Code-aided Frame Synchronization

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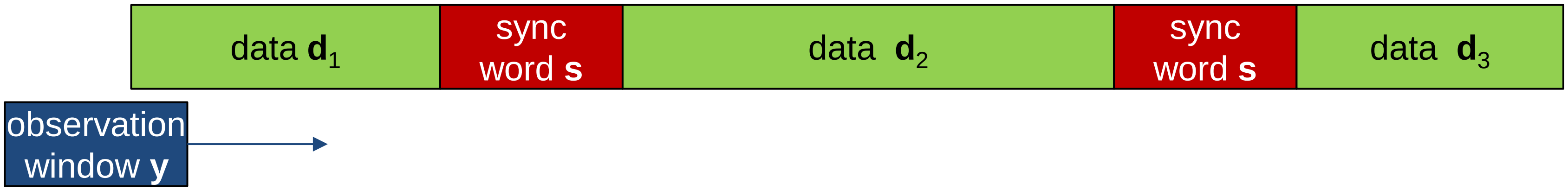
State of the Art

- Problem: Find start of frame, typically marked with a sync word
- Typical frame structure



Typical approach

- Sliding observation window of length N_S
- Compare received symbols $\boldsymbol{y}_n \triangleq [y_n, y_{n+1}, \dots, y_{n+N_S-1}]$ with known sync word $\mathbf{s} = [s_1, s_2, \dots, s_{N_S}]$
- For each position of the observation window, compute a metric $\Lambda(\mathbf{y}_n)$
- Commonly used metric: hard or soft correlation

Frame Structure: Periodic or not

Two cases for frame structure:

1. Periodically inserted sync word [Massey 1972]
   - Constant frame length $N_\mathrm{f} = N_\mathrm{s} + N_\mathrm{c}$
   - Find position which maximizes metric: $n^* = \arg\max\{\Lambda(\mathbf{y}_n)\}$

2. One-shot frame synchronization [Chiani 2006]
   - Frame length is variable or unknown
   - Delay or memory constraints do not allow to process the entire frame

   ⇒ **Hypothesis testing**

$$\begin{aligned} \mathcal{H}_0&: \quad \mathbf{y} = \mathbf{d} + \mathbf{w} \quad \text{data} \\ \mathcal{H}_1&: \quad \mathbf{y} = \mathbf{s} + \mathbf{w} \quad \text{sync word} \end{aligned}$$

[Massey 1972] J. L. Massey, "Optimum frame synchronization", *IEEE Trans. Commun.*, April 1972.
[Chiani 2006] M. Chiani, M. G. Martini, "On sequential frame synchronization in AWGN channels", *IEEE Trans. Commun.*, Feb. 2006.

Hypothesis Testing with Likelihood Ratio Test (LRT)

- Likelihood Ratio Test (LRT)

$$\Lambda(\mathbf{y}) \triangleq \frac{p(\mathbf{y} \mid \mathcal{H}_1)}{p(\mathbf{y} \mid \mathcal{H}_0)} \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda$$

y is sync word ($\mathcal{D}_1$)

y is not sync word ($\mathcal{D}_0$)

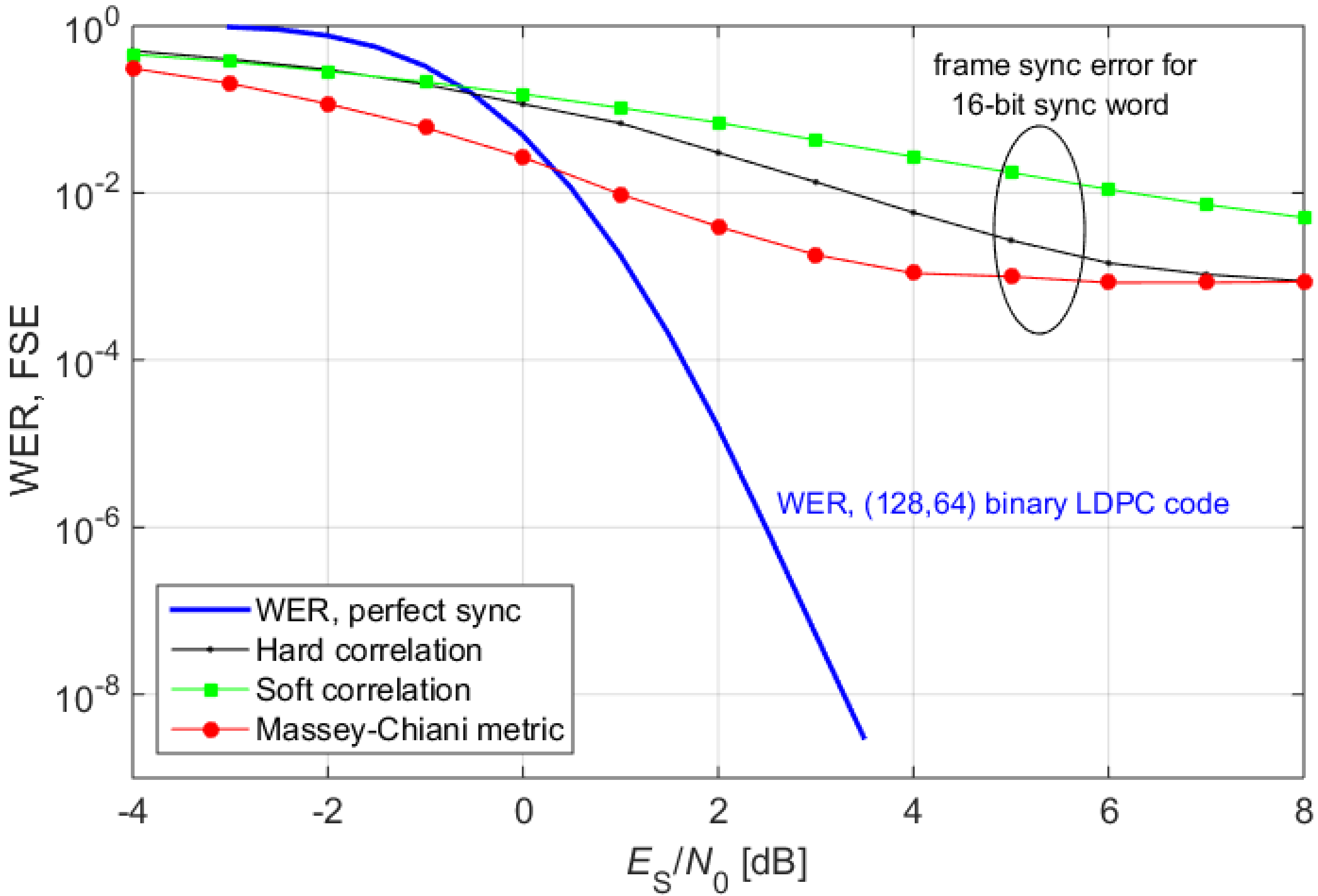
  - „mixed data“ case is neglected
- Channel model: BI-AWGN

$$y_n = x_n + w_n, \qquad x_n \in \{-1,1\}, \qquad w_n \sim \mathcal{N}(0, N_0/2)$$

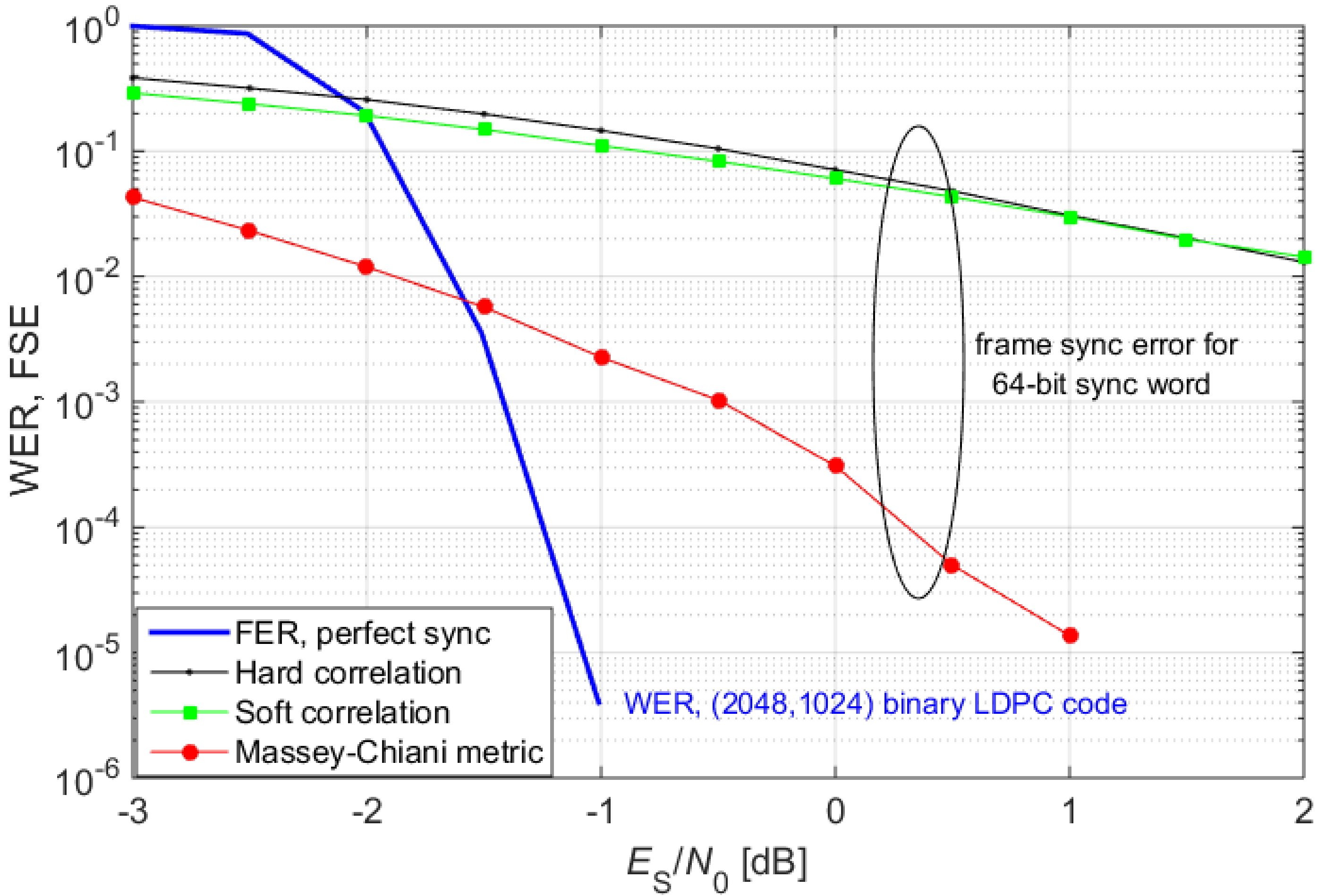
This leads to the metric (Massey-Chiani)

$$\Lambda_{\mathrm{MC}}(\mathbf{y}) = \sum_{n=1}^{N_s} \frac{2}{N_0} s_n y_n - \ln\cosh\left(\frac{2}{N_0} y_n\right)$$

Frame Syncronization Error for Deep-Space Uplink vs. Word Error Rate of new Channel Code



FSE and WER for (2048,1024) LDPC code (deep-space downlink)



Observations and possible Enhancement: Exploit Additional Structure in the Frame

Observations

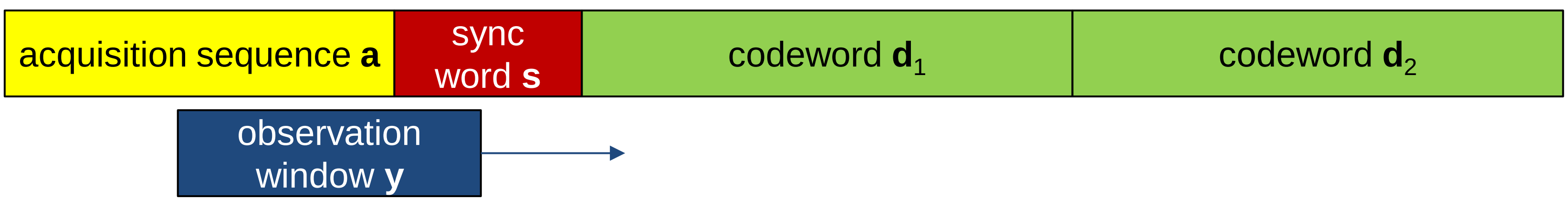
- Massey-Chiani metric is significantly better than correlation
- However, FER is limited by sync errors, not by decoding errors

  ⇒ increase length of sync word ?

  ⇒ exploit additional information !

Additional structure:

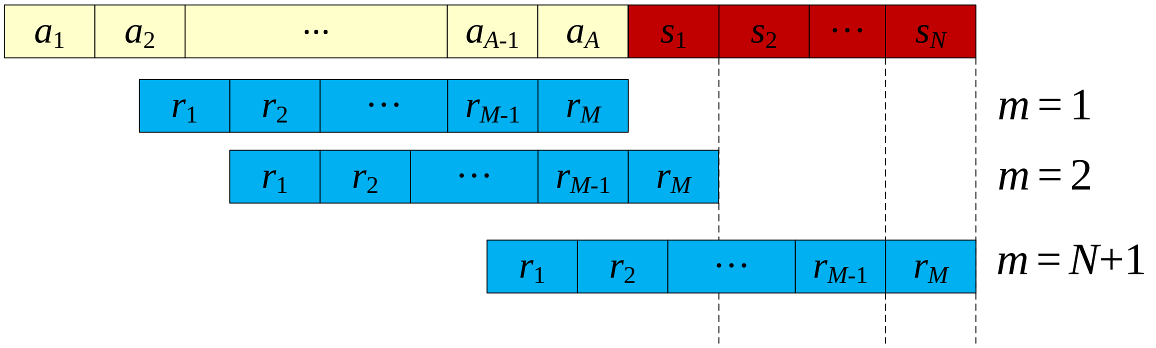
- Sync word is often preceded by an acquisition or idle sequence
- Channel code



A: Exploit Acquisition Sequence

- The acquisition sequence is an alternating ± 1 sequence
- Consider this information in LRT
- Mixed data case is not negligible anymore
- Increase size of observation window: $\boldsymbol{y}_n \triangleq [y_n, y_{n+1}, \dots, y_{n+M-1}]$ with $M \geq N_s$

- Example positions of extended observation window



- Hypotheses:

$$\mathcal{H}_0: \; m = 1, 2, \dots, N_s$$
$$\mathcal{H}_1: \; m = N_s + 1$$

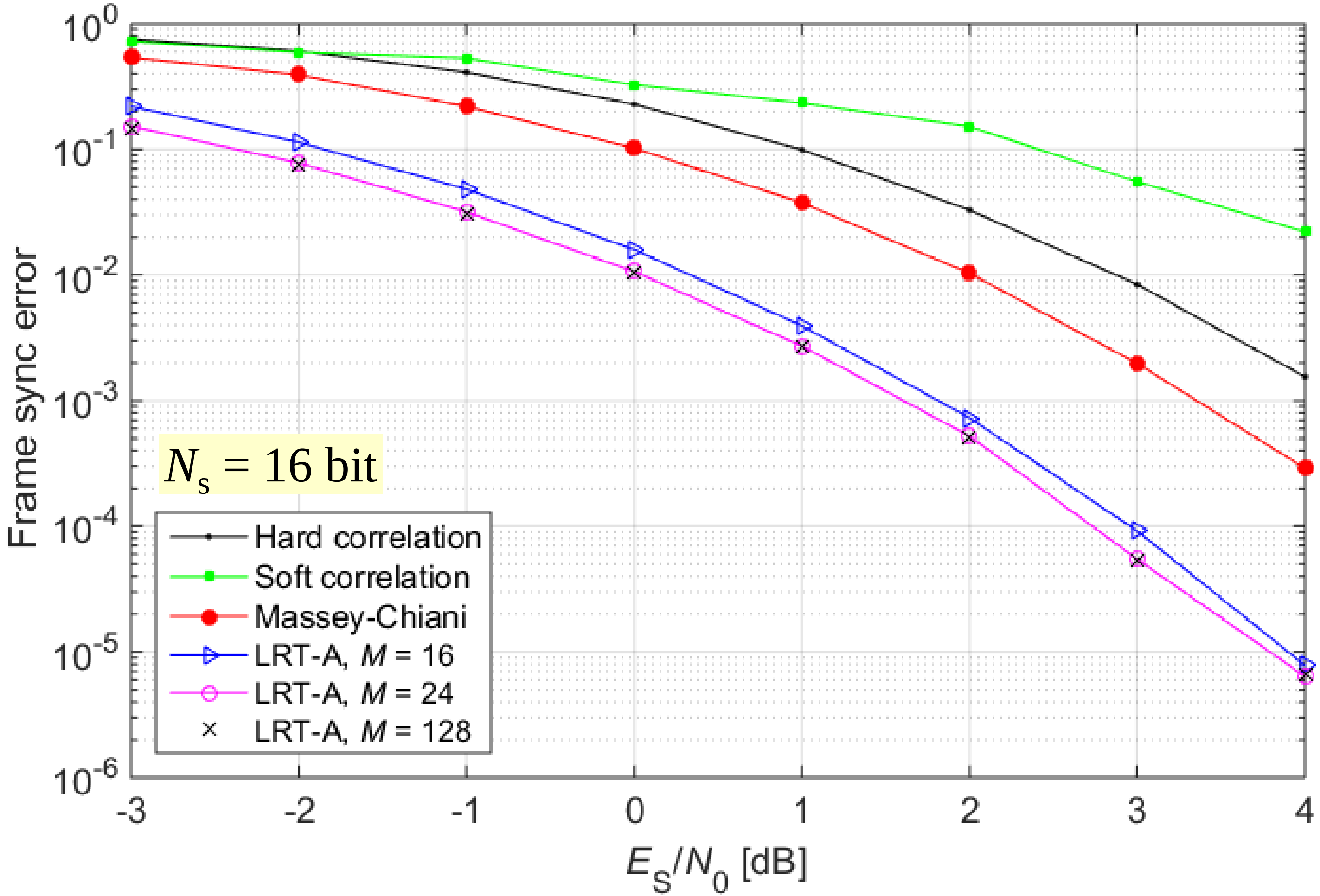
LRT considering acquisition sequence

- Likelihood ratio test leads to

$$\Lambda_{\mathrm{LRT-A}}(\mathbf{y}) = \ln\cosh\left(\frac{2}{N_0}\sum_{n=1}^{M-N_s}(-1)^n y_n\right) + \ln\cosh\left(\frac{2}{N_0}\sum_{n=M-N_s+1}^{M} s_{n-M+N_s} y_n\right) - \ln\sum_{m=1}^{N_s}\rho_m \cosh\left(\frac{2}{N_0}\sum_{n=1}^{M-m+1}(-1)^n y_n\right)\cosh\left(\frac{2}{N_0}\sum_{n=M-m+2}^{M} s_{n-M+m-1} y_n\right)$$

  - all positions of observation window have to be considered

A: Simulation Results for 16-bit sync word



Observations

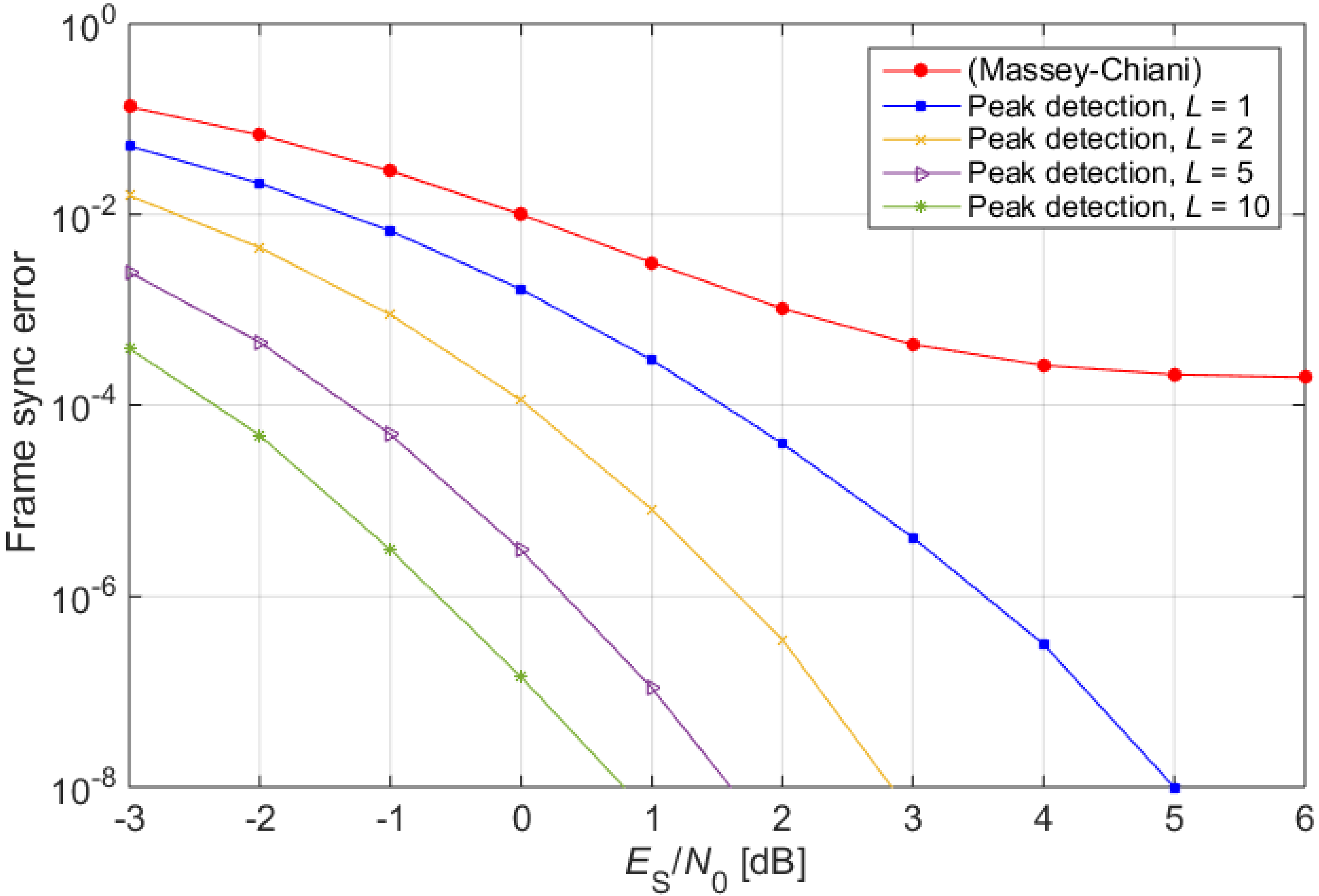
- Significant improvement by considering preceding acquisition (or idle) sequence
- Small improvement by extending observation window beyond length of sync word

B: Exploit Acquisition Sequence and (perfect) Error Detection

- Long observation window which contains sync word with high probability
- Find peak of metric
  $\Rightarrow$ detection of maximum, like in periodic case
- Channel code provides error detection: eliminate false alarms
- Consider not only position with maximum metric, but the first L positions

DLR

B: Simulation results for 16-bit sync word, 64-bit buffer (perfect error detection)



Observations method B

- Significant improvement by exploiting error detection capabilities of channel code (here assumed ideal)

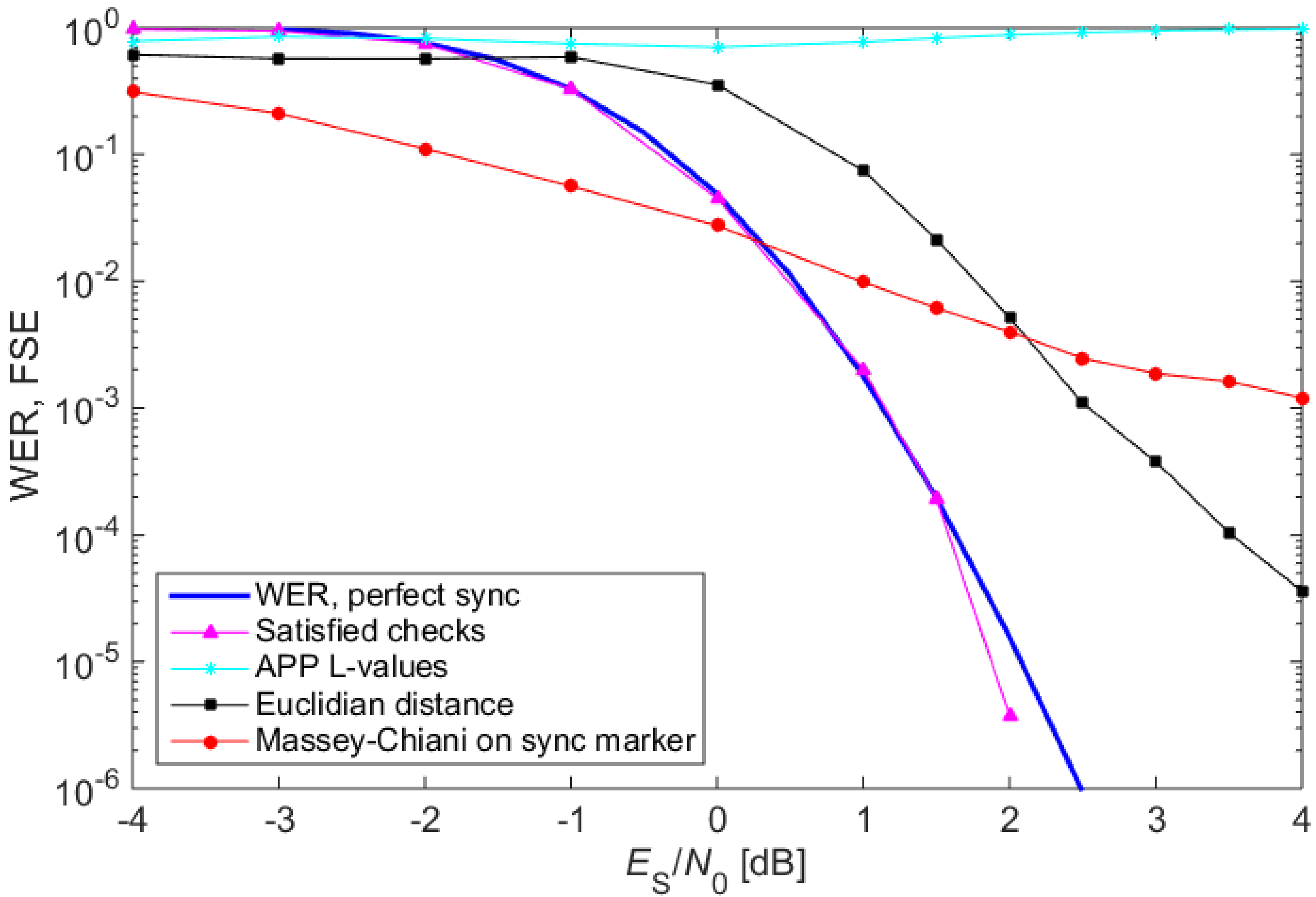
C: Frame sync without sync word: Code-based only

Metrics

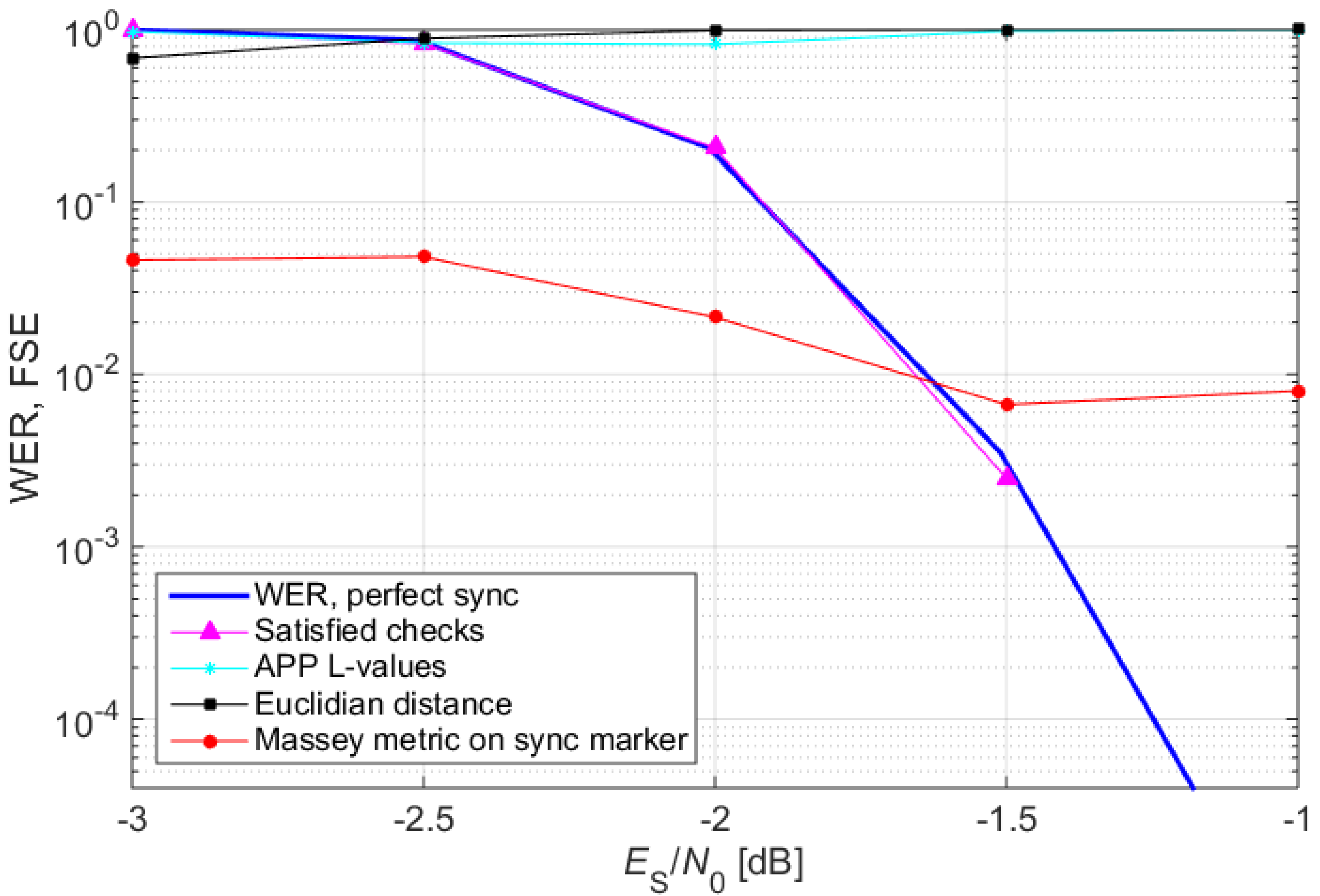
1. Number of satisfied parity checks
2. Sum of magnitude of APP L-values
3. Euclidian distance between reconstructed modulated sequence and received sequence

[Hamkins 2011] J. Hamkins, “Frame Synchronization Without Attached Sync Markers”, IEEE Aerospace Conf. 2011.
Earlier works: Matsumoto and Imai,2002. Wymeersch et al., 2003, 2006. Lee et al., 2007, 2008.

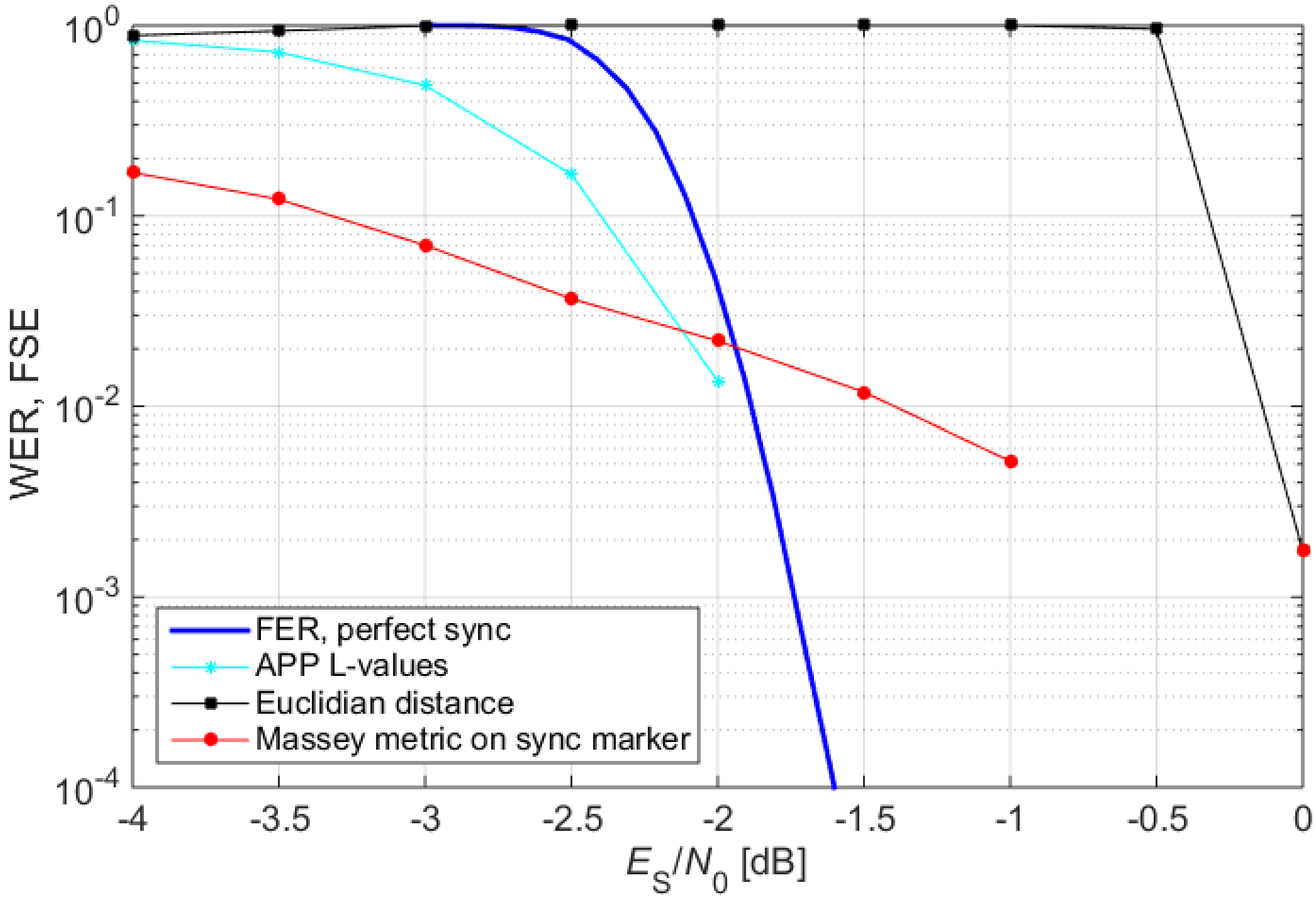
C: (128, 64) binary LDPC code
16-bit sync word



C: (2048,1024) binary LDPC code (CCSDS AR4JA) 64-bit sync word



C: (3576,1784) CCSDS turbo code



Discussion

- LDPC: Only number of satisfied check nodes performs well
- Turbo: Sum of posterior L-values works well

✓ Code-aided frame sync can match performance of channel code

× High complexity

× Different optimum metrics for turbo and LDPC codes

[Results are preliminar]

Summary and Outlook

- Presented results are based on receiver enhancements
- A: Frame sync based on sync marker alone results in poor performance
- B: Exploitation of error detection is not always feasible (or desired)
- C: Code-only based frame sync has high complexity
- Way forward: Joint design of channel code and sync constraints …