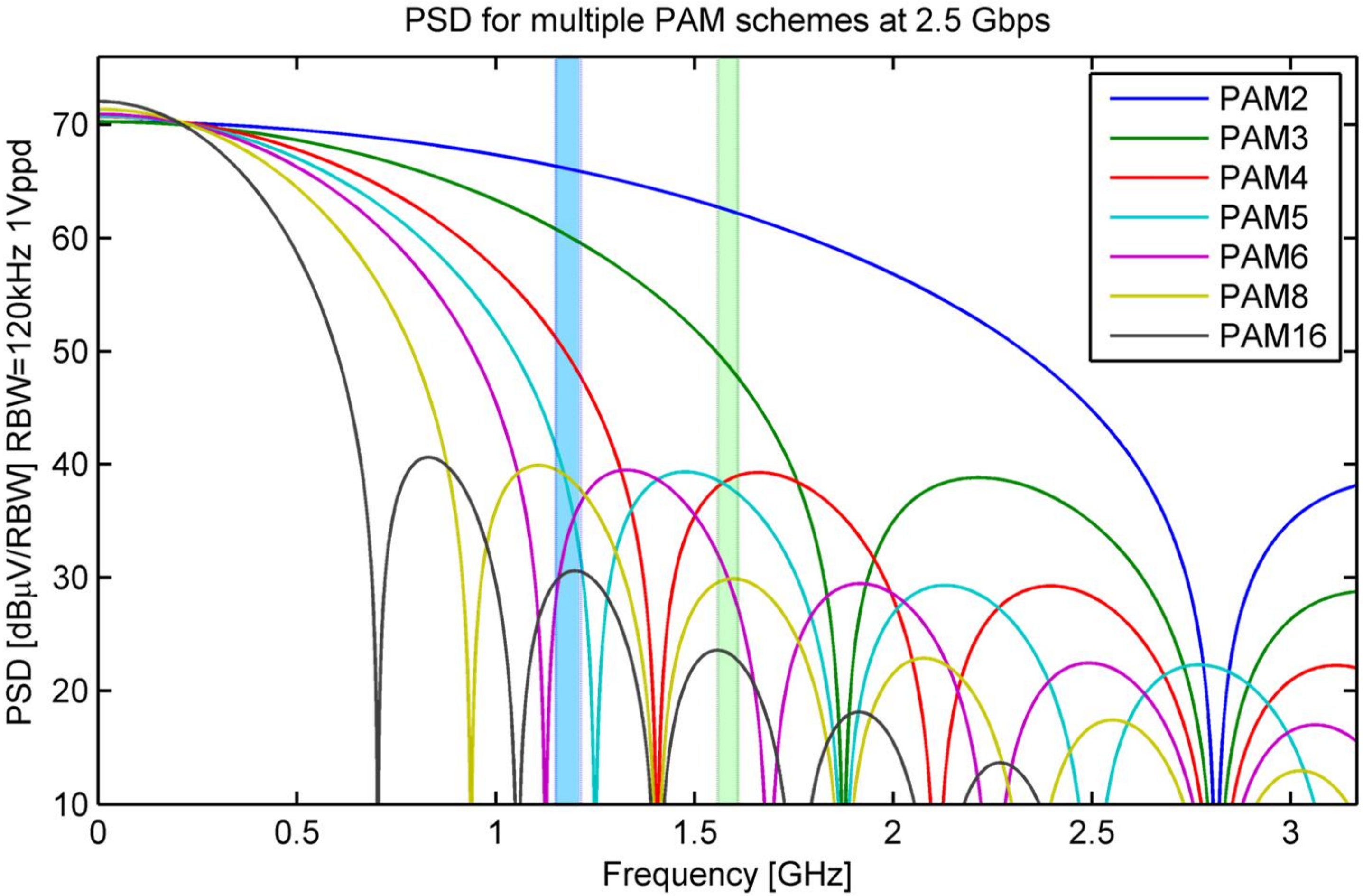
Enabling new options for 2.5Gbps

- Assuming the high quality cabling of 10Gbps is ‘easy’ in standardization, but means overkill for a 2.5Gbps link
- 2.5Gbps with PAM3 or PAM4 allows:
  - Allowing lower cost cabling, maybe STP with foil-only possible
  - Extension of cable length beyond 15m
    - for example 40m like 1000BASE-T1 (for non-automotive applications)
  - Keep signal PSD away from GNSS bands
  - Potentially even enables 2.5Gbps over UTP for many use cases
    - lower bandwidth should ease CMC design

Emission considerations

- Currently only cable mode-conversion considered
  – Implicitly an ideal transmit signal assumed
- Difficult to drive nice differential signals at high speed
- Benefit to avoid a high PSD in emission critical bands
  – GNSS: close to 1200MHz and 1600MHz
- Certainly avoid baudrate-harmonic spurs in GNSS bands
- GNSS bands indicated by blue and green shaded ranges

2.5GBASE-T1



- PSD of PAM3/PAM4 much lower in GNSS bands than PAM2
- PSD >1GHz can be improved with some filtering for PAM≥3

Summary: 2.5Gbps

PAM (bits/symbol)	2 (1)	3 (1.5)	4 (2)	6 (2.5)	8 (3)
Baudrate [Gbaud]	2.813	1.875	1.406	1.125	0.938
Nyquist BW [GHz]	1.406	0.938	0.703	0.563	0.469
1G compatibility	–	++	+	o	o
Power efficiency	+	++	++	–	–
Emission/UTP	––	+	++	++	++
Nyquist loss [dB]	19.2	15.1	12.7	11.2	10.1
Nyquist eye [mV]	109	88	77	55	45
SNR margin	35.5	35.0	34.3	32.2	30.2
Line coding	o	+	o	+	o

- 1Vppd & 12.5% coding overhead assumed
- Nyquist loss for agreed baseline Insertion Loss
- PAM3 and PAM4 show as best options

Summary: 10Gbps

PAM (bits/symbol)	2 (1)	3 (1.5)	4 (2)	6 (2.5)	8 (3)
Baudrate [Gbaud]	11.25	7.5	5.625	4.5	3.75
Nyquist BW [GHz]	5.625	3.75	2.813	2.25	1.875
2.5G-PAM4 compatibility	−−	−	++	−	+
2.5G-PAM3 compatibility	−−	++	o	−	−
2.5G-PAM2 compatibility	++	+	+	−	+
Power efficiency	−	o	+	o	−
Nyquist loss [dB]	46.9	35.7	29.7	25.7	22.9
Nyquist eye [mV]	4.5	8.2	11.0	10.3	10.2
SNR margin	14.3	18.5	19.3	18.6	17.5
Line coding	o	+	o	+	o

- PAM4 come out best overall
- Emission/UTP criteria left out: bad for all options

Conclusion

- For 10Gbps the best option seems PAM4
  - PAM8 (16) uses less bandwidth but have worse SNR, (very) small margin for interference, and make the DSP more complex
  - PAM2&3 take too much BW and require more expensive cables
  - With PAM5 it is not easy to materialize the symbol rate reduction
- For 2.5Gbps the best option seems PAM4 too
  - Reasonably simple to make it compatible with 1Gbps PAM3 and even lower symbol rate than PAM3
  - Straightforward compatible with 5/10Gbps
  - Good enough interference tolerance
  - Less BW, less IL, lower clocks, and better emission wrt PAM2
  - Enabling lower quality cabling, maybe even UTP
  - Enable extension of cable length

Open shielded-cable topics

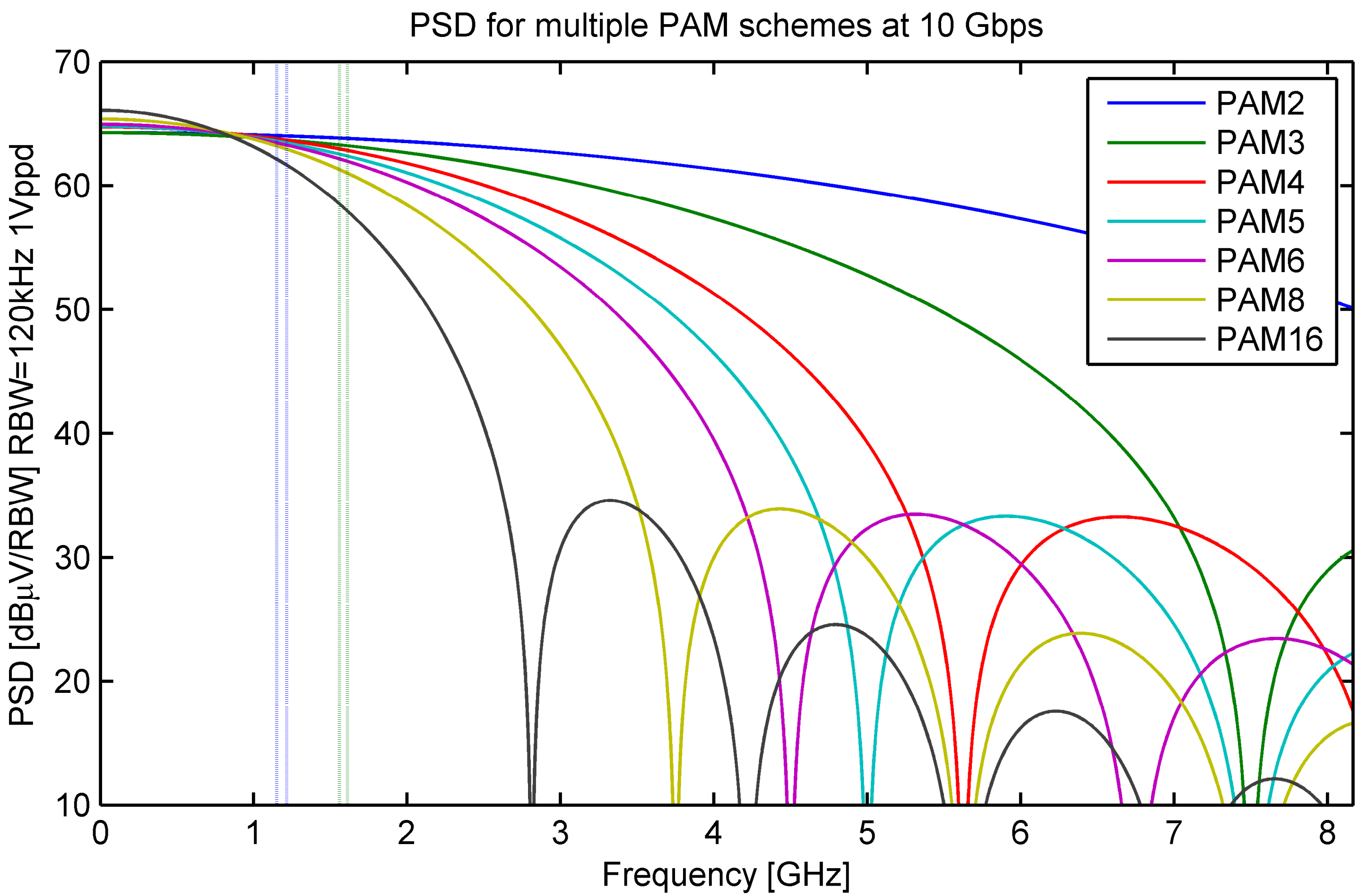
- What coupling networks are expected to be used?
  - CMC performance gets worse at high-frequencies
  - Capacitive-only sufficient? → transceiver AC-CM directly hits MDI
- How will the shields typically be connected in the system?
  - How to deal with ground bounce?
- Which ESD levels will be expected from transceiver pins?
  - High ESD level = high parasitic load = bad RL at high freq
- Which BCI/RFI tolerance levels will required?
- System boundary conditions may limit max frequency

Asymmetry (“the pink elephant”)

- Many links naturally have an asymmetric traffic profile
  - Especially sensors, cameras & displays
- PHYs for (highly) asymmetric payload can be implemented more efficient than PHYs for roughly symmetric payload
- Without enabling asymmetry NGAUTO PHYs might not be able to effectively address several multi-gig use cases
- There is precedent already in IEEE to do asymmetric links
  - EPON did it: **76.2.2 Dual-speed Media Independent Interface**
- IMO it could be wise to address this in NGAUTO

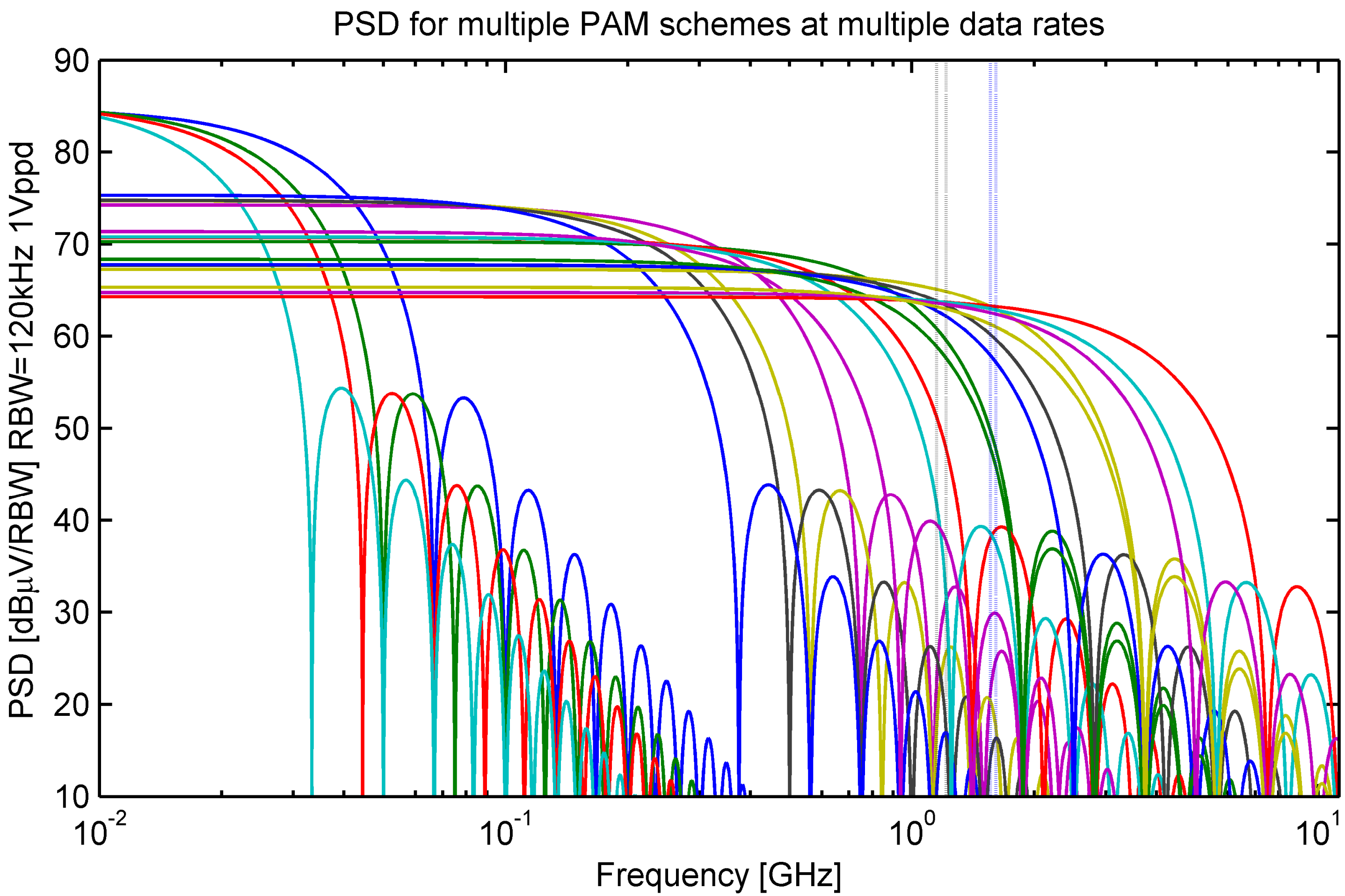
Back-Up

10GBASE-T1



- All PAM candidates have high PSD level in GNSS bands

Speed-PSD comparison



- Low-frequency plateau scales inversely with √baudrate
- 100/1000BASE-T1 baseband lobes don't hit GNSS bands

Normalized PAM signal power

- Assuming constant peak-peak voltage
- Reference: PAM2=1