448G Modulation Proposal

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Overview

- **Motivation**
- **PAM4m5 Modulation**
- **Alphabet Construction**
- **448G PAM6m8**
- **Summary**

Motivation

- **Channel loss for 448G channels over copper is challenging**

- **PAM6 at Nyquist=89.6 GHz and PAM8 at Nyquist=74.66 GHz are best current candidates**
  - Even here the proposed channels have difficult insertion loss

- **Maintain the following**
  - Continue using the standard Differential Pair wiring
  - No additional throughput loss (target 448G operation)
  - No changes to clocking or clock rates
  - Maintain current TX and RX architectures
    - DAC based TX
    - AFE + ADC + DSP based receiver

- **Add a Soft FEC as another DSP option**
  - DFE or MLSE or Soft FEC

Motivation: Soft FEC

- **Entangle the DFE channel with a Soft FEC**

- **Target to reduce the Pre-KP FEC Symbol Error Rate (SER) by 2 or more decades**

- **Latency Target**
  - KP FEC is 5440 bits + t15 RS Decoding
  - Previous discussions permitted 2x and even 4x interleaving of KP FEC
  - Set soft FEC target latency at (0.25 to 1.0) x 5440 bits

- **Gates are efficient**
  - 3 nm or lower geometry
  - Gates/unit area continues to scale favorably
  - Try not to use SRAM as this does not scale well

- **Cooperates well with following KP FEC**

- **Follow Receiver Progression**
  - Analog Sampler Based DFE → ADC+DSP → ADC+DSP+SoftFEC

PAM4m5 Modulation

- **PAMXmY Modulation**
  - X represents the Baud rate PAM levels
  - Y represents the actual levels used
  - Baud rate is determined by PAM4 modulation with additional levels from PAM5 used by FEC
- **Signal Levels**
  - PAM4 {-3,-1,+1,+3}
  - PAM5 {-2,-1,0,+1,+2}
    - Power needs to be scaled appropriately so that average TX power matches PAM4
    - For discussion we keep these levels
- **Combine multiple PAM5 symbols to give us extra bit(s) for use by FEC**
  - 4 Symbols together provide 9 bits of information
    - 4 Symbols of PAM5 gives 625 possibilities
    - Use 512 of them to give us 9 bits of information
  - The extra bit can be used by a FEC (8/9 code rate)

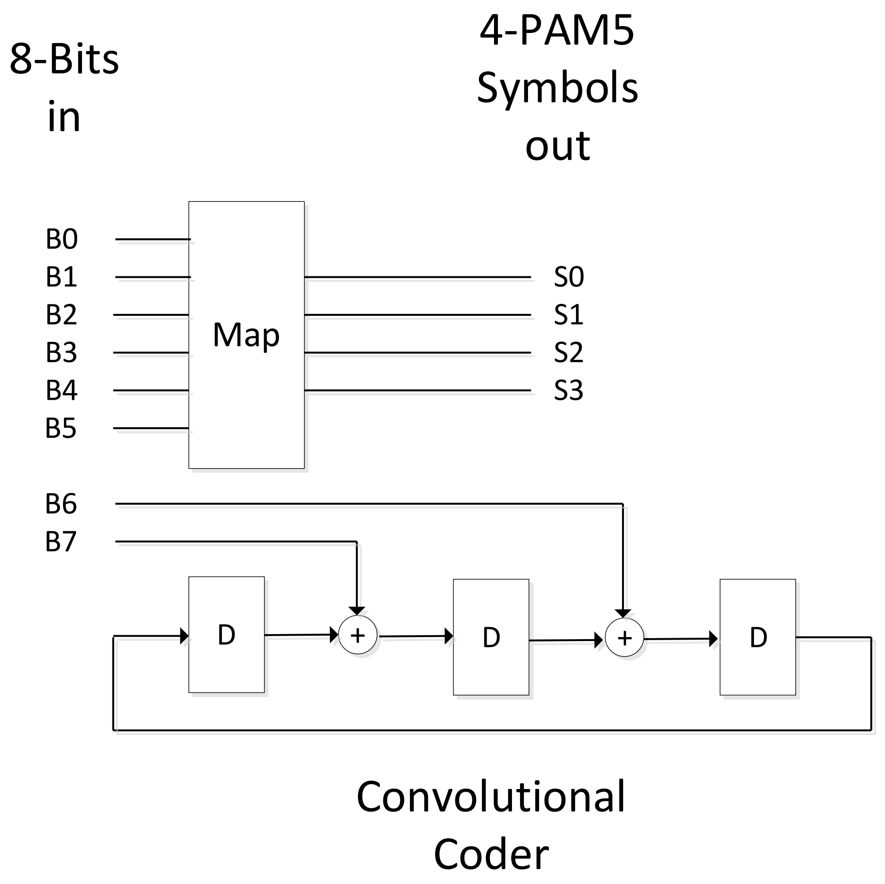
PAM4m5 Convolutional Coding (CC)

- **8-bits of information to generate 4 PAM5 symbols**

- **2-bits to drive an encoding state**
- **6-bits to drive the mapping of the PAM5 signals**

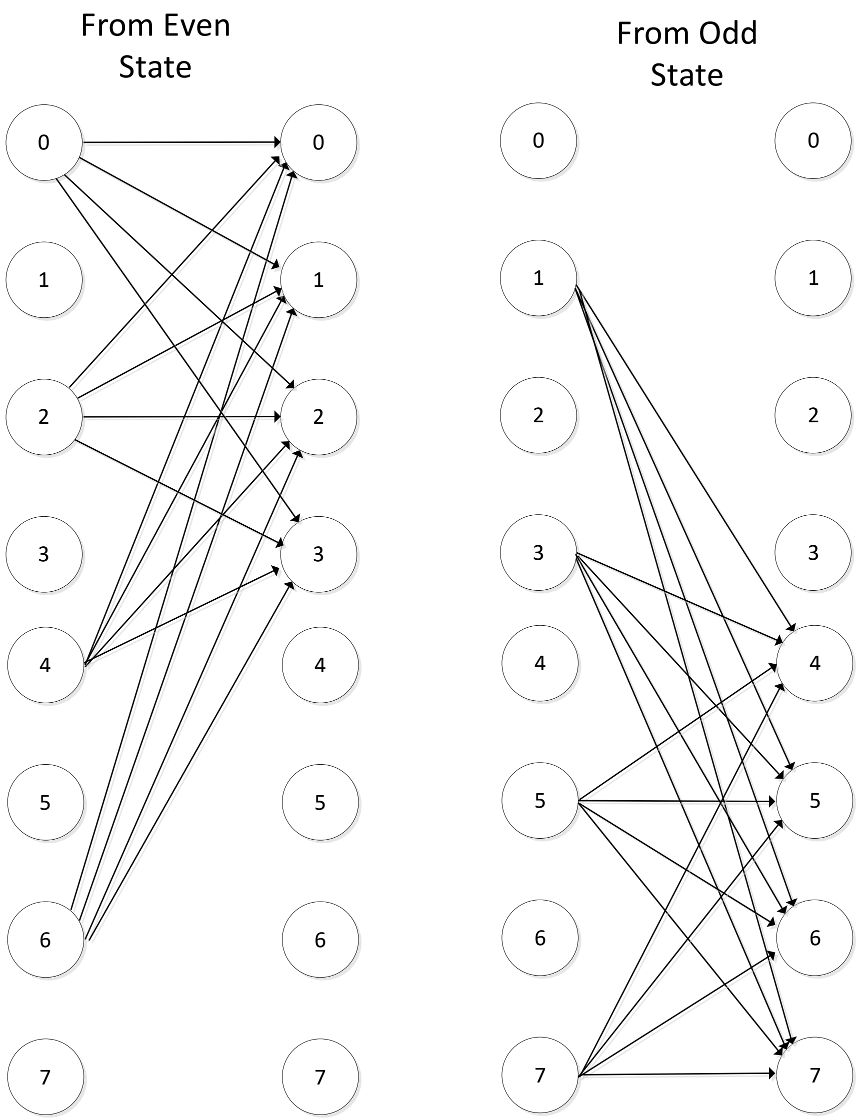
- **Define a Symbol Group (SG) as 4 consecutive PAM5 symbols conveying 9-bits of information**

- **Leads to an 8-state Encoder (8-state trellis)**



Convolutional Coding: Trellis

- **8 state trellis**
- **Each state has 4 inputs**
- **Define a Transition Group (TG) as collection of 64 SGs that define an arc in the trellis**
- **Even numbered states are connected to states 0,1,2 and 3 (4 different TGs)**
- **Odd numbered states are connected to states 4,5,6 and 7 (4 different TGs)**
- **8 different TGs are needed (8*64=512)**
- **Define the alphabet as the full set of 8 TGs**



Alphabet Selection

- **Alphabet Optimization**
  - Find the best Alphabet to give the lowest SER performance
  - Several revisions of customized NP-Complete solver

- **Ideal Alphabet rules**
  - DC Offset is 0 (DC)
    - Maintain DC balance without any other circuitry
  - Nyquist transitions are minimized (-2 to 2 or 2 to -2) (NYQ)
    - Minimize the use of full BW transitions
  - Minimize Average TX Power Consumption (PWR)
    - Lower Average TX power for best SNR

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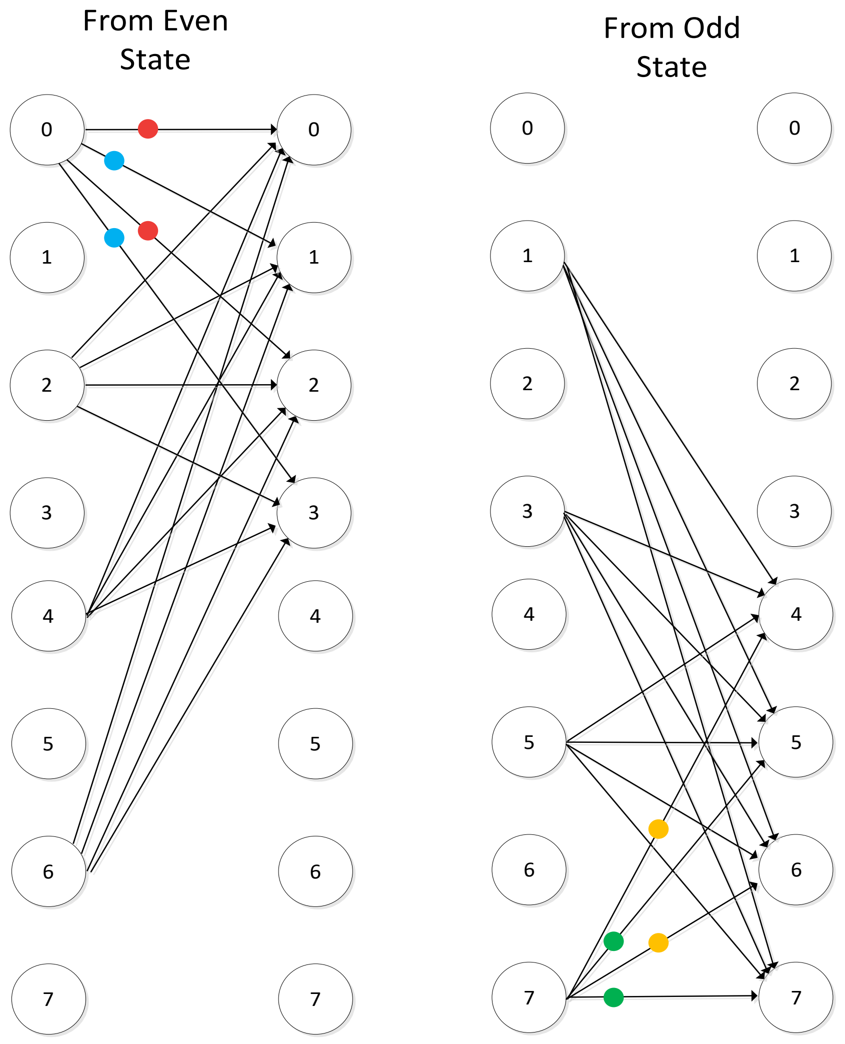
Alphabet Selection (cont)

- **Ideal Alphabet rules**
  - Remove all full SG DFE propagation errors in one TG
    - DFE errors are known to propagate in an alternating pattern of +1,-1,+1,-1
      - Zig = (+1,-1,+1,-1)
      - Zag = (-1,+1,-1,+1)
    - No two elements within one TG can differ by a Zig or a Zag (ZZ)
  - Remove all 3-symbol DFE propagation errors in one TG
    - (+1,-1,+1,x) or (-1,+1,-1,x) or (x,+1,-1,+1) or (x,-1,+1,-1)
  - Squared distance of all elements within a TG is >2 (D)
    - Distance between SGA an SGB
      - (S0A-S0B)^2 + (S1A-S1B)^2 + (S2A-S2B)^2 + (S3A-S3B)^2
  - Squared distance between alternate TG pairs is >=2 (Alternate Distance (AD))

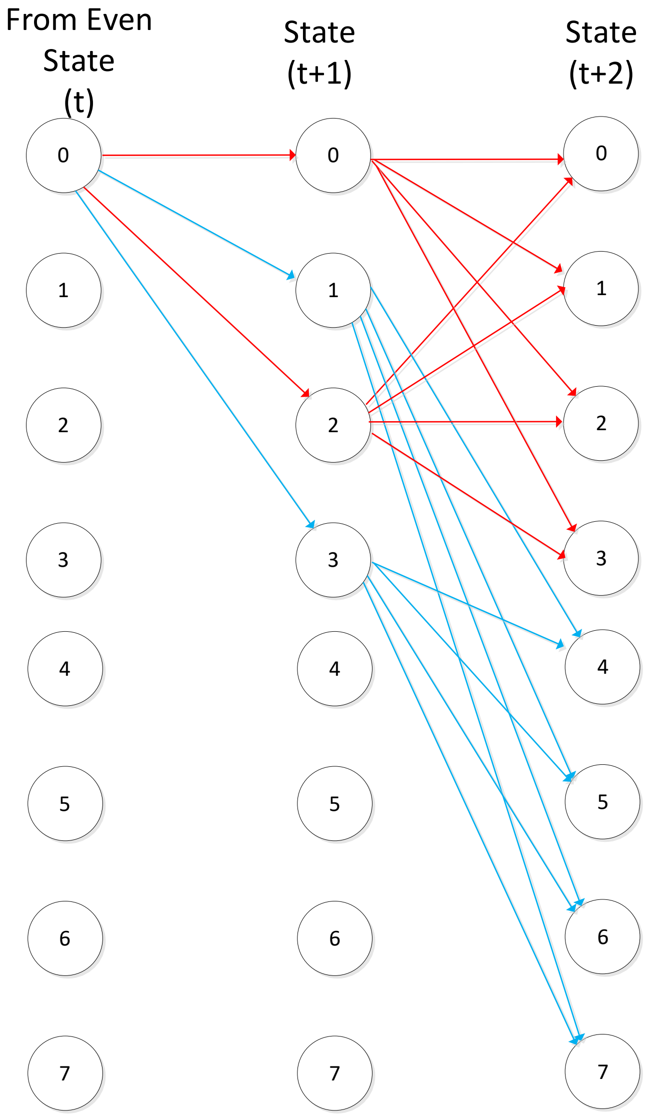
Alphabet Selection (cont)

- **Trellis Convergence gives us one more rule**
- **Squared distance between alternate TG pairs is >=2 (AD)**
  - Ie. All elements of TG0 and TG2 have a minimum distance of at least 2
- **Divide the 8 TGs into 4 pairs as indicated by different colored pairs**
- **Note the 4 TGs entering each state will be different**
  - Same TGs used by even states but rotated in 4 different ways



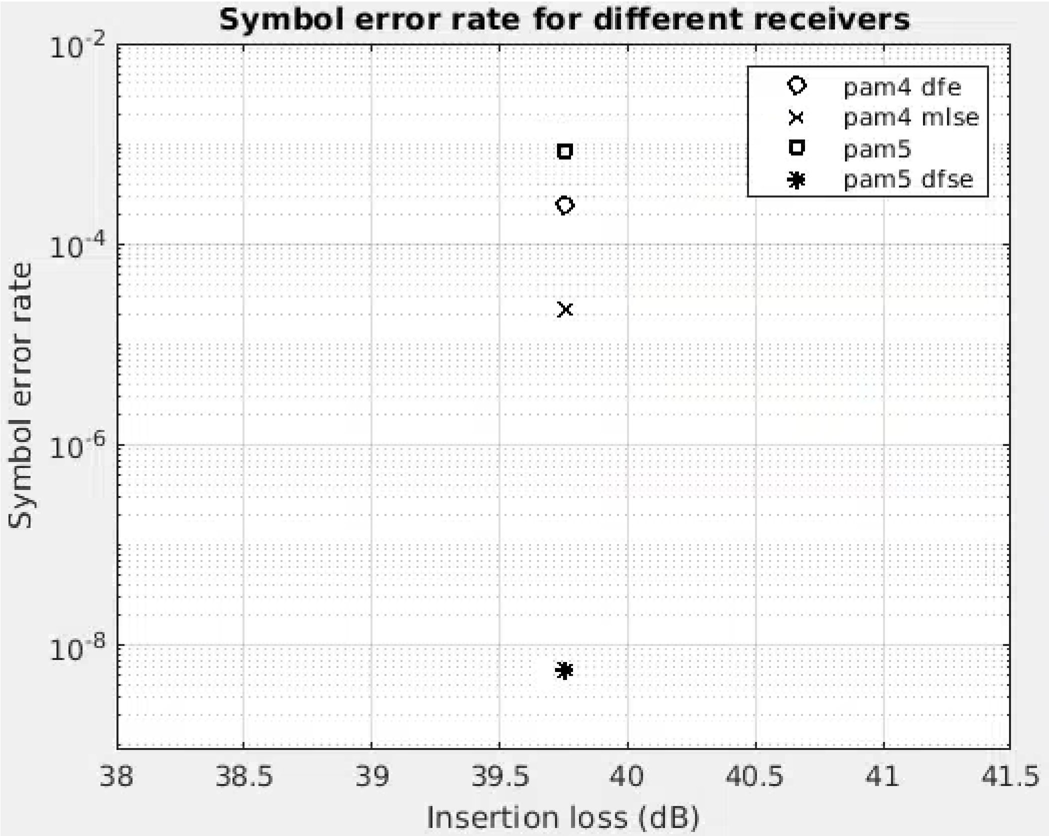
Alphabet Selection: Trellis Convergence

- **Why enforce AD rule?**
- **Red transitions from state 0 at time t can reconverge at time t+2**
  - States 0 through 3
- **Blue transition from state 0 at time t also compete at time t+2**
  - States 4 through 7
- **Red vs. Blue starting from time t cannot reconverge until at least time t+3**
  - Trellis itself will keep alternate colors apart longer



PAM4m5 Proof of Concept (POC) Performance

- **39.75 dB IL Channel, with standard AFE, ADC and DSP operation**
  - Same receiver used for each case with FFE and DFE taps adapted appropriately.
  - Tested at 128 Gbps
- **Native PAM5**
  - Nyquist scaled lower by 8/9 running classical DFE receiver
- **Native PAM4**
  - Receiver struggling to meet SER=1e-4
- **PAM4 MLSE receiver shows ~20x Ser improvement (~1.6 dB)**
- **PAM5 DFSE (Decision Feedback Sequence Estimation) receiver**
  - Alphabet “3a” shows good performance
  - Enhanced CC receiver operation



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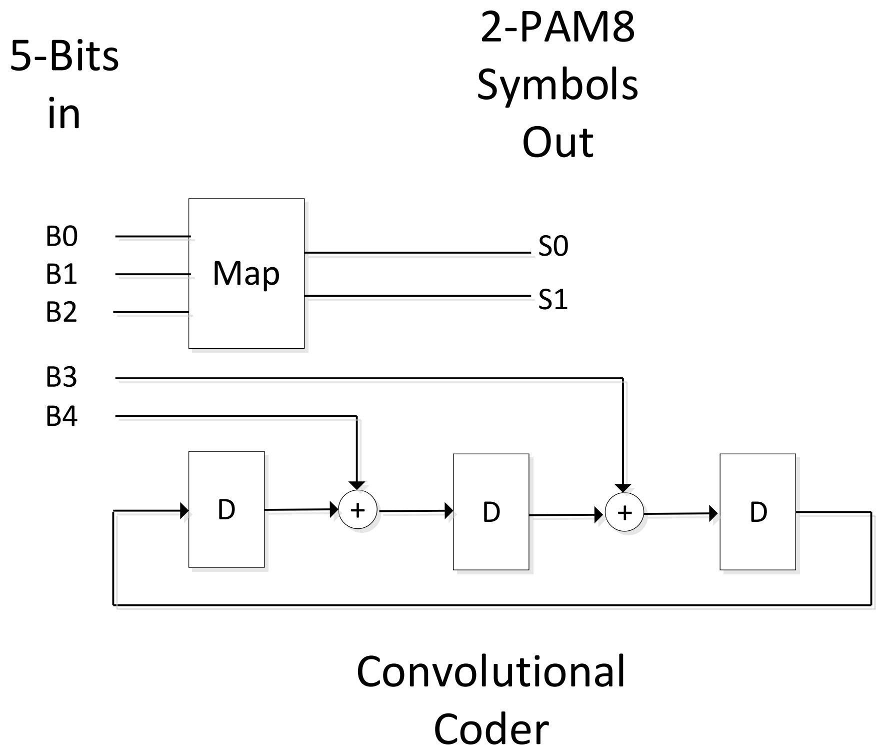
Operation at 448G

- **PAM6m8**
  - Baud rate according to PAM6 (89.6 GHz Nyquist) modulation at PAM8
  - SG is 2 symbols long
  - Each TG has 8 elements (encode 3 bits)
  - 8-state trellis requiring 8 TGs
    - 64 elements in the Alphabet
    - No free space in this case, all 64 possibilities for 2 PAM8 symbols will be used.
  - Code Rate is 5/6 (5 bits in 6 bits out)



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448G Alphabet

- **Some properties not available for optimization**
  - DC, PWR, NYQ (All available patterns used)
- **PAM8 levels**
  - {-7, -5, -3, -1, +1, +3, +5, +7}
- **Divide Symbols into two sets PAM2 and PAM4**
  - PAM2
    - Distance of 4 levels between alternates
    - A={-7, +1}, B={-5, +3}, C={-3,+5}, D={-1,+7}
    - Encodes 1 bit of information
  - PAM4
    - Distance of 2 levels between alternates
    - X={-7,-3,+1,+5}, Y={-5, -1, +3, +7}
    - Encodes 2 bits of information

448G Alphabet (cont)

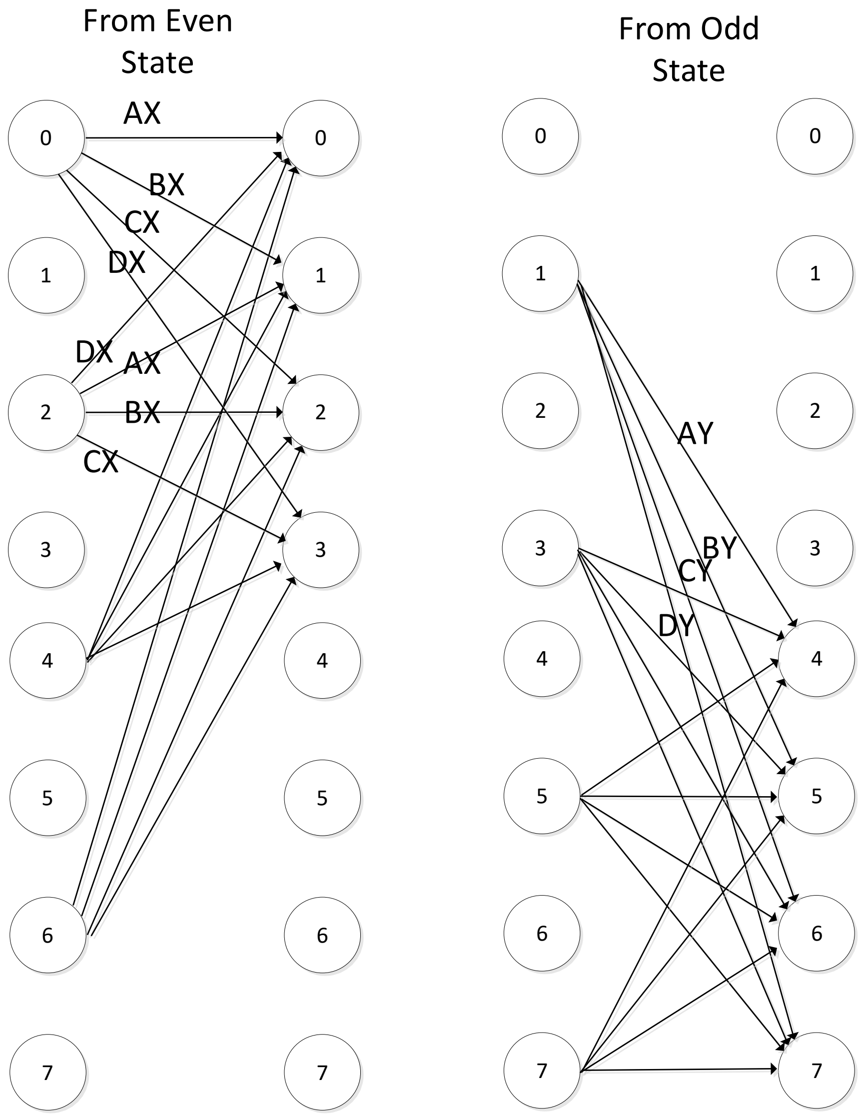
- **Each 2 symbols must carry 3-bits of information**
  - One symbol is ABCD (1-bit)
  - One symbol is XY (2-bits)

- **For Alternate Distance we use the following pairs**
  - A with C and B with D

- **Full transition table is shown**
  - Use of TGs rotates for each even or odd pair
  - Make sure that all 4 TGs entering a state are different

Transition Table

From	To	TG
0	0	AX
0	1	BX
0	2	CX
0	3	DX
1	4	AY
1	5	BY
1	6	CY
1	7	DY
2	0	DX
2	1	AX
2	2	BX
2	3	CX
3	4	DY
3	5	AY
3	6	BY
3	7	CY
4	0	CX
4	1	DX
4	2	AX
4	3	BX
5	4	CY
5	5	DY
5	6	AY
5	7	BY
6	0	BX
6	1	CX
6	2	DX
6	3	AX
7	4	BY
7	5	CY
7	6	DY
7	7	AY



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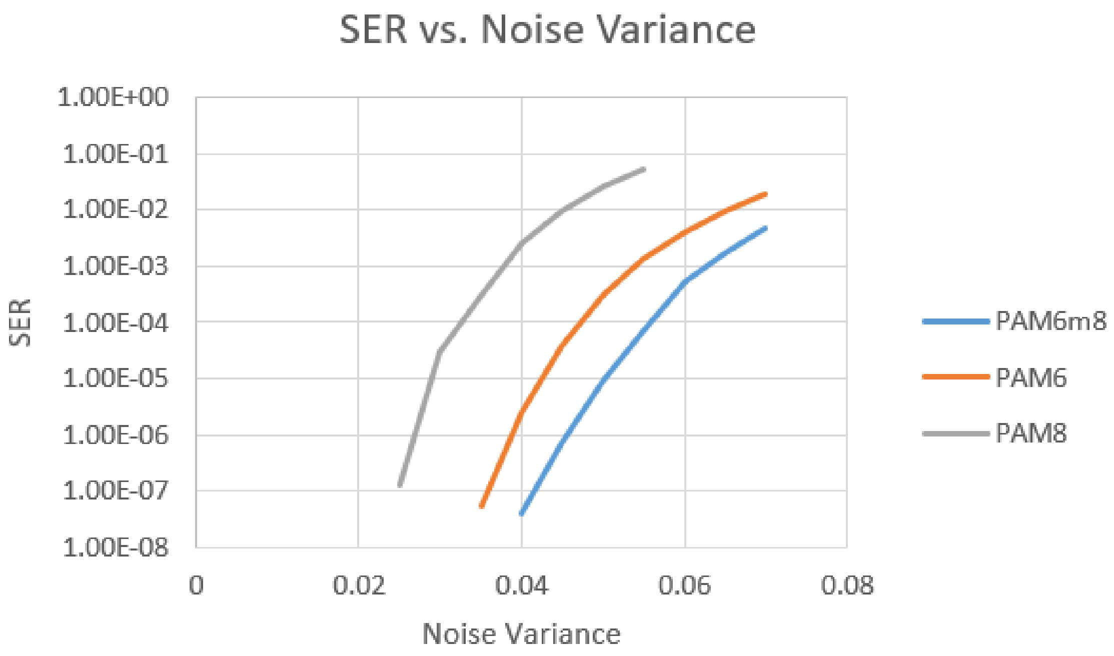
PAM6m8 Results

- **Test with 1-tap DFE channel**
  - 1+D*0.875+noise
- **Test Cases**
  - PAM8 DFE
  - PAM6 DFE
  - PAM6m8 DFSE
- **Standard CC implementation**
- **Preliminary Coding gain for PAM6m8 vs. PAM6 is 1.5 dB**



Summary

- **Motivation**
  - Add a low latency softFEC to the standard DSP receiver to improve efficiently improve receiver margin
  - Use higher modulation levels to provide parity bits for FEC operation

- **PAM4m5**
  - Promising proof of concept results showing 3+ decades of SER improvement over standard MLSE PAM4 receiver

- **PAM6m8**
  - Initial work for standard CC receiver at 448G presented

- **Future Work**
  - 6m8 Alphabet Exploration
  - Enhanced CC decoder to improve performance
  - Operation at 74.66GHz

Thank You