Performance Evaluation of Inner FEC Synchronization Methods

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Introduction

- Binary(128,120) code has been adopted as inner FEC code for 200G/lane optical PMDs, then a method to find the FEC codeword boundaries is necessary.
- Two synchronization methods, inner FEC self-sync and frame sequence(FS) sync, were proposed.
  - Self-sync uses the intrinsic feature of inner FEC code, as proposed in he_3dj_03b_2307.
  - FS sync uses the inserted fixed pattern, alignment marker, as proposed in farhood_3dj_01a_230206, barakatain_3dj_01a_2303.
- This presentation shows performance evaluation of self-sync and FS sync, with burst error considered, and proposes self-sync as inner FEC codeword synchronization method.

Performance evaluation of synchronization methods

- The purpose of synchronization is to find the boundaries of codewords for proper decoding on the receiving side, and to maintain the correct boundaries during normal operation.
- Performance of synchronization methods can be evaluated with the following 4 parameters:

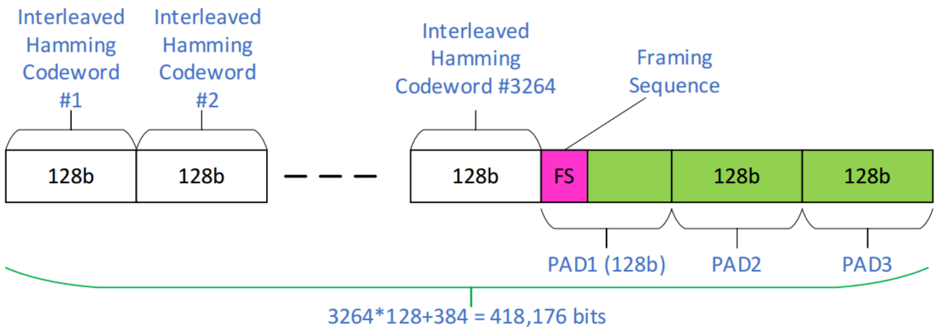
	Parameters	Description
1	Mean time to false-lock (MTTFL)	Mean time that it locks to a wrong position. Higher is better. Should never happen. (longer than AOU)
2	Mean time to false-unlock (MTTFU)	Mean time that the lock breaks during normal operation. Higher is better. Should never happen. (longer than AOU)
3	Mean time to lock (MTTL)	Mean time to find the codeword boundary on a bit stream. Lower is better.
4	Mean time to unlock (MTTU)	Mean time to drop sync when needs to. Lower is better.

- In the following slides, we will evaluate FS sync and self-sync based on these 4 parameters.
  - Various potential BERs
  - AWGN channel, burst channel (DFE based model)
  - Different padding insertion methods

Padding insertion methods

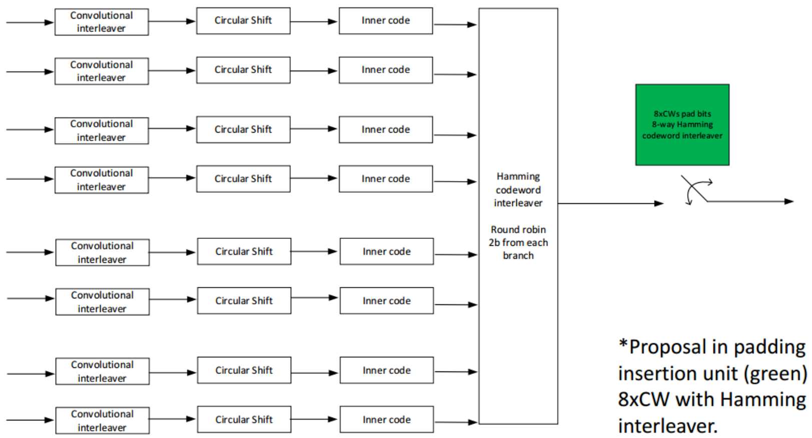
- Two padding insertion methods were proposed as in [farhood_3dj_01a_230206] and [rechtman_3dj_01a_2305].
- For each padding insertion method, both self-sync and FS sync can be used.
  - FS sync is better to be performed on 200G/lane data stream.
    - Sync probability is almost the same for the two insertion methods, but the 4 parameters will be different due to different insertion intervals.
  - Self-sync is performed on deinterleaved codeword streams. Padding can be located after codeword sync is obtained.
    - Sync probability is the same for the two insertion methods, so are the 4 parameters.
- Both padding insertion methods are analyzed in this presentation.

3x CWs padding for every 3264 CWs



From [farhood_3dj_01a_230206]

8x CWs (interleaved) padding for every 8704 CWs

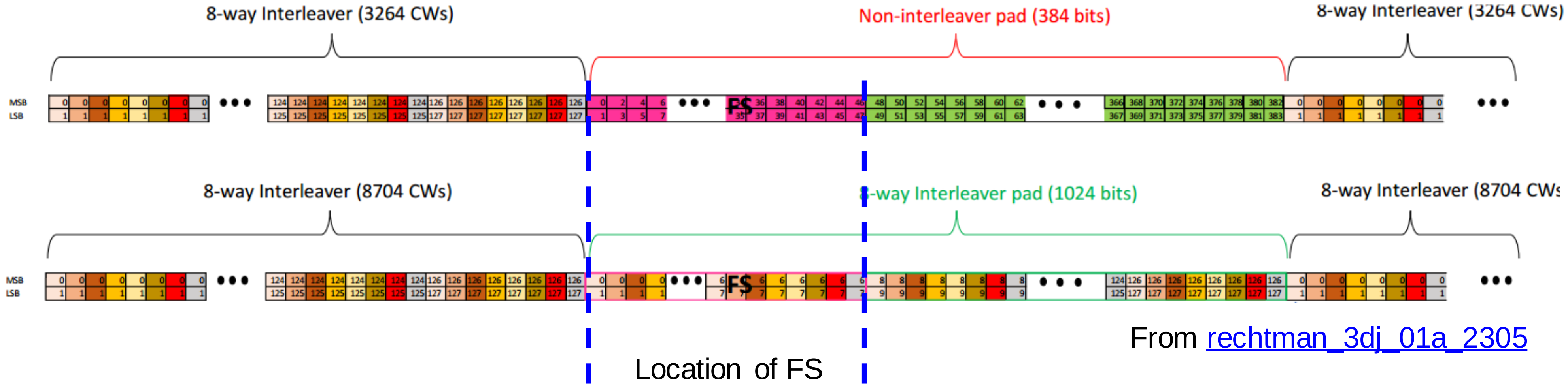


*Proposal in padding insertion unit (green) 8xCW with Hamming interleaver.

From [rechtman_3dj_01a_2305]

FS sync method

- FS sync method reuses CM portion of 400G PCS AM with similar locking approach.
  - 48-bit FS (12 half-byte nibbles), as proposed in [patra_3dj_01b_2303] and [huang_3dj_01_2307.]
  - If ***t*** or more nibbles in the candidate block match, it is recognized as a valid FS.
  - Lock state established when there are ***x*** successive valid FS.
  - Unlock when there are ***y*** successive invalid FS.
- FS sync is performed on the 200G/lane data stream.



From rechtman_3dj_01a_2305

FS sync performance calculation with AWGN channel

- Calculation of 4 parameters :
  - p_w = P(a valid FS at a wrong location) = $\sum_{i=t}^{12}\binom{12}{i} * p_0^i * (1-p_0)^{12-i}$, with $p_0 = (0.5)^4$。
  - p_c = P(an invalid FS at a correct location) = $\sum_{i=0}^{t-1}\binom{12}{i} * p_1^i * (1-p_1)^{12-i}$, with $p_1 = (1-\mathrm{BER})^4$, where BER indicates channel errors.
  - P_{fl} = P(false-lock) = Q * P(false lock at a wrong location) = Q * p_w^x.
    - Consider worst case when lock process starts from the next PAM4 symbol of correct location, then Q = L/2–1 wrong locations must be checked, where L is FS interval†.
    - **Mean time to false-lock** $MTTFL = x * L/P_{fl}\ /226.875e9\ /(3600*24*365)$ (years).
  - P_{fu} = P(false-unlock) = p_c^y.
    - **Mean time to false-unlock** $MTTFU = (y-1) * L/P_{fu}\ /226.875e9\ /(3600 * 24 * 365)$(years).
  - P_{lf} = P(fail to lock at the correct location after checking all possible Q positions) = $\sum_{i=0}^{x-1}(1-p_c)^i * p_c$.
    - **Mean time to lock** $MTTL = x * L/(1-P_{lf})/226.875e9$ (seconds).
  - P_{uf} = P(fail to unlock when needs to) = $1-(1-p_w)^y$.
    - **Mean time to unlock** $MTTU = (y-1) * L/(1-P_{uf})\ /226.875e9$ (seconds).

† For 3*128 insertion case, L=3267*128. For 8*128 insertion case, L=8712*128.

FS sync with AWGN channel

- Mean time to false-unlock is affected by channel BER, while mean time to false-lock is not.
- The sync method needs to work well within a range of BER.
  - We consider the BER range from 2E-3 to 5E-3 based on different “bypass” modes discussed previously.
- A proper choice is t = 9, x = 4, y = 6.
  - For simplification, table below is based on 3x128 padding insertion. (MTTX Values for 8x128 padding insertion is 8/3 times higher)

threshold t	Mean time to false-lock (years)					
	x = 2	x = 3	x = 4	x = 5	x = 6	x = 7
10	1.96E+02	5.51E+12	1.37E+23	3.22E+33	7.23E+43	1.58E+54
9	7.72E-02	4.30E+07	2.13E+16	9.89E+24	4.41E+33	1.91E+42
8	6.64E-05	1.09E+03	1.58E+10	2.15E+17	2.82E+24	3.58E+31
7	1.10E-07	7.58E-02	4.53E+04	2.54E+10	1.37E+16	7.17E+21

For t = 9, x = 4, y = 6. AWGN channel		
Parameters	**BER = 3E-3**	**BER = 5E-3**
Mean time to false-lock (years)	2.13E+16	2.13E+16
Mean time to false-unlock (years)	4.41E+17	3.05E+12
Mean time to lock (μs)	7.4	7.4
Mean time to unlock (μs)	9.2	9.2

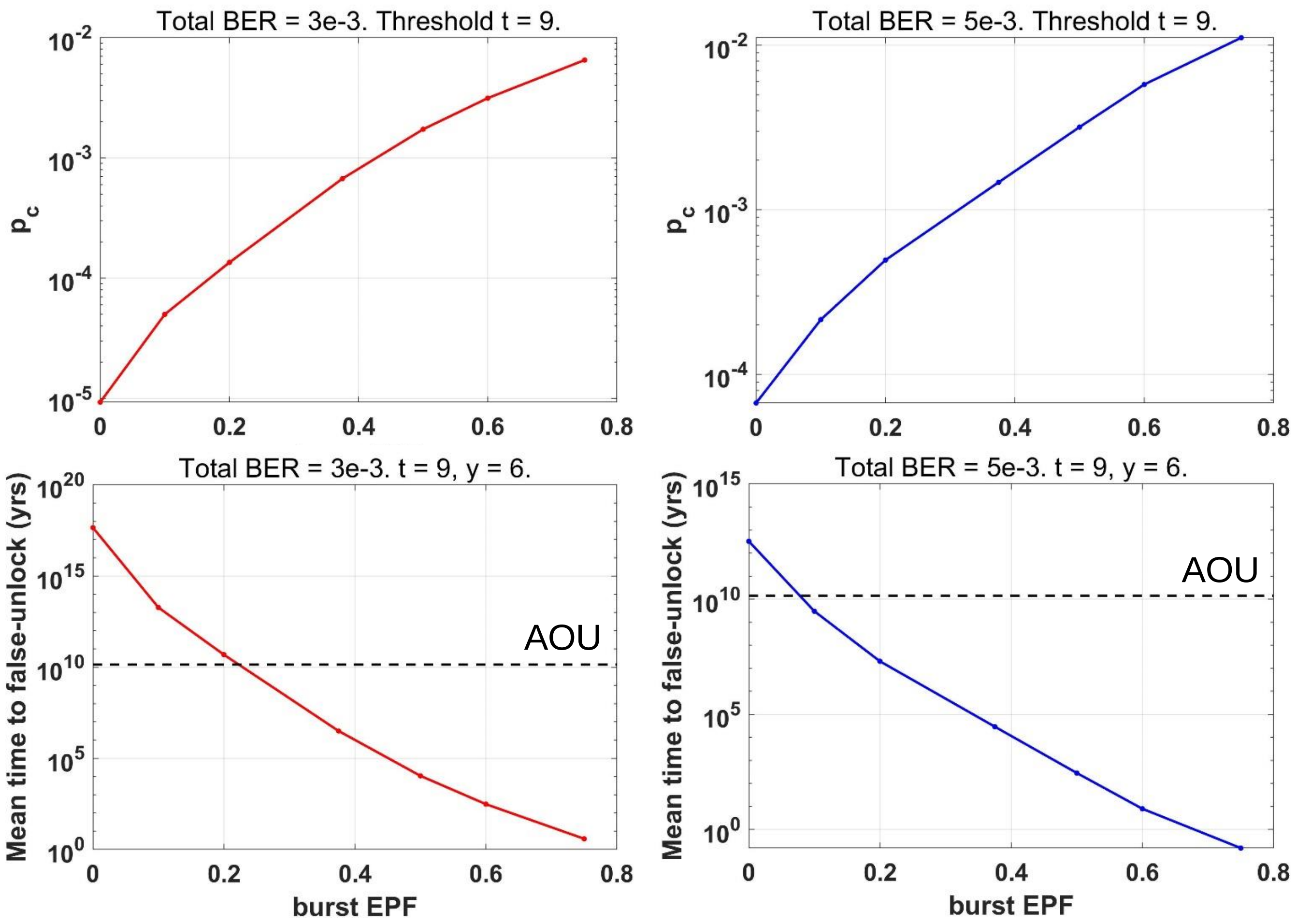
total BER	threshold t	Mean time to false-unlock (years)					
		y = 3	y = 4	y = 5	y = 6	y = 7	y = 8
2.00E-03	10	9.88E-02	1.40E+03	1.77E+07	2.09E+11	2.37E+15	2.61E+19
	9	1.69E+04	1.33E+10	9.36E+15	6.14E+21	3.87E+27	2.37E+33
	8	8.04E+09	4.95E+17	2.70E+25	1.38E+33	6.81E+40	3.26E+48
	7	9.82E+15	6.45E+25	3.77E+35	2.06E+45	1.08E+55	5.54E+64
3.00E-03	10	2.82E-03	1.22E+01	4.72E+04	1.70E+08	5.91E+11	1.99E+15
	9	1.43E+02	2.31E+07	3.29E+12	4.41E+17	5.67E+22	7.08E+27
	8	2.01E+07	1.68E+14	1.25E+21	8.69E+27	5.80E+34	3.77E+41
	7	7.26E+12	4.31E+21	2.28E+30	1.13E+39	5.36E+47	2.48E+56
4.00E-03	10	2.33E-04	4.40E-01	7.37E+02	1.16E+06	1.75E+09	2.57E+12
	9	5.00E+00	2.62E+05	1.22E+10	5.35E+14	2.24E+19	9.16E+23
	8	2.95E+05	6.03E+11	1.10E+18	1.87E+24	3.05E+30	4.85E+36
	7	4.47E+10	4.87E+18	4.72E+26	4.28E+34	3.73E+42	3.16E+50
5.00E-03	10	3.43E-05	3.42E-02	3.03E+01	2.52E+04	2.01E+07	1.56E+10
	9	3.78E-01	8.37E+03	1.65E+08	3.05E+12	5.41E+16	9.34E+20
	8	1.14E+04	7.87E+09	4.83E+15	2.78E+21	1.54E+27	8.25E+32
	7	8.81E+08	2.59E+16	6.77E+23	1.66E+31	3.90E+38	8.93E+45

Similar evaluations were provided in barakatain_3dj_01a_2303.

FS sync with burst channel

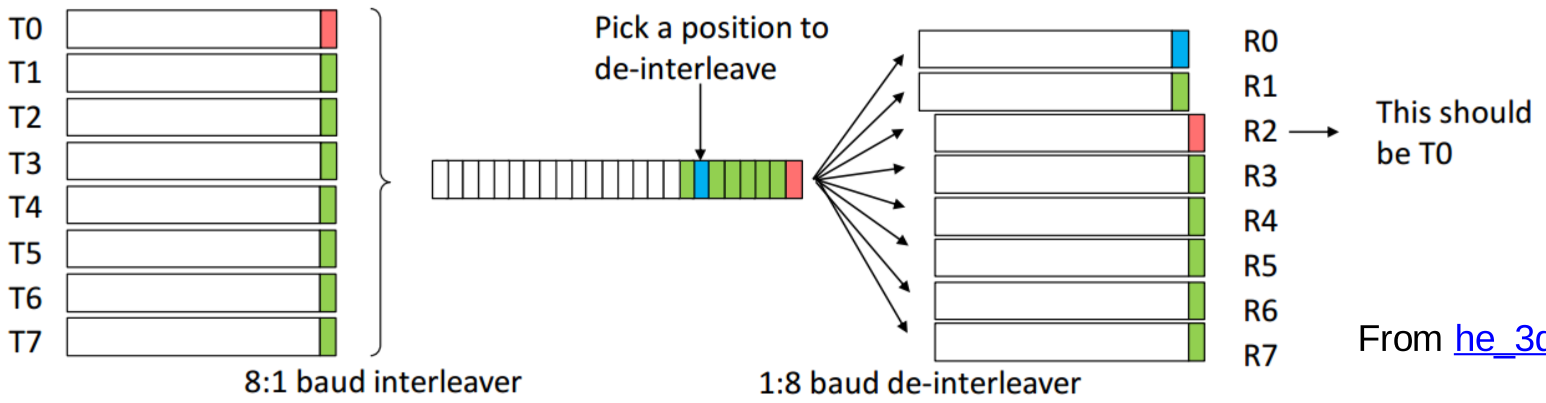
- As FS is not protected by the inner FEC or the 8:1 Baud interleaver, the probability p_c (probability of an invalid FS at a correct location) will be affected by burst errors, so MTTFU can be degraded.
  - The results are difficult to calculate but can be quickly evaluated by simulations, as shown below for 3x128b padding insertion.
- For EPF(error propagation factor) > 0.2, MTTFU will be lower than AOU with the chosen t/x/y.
  - Unwanted link interruption during normal operation.
- A larger value of *y* is needed to ensure sufficient MTTFU.
  - *y*=12 is the minimum number for an acceptable MTTFU with EPF=0.75.
  - Leads to more complexity and longer MTTU.
- For 8x128b padding insertion, y = 12 is also required.
  - Values below except for MTTFL can be multiplied by 8/3.

For t = 9, x = 4, y = 12. Burst EPF = 0.75		
Parameters	**BER = 3E-3**	**BER = 5E-3**
Mean time to false-lock (years)	2.13E+16	2.13E+16
Mean time to false-unlock (years)	1.11E+14	1.84E+11
Mean time to lock (µs)	7.6	7.7
Mean time to unlock (µs)	20.3	20.3



Self-sync method

- Self-sync uses the intrinsic feature of inner FEC code.
  - Perform self-sync on the de-interleaved codeword streams.
  - **Steps:**
    - **Search and Test**: Start the search from any candidate position, check ***N*** codewords, see if at least ***n*** of them are good.
      - If so, go to Validate. If not, shift potential start to next position (PAM4 symbol) and try again.
    - **Validate**: See if at least ***p*** in the following ***P*** codewords are also good.
      - If so, sync established. If not, go back to Search and Test.
    - **Monitor and Drop**: When there are ***m*** codewords are invalid in the following ***M*** codewords, drop sync and restart Search and Test.
- FS pattern comparison using the known codeword boundaries to identify padding.
  - FS pattern comparison can still be performed on the 200G/lane data stream for simpler padding definition.



From he_3dj_03b_2307

Self-sync performance calculation with AWGN channel

- Calculation of 4 parameters :
  - p_w = P(a CW is recognized as a good CW† at a wrong location) = $(2)^{-8}$.
  - p_c = P(a CW is recognized as a good CW† at a correct location) = $(1-\mathrm{BER})^{128}$, where BER indicates channel errors.
    - The probability of 2 errors in one PAM4 symbol is negligible, so degradation of XOR encoding is neglected. CWs with >=4 errors are also neglected.
  - P(T1) = P(search and test, at least n CWs are good at a wrong location) = $\sum_{i=n}^{N}\binom{N}{i} * p_w^i * (1-p_w)^{N-i}$.
  - P(T2) = P(search and test, less than n CWs are good at a correct location) = $\sum_{i=0}^{n-1}\binom{N}{i} * p_c^i * (1-p_c)^{N-i}$.
  - P(V1) = P(validate, at least p CWs are good at a wrong location) = $\sum_{i=p}^{P}\binom{P}{i} * p_w^i * (1-p_w)^{P-i}$.
  - P(V2) = P(validate, less than p CWs are good at a correct location) = $\sum_{i=0}^{p-1}\binom{P}{i} * p_c^i * (1-p_c)^{P-i}$.
  - P_{fl} = P(false-lock) = Q * P(false lock at one wrong location) = Q * P(T1) * P(V1) .
    - Consider worst case when lock process starts from the next PAM4 symbol of correct location, then Q = 128/2 – 1 wrong locations must be checked.
    - **Mean time to false-lock** $MTTFL$= (N+P+1)*128 / P_{fl} / 28.36e9 / (3600*24*365) / 8 (years). The last number 8 is for 8*25G.
  - P_{fu} = P(false-unlock) = $\sum_{i=0}^{M-m}\binom{M}{i} * p_c^i * (1-p_c)^{M-i}$.
    - **Mean time to false-unlock** $MTTFU$ = M*128 / P_{fu} / 28.36e9 / (3600*24*365) / 8 (years).
  - P_{lf} = P(lock fail at the correct location after checking Q positions) = P(T2) + (1- P(T2)) * P(V2).
    - **Mean time to lock** $MTTL$ = (N+P+1)*128 / (1 - P_{lf}) / 28.36e9 (seconds).
  - P_{uf} = P(unlock fail when needs to) = $\sum_{i=M-m+1}^{M}\binom{M}{i} * p_w^i * (1-p_w)^{M-i}$.
    - **Mean time to unlock** $MTTU$ = M*128 / (1 - P_{uf}) / 28.36e9 (seconds)

† This includes the probability of an invalid CW skips error checking.

Performance comparison between self-sync and FS sync under AWGN

- MTTFU is affected by channel BER while MTTFL is not.
- The BER range from 2E-3 to 5E-3 is assumed.
- For easier calculation, let N = P = 50, n = p = 13, M = 150, m = 140.
  - **Self-sync outperforms FS sync in every parameter.**
- Self-sync does not require additional logic due to intrinsic decoding functions.
- Self-sync itself is protocol agnostic, and does not rely on padding content definition.

Self-sync

N = P = 50, n = p = 13, M = 150, m = 140. AWGN channel				
Parameters	**BER = 2E-3**	**BER = 3E-3**	**BER = 4E-3**	**BER = 5E-3**
Mean time to false-lock (MTTFL) (years)	6.66E+22	6.66E+22	6.66E+22	6.66E+22
Mean time to false-unlock (MTTFL) (years)	6.99E+60	1.99E+41	1.86E+28	3.26E+18
Mean time to lock (MTTL) (μs)	<1	<1	<1	<1
Mean time to unlock (MTTU) (μs)	<1	<1	<1	<1

FS sync

t = 9, x = 4, y = 6. AWGN channel				
Parameters	**BER = 2E-3**	**BER = 3E-3**	**BER = 4E-3**	**BER = 5E-3**
Mean time to false-lock (MTTFL) (years)	2.13E+16	2.13E+16	2.13E+16	2.13E+16
Mean time to false-unlock (MTTFL) (years)	6.14E+21	4.41E+17	5.35E+14	3.05E+12
Mean time to lock (MTTL) (μs)	7.4	7.4	7.4	7.4
Mean time to unlock (MTTU) (μs)	9.2	9.2	9.2	9.2

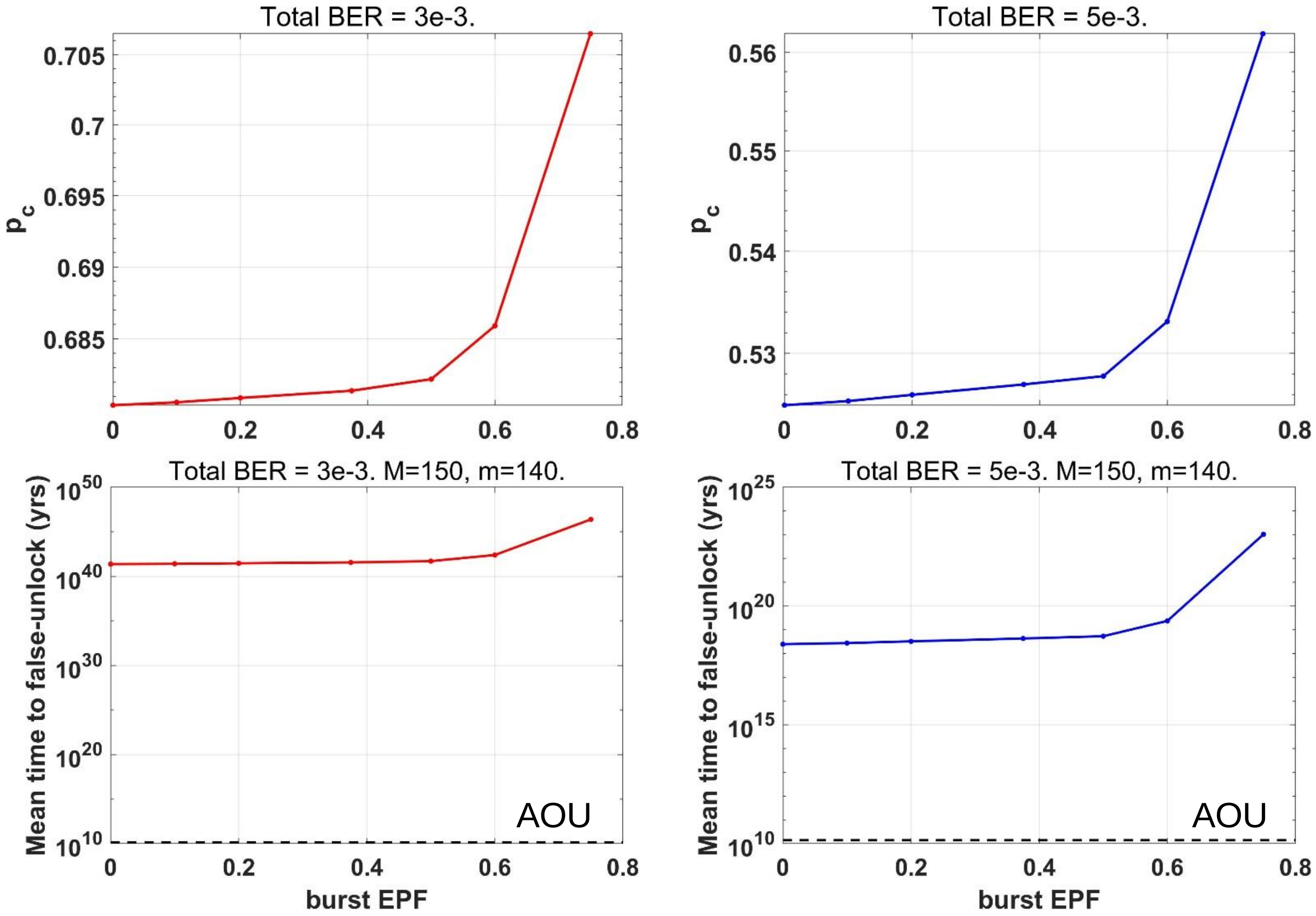
(Based on 3x128 Padding Insertion)

Self-sync with burst channel

- Even with the Baud interleaver, burst error still affects probability p_c (a codeword is good at a correct location), so MTTFU changes with BER and EPF.

- Self-sync performance will not degrade with burst error when measured BER is limited.

- If 8x128b padding is used, padding CWs do not need special processing.
  - All CWs received can be used for self-sync.



Locating padding after self-sync

- After self-sync is done, padding can be located based on codeword boundaries.
  - Padding can be confirmed by identifying ***x*** successive valid FS.
  - FS compare is recommended to be performed on 200G data streams to avoid complex definition of padding.
  - P_{fl} = P(false-lock) = Q * P(false lock at a wrong location) = Q * p_w^x.
    - Due to known codeword boundaries, Q is reduced from L/2–1 to L/128/8–1.
      - The reliability is improved by 500+ times comparing to FS search.
    - MTTFL = $x * L/P_{fl}$ / 226.875e9 / (3600*24*365) (years).

- Once in FS lock state, FS lock monitoring **may** not be needed.
  - The location of FS is always bind to codeword boundary.
  - Maintaining FS lock/unlock state machine could improve robustness and interoperability if one chooses to use FS sync.

Summary

- A self-sync method is proposed for inner FEC.
- FEC codeword boundary detection is inherent, no additional logic is required.
- Self-sync performs better than FS sync in every evaluated aspect.
  - Mean time to false-unlock of FS sync is sensitive to burst errors and decreases sharply with increased EPF.
  - Self-sync performance will not degrade with burst error.
- The self-sync method itself is "protocol agnostic"
  - It does not rely on padding content definition.
  - It could be used for the two different padding insertion proposals.
- FS pattern comparison is still needed to locate padding CWs after self-sync is established.
  - FS pattern comparison is recommended to be performed on the 200G/lane data stream.

Thank you