

Using Ensemble NRZ Coding for 400GE Electrical Interfaces

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IEEE 802.3 400GE Study Group
May 17, 2013
Victoria, BC

- **This presentation includes technology that may be the subject of multiple patent applications, applications in process, and patents by Kandou Bus, S.A.**
- **Assuming that this Study Group results in a PAR, that Kandou Bus, S.A. is committed to filing an Letter of Assurance against that PAR. (IEEE Patcom will not accept a LOA against a study group.)**
- **That LOA will guarantee that licenses to patents derived from these applications will be available on a Reasonable And Non-Discriminatory basis, should Kandou's technology be adopted into the 400GE specification**

This proposal addresses the technical feasibility of 400GE backplane & module electrical I/F

- **Having an electrical backplane and module I/F for 400GE are highly desirable objectives**
- **During the CFI period, discussions have focused on a 16 wire interface**
 - **51 GBaud NRZ is one possibility**
 - **26 GBaud PAM-4 is another possibility**
- **The 8-wire interface used by 802.3ap and 802.3bj was thought to be immediately infeasible.**
 - **A differential solution would require 100+ Gb/s links.**

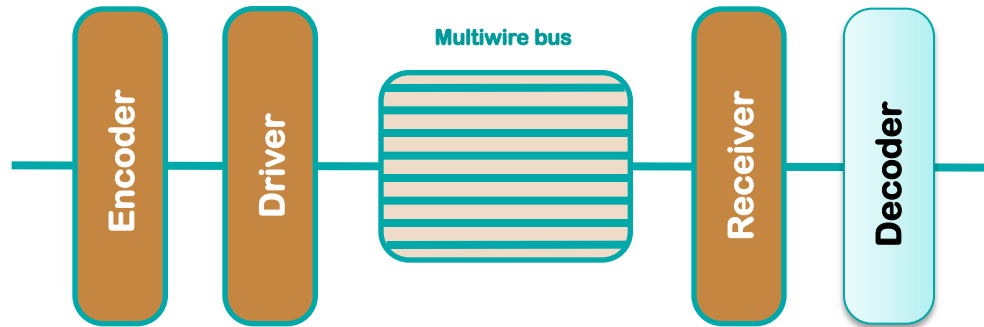
Technical feasibility of 400GE backplane & module electrical I/F (cont.)

- Pursuing 51 Gb/s for 400GE electrical interfaces is asking for problems
 - The semiconductor processes to support 51 Gb/s are not here yet and are not likely to emerge for some years.
 - The short wavelength of 51 Gb/s signals makes them fragile
 - 51 Gb/s DFEs will be hard to implement
 - These problems will be especially acute with 51 Gb/s backplanes
- The necessary unrolled portion of PAM-4 DFEs will get hard to implement at 26 Gbaud
 - Two clocks of unrolling results in 16 speculative values
- Ensemble NRZ presents an alternative that makes these interfaces more technically feasible

Ensemble NRZ proposal

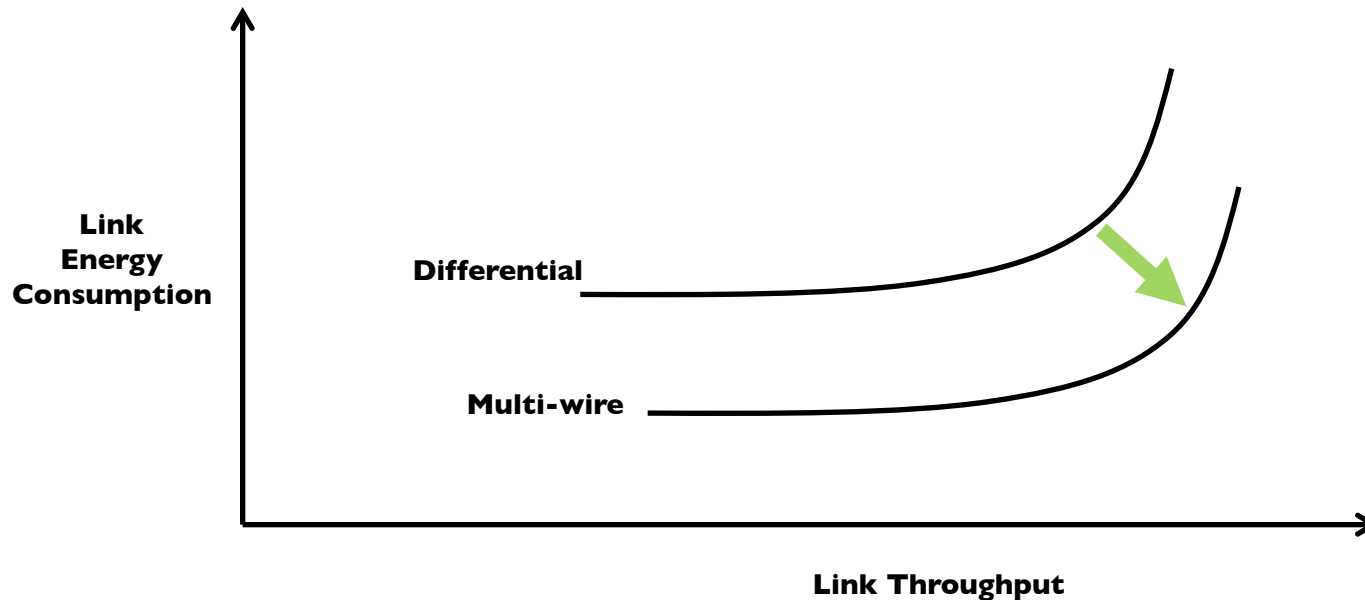
- We are proposing the use of a particular form of multi-wire signaling called Ensemble NRZ signaling for use in the 400GE backplanes
 - Ensemble NRZ decreases the needed symbol rate of links through the use of a four-wire ensemble.
 - If Ensemble NRZ is used for 400GE backplanes, the symbol rate will be 34 GBaud for a 16 wire, 12 lane interface
 - 16 wires, eight lanes of NRZ at 51 GBaud delivers the same bandwidth
 - 34 is much less than 51
 - Ensemble NRZ receivers are reference-less
- The channel for Ensemble NRZ is different
 - Ensemble NRZ requires a low skew group of 4 wires.
 - The optimal channel configurations are 3 dimensional.
- Ensemble NRZ lets you keep NRZ

Overview of general multi-wire Signaling



- **Multi-wire signaling delivers high-speed and energy efficient I/O and serial links**
 - **Allows a variety of combinations of 1.5-4x of the speed with ½ to ¼ of the line power**
 - **Power-efficient multi-wire driver and receiver architectures are matched to the signaling method**
- **Supports good signal integrity with excellent CM, XTLK & SSO noise resistance**
 - **Can reduce the number of active aggressors by code design**
- **Provides high pin efficiency**
- **Delivers robust, reference-less receivers**
 - **Some receivers do not need a decoder (including the Ensemble NRZ receivers)**
- **Requires an ensemble composed of a low-skew group of wires**
- **Kandou has produced a prototype using a more complex code that delivers 128 Gb/s over 8 wires at 3.8 pJ/bit over a -15 dB channel**

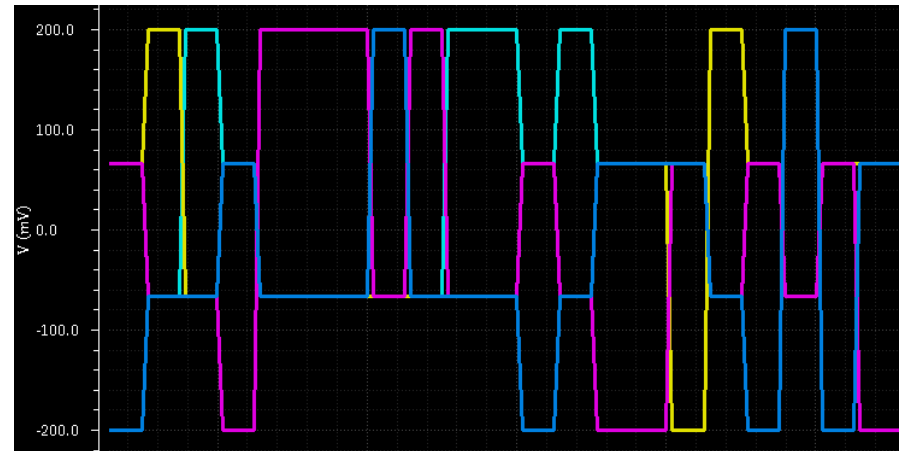
Multi-wire techniques advance the Energy-Throughput Frontier



Increases the throughput and lowers the energy consumption at the same time.

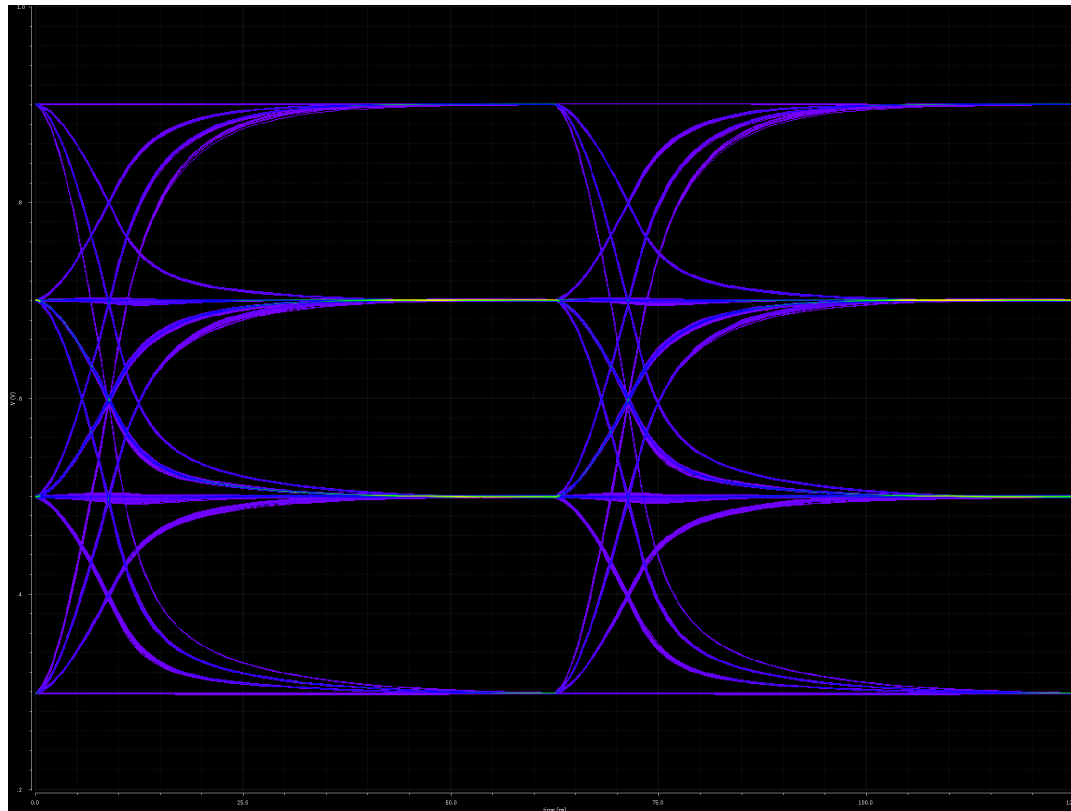
The Ensemble NRZ Transmitter

- Ensemble NRZ coding, also known as Hadamard 4-wire transform coding is a method of delivering 3 bits over an ensemble of 4 wires
 - The symbol rate is 2/3rds of what is required for differential NRZ for the same throughput
 - The line power is 1/3 of the three differential NRZ channels that are otherwise needed at the same rate and throughput
- The 4 wires in the ensemble must have low intra-ensemble skew, on the same order as differential's intra-pair skew
 - Ensembles are terminated jointly to an AC ground at the receiver
- The transmit codewords are:
 - the 4 permutations of $(1, -1/3, -1/3, -1/3)$
 - plus
 - the 4 permutations of $(-1, 1/3, 1/3, 1/3)$



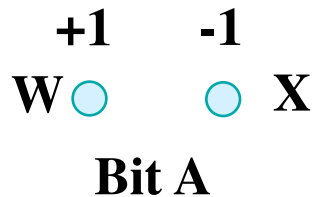
Typical Ensemble NRZ Waveform

- **Transmit Ensemble NRZ waveform**
 - Viewed single-ended
 - Only two levels present at any given time



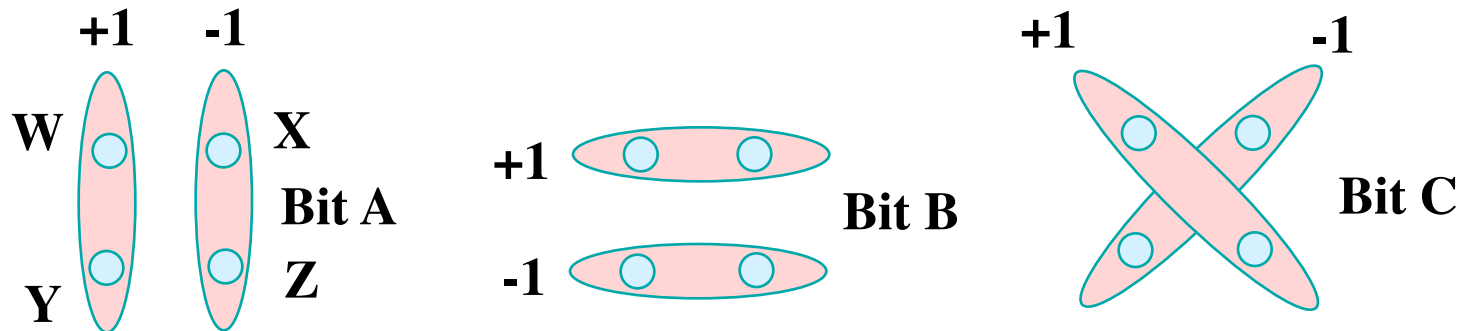
A differential NRZ Transmitter calculates the 2x2 Hadamard Transform

- The transmit vector is obtained by multiplying the one input bits by the 2x2 Hadamard Transform
 - +1 +1 (not used)
 - +1 -1 Input A
 - W X <= Outputs
 - The result looks like the following diagram:

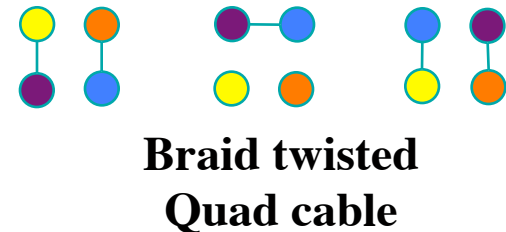
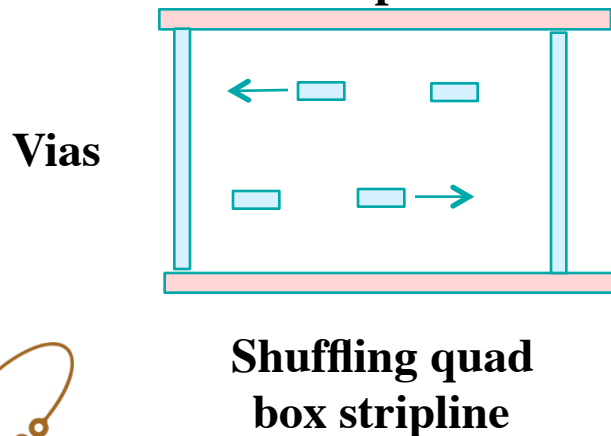
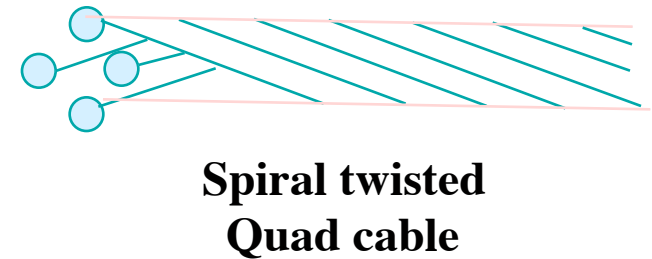
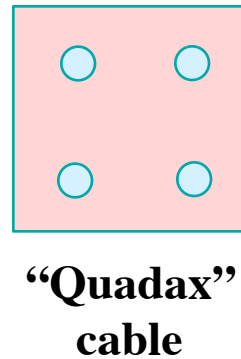
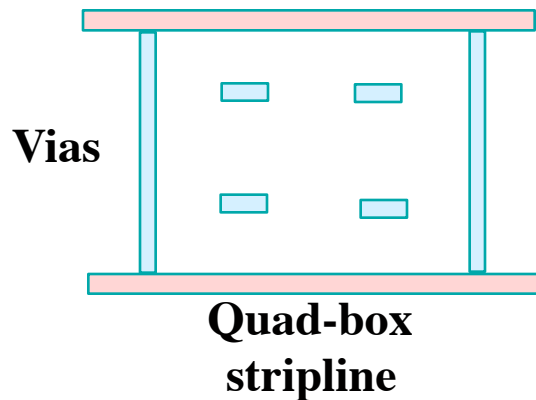


The Ensemble NRZ Transmitter calculates the 4x4 Hadamard Transform

- The transmit vector is obtained by multiplying the three input bits by the 4x4 Hadamard Transform
 - +1 +1 +1 +1 (not used)
 - +1 -1 +1 -1 Input A
 - +1 +1 -1 -1 Input B
 - +1 -1 -1 +1 Input C
 - W X Y Z <= Outputs
 - The computation can be done either digitally (preferred) or in analog.
 - The transform is 100% linear (linear implementations can carry analog video)
 - The result looks like the following diagrams:



- **Good channels for Ensemble NRZ have four balanced and moderately spaced channels in a 3D structure**
 - Quad-box Stripline, “Quadax” Cable, Twisted Quad Cable, micro-coax
 - Alternating structures get closer to full balance for wires across the ensemble



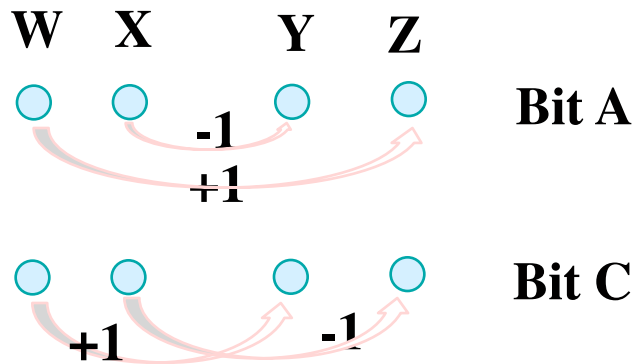
The Ensemble NRZ Receiver

- The receiver consists of three analog multi-input comparators that invert the 4x4 Hadamard Transform:
 - Name the received values w , x , y and z
 - Compare $(w+x)$ to $(y+z)$
 - Compare $(w+y)$ to $(x+z)$
 - Compare $(w+z)$ to $(x+y)$
 - These correspond to the rows of the Hadamard Transform
- Summed comparisons yield binary eyes
 - There is no receive digital decoder – the calculation is done in analog
 - The receiver can also be implemented with DSPs
 - An Ensemble NRZ receiver can easily be made to have a differential mode

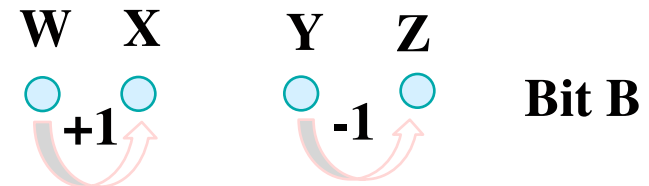
Ensemble NRZ on equally-spaced and pair Channels

- **Ensemble NRZ can also do well on pair-oriented or 2-D channels:**
 - A linear set of equally spaced wires
 - Channels of two skew-constrained pairs as long as the wires within the pairs are not so close that there is a strong common-mode extinction
 - For each of these channels, the bit lane that is derived from the part of the Hadamard matrix with two +1's on one pair and two -1 on the other pair will be somewhat weaker than the other two and has a later sampling point
 - That weaker bit lane can be strengthened with extra gain since Ensemble NRZ has a linear response

Stronger channels



Weaker channel



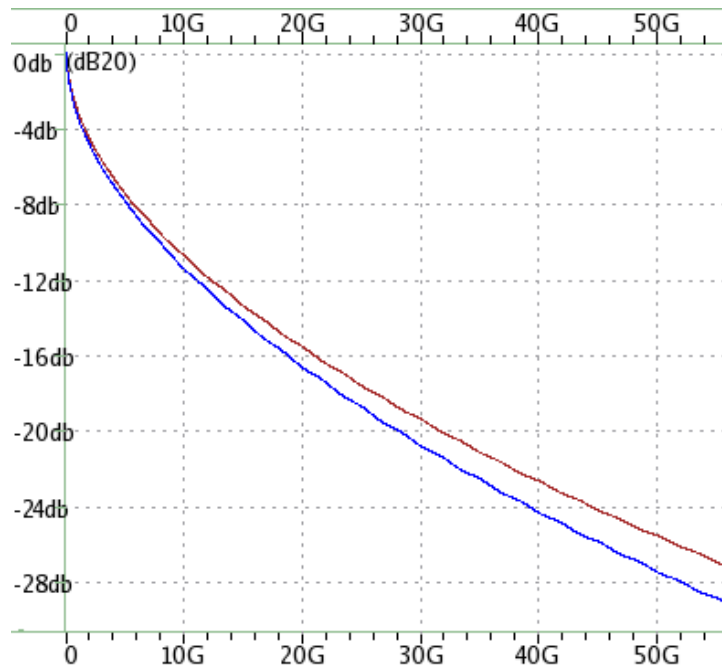
Simulation of Ensemble NRZ

- **We simulated the performance of Ensemble NRZ over two differential pairs**
 - **25 Gb/s per wire, 3 lanes over 4 wires (34 Gbaud)**
 - **18 dB loss at 25 GHz (20dB at 28 GHz) channel used**
 - **Suitable for a module interconnect**
 - **Suitable for an apples to apples comparison against NRZ**
 - **Megtron 6 material**
 - **A Tx FIR was not needed to make this simulation work**
 - **Rx CTLE parameters:**
 - **Poles at 1.6, 8, 32, 48 and 48 GHz**
 - **Zeros at 1, 5.2 & 16 GHz**
 - **DC gain = 1**
 - **Channel has two loosely coupled microstrip differential pairs**



Channel for Simulation of Ensemble NRZ

- **Megtron 6 Channel used**
 - **VSR channel suitable for module interconnect**
 - **Backplane channels are likely possible**

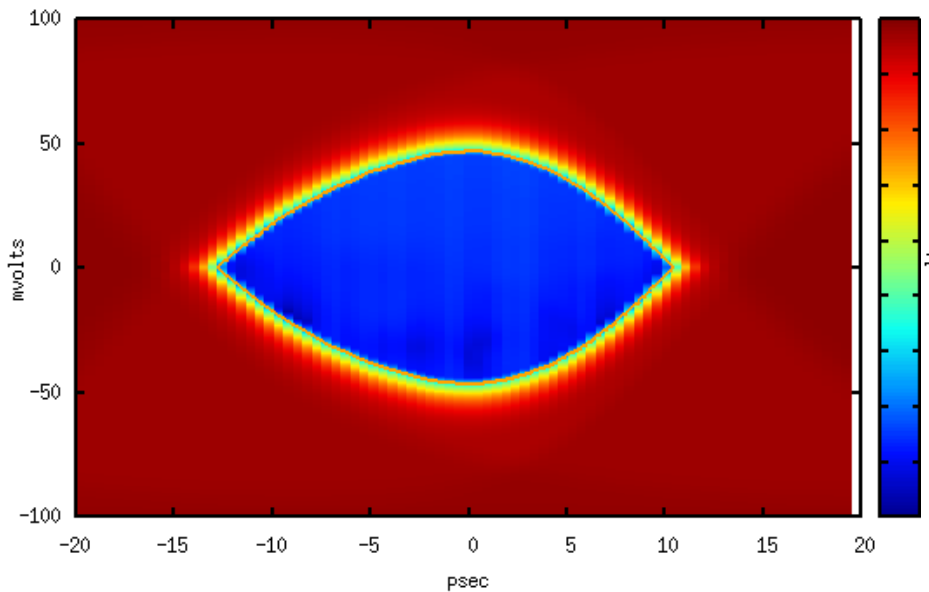


Loss on the two stronger channels
Loss on the weaker channel

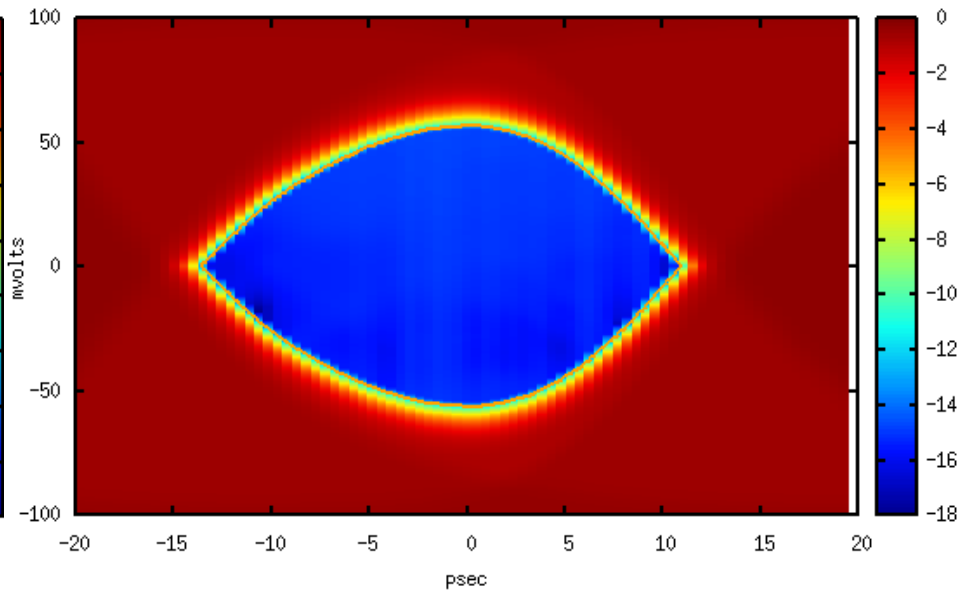
Simulation of Ensemble NRZ

- **Receive Ensemble NRZ Rx Eyes**
 - 25 Gb/s per wire, 3 lanes over 4 wires (34 Gbaud)
 - Simulation includes only the intra-ensemble ISI and crosstalk effects
 - Other impairments should be added

Weaker channel – 93mv, 24ps



Stronger channels - 112mv, 25ps



Ensemble NRZ Performance – Power & EMI

- **Ensemble NRZ saves power**
 - The line power consumption of the four wire ensemble is equivalent to one differential NRZ channel
 - The line power consumption is 33% that of the three differential NRZ channels needed to achieve the same throughput (with the same levels and symbol rate)
 - The line power consumption is 75% of two differential PAM-3 channels with the same levels and symbol rate
- **The EMI performance is slightly better than NRZ**
 - The emitted fields are well balanced from the four wires
 - The much lower launch energy reduces the radiated energy enough to offset the somewhat lower coupling of the wires

Ensemble NRZ performance - SNR & ISI

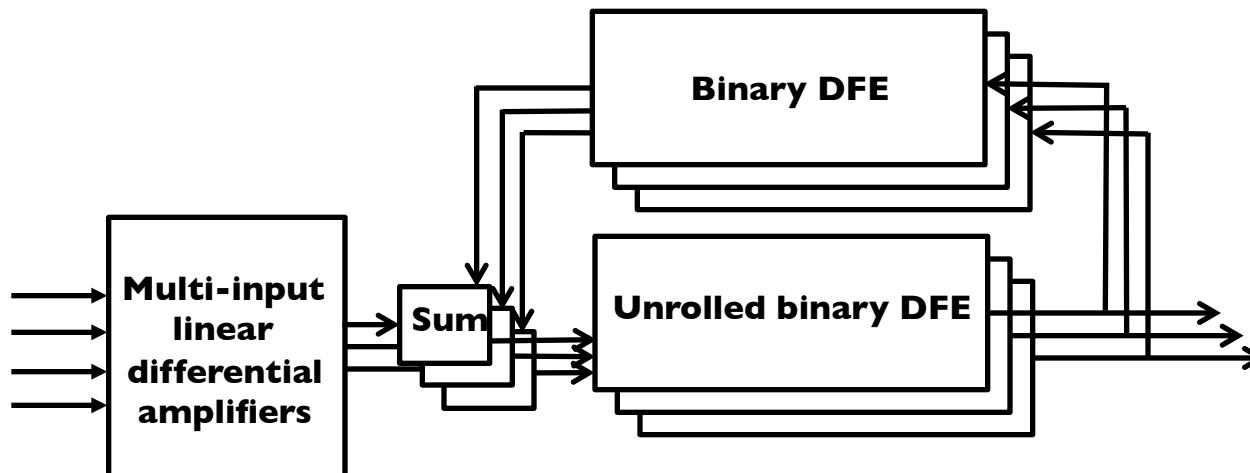
- **The Ensemble NRZ SNR tolerance is 6dBs worse than NRZ**
 - **Similar to that of PAM-3**
- **Ensemble NRZ resembles NRZ in its tolerance of inter-symbol interference (ISI)**
 - **The pulse response of the binary output of the three multi-input comparators is the same the pulse response as an NRZ receiver**
 - **For channels with linear equalization, the sensitivity to residual ISI as compared to NRZ is the ISI-Ratio**
 - **ISI-Ratio(NRZ) = 1**
 - **ISI-Ratio(Ensemble NRZ) = 1 (the same)**
 - **ISI-Ratio(PAM-3) = 2**
 - **ISI-Ratio(PAM-4) = 3**

- **400GE is a large enough change from 100GE that most channels will have a new design anyway**
 - It is not a particular limitation to constrain the skew of the wires
 - It is a matter of making the choice to do so
 - It is not a particular limitation to use 3D orientations
 - Good operation over pairs should allow the use of pair-oriented connectors
- **Ensemble NRZ implementations can be made backwards compatible to differential**
 - The comparators used for Ensemble NRZ are similar to those used for differential
 - As we shall see, Ensemble NRZ interfaces can use classic binary DFEs

- **Decision Feedback Equalizers (DFEs) are a key technology for high speed links**
 - They use the output of the final decision to equalize for the channel
 - They are a closed-loop equalization technology
 - They are highly accurate because they use a regenerated signal at the receiver
 - They also can cancel reflections that occur much later because of the easy digital storage of the decisions
 - Many high speed specifications effectively require them
- **Implementations of non-NRZ DFEs are difficult**
 - The highest speed portions of DFEs are often “unrolled”
 - The complexity of unrolled DFEs increases exponentially with non NRZ eyes

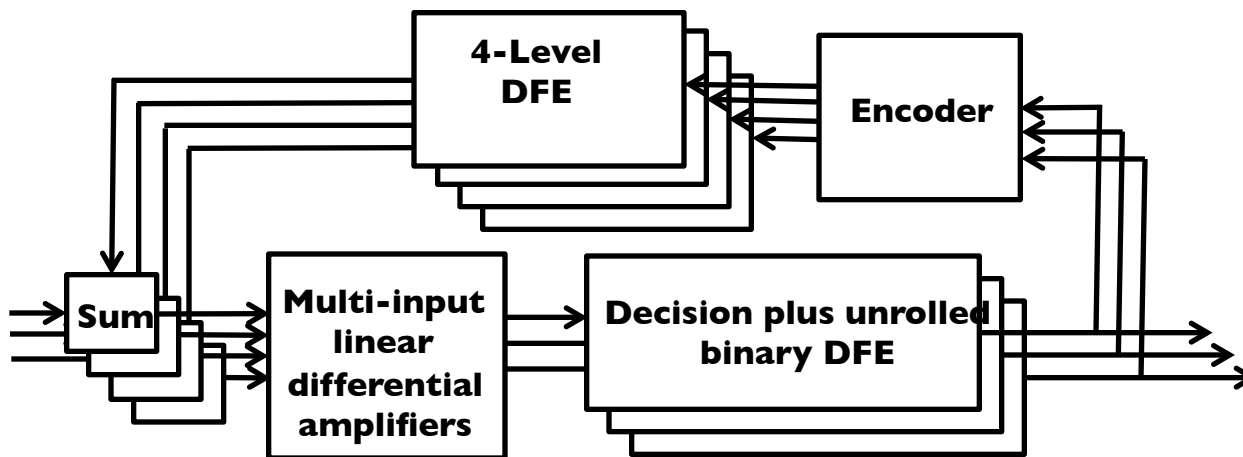
Preferred Ensemble NRZ DFE architecture

- **This preferred form of DFE is compatible with Ensemble NRZ coding**
 - 3 unrolled binary DFEs for the first 1-3 clocks
 - 3 regular binary DFEs for the rest
 - This architecture relies on the difference in the reflections being reasonably constrained between the wires
 - These are classic high-speed DFEs unchanged



Alternative Ensemble NRZ DFE architecture

- An alternative DFE architecture is compatible with Ensemble NRZ coding and can handle unbalanced reflections at the cost of considerable complexity and power
 - This is not the preferred architecture
 - Because this is so much harder, it is worth specifying the reflection imbalance
 - **Compromise binary DFE on the high-speed unrolled portion**
 - Relies on the reflections that are near the receiver being somewhat balanced between the wires
 - **Re-encoded ensemble 4-level DFE for the non-unrolled portion**
 - Allows for arbitrary reflections outside of the unrolled interval



- **Ensemble NRZ encoding allows 400GE to achieve technical feasibility for the possible objective of 16-wire backplane and module interface links**
 - Ensemble NRZ reduces the excessive link rate needed by NRZ links, allowing their construction with existing and well-understood implementation techniques
 - Ensemble NRZ employs a relatively simple circuit
 - Ensemble NRZ relies on a low-skew four wire ensemble
 - Ensemble NRZ's linear nature allows implementation flexibility
- **The use of Ensemble NRZ saves power over NRZ**
- **Ensemble NRZ supports channels with frequency impairments similar to what NRZ requires**
 - Ensemble NRZ is much more like NRZ than PAM solutions are
- **Ensemble NRZ allows binary DFEs to be used**
 - Ensemble NRZ can use ordinary binary DFE circuits if the differences in the reflections are constrained