PHY Proposal for 10GBASE-T: Encoding, Mapping & Framing

George Zimmerman & Brett McClellan - SolarFlare Communications

Supporters:

Rick Rabinovich, Spirent
Michael Laudon, Force 10 Networks
Mike Bennett, Lawrence Berkeley National Laboratory
Paul Kish - Nordx/CDT
Shadi AbuGhazaleh-Hubbell Premise Wiring
Sterling Vaden- Superior Modular Products
Bernie Hammond - Krone

Outline

- Basic Formula
- Why PAM-10?
- 4D 8 State PAM-10 TCM
- Mapping
- Scrambler
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- Conclusion

Line Coding: Basic Formula

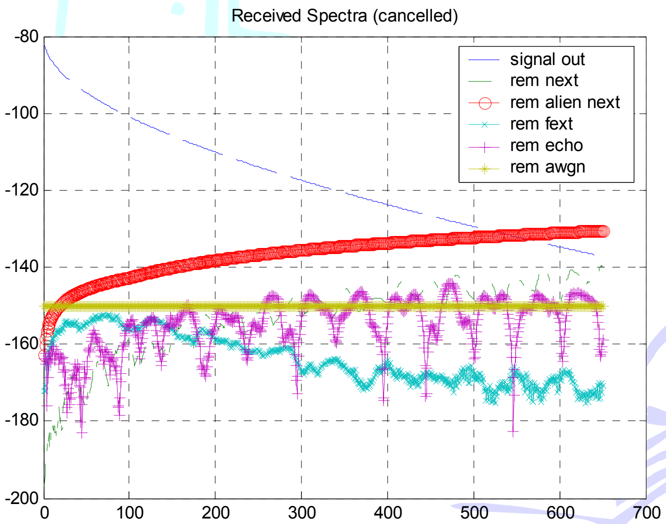
- Start with 1000BASE-T
- Take away half duplex / carrier sense
- Support 10Gbps Data Rate: Optimize baud rate for line
  - 8 bits / baud -> 12-bits / baud
  - PAM5 @ 125Mbaud -> PAM10 @ 833.33 Mbaud
- 4D 8-state TCM
  - Same scrambler as 1000BASE-T
  - Same encoder as 1000BASE-T
    - Take away the “packetized” TCM
      - No convolutional reset or mode switching
  - Same 4D mapping technique as 1000BASE-T
- Support 802.3 Clause 46
  - XGMII Frame Structure and Control

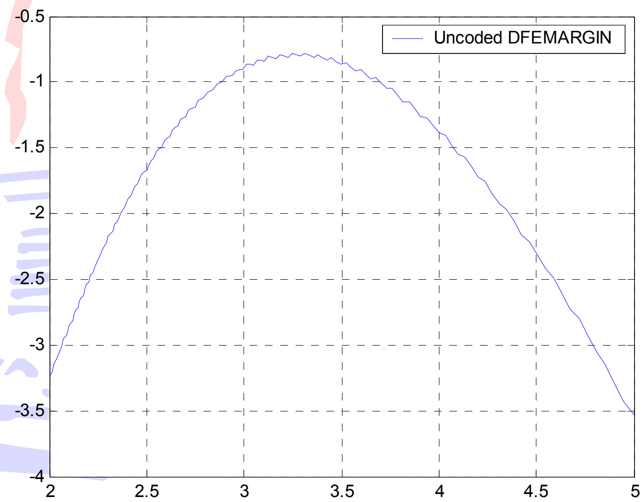
Why PAM10?

- Based on calculations from the channel impairments, the maximum channel capacity is achieved with a baud rate of around 800MHz.
- Minimal data framing complexity with byte oriented modulation
  - 2 byte/baud -> 625 Mbaud (1 dB equalization loss)
  - 1 bytes/baud -> 1.25 Gbaud (2.5-2.9 dB loss)
- 1.5 byte/baud -> 833.33 Mbaud
  - Hits the channel capacity sweet spot
  - Minimal additional framing complexity
- 4D PAM10 for Trellis Coded Modulation
  - Additional 2 levels per pair provide redundancy for FEC

Why PAM-10?: Optimal Baud Rate

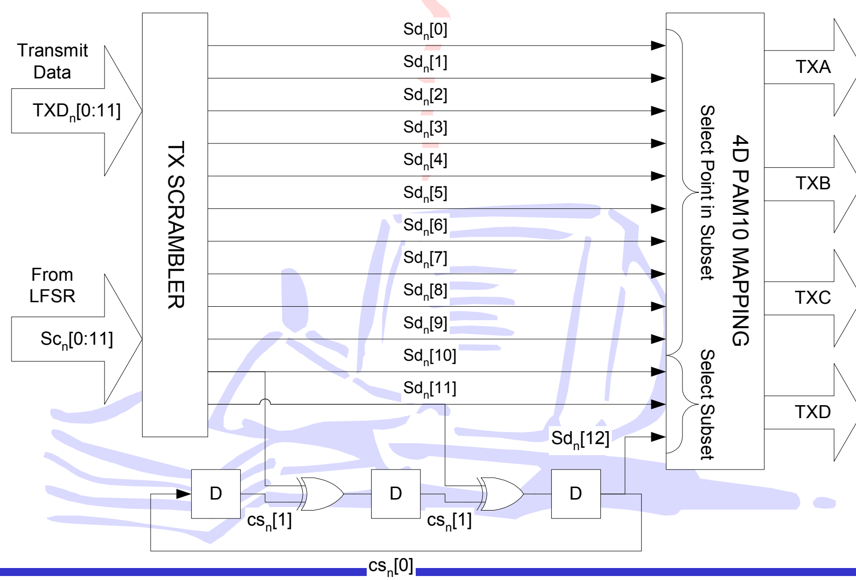
- **Solarsep7a_varlen simulations: Model 1**
  - **No ANEXT Canc., 100m Cat7 IL, Baseline ANEXT (62.5 dB at 100 MHz, split slope), Default Cancellation parameters**
- **833 Mbaud = 3 bits/baud SNR = 29.4 dB**
- **Margin peak = 770 Mbaud, 0.12 dB better margin**





4D 8-State PAM10 TCM

- **4D 8-state Ungerboeck code from 1000BASE-T**
  - **12-bits -> 13 bits per baud**
- **Continuous Trellis Coding**
  - **Encoder runs on a continuous basis**
  - **No need to switch modes between Data and Idle**
  - **Idle and Control symbols are covered by TCM**



4D PAM10 Mapping

- PAM10
  - { -9 -7 -5 -3 -1 +1 +3 +5 +7 +9 }
- 13-bits / baud
  - 2^13 = 8192 data symbols
  - 4D PAM10 has 10,000 constellation points
  - Remaining 1808 points are used for constellation shaping and control symbol mapping
- Constellation shaping
  - Eliminate any 4D points with two or more +/- 9's
  - 0.64 dB of shaping gain

1D PAM Level Rate of Occurrence in the 4D Mapping (8192 points)

-9	-7	-5	-3	-1	+1	+3	+5	+7	+9
512	896	896	896	896	896	896	896	896	512

4D PAM10 Data Symbol Mapping

- Parity + 2 MSB's (Sd_n12:10) select 1 of 8 subsets
- 10 LSB's select a point within the subset
  - Sd_n9 selects normal mapping or ESC code (+/- 9)
  - Sd_n8 selects X or Y primary subset
  - Sd_n7:0 selects a point within the subset
    - when Sd_n9 ==1, Sd_n7:6 selects on which pair the ESC code is transmitted
- Balanced constellation
  - No polarity scrambler is required
    - Remaining 4 LFSR outputs are used to scramble the 4 additional data bits

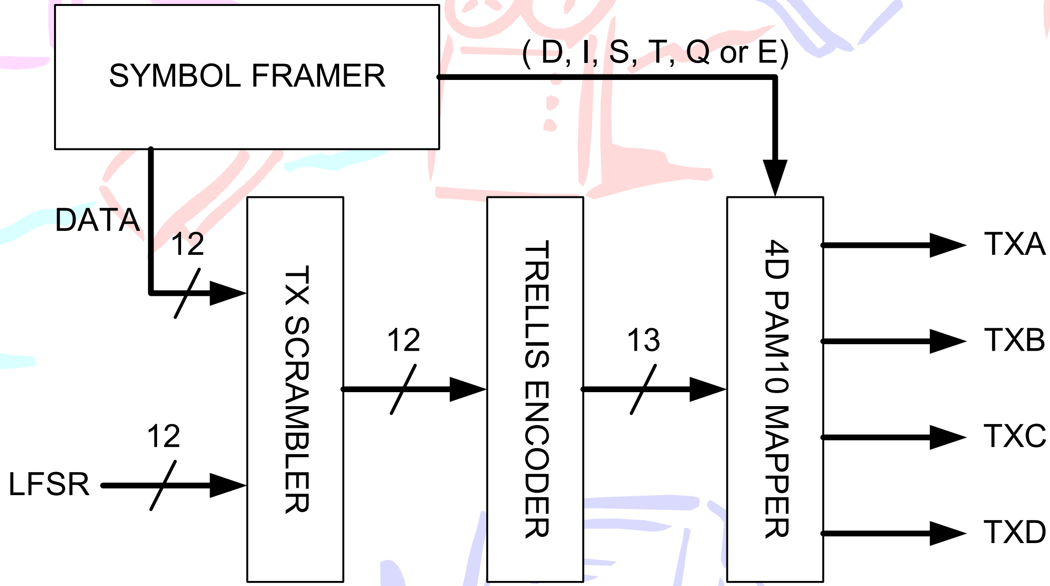
4D PAM10 Partitioning

Pair B \ Pair A	-9	-7	-5	-3	-1	+1	+3	+5	+7	+9
+9		YY	XY	YY	XY	YY	XY	YY	XY	
+7	XX	YX	XX	YX	XX	YX	XX	YX	XX	YX
+5	XY	YY	XY	YY	XY	YY	XY	YY	XY	YY
+3	XX	YX	XX	YX	XX	YX	XX	YX	XX	YX
+1	XY	YY	XY	YY	XY	YY	XY	YY	XY	YY
-1	XX	YX	XX	YX	XX	YX	XX	YX	XX	YX
-3	XY	YY	XY	YY	XY	YY	XY	YY	XY	YY
-5	XX	YX	XX	YX	XX	YX	XX	YX	XX	YX
-7	XY	YY	XY	YY	XY	YY	XY	YY	XY	YY
-9		YX	XX	YX	XX	YX	XX	YX	XX	

2D Constellation Points of 4D PAM10 Mapping

Control Symbol Mapping cont.

- **Symbol Framer determines control symbol mapping**



Control Symbol Mapping

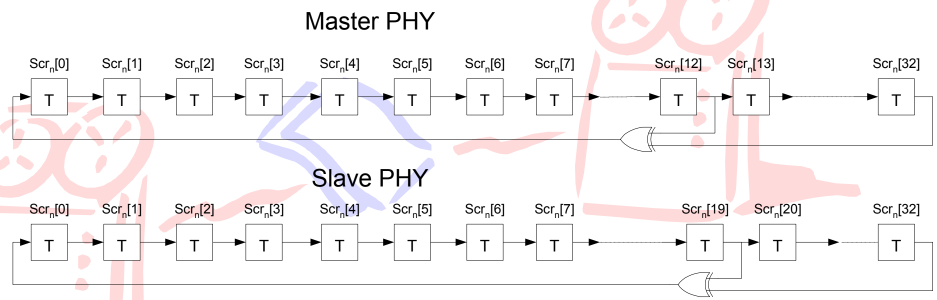
- Map control characters into unused constellation
  - Map to 4D PAM10 symbols containing two +/- 9’s
  - 4D Symbols fall within the subset selected by encoder
  - Symbols are DC balanced
  - Examples:

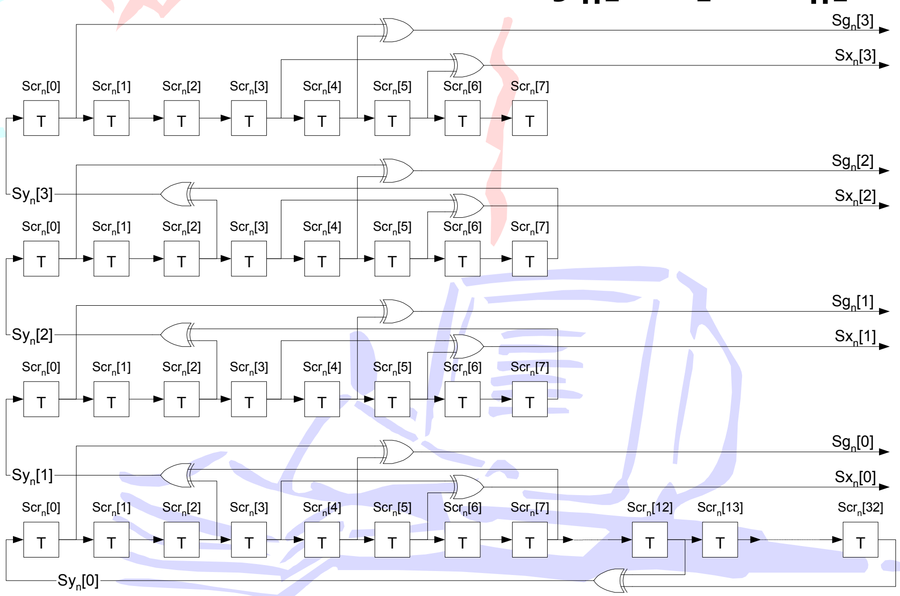
	TXA	TXB	TXC	TXD
START	+/- 5	+/- 9	+/- 5	+/- 9
TERMINATE	+/- 9	+/- 9	+/- 7	+/- 7
ERROR	+/- 1	+/- 1	+/- 9	+/- 9
Q	+/- 1	+/- 9	+/- 1	+/- 9
IDLE*	+/- 9	+/- 9	+/- 3	+/- 3

- Infrequent nature of control symbols allows shaping gain to be maintained

Side Stream Scrambler

- From 1000BASE-T
  - Master TX polynomial
    - $G_M(x) = 1 + x^{13} + x^{33}$
  - Slave TX polynomial
    - $G_M(x) = 1 + x^{20} + x^{33}$
  - 12 scrambler bit streams: $Sy_n[3:0]$, $Sx_n[3:0]$, $Sg_n[3:0]$

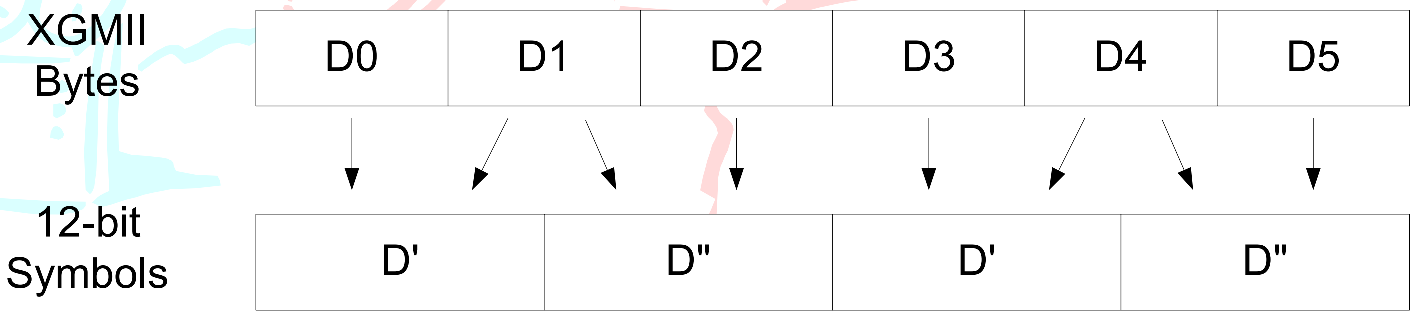




1000BASE-T Scrambler

Data Framing

- **Data bytes are taken in groups of six and parsed into 4 12-bit symbols**
  - **Every third byte is split in half**



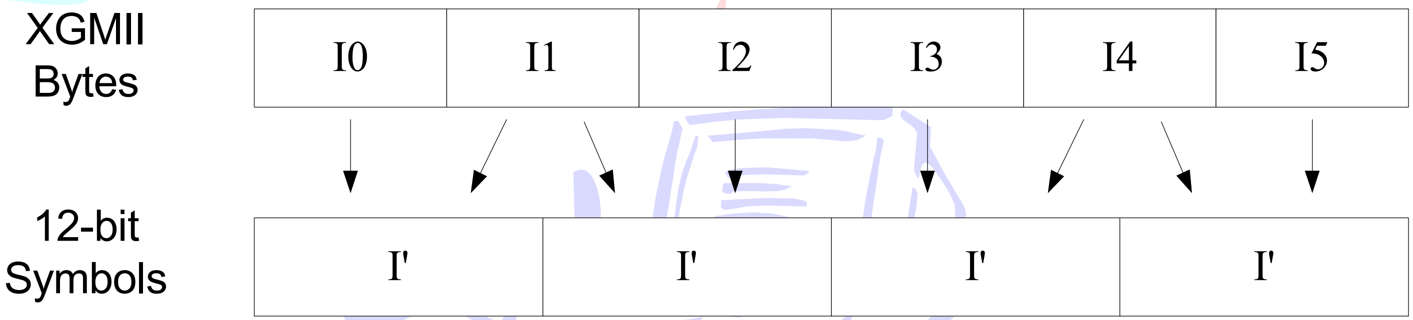
Data Framing cont.

- **Three XGMII transfers per two framing blocks**

	n	n+1	n+2
Lane 0	D0	D4	D2
Lane 1	D1	D5	D3
Lane 2	D2	D0	D4
Lane 3	D3	D1	D5

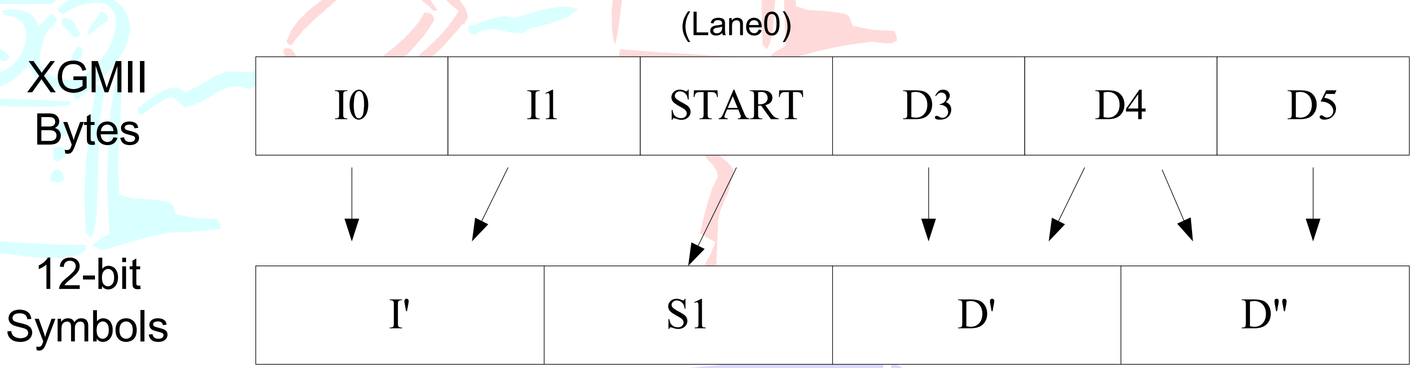
IDLE

- **XGMII IDLE bytes are replaced with 4D PAM10 trellis coded Idle symbols**
  - **Idle is differentiated from data by using double ESC symbols**
  - ***Average TX power is maintained by mixing in non-ESC symbols**



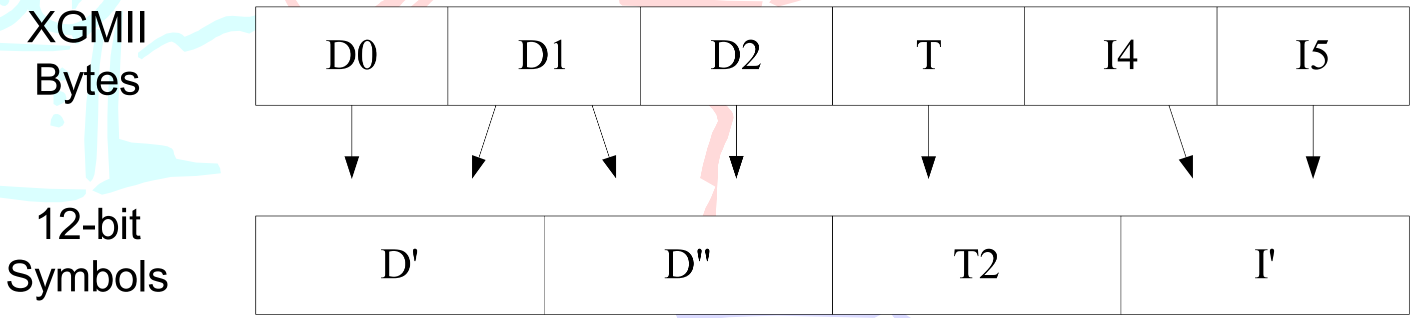
START

- **START (Start of Frame) moves into the prior/current symbol in the IPG**
  - **Data bytes are left unaffected**



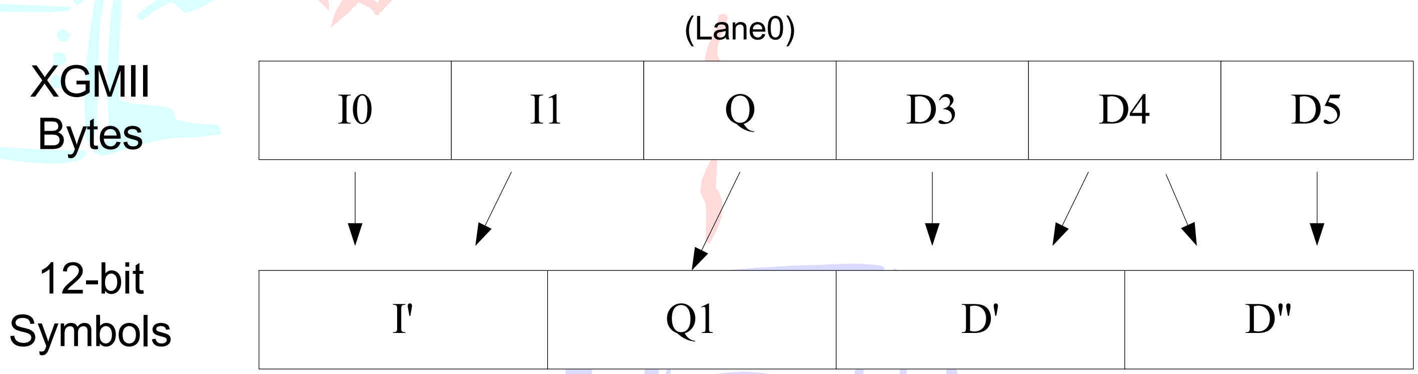
TERMINATE

- **TERMINATE (End of Frame) moves into the next/current symbol in the IPG**
  - **Data bytes are left unaffected**

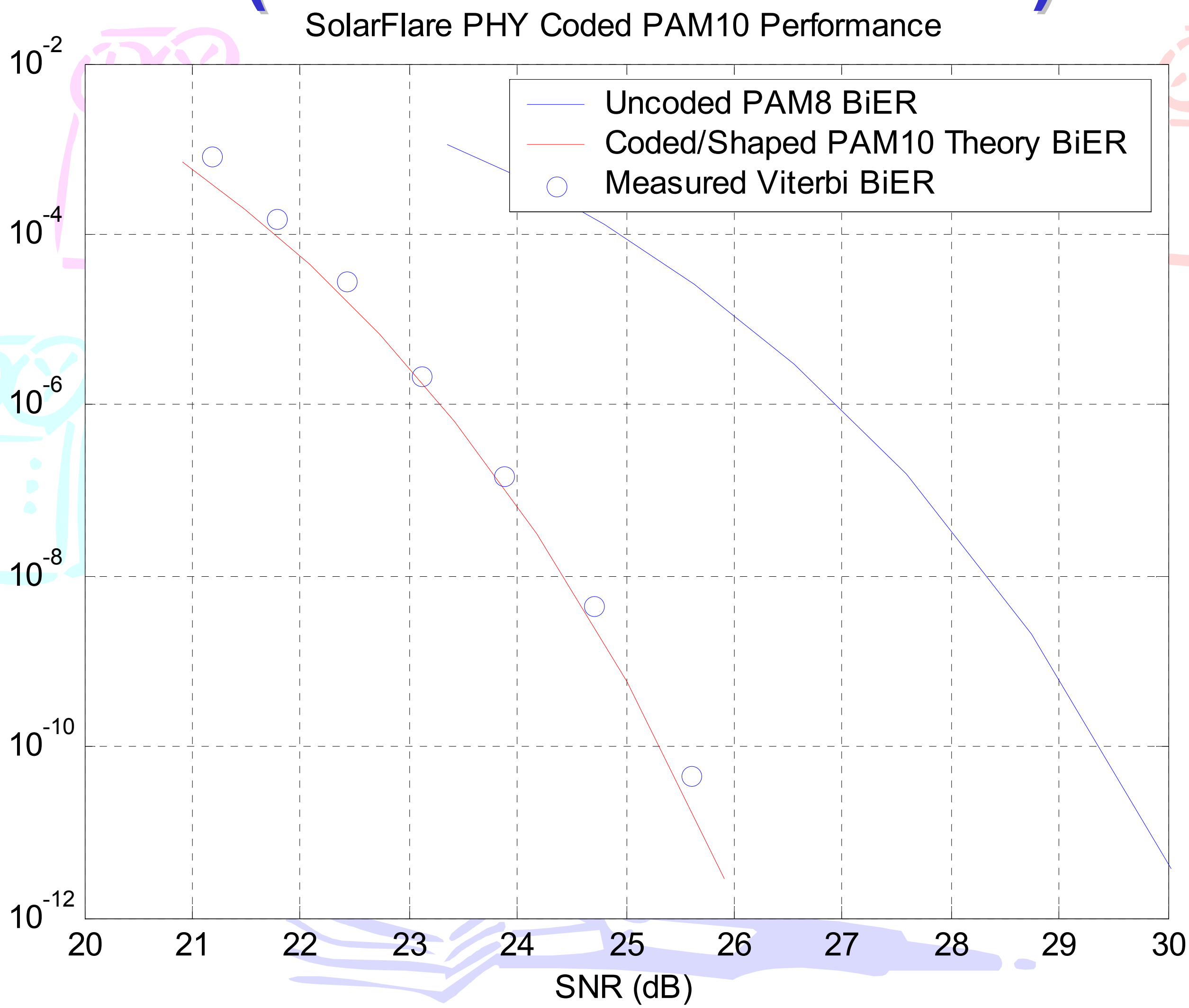


Ordered Sets

- **Q (Sequence) symbol moves into the prior/current symbol in the Idle stream**
  - **Data bytes are left unaffected**



4D 8-State PAM10 Performance (Simulations: AWGN)



Relative Complexity Estimates

- Baseline Complexity: 4.7M gate equivalents 90nm
  - Based on existing (.13u), proven hardware design for 10GBASE-T on existing Cat6 for this proposal
    - Includes complexity for impairments from cabling configurations in the real world, but not in standards environments
    - Includes several complexity reductions for signal processing elements (estimated 6X reduction)
- Competitive Complexity:
  - Cancellers & equalizers:
    - Scale linearly with baud rate (optimistic), pessimistic would scale as the square of baud rate
    - Scale linearly with data word length – optimistic "effective symbol" scaling (+2 bits) assumed for TH precoding, proposal would scale as output symbol (+6 bits)
  - Coding: LDPC estimates from seki_1_0304, slide 4 (2-3M gates); RS complexity from Ungerboeck verbal (500k gates)

Performance Comparisons, Model 1

- **No ANEXT Cancellation, 100m Cat7 IL, Baseline ANEXT (62.5 dB at 100 MHz, split slope), Default Cancellation parameters**

Uncoded DFE Margin Peak	**-0.78**	**dB**	**770**	**MHz**					
Proposal	**1e-12 SNR reqd**	**Bits/ sym/ pair**	**Ovrhd for Ctl**	**Baud Rate (MHz)**	**Opt DFE SNR at rate**	**Margin**	**dB from max**	**dB from DFE peak**	**Relative Complexity**
SF 4D-4W TCM PAM10	26.2	3	0.00%	833	29.36	3.16	-3.31	-0.12	1.000
Keyeye PAM-4	24	2	3.13%	1289	20.15	-3.85	-10.3	-3.1	0.773
Rao_Nov2003	19.9	2.683	7.30%	1000	25.52	5.62	-0.85	-2.01	1.875
Rao_Mar2004	19.9	2.683	3.13%	961	26.37	6.47	0	-1.16	1.817
Ter. 12-PAM (2048,1723)	23.8	3.182	5.00%	825	29.58	5.78	-0.69	-1.01	1.860
Ter. 12-PAM (1024,781)	22.8	3.029	3.00%	850	28.95	6.15	-0.32	-0.71	1.905
Powell 4DTCM+RS(2.66b/syn	21.4	2.66	3.13%	969	26.2	4.8	-1.67	-1.19	1.807
Ung. 4DTCM+RS(2.5775b/s)	19.9	2.578	3.13%	1000	25.52	5.62	-0.85	-1.36	1.863
Plato PAM-5	20.5	2	0.00%	1250	20.8	0.3	-6.17	-2.45	1.125

Performance Comparisons, Model 3

- **No ANEXT Cancellation, 100m Cat6 IL, Baseline ANEXT (64.5 dB at 100 MHz, split slope), Default Cancellation parameters**

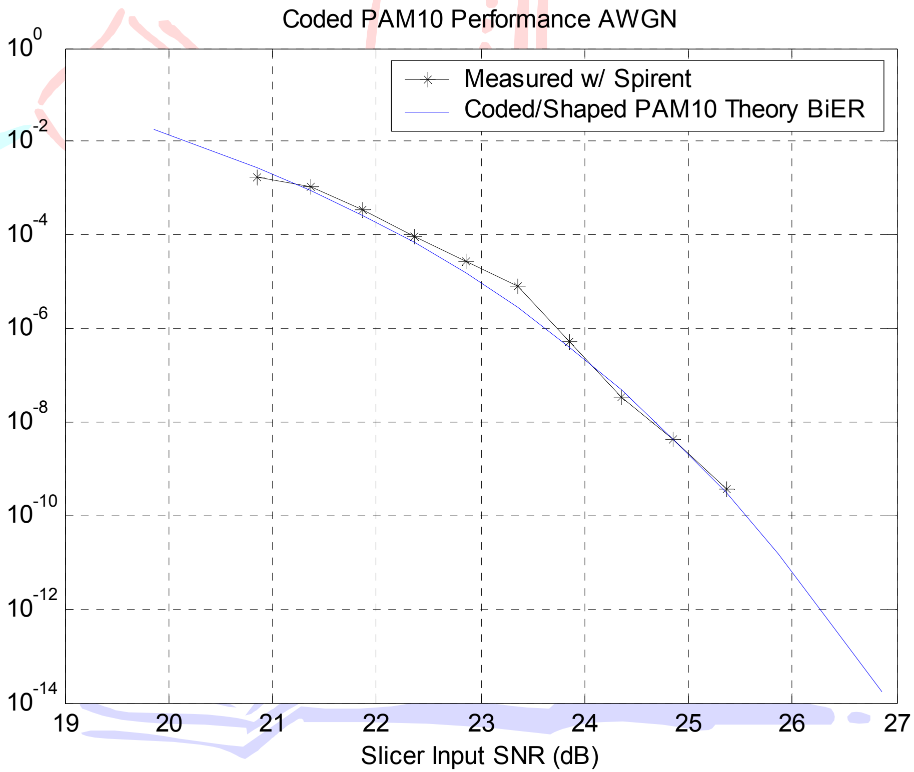
Standards Code Performance Summary									
Max Margin	**6.07**	**dB**							
Uncoded DFE Margin Peak	**-0.87**	**dB**	**740**	**MHz**					
Proposal	**1e-12 SNR_req**	**Bits/sym/pair**	**Ovrhd for Ctl**	**Baud Rate (MHz)**	**Opt DFE SNR at rate**	**dB Margin**	**dB from max**	**dB from DFE peak**	**Relative Complexity**
SF 4D-4W TCM PAM10	26.2	3	0.00%	833	29.13	2.96	-3.11	-0.2	1.000
Keyeye PAM-4	24.0	2	3.13%	1289	19.67	-4.33	-10.4	-3.3	0.770
Rao_Nov2003	19.9	2.68	7.30%	1000	25.07	5.17	-0.9	-1.22	1.870
Rao_Mar2004	19.9	2.68	3.13%	961	25.97	6.07	0	-0.92	1.820
Ter. 12-PAM (2048,1723)	23.8	3.18	5.00%	825	29.36	5.56	-0.51	-0.18	1.860
Ter. 12-PAM (1024,781)	22.8	3.03	3.00%	850	28.7	5.9	-0.17	-0.3	1.910
Powell 4DTCM+RS(2.66b/syr	21.4	2.66	3.13%	969	25.79	4.39	-1.68	-1	1.810

PHY Parameter Highlights

- ADC: 10 bits, 9 ENOB
- DAC: 10 bits, 9 ENOB
- Jitter: 4 psec RMS
- TX Power: 6 dBm (2.5-3Vpp for PAM-10, depends on measurement point)
- TX PSD: -80 dBm/Hz peak, with PAM spectrum
- Intrinsic latency: < 20 nsec
- TX equalization: none
- Margins w/noise, impairments & limits
  - Models 1,2,3 2.6, 2.9, 2.1 dB
- Power estimate (90nm): 8.1W

Measured Performance

- Laboratory IC transceiver results on Cat5e cabling
- Includes Jitter, A/D, EMI Ingress, and additive noise source



Conclusion

- PAM-10 833 Mbaud line coding proposal is based on proven 1000BASE-T technology with extensions to meet performance goals
- PAM-10 833 Mbaud 3 bits/baud proposal will meet the reach requirements
- PAM-10 833 Mbaud 3 bits/baud proposal balances complexity with performance
- PAM-10 833 Mbaud 3 bits/baud proposal has intrinsic latency to scale to meet future needs
- PAM-10 833 Mbaud 3 bits/baud proposal is the only complete solution to date with complexity proven in hardware

Motions

- Motion #1: Move that the 802.3an Task Force adopt a 10-level pulse amplitude modulation (PAM10) with a symbol rate of 833 Mbaud for D1.0 of Clause 55 as presented in (mcclellan_1_0504.pdf).
  - Moved By:
  - Seconded By:
  - Yes: No: Abstain:
- Motion #2: Move that the 802.3an Task Force adopt the 4D 8-State PAM10 TCM and 4D PAM10 Mapping for D1.0 of Clause 55 as presented in (mcclellan_1_0504.pdf).
  - Moved By:
  - Seconded By:
  - Yes: No: Abstain:
- Motion #3: Move that the 802.3an Task Force adopt the XGMII Frame Structure and Control for D1.0 of Clause 55 as presented in (mcclellan_1_0504.pdf).
  - Moved By:
  - Seconded By:
  - Yes: No: Abstain:

Backup

4D PAM10 Partitioning

- 1D values:{ -9, -7, -5, -3, -1, +1, +3, +5, +7, +9 }
- This set can be split into two subsets:

  X = { -9, -5, -1, +3, +7 }

  Y = { -7, -3, +1, +5, +9 }
- 2D 10X10 constellation:

  { (-9,-9), (-9,-7), ………, (+9,+7), (+9,+9) }
- We can divide this constellation into 4 subsets:

  XX = { (-9,-9), (-9,-5), ……, (+7,+3), (+7,+7) }

  XY = { (-9,-7), (-9,-3), ……, (+7,+5), (+7,+9) }

  YX = { (-7,-9), (-7,-5), ……, (+9,+3), (+9,+7) }

  YY = { (-7,-7), (-7,-3), ……, (+9,+5), (+9,+9) }

4D PAM10 Partitioning cont.

- **4D 10X10X10X10 constellation:**

  { (-9,-9,-9,-9), (-9,-9,-9,-7), …, (+9,+9,+9,+7), (+9,+9,+9,+9) }

- **We can divide this constellation into 16 subsets:**

  XXXX = { (-9,-9,-9,-9), (-9,-9,-9,-5), ……, (+7,+7,+7,+3), (+7,+7,+7,+7) }

  XXXY = { (-9,-9,-9,-7), (-9,-9,-9,-3), ……, (+7,+7,+7,+5), (+7,+7,+7,+9) }

  …..

  YYYX = { (-7,-7,-7,-9), (-7,-7,-7,-5), ……, (+9,+9,+9,+3), (+9,+9,+9,+7) }

  YYYY = { (-7,-7,-7,-7), (-7,-7,-7,-3), ……, (+9,+9,+9,+5), (+9,+9,+9,+9) }

- **While the minimum distance between the points in the original 10X10X10X10 constellation was dmin=2, the distance between points within any of the sixteen subsets is dmin = 4.**

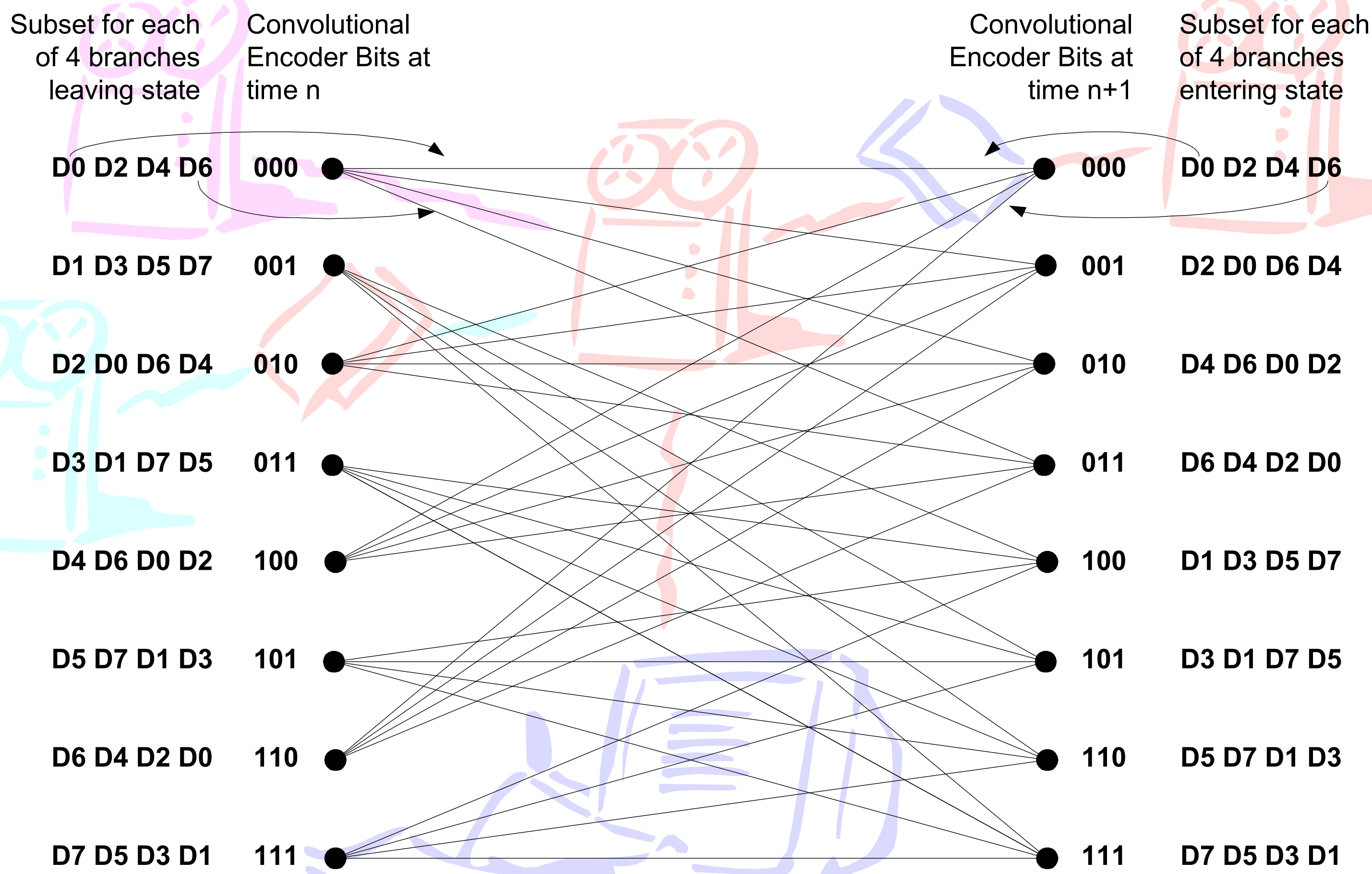
4D PAM10 Partitioning cont.

- For the 4D 8-state trellis code we need only 8 sublattices. Therefore, we combine pairs of the subsets shown above to get 8 subsets, D0 to D7:

D0 = XXXX + YYYY	D4 = XYYX + YXXY
D1 = XXXY + YYYX	D5 = XYYY + YXXX
D2 = XXYY + YYXX	D6 = XYXY + YXYX
D3 = XXYX + YYXY	D7 = XYXX + YXYY

- Each subset contains 1250 points and with this grouping the minimum distance between points within any subset is still dmin = 4.

4D 8-State TCM w/ Partitioning



Trellis Diagram for 4D 8-State Trellis Code