Line modulation considerations for 2.5Gbps and 10Gbps Automotive Ethernet

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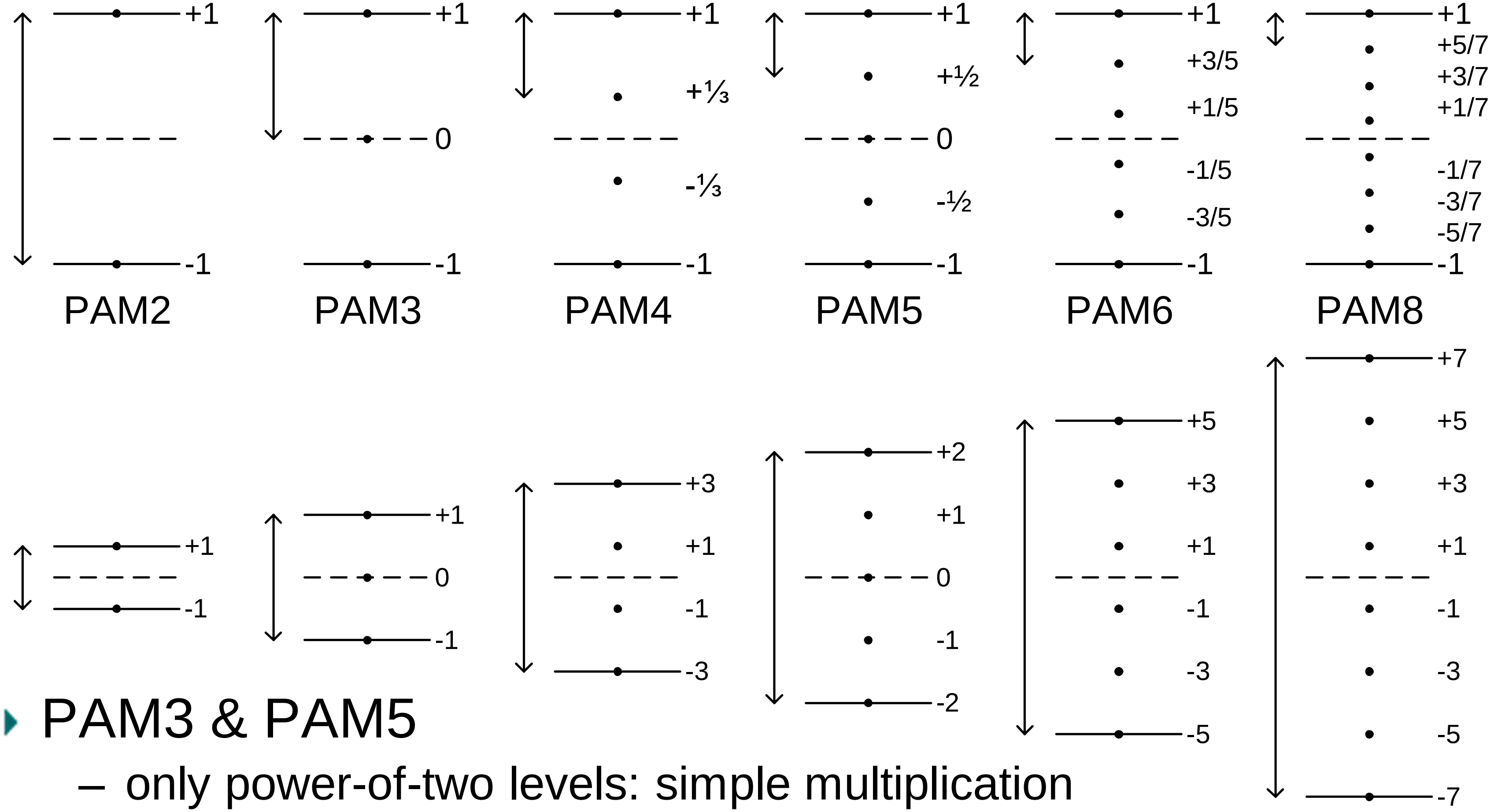
Aspects to consider

- SNR margin & Interference tolerance
  - Extensively explored in Sujan's contribution
- Speed-grade modulation compatibility
- Power efficiency
- PSD & emission
  - specifically content in GNSS bands

Modulation compatibility

- This is not just about 2.5Gbps and 10Gbps
- Already 100Mbps and 1Gbps standards existing
  - Both use PAM3
- 2.5Gbps is not just a down-scaled 10Gbps link
  - Should provide an efficient 2.5Gbps too
- Applications existing for 2.5Gbps links
  - that are really efficient for that rate
  - but which cannot and need not to support 10Gbps

PAM options: reference levels



- PAM3 & PAM5
  - only power-of-two levels: simple multiplication
  - PAM5 includes the constellation points of PAM3
- PAM4 & PAM8 don't have these properties

Power efficiency

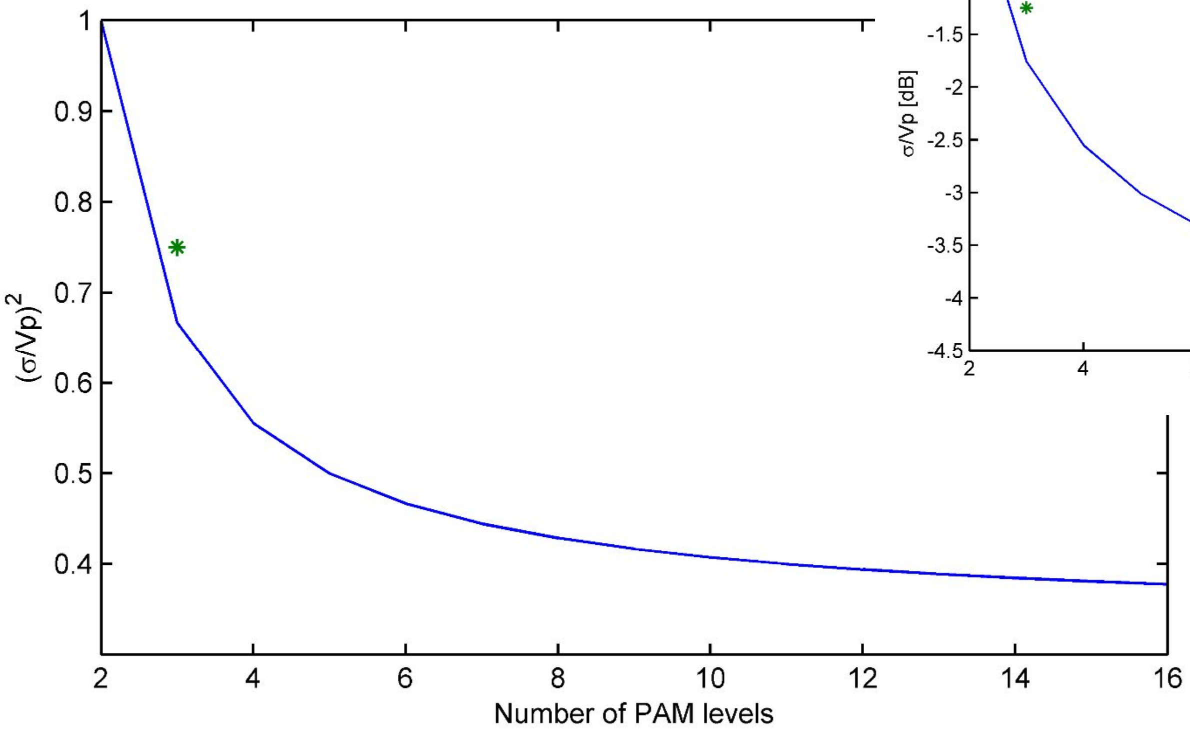
- DSP
- Line power
- Front-end power

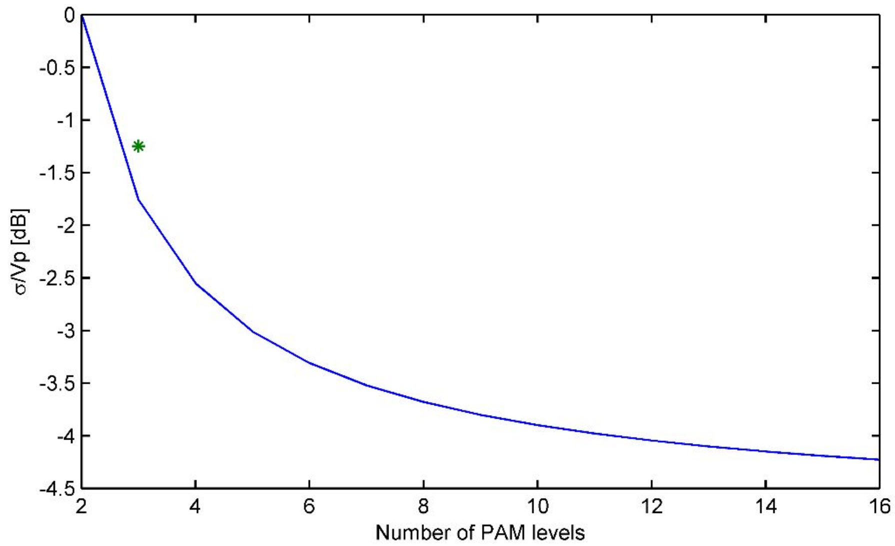
DSP impact

- 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 and PAM5
- Multiplication with {±1, ±3} adds complexity
  - PAM4
- Multiplication with {±1, ±3, ±5, ±7} adds more complexity
  - PAM8
- Lower baudrate eases timing closure
  - lower power
  - benefit of PAM3 over PAM2 (no multiplication downside)
  - benefit for PAM4 and PMA8 is lost by multiplication downside

Normalized PAM signal power

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





PAM5

- $b = {}^2\log(5) = 2.322 \rightarrow 2\frac{1}{4} < b < 2\frac{1}{3}$
- allows 9 bits mapped to 4 PAM5 symbols
  - 12.5% lower symbol rate than PAM4
  - allows to offset the coding overhead
  - implies complicated coding to realize this improvement
- However the 5th level can be used alternatively
  - use PAM5 to transmit 2-bits/symbol
  - apply a 2B1Q line code to improve signal properties
    - run length limit
    - running digital sum

PAM options: key metrics

PAM	Theory bits/sym	Actual bits/sym	$(\sigma/V_p)^2$	Baudrate [Gbaud] (2.5Gbps)	Baudrate [Gbaud] (10Gbps)
2	1.000	1	1	2.8125	11.25
3	1.585	1.5	0.75	1.875	7.5
4	2.000	2	0.556	1.40625	5.625
5	2.322	2.25	0.5	1.250	5
5	2.322	2 (2B1Q)	0.5	1.40625	5.625
6 (3x2)	2.585	2.5	0.467	1.125	4.5
8	3	3	0.429	0.9375	3.750

- Preliminarily assuming ~12.5% coding overhead
  – similar to 1000BASE-T1

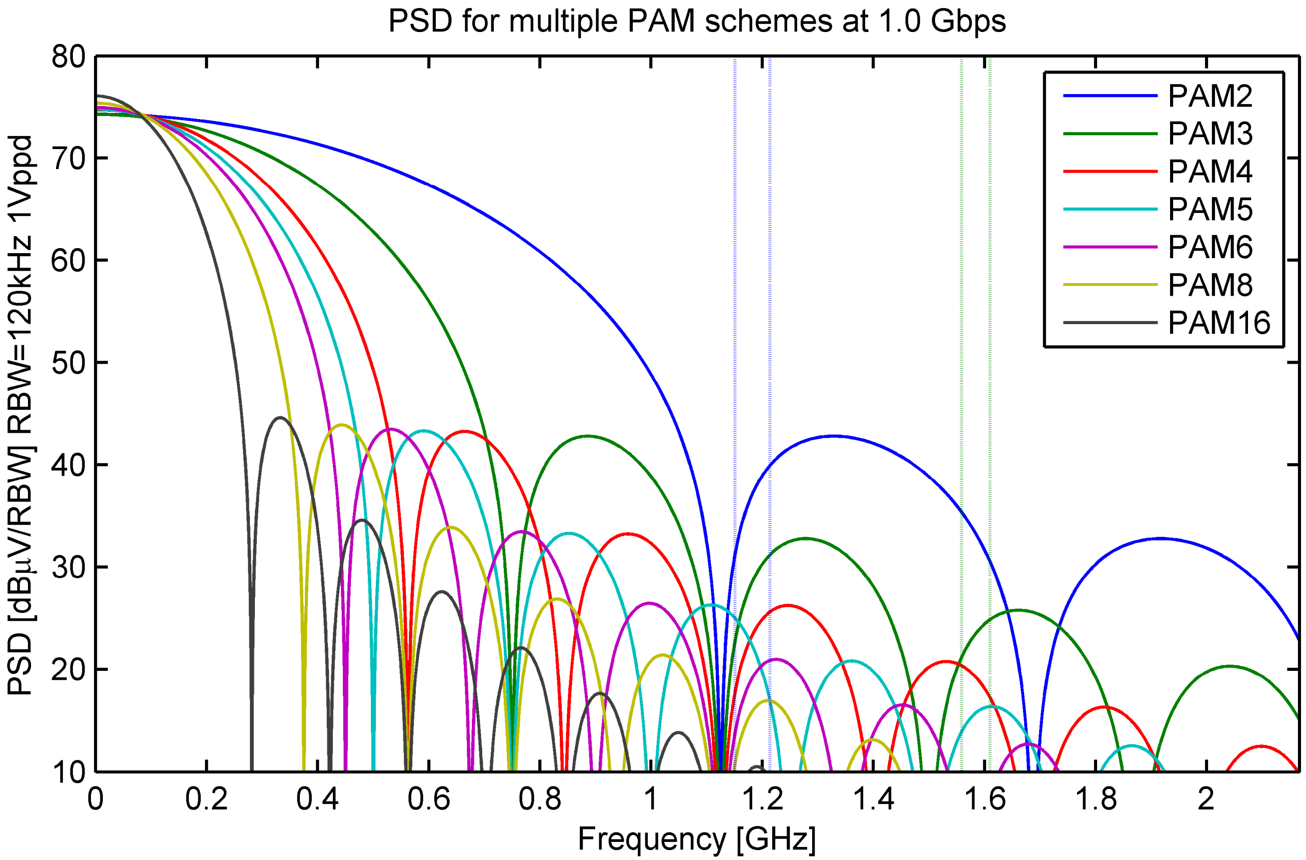
Front-end power considerations

- Prefer to keep transmit signal amplitude low (~1Vppd)
  - saving power
  - ease TX design challenges
  - allow lower supply level in future
- ADC power estimates based on FOM
  - Walden: $FOM_W = P/BW/2^{ENOB}$ → Energy/ConvStep
  - Schreier: $FOM_S = SNDR + {}^{10}\log(BW/P)$ → dB
  - Achievable FOM degrades for higher speeds
    - Implies a BW^2 P-dependency for f>100MHz
  - The first 8 bits up to a few hundred MHz are ‘cheap’
  - State-of-art high-speed ADC FOM@5GHz ~150dB and ~100fJ/conv
  - For 10Gbps PAM4/5 a 5.0-5.6Gsps ADC is needed
  - Channel loss ~30dB necessitate high resolution ADC
  - 10-bit <250mW → FOM_W~90fJ/conv
  - Pushing the envelope on ADC? Time to market? Power efficiency?

Emission considerations

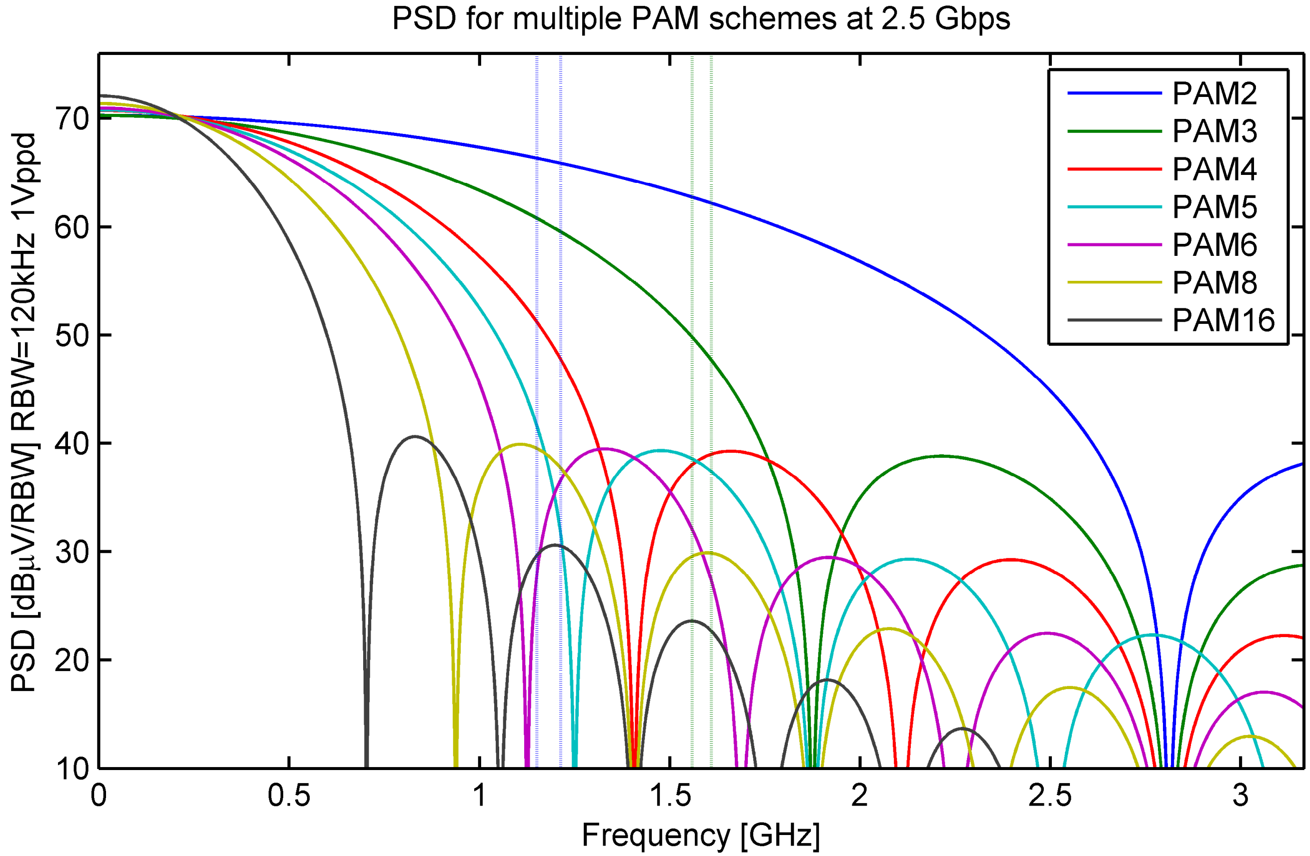
- Currently only cable mode-conversion considered
  – Implicitly an ideal transmit signal assumed
- Difficult to drive nice differential signals at high speed
- Benefit to avoid a high PSD in emission critical bands
  – GNSS: close to 1200MHz and 1600MHz
- Certainly avoid baudrate-harmonic spurs in GNSS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

1000BASE-T1



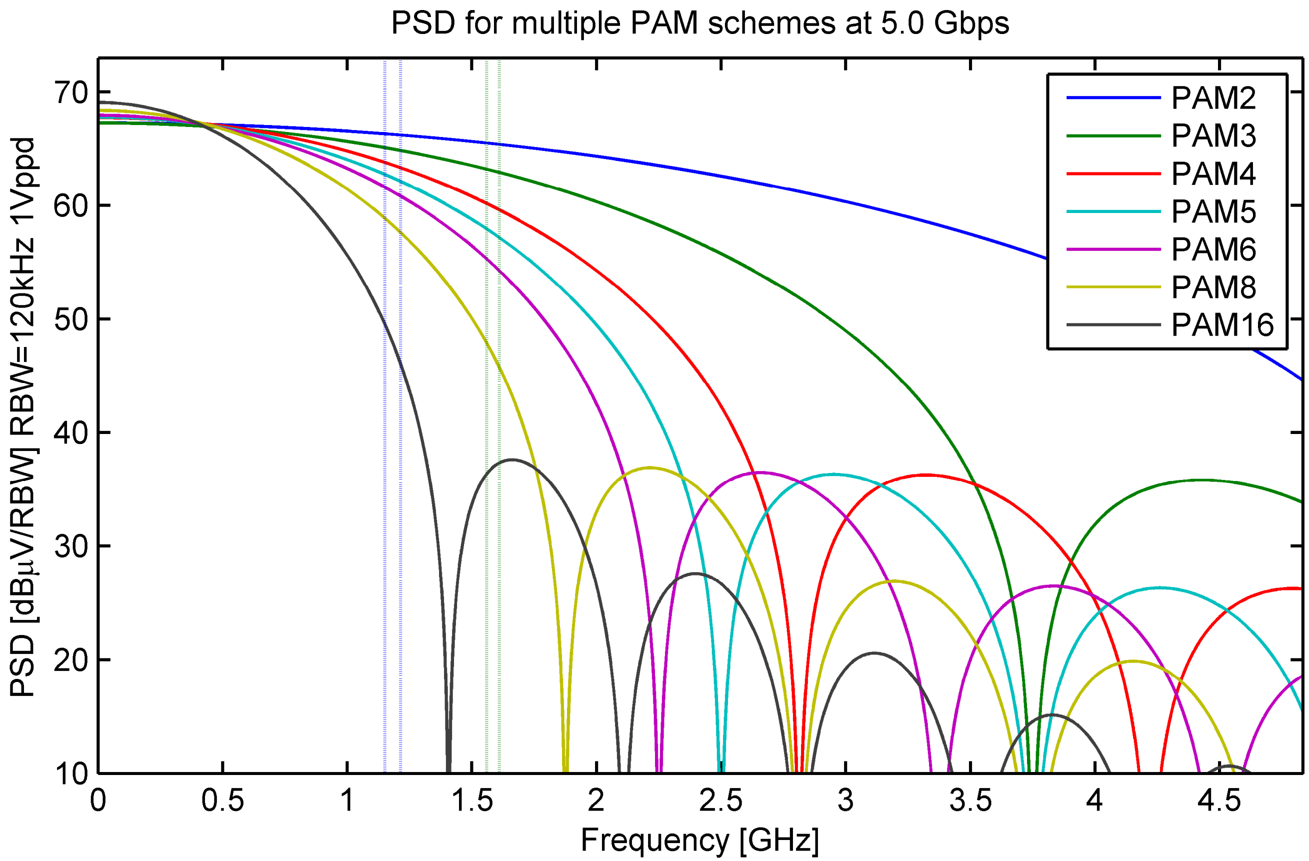
- For 1000BASE-T1 PAM2 would have been an option
  - but PAM3 was better there too for multiple reasons

2500BASE-T1



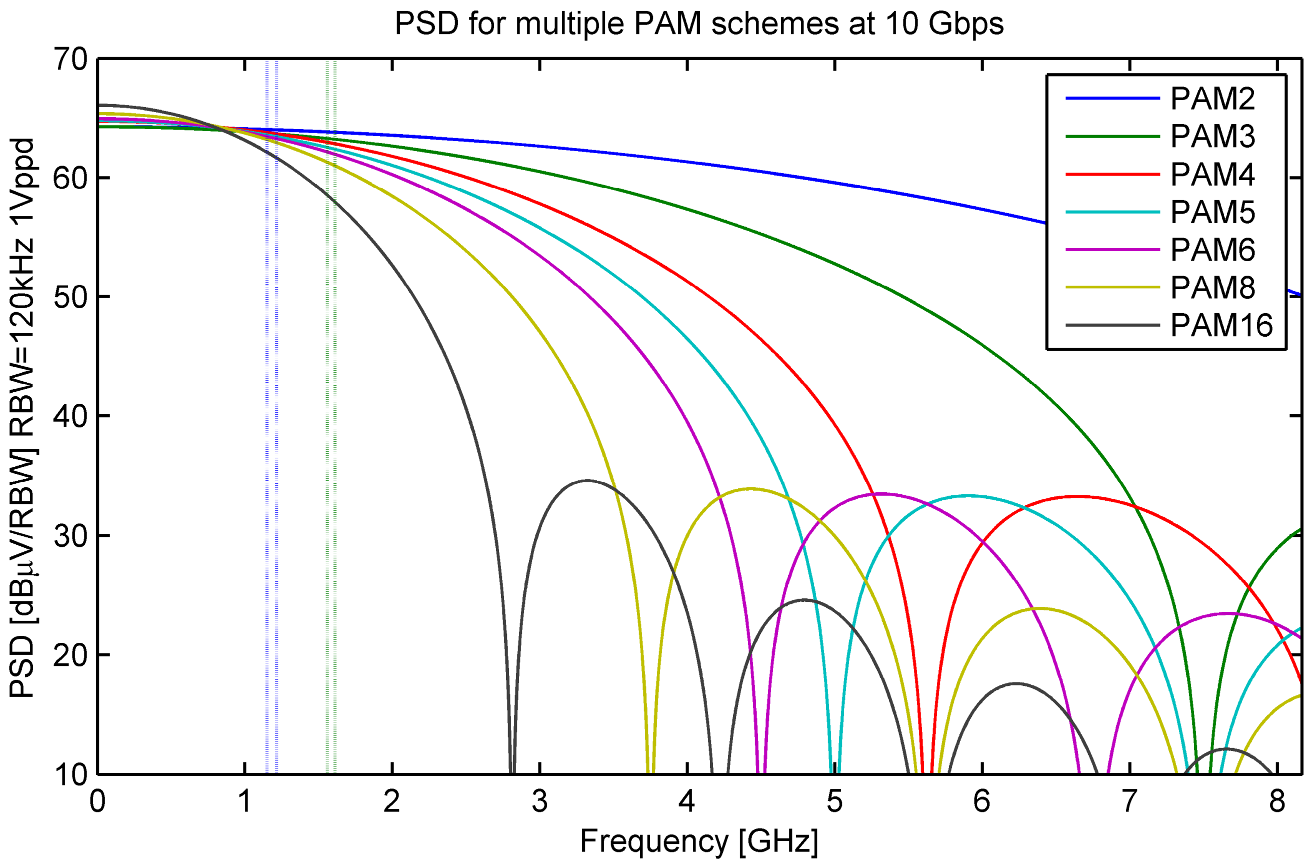
- PSD of PAM3 substantially lower in GNSS bands than PAM2
  - PAM4 even less, but that has other disadvantages
- PSD >1GHz can be further improved with some filtering

5GBASE-T1 (provisional)



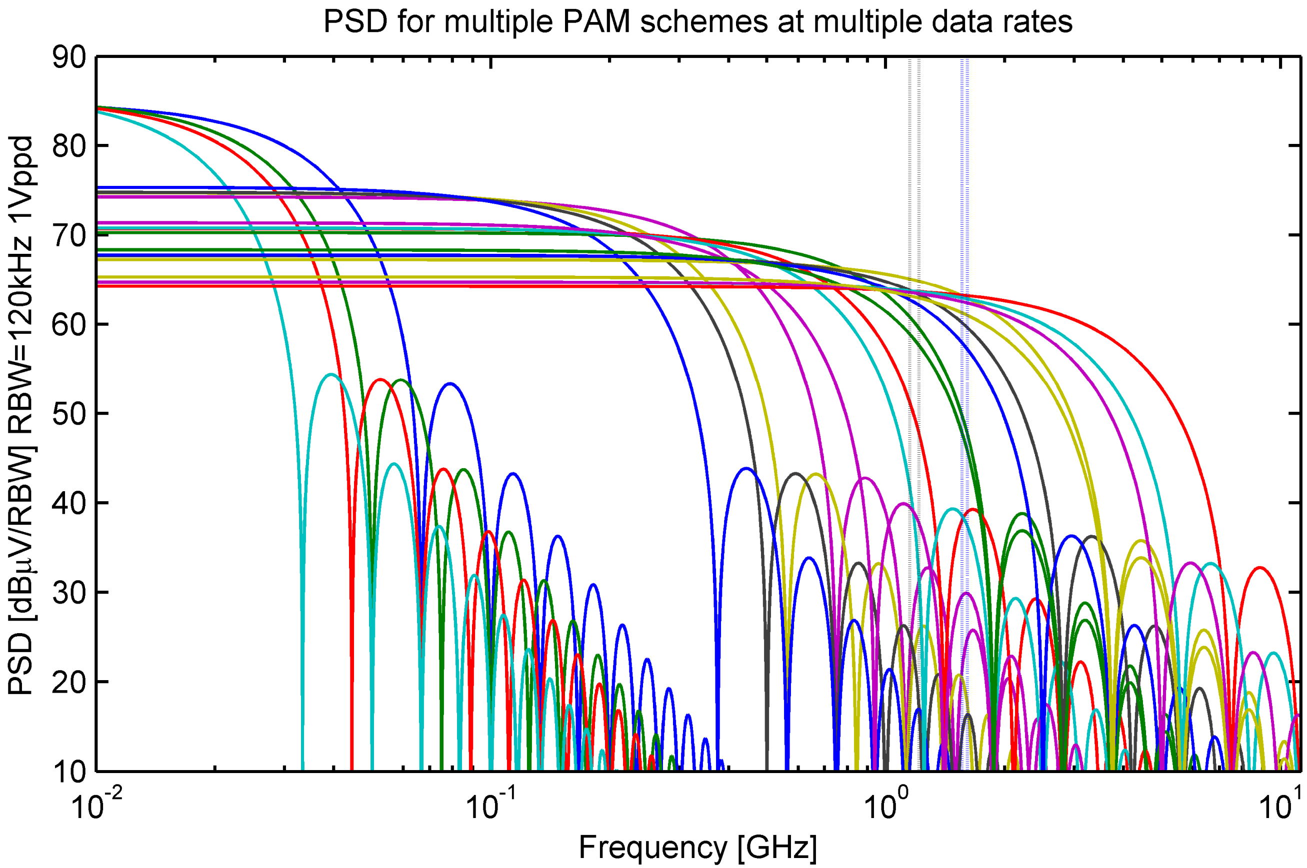
- PAM8/16 favorable regarding PSD in GNSS bands
  - PAM16 is not a serious candidate wrt interference tolerance

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

Summary: 2.5Gbps

PAM	2	3	4	5a	5b	8
Baudrate [Gbaud]	2.813	1.875	1.406	1.250	1.406	0.938
Nyquist BW [GHz]	1.406	0.938	0.703	0.625	0.703	0.469
100M/1G match	+	++	−−	+	+	−−
Line coding	−	+	−	+	+	−
Power efficiency	+	++	−	++	+	−−
Emission	−−	+	++	++	++	++
Nyquist loss [dB]	19.2	15.1	12.7	11.9	12.7	10.1
Ideal eye	1	0.5	0.33	0.25	0.25	0.14
SNR margin	++	++	+	+	+	o
Interference robust	+++	++	+	+	+	−−

- 12.5% coding overhead assumed
- Nyquist loss for defined baseline Insertion Loss
- PAM3 shows up as best option (PAM5 second best)

Summary: 10Gbps

PAM	2	3	4	5a	5b	6	8
Baudrate [Gbaud]	11.25	7.5	5.625	5	5.625	4.5	3.75
Nyquist BW [GHz]	5.625	3.75	2.813	2.5	2.813	2.25	1.875
100M/1G similarity	+	++	−−	+	+	−−	−−
Line coding	−	+	−	+	+	+	−
Power efficiency	−	o	+	+	+	o	o
Emission	−−	−−	−−	−−	−−	−	−
Nyquist loss [dB]	46.9	35.7	29.7	27.5	29.7	25.7	22.9
Ideal eye	1	0.5	0.33	0.25	0.25	0.20	0.14
SNR margin	−	+	+	+	+	o	−
Interference robust	+++	++	+	+	+	o	−−

- PAM4 and PAM5 come out best overall
  - PAM5
- All options have at least one downside

Compatibility table

100M/1G	2.5G	5/10G	Compatible
PAM3	PAM3	PAM5	☺
PAM3	PAM5	PAM5	☺
PAM3	PAM3	PAM4	😐
PAM3	PAM2	PAM4	☹
PAM3	PAM4	PAM4	☹
PAM3	PAM8	PAM5/8	☹

Conclusions

- For 2.5Gbps PAM3 is the winner (PAM5 second best)
  - easy backward compatibility with 1Gbps
  - excellent interference tolerance
  - less BW, less IL, lower clocks, and better emission wrt PAM2
  - lower power DSP
- For 10Gbps it's a trade-off
  - Choice depends on the factor that is given the highest priority
  - If SNR has priority PAM4 or PAM5 are the clear winners
  - For signaling and DSP perspective PAM5 has benefits over 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
- Efficient 2.5Gbps solution requires its <u>own</u> optimal choice