PAM4 transmitter training protocol

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Introduction

- 10GBASE-KR (Clause 72) defines a start-up protocol that enables a receiver to control the equalizer of the remote transmitter
- This start-up protocol has been leveraged by subsequent PHYs operating over electrical backplanes to direct attach copper cable assemblies
- This is a useful feature that should be carried forward to PHYs based on 50 Gb/s per lane operating over backplane and copper cables
- This presentation proposes modifications to the protocol to make it more suitable for these next-generation applications

Assumptions and provisions

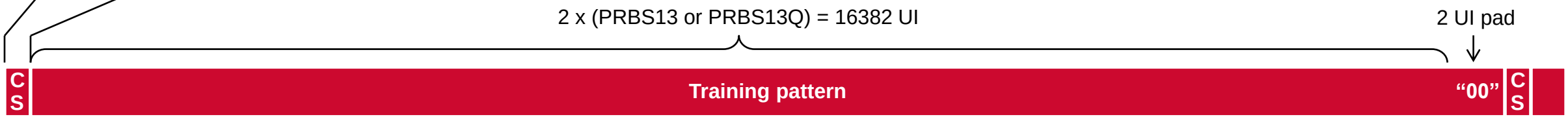
- PAM4 for 50 Gb/s per lane over backplanes and copper cables
- The transmitter equalizer will include additional taps
- Include a mechanism to select optional precoding (should it be added)

Transmitter training signal

Control and status (CS) fields

1 x 32 UI	**Frame marker**	16 x “3”, 16 x “0”
4 x 32 UI	**Control**	16 “cells”, 8 UI per cell
		Differential Manchester encoded
		(using “0” and “3” levels)
4 x 32 UI	**Status**	16 “cells”, 8 UI per cell
		Differential Manchester encoded
		(using “0” and “3” levels)

- Based on IEEE Std 802.3-2015, 72.10
- Support for PAM4 training pattern
- Higher ratio of training pattern to control/status



10GBASE-KR definition (for comparison):

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Control and status fields

Control register encoding

Cell	Name	Description
15:14	Reserved	Transmit as 0, ignore on receipt
13:12	Initial condition request	13 12 1 1 = Preset 3 (TBD) 1 0 = Preset 2 (TBD) 0 1 = Preset 1 (no equalization) 0 0 = Individual coefficient control
11:10	Reserved	Transmit as 0, ignore on receipt
9	Modulation request*	1 = Request PAM4 0 = Request PAM2/NRZ
8	Precoding request*	1 = Request precoding on 0 = Request precoding off
7:5	Reserved	Transmit as 0, ignore on receipt
4:2	Coefficient select	4 3 2 1 1 0 = $c(-2)$ 1 1 1 = $c(-1)$ 0 0 0 = $c(0)$ 0 0 1 = $c(1)$
1:0	Coefficient request	1 0 1 1 = No equalization (0) 1 0 = Decrement 0 1 = Increment 0 0 = Hold

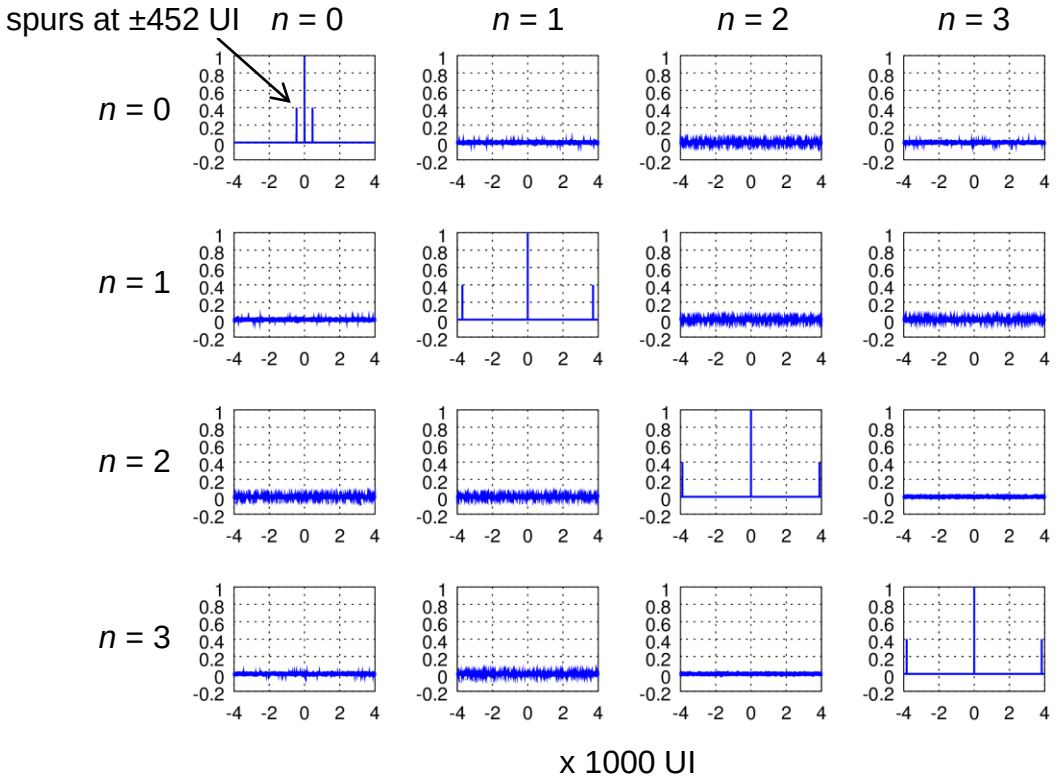
* Modulation and precoding apply to the training pattern only.

Status register encoding

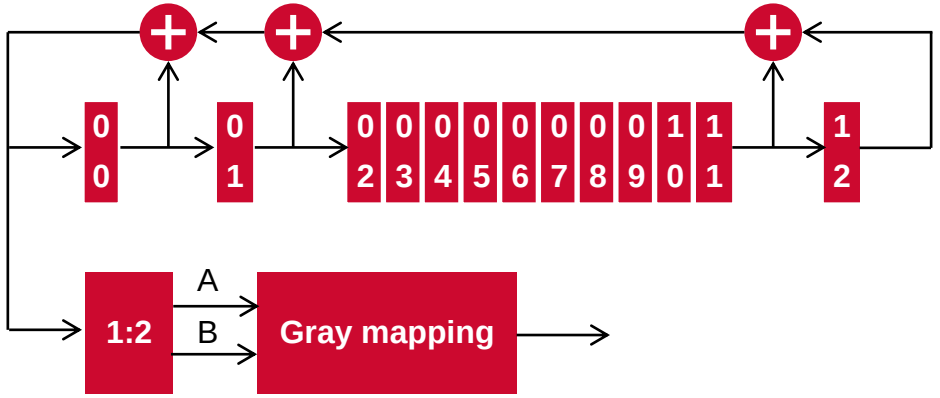
Cell	Name	Description
15	Receiver ready	1 = Training is complete and the receiver is ready for data 0 = Request for training to continue
14:12	Reserved	Transmit as 0, ignore on receipt
11	Modulation status*	1 = PAM4 0 = PAM2/NRZ (default)
10	Precoding status*	1 = Precoding on 0 = Precoding off
9	Receiver frame lock	1 = Frame boundaries identified 0 = Frame boundaries not identified
8	Initial condition status	1 = Updated 0 = Not updated
7:5	Reserved	Transmit as 0, ignore on receipt
4:2	Coefficient select echo	4 3 2 1 1 0 = $c(-2)$ 1 1 1 = $c(-1)$ 0 0 0 = $c(0)$ 0 0 1 = $c(1)$
1:0	Coefficient status	1 0 1 1 = Coefficient not supported 1 0 = Coefficient at limit 0 1 = Updated 0 0 = Not updated

Training pattern

n	Polynomial_*n*, *G*(*x*)	Notes
0	$1 + x + x^2 + x^{12} + x^{13}$	PRBS13Q polynomial
1	$1 + x^2 + x^3 + x^7 + x^{13}$	
2	$1 + x^2 + x^4 + x^8 + x^{13}$	
3	$1 + x^2 + x^5 + x^9 + x^{13}$	



Generator example (*n* = 0)



NOTE: A is the bit arriving first

- Based on IEEE Std 802.3-2015, 92.7.12
- Configurable generator polynomial and seed to avoid correlated interference between lanes
- When modulation status is PAM2, map A (or B) bits to “0” and “3” levels
  - A and B are shifted copies of the PRBS13 sequence
- Gray-mapped PAM4 symbols may optionally be precoded

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Principles of operation

- Define only the response to defined requests
- Use of defined requests is beyond the scope of the standard
- Frame lock diagram similar to Figure 72-4 accounting for different frame marker intervals
- Training state diagram similar to Figure 72-5
- New coefficient update state diagram to account for initial condition control and individual coefficient processing

Coefficient update state diagram

coef_req: Enumerated variable derived from the coefficient request bits from control field of the received training frames. This variable may be one of the following values: hold, decrement, increment, no equalization.

coef_sel: Variable derived from the coefficient select bits from the control field of the received training frames. It is assigned a signed integer value that is the 2's complement interpretation of the bits.

coef_sts: Enumerated variable that may be assigned one of the following values: not updated (not_upd), updated, coefficient at limit, coefficient not supported.

ic_req: Enumerated variable derived from the "initial condition request" bits from the control field of the received training frames. This variable may be one of the following values: individual control (ind_ctl), preset 1, preset 2, preset 3.

ic_sts: Enumerated variable that may be assigned one of the following values: not updated (not_upd), updated.

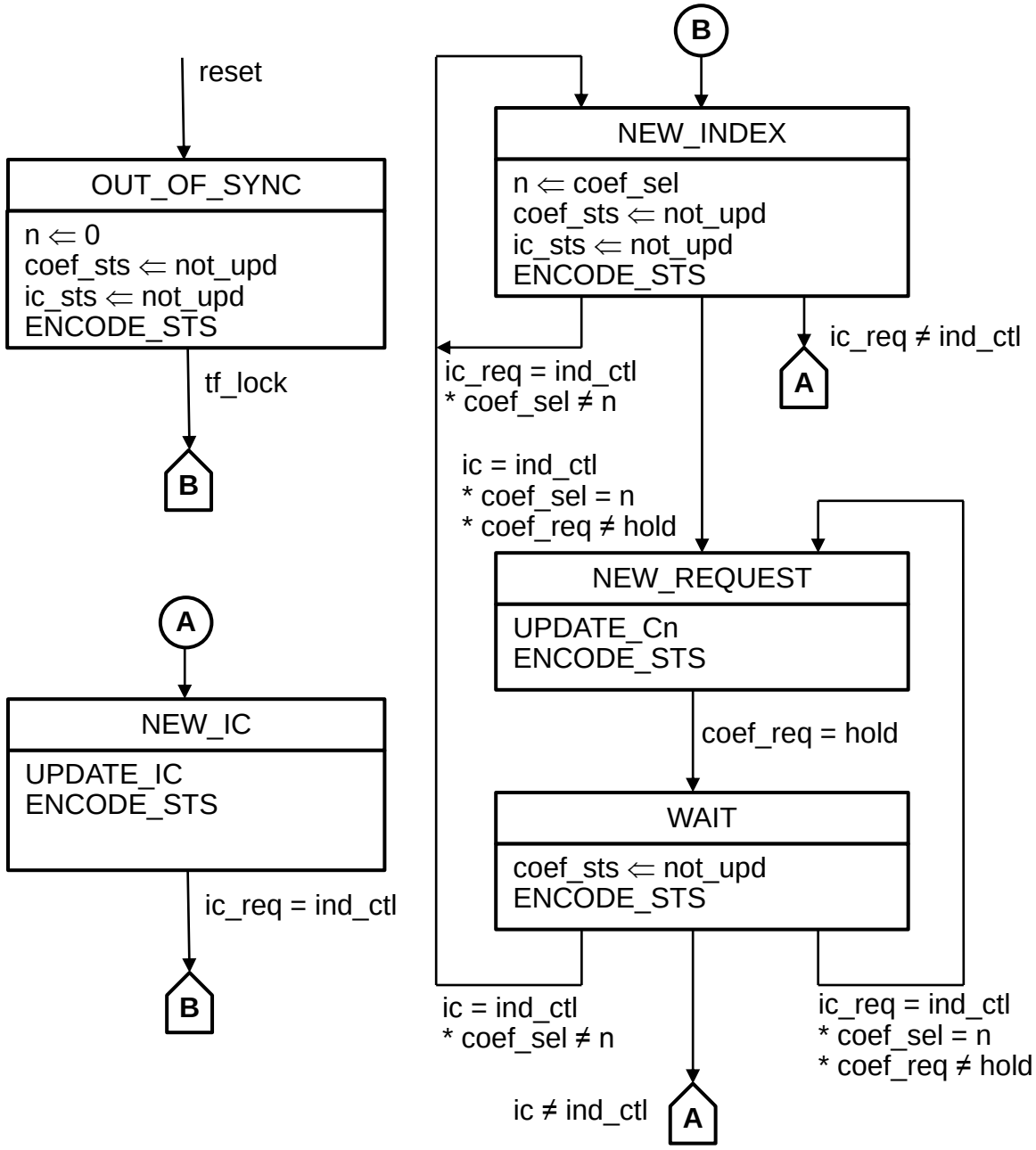
n: Variable that stores the most recent value of coef_sel.

tf_lock: Boolean variable that is true when the training frame marker positions have been identified and is false otherwise.

ENCODE_STS: Function that encodes portions of the status field of transmitted training frames. The variable tf_lock is mapped to the receiver frame lock bit, n is mapped to the coefficient select echo bits, coef_sts is mapped to the coefficient status bits, and ic_sts is mapped to the initial condition status bit.

UPDATE_Cn: Function that updates the value of *c*(n) based on the current values of n and coef_req. The result of the update is stored in the variable coef_sts.

UPDATE_IC: Function that updates all equalizer coefficients based on the current value of ic_req. The result of the update is stored in the variable ic_sts.



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Coefficient update state diagram, continued

UPDATE_Cn algorithm:

```
if n in n_list

    if coef_req = increment
        c(n) = c(n) + cn_stp
    else if coef_req = decrement
        c(n) = c(n) – cn_stp
    else if coef_req = no equalization
        c(n) = 0
    else
        c(n) = c(n)

    if c(n) > cn_max
        c(n) = cn_max
        coef_sts = coefficient at limit
    else if cn < cn_min
        c(n) = cn_min
        coef_sts = coefficient at limit
    else
        coef_sts = updated

else
    coef_sts = coefficient not supported
```

UPDATE_IC algorithm:

```
if ic_req = preset 1
    <set coefficients to preset 1>
else if ic_req = preset 2
    <set coefficients to preset 2>
else if ic_req = preset 3
    <set coefficients to preset 3>
else
    <no action>

ic_sts = updated
```

n_list: Set of valid coefficient indices

c(n): The current value of the coefficient n

cn_stp: Step size for coefficient c(n)

cn_min: Minimum value for coefficient c(n)

cn_max: Maximum value for coefficient c(n)

- Functions are called once upon entry into a state sequentially in the order listed

Additional principles of operation

- The default modulation for the training pattern is PAM2/NRZ
- Precoding is off by default
- Precoding mode is independent of the mode chosen for the opposite direction of the link
- Receiver may request changes to modulation (or precoding) at any point during the training process
- Modulation (and precoding) apply to the training pattern only; encoding of frame marker, control field, status field, and “00” pad are unchanged
- The precoding mode at the end of transmitter training is used for “mission” data
- When the “Receiver frame lock” flag is 1, the receiver shall respond to requests within TBD ms (2 ms in 92.7.12)

Management provisions

- Local device (LD) and link partner (LP) control and status registers (per lane)
- PMD training pattern register: polynomial identifier, seed (per lane)
- Enable and restart training control bits (per lane)
- Frame lock, start-up protocol status, training failure status bits (per lane)

Summary and conclusions

- The Clause 72 start-up protocol is a useful feature that should be carried forward to PHYs based on 50 Gb/s per lane operating over backplane and copper cables

- This presentation proposes modifications to the protocol to make it more suitable for these next-generation applications
  - Support for PAM4 training patterns
  - Higher ratio of training pattern to control/status
  - Support for additional transmitter equalizer taps
  - Enable selection of optional precoding