ELEC6014 AWCNSs: Advanced Topic Seminar

Accurate Acquisition of MIMO Channel State Information: How Big the Problem

Professor Sheng Chen

Electronics and Computer Science

University of Southampton

Southampton SO17 1BJ, UK

E-mail: sqc@ecs.soton.ac.uk

Acknowledgements: Peichang Zhang, Lajos Hanzo

MIMO Wonderland

- Coherent MIMO: promises **wonderland** of **diversity** and/or **multiplexing** gains
  - Reaching MIMO promised land requires accurate MIMO CSI estimate
- **Challenge**: acquisition of accurate MIMO channel state information
  - Without sacrificing system throughput too much
  - Avoiding significant increase in computational complexity
- **Training** based or pure **blind** methods cannot meet these needs
- No-coherent or **differential** MIMO does not require CSI but suffers from 3 dB penalty in SNR and less design freedom
- Existing state-of-the-art: **semi-blind** iterative channel estimation and turbo detection-decoding
  - Using a very small training overhead to obtain initial MIMO CSI estimate
  - Using soft decisions from turbo detector-decoder to update MIMO CSI

Challenge/Motivation

- The best **existing** state-of-the-arts suffer from some serious drawbacks:

  1. Introduce **extra iterative loop** between CE and turbo detector-decoder ⇒ increase complexity considerably
  2. Use **entire frame** of L_F detected soft bits for CE ⇒ SDD least squares channel estimate imposes complexity $\mathcal{O}\big(L_F^3\big)$ unacceptably high
  3. Error propagation **severely degrade** achievable performance ⇒ fail to approach optimal ML turbo detection-decoding bound associated with perfect CSI

- It seems reaching **MIMO wonderland** necessary to implant substantial training overhead, which dramatically erodes system's throughput

- **Or is it?** Our objective is to demonstrate MIMO wonderland can be reached

  – with aid of very modest (minimum) training overhead
  – without significantly increasing complexity associated with the optimal ML turbo detector-decoder of perfect CSI

Reaching MIMO Wonderland

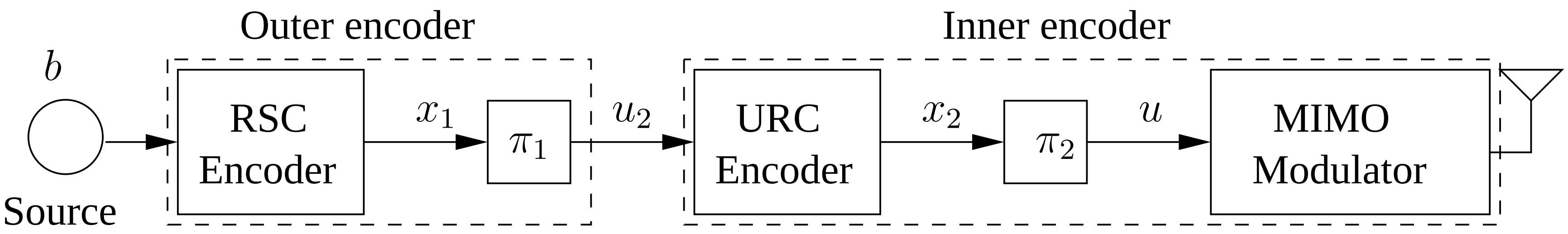
- Block-of-bits selection based soft-decision aided CE scheme:
  - select just-sufficient-number of high-quality blocks of bits or detected symbols for channel estimation

- Our BBSB-SCE and three-stage turbo detector-decoder:
  1. CE naturally embedded in original turbo detection-decoding process ⇒ **no extra iterative loop** between CE and turbo detector-decoder
  2. Only utilize more reliable detected symbols ⇒ **not entire frame** of detected soft bits for CE, dramatically reducing complexity
  3. **Attain optimal** ML turbo detector-decoder bound associated with perfect CSI, while imposing similar complexity

- P. Zhang, S. Chen and L. Hanzo, "Near-capacity joint channel estimation and three-stage turbo detection for MIMO systems," *WCNC 2013* (Shanghai, China), April 7-10, 2013 (best paper award)
- –, "Embedded iterative semi-blind channel estimation for three-stage-concatenated MIMO-aided QAM turbo-transceivers," *IEEE Trans. Vehicular Technology*, 63(1), 439–446, 2014

Three-Stage Turbo Encoder

- **Three-stage turbo encoder** employed at transmitter:



  - Two-stage **inner** encoder is formed by L-QAM MIMO modulator with unity-rate-code (URC) encoder
  - **Outer** encoder employs half-rate recursive systematic code

- Low-complexity memory-1 URC has **infinite impulse response**
  - Spread **extrinsic** information beneficially across the iterative decoder components without increasing its delay
  - Extrinsic information transfer curve is capable of reaching (1.0, 1.0) point of perfect convergence in EXIT charts
  - A necessary condition for **near-capacity** operation and for achieving **vanishingly small** bit error rate

MIMO System Model

- MIMO system employs N_T transmit antennas and N_R receive antennas for communication over flat Rayleigh fading environment

$$\boldsymbol{y}(i) = \boldsymbol{H}\boldsymbol{s}(i) + \boldsymbol{v}(i)$$

  - $\boldsymbol{y}(i) \in \mathbb{C}^{N_R}$: received signal vector
  - $\boldsymbol{H} \in \mathbb{C}^{N_R \times N_T}$ MIMO channel matrix whose elements obey $\mathcal{CN}(0,1)$
  - $\boldsymbol{s}(i) \in \mathbb{C}^{N_T}$: transmitted L-QAM symbol vector
  - $\boldsymbol{v}(i) \in \mathbb{C}^{N_R}$: AWGN vector whose elements obey $\mathcal{CN}(0, N_{\text{o}})$
  - $\{u_k\}_{k=1}^{\text{BPB}}$: bits that are mapped to $\boldsymbol{s}(i)$
  - Frame of received MIMO data sequence $\boldsymbol{Y}_{\text{d}M_F} = [\boldsymbol{y}(1)\ \boldsymbol{y}(2) \cdots \boldsymbol{y}(M_F)]$

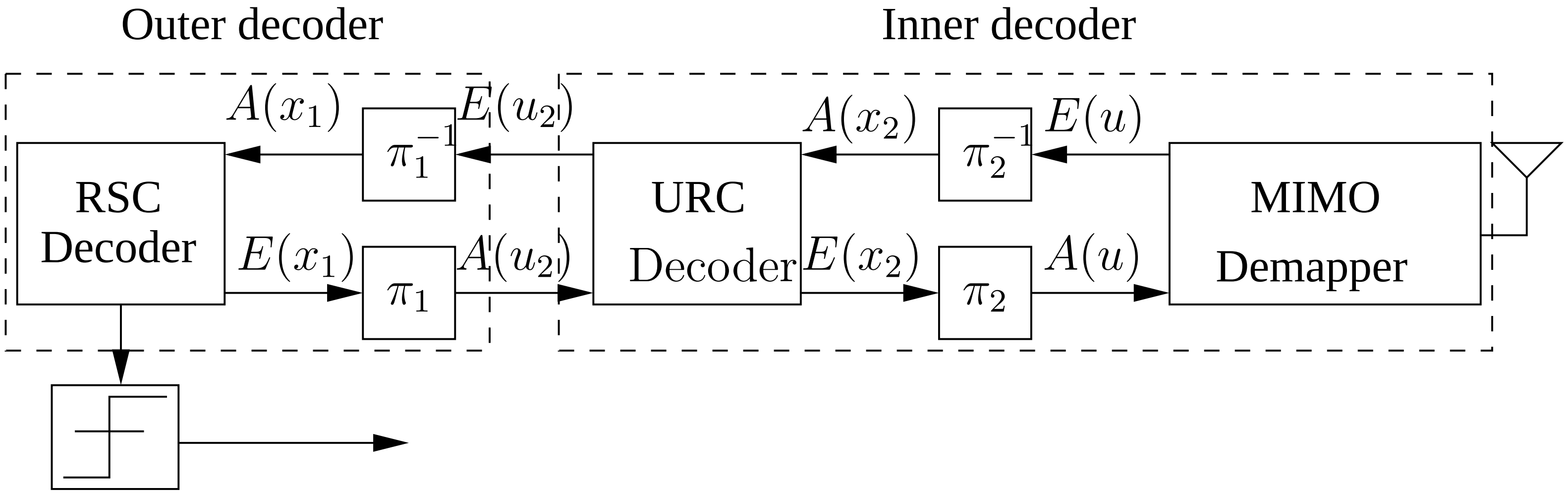
- Number of bits per symbol: BPS $= \log_2(L)$; number of bits per block: BPB $= N_T \cdot \log_2(L)$

- A frame contains M_F symbol vectors, or $L_F =$ BPB $\cdot\, M_F$ bits

- System SNR $= E_{\text{s}}/N_{\text{o}}$, with E_{s} being average symbol energy

Three-Stage Turbo Decoder

- **Three-stage turbo decoder** employed at receiver:



- Upon obtaining *a priori* LLRs $\left\{L_a(u)\right\}_{k=1}^{\text{BPB}}$ from **channel decoder**, ML MIMO **soft-demapper** produces *a posterior* LLRs:

$$L_p\left(u_k\right) = L_p(k) = \ln \frac{\sum\limits_{\boldsymbol{s}^n \in \{\boldsymbol{s}_{u_k=1}\}} \exp(p_n)}{\sum\limits_{\boldsymbol{s}^n \in \{\boldsymbol{s}_{u_k=0}\}} \exp(p_n)}$$

$$p_n = -\frac{\|\boldsymbol{y}(i) - \boldsymbol{H}\boldsymbol{s}^n\|^2}{N_{\text{o}}} + \sum_{k=1}^{\text{BPB}} \tilde{u}_k L_a(u_k)$$

$\left\{\tilde{u}_k\right\}_{k=1}^{\text{BPB}}$ are the corresponding bits that map to the specific symbol vector $\boldsymbol{s}^n$

Three-Stage ML Turbo Detector-Decoder

- Given the CSI $\boldsymbol{H}$, computational complexity of the three-stage **optimal maximum likelihood** turbo receiver

$$C_{\text{ideal}} = I_{\text{out}}\Big(C_{\text{RSC}} + I_{\text{in}}\big(C_{\text{ML}} + C_{\text{URC}}\big)\Big)$$

  - C_{RSC}, C_{URC} and C_{ML}: complexity of **RSC decoder**, **URC decoder**, and **ML soft-demapper**, respectively
  - Two-stage inner turbo loop: I_{in} iterations; outer turbo loop: I_{out} iterations
  - For larges MIMOs, use reduced-complexity near-optimum detectors, e.g. K-best sphere detector, to avoid exponentially increasing complexity of ML

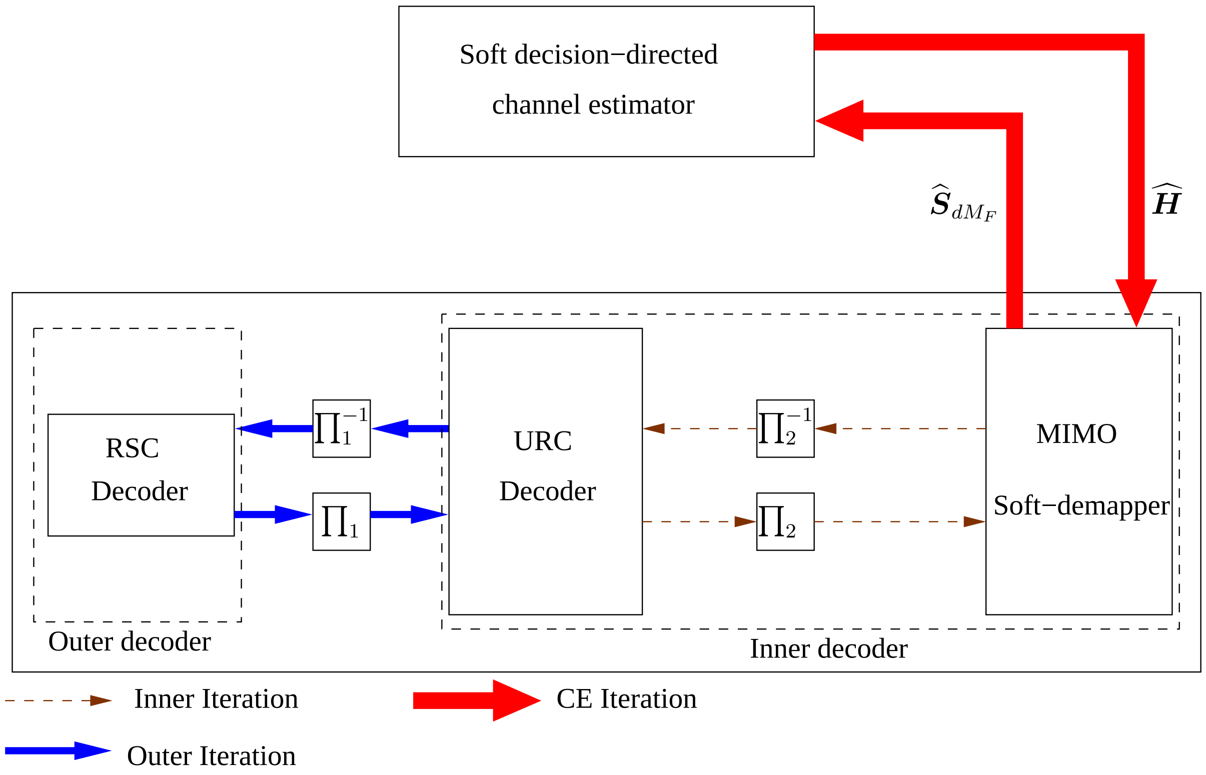
- For **unknown** CSI, **training** based LS estimator may be employed to obtain $\boldsymbol{H}$

$$\widehat{\boldsymbol{H}}_{LSCE} = \boldsymbol{Y}_{tM_T}\boldsymbol{S}_{tM_T}^{\text{H}}\big(\boldsymbol{S}_{tM_T}\boldsymbol{S}_{tM_T}^{\text{H}}\big)^{-1}$$

  - given $M_T \geq N_T$ training data $\boldsymbol{Y}_{tM_T} = \big[\boldsymbol{y}(1)\ \boldsymbol{y}(2)\cdots\boldsymbol{y}(M_T)\big]$ and $\boldsymbol{S}_{tM_T} = \big[\boldsymbol{s}(1)\ \boldsymbol{s}(2)\cdots\boldsymbol{s}(M_T)\big]$ $\Rightarrow$ Unless M_T is sufficiently large, accuracy is poor

Existing State-of-the-Arts

- To maintain system's throughput, use small (M_T close to N_T) training data to obtain initial $\widehat{\boldsymbol{H}}_{LSCE}$, then use soft-decision based LS estimator



- To fully exploit error correction capability, soft-decision channel estimation takes place **after convergence** of three-stage turbo detection-decoding
  - This introduces the **additional CE loop**

Complexity/Performance of Existing State-of-the-Arts

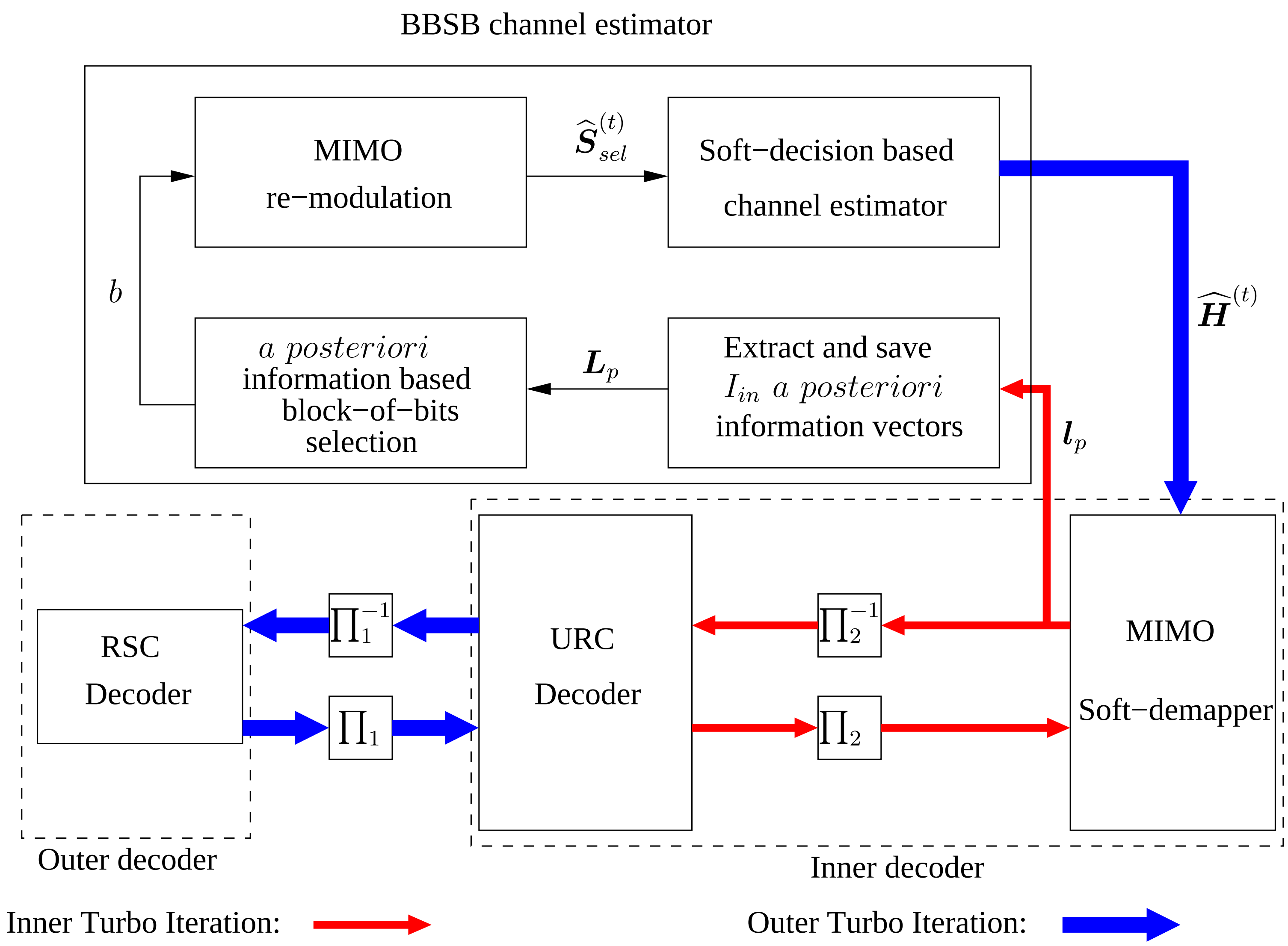
- Able to rely on **very small training overhead** M_T
  - Three-stage turbo detector-decoder improve reliability of detected bits
  - Which assists soft-decision channel estimator to provide more accurate CE
  - Iterations result in increasingly more reliable turbo detector-decoder output

- Although very powerful with excellent performance, having following drawbacks
  1. Have to use **entire frame** of M_F soft-decision detected symbol vectors for DD LSCE, with complexity $\mathcal{O}\big(M_F^3\big)$
  2. Need **extra** CE iterative loop, which requires $I_{\rm ce}$ iterations to converge
  3. Cannot attain idealised optimal ML three-stage turbo detector-decoder bound associated with perfect CSI (**still unable** to reach MIMO promised land)

- Total complexity: $C_{\rm con} = I_{\rm ce} \cdot \mathcal{O}\big(M_F^3\big) + I_{\rm ce} \cdot C_{\rm ideal}$
  - Repeat three-stage turbo detection-decoding $I_{\rm ce}$ times
  - As M_T typically in thousands, $\mathcal{O}\big(M_F^3\big)$ is **extremely high**
  - Complexity is **significantly higher** than $C_{\rm ideal}$

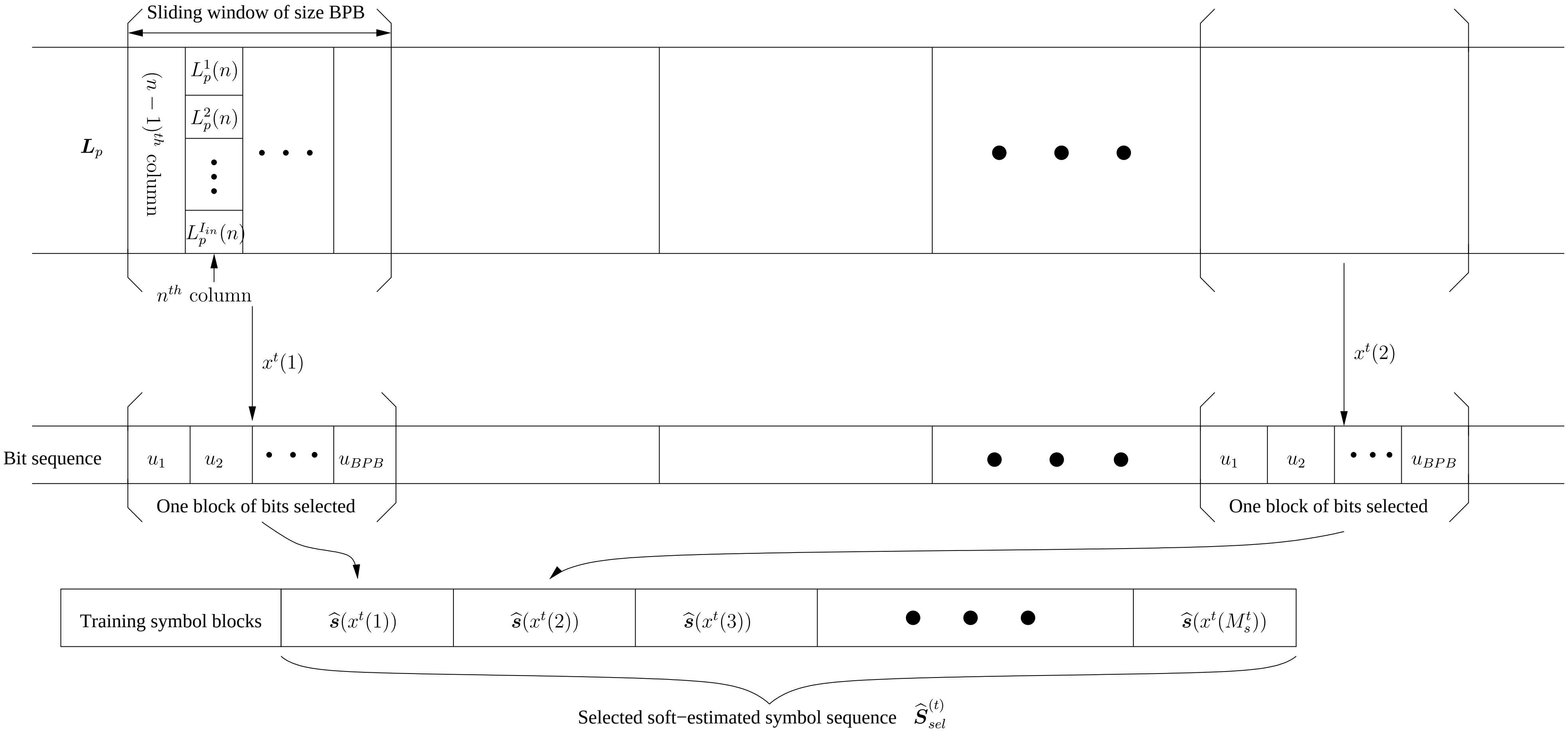
How to Reach MIMO Wonderland

- **Proposed scheme**: soft-decision based channel estimator naturally embedded in original iterative process of three-stage turbo detector-decoder ⇒ **no extra CE loop**



Select Reliable Blocks of Bits (1)

- How can we get rid of extra **CE loop**: figure out a clever way of only selecting **high-quality** blocks of bits or symbols $\Rightarrow$ no need to wait for convergence of three-stage turbo process



- Inner decoder iterations yield I_{in} *a posterior* soft decisions $\left\{L_p^1(n), L_p^2(n), \cdots, L_p^{I_{\text{in}}}(n)\right\}$ for nth bit $\Rightarrow$ information regarding whether nth detected bit is **reliable or not**

Select Reliable Blocks of Bits (2)

1. nth bit is **reliable**: if nth column of *a posterior* information matrix $\boldsymbol{L}_p \in \mathbb{C}^{I_{\text{in}} \times L_F}$ satisfies

$$\frac{|L_p^1(n) - L_p^2(n)| + |L_p^2(n) - L_p^3(n)| + \cdots + |L_p^{I_{\text{in}}-1}(n) - L_p^{I_{\text{in}}}(n)|}{|\mu|} \in (0, T_h)$$

   where μ is the mean of the column, and T_h a pre-defined block-of-bits **selection threshold**
   - Soft decisions for nth bit relatively similar $\Rightarrow$ a stable state may be reached by turbo decoder and stable decisions of the inner decoder are likely to be the **correct** ones
   - Experience suggests most of chosen bit blocks or symbols are selected according to *Criterion 1*

2. nth bit is **reliable**: if soft decisions have same sign and their absolute values in monotonically **ascending**

$$|L_p^1(n)| < |L_p^2(n)| < \cdots < |L_p^{I_{\text{in}}}(n)|, \ \text{sign}\{L_p^1(n)\} = \text{sign}\{L_p^2(n)\} = \cdots = \text{sign}\{L_p^{I_{\text{in}}}(n)\}$$

   - Correct decisions may experience iteration gain leading to **increasing** absolute values of soft-decisions as number of inner iterations increases
   - This type of reliable decisions could be missed by *Criterion 1* and hence we have *Criterion 2*

- Fully exploit information provided by entire inner turbo iterative process $\Rightarrow$ capable of making **high-confidence** decision regarding whether nth detected bit is reliable or not

Select Reliable Blocks of Bits (3)

- Sliding-window with **window-size** of BPB bits: only when BPB **consecutive** detected bits of a block are all regarded as correct, corresponding symbol vector is selected for CE
- This process yields an integer-index vector $\boldsymbol{x}^t = \left[x^t(1)\ x^t(2) \cdots x^t(M_s^t)\right]^{\mathrm{T}}$ at the t-th outer turbo iteration, in which
  - $x^t(i)$ is **position** or index of ith selected symbol vector in transmitted symbol vector sequence
  - corresponding observation vectors $\boldsymbol{Y}_{\text{sel}}^{(t)} = \left[\boldsymbol{y}(x^t(1))\ \boldsymbol{y}(x^t(2)) \cdots \boldsymbol{y}(x^t(M_s^t))\right]$
- Number of the **selected** symbol vectors M_s^t varies within $\{1, 2, \cdots, M_{\text{sel}}\}$, where $M_{\text{sel}} \ll M_F$ is the maximum number of blocks imposed for CE
  - whenever the number of selected reliable symbol vectors M_s^t reaches the limit M_{sel}, the sliding-window process ends
  - otherwise, the sliding-window process examines all the possible bit blocks and outputs the M_s^t selected symbol vectors
- Given $\boldsymbol{x}^t$, we have **soft-estimated** symbol vectors $\widehat{\boldsymbol{S}}_{\text{sel}}^{(t)} = \left[\widehat{\boldsymbol{s}}(x^t(1))\ \widehat{\boldsymbol{s}}(x^t(2)) \cdots \widehat{\boldsymbol{s}}(x^t(M_s^t))\right]$ in which mth element of $\widehat{\boldsymbol{s}}(x^t(n))$:

$$\widehat{s}^m(x^t(n)) = \sum_{l=1}^{L} s^l \Pr\{s^m(x^t(n)) = s^l\} = \sum_{l=1}^{L} s^l \cdot \frac{\exp\left(\sum_{j=1}^{\text{BPS}} \widetilde{u}_j L_a(u_j)\right)}{\prod_{j=1}^{\text{BPS}} \left(1 + \exp\left(L_a(u_j)\right)\right)}$$

where $\{\widetilde{u}_j\}_{j=1}^{\text{BPS}}$ represents the bit mapping for L-QAM symbol set $\{s^l\}_{l=1}^{L}$

Complexity/Performance of Proposed Scheme

- **Soft** decision-directed LSCE with **complexity** $< \mathcal{O}\big(M_{\rm sel}^3\big)$

$$\widehat{\boldsymbol{H}}^{(t+1)} = \boldsymbol{Y}_{\rm sel}^{(t)}\big(\widehat{\boldsymbol{S}}_{\rm sel}^{(t)}\big)^{\rm H}\Big(\widehat{\boldsymbol{S}}_{\rm sel}^{(t)}\big(\widehat{\boldsymbol{S}}_{\rm sel}^{(t)}\big)^{\rm H}\Big)^{-1}$$

  - $M_F = 1000$, $M_{\rm sel} = 100$: complexity more than 10^3 times smaller than $\mathcal{O}\big(M_F^3\big)$

- Because our LSCE is naturally **embedded** in original turbo process, total complexity

$$C_{\rm pro} \le I_{\rm out} \cdot \mathcal{O}\big(M_{\rm sel}^3\big) + C_{\rm ideal}$$

  - Since $I_{\rm out} \cdot \mathcal{O}\big(M_{\rm sel}^3\big) \ll C_{\rm ideal}$, we have $C_{\rm pro} \approx C_{\rm ideal}$

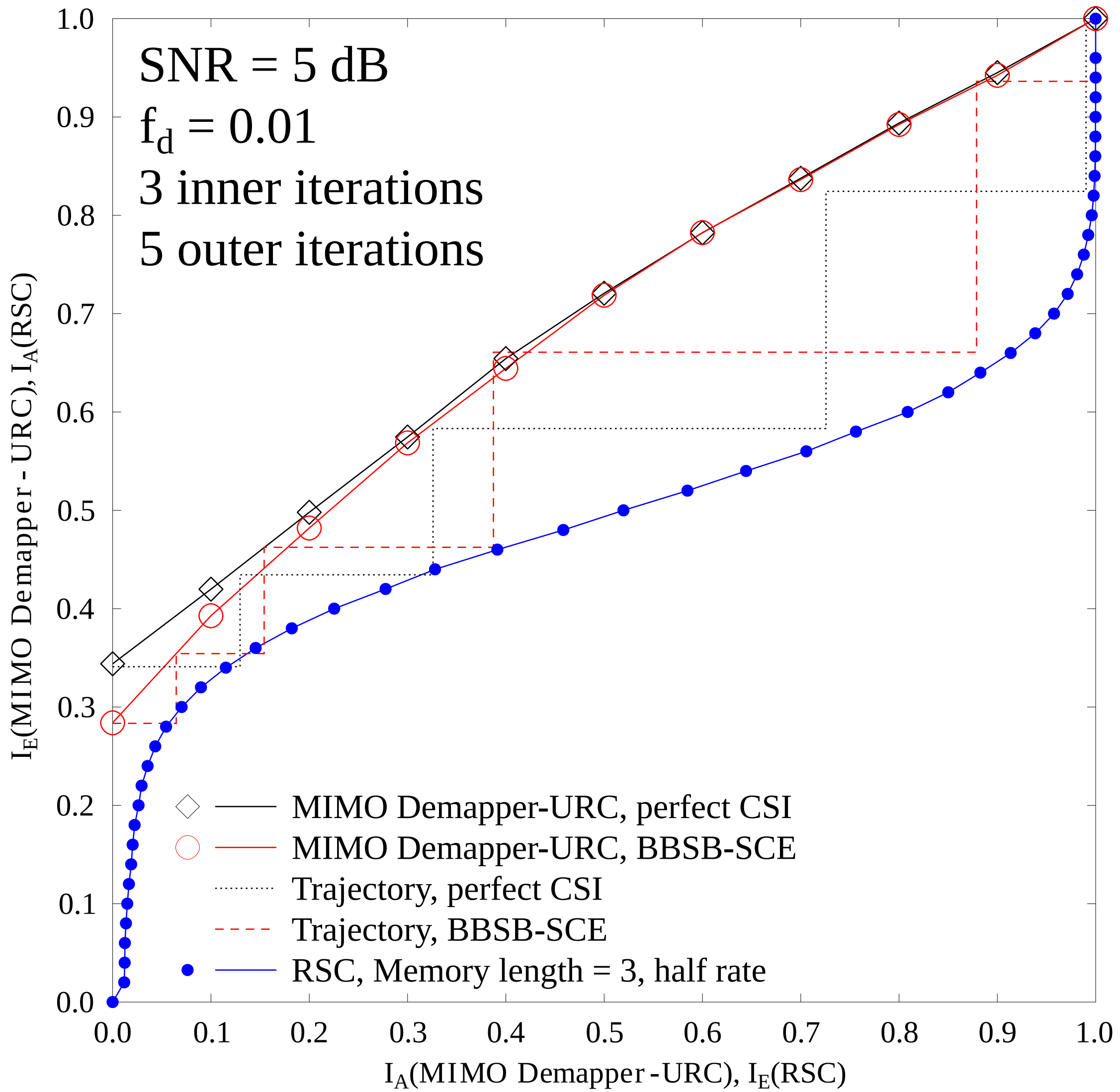
- Because only use reliable decisions in CE, error propagation is dramatically alleviated, coupled with turbo effect
  - With minimum training overhead, capable of **attaining** idealised optimal three-stage turbo detection-decoding bound associated with perfect CSI
  - Impose **similar** complexity to idealised three-stage turbo detector-decoder

Simulation System (1)

1. **Quasi-static Rayleigh fading** MIMO: $N_T = N_R = 4$ and $L = 16$-QAM
   - Channel taps are static within frame and faded between frames at normalised Doppler frequency $f_d = 0.01$
   - All the results were averaged over 100 channel realisations
2. **Interleaver length** of $L_F = 16,000$ bits, or $M_F = 1000$ symbol vectors
   - RSC generator polynomials: $G_{RSC} = [1, 0, 1]_2$, $G^r_{RSC} = [1, 1, 1]_2$
   - URC generator polynomials: $G_{URC} = [1, 0]_2$, $G^r_{URC} = [1, 1]_2$
3. Transmitted signal power normalised to unity, SNR defined as $\frac{1}{N_o}$
   - Number of initial training data blocks: $M_T = 6$ (close to minimum of 4), **training overhead** 0.6%
   - Blocks-of-bits selection limit set to $M_{sel} = 100$

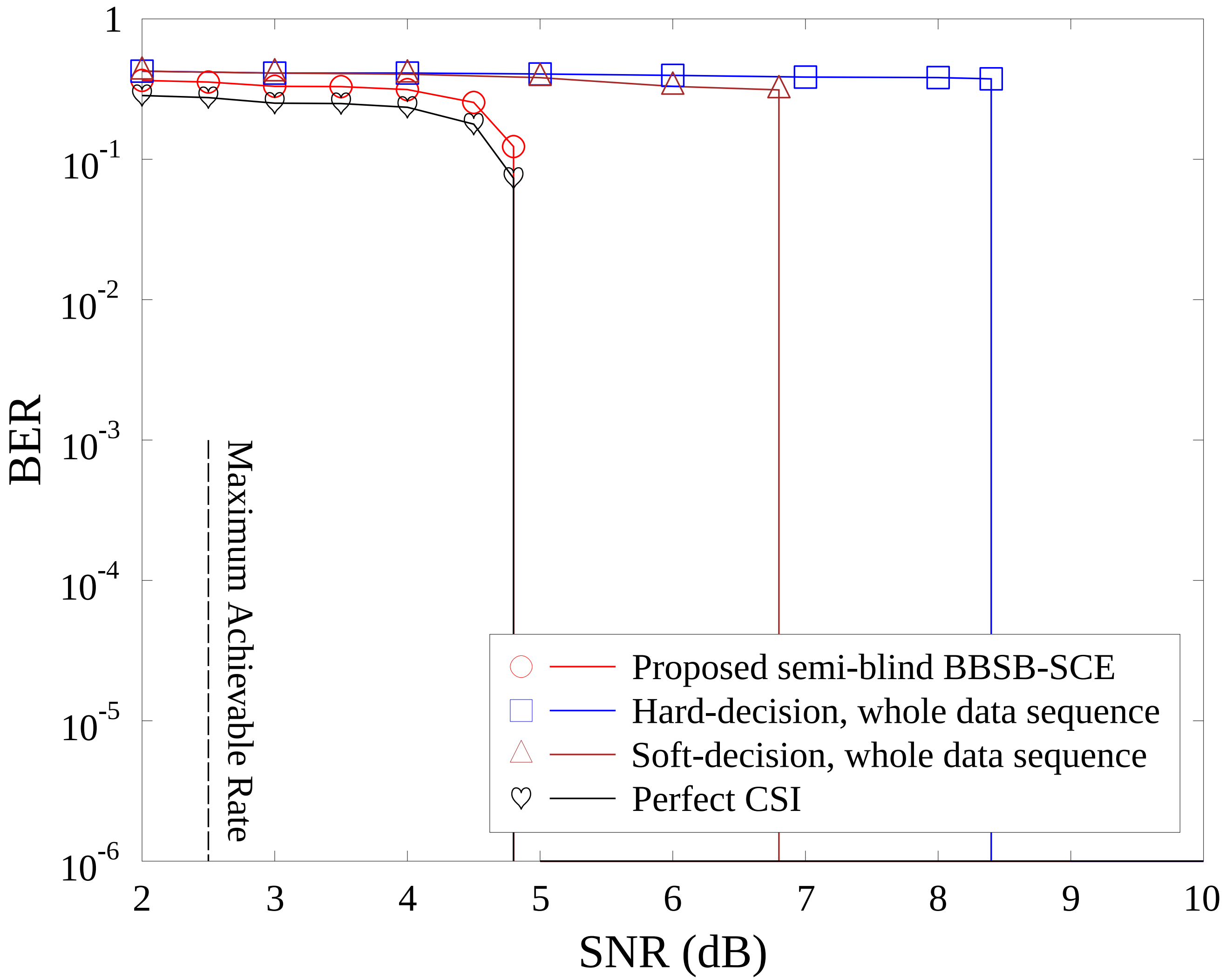
EXIT Chart Analysis

- **EXIT chart** analysis of our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver with the block-of-bits selection threshold of $T_h = 1.0$, in comparison to the perfect-CSI scenario



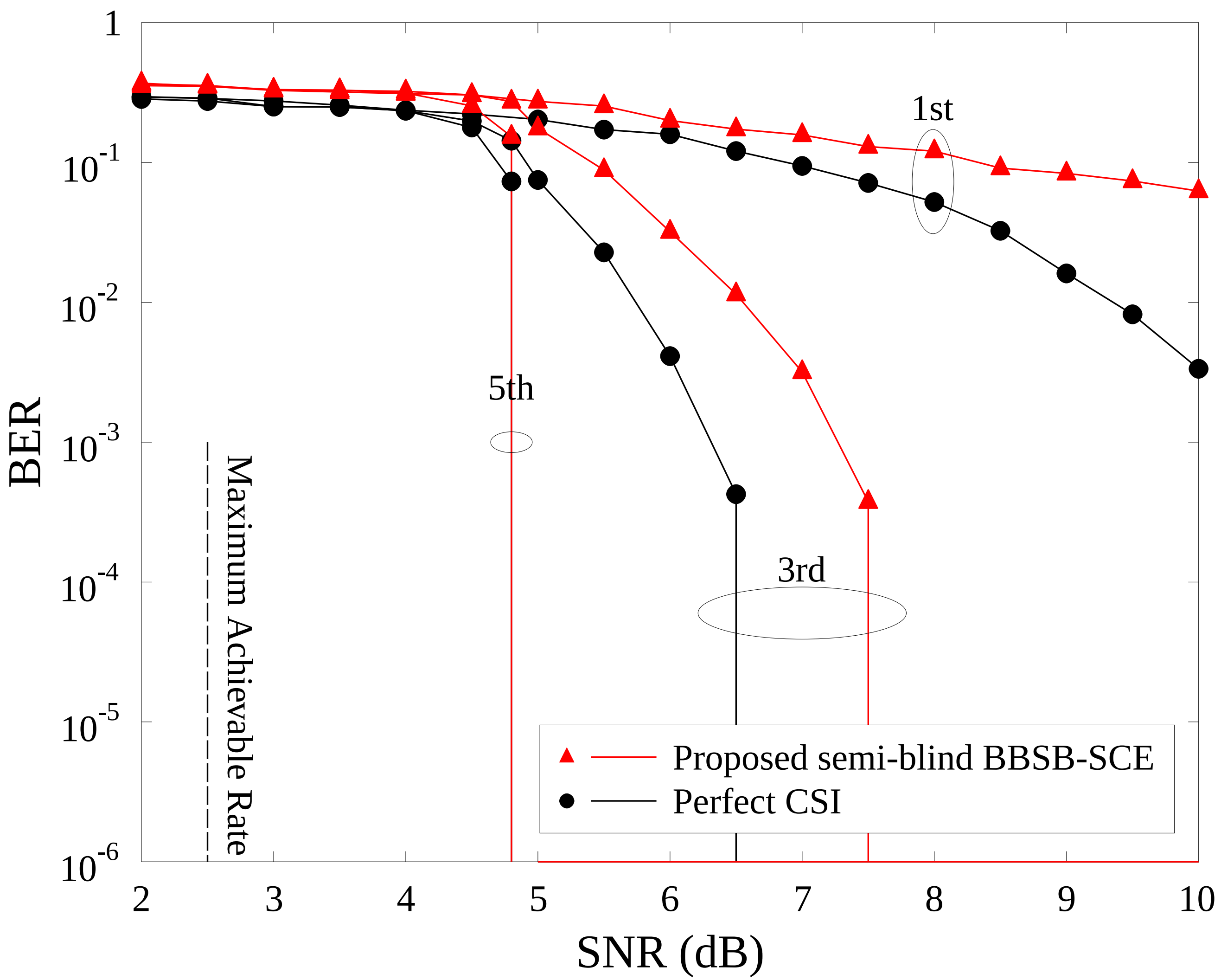
BER Performance comparison

- **BER** comparison: the proposed joint BBSB-SCE and three-stage turbo receiver with a block-of-bits selection threshold of $T_h = 1.0$, the perfect CSI scenario as well as the conventional joint CE and three-stage turbo receivers employing the entire detected data sequence for the soft-decision and hard-decision aided channel estimators, respectively



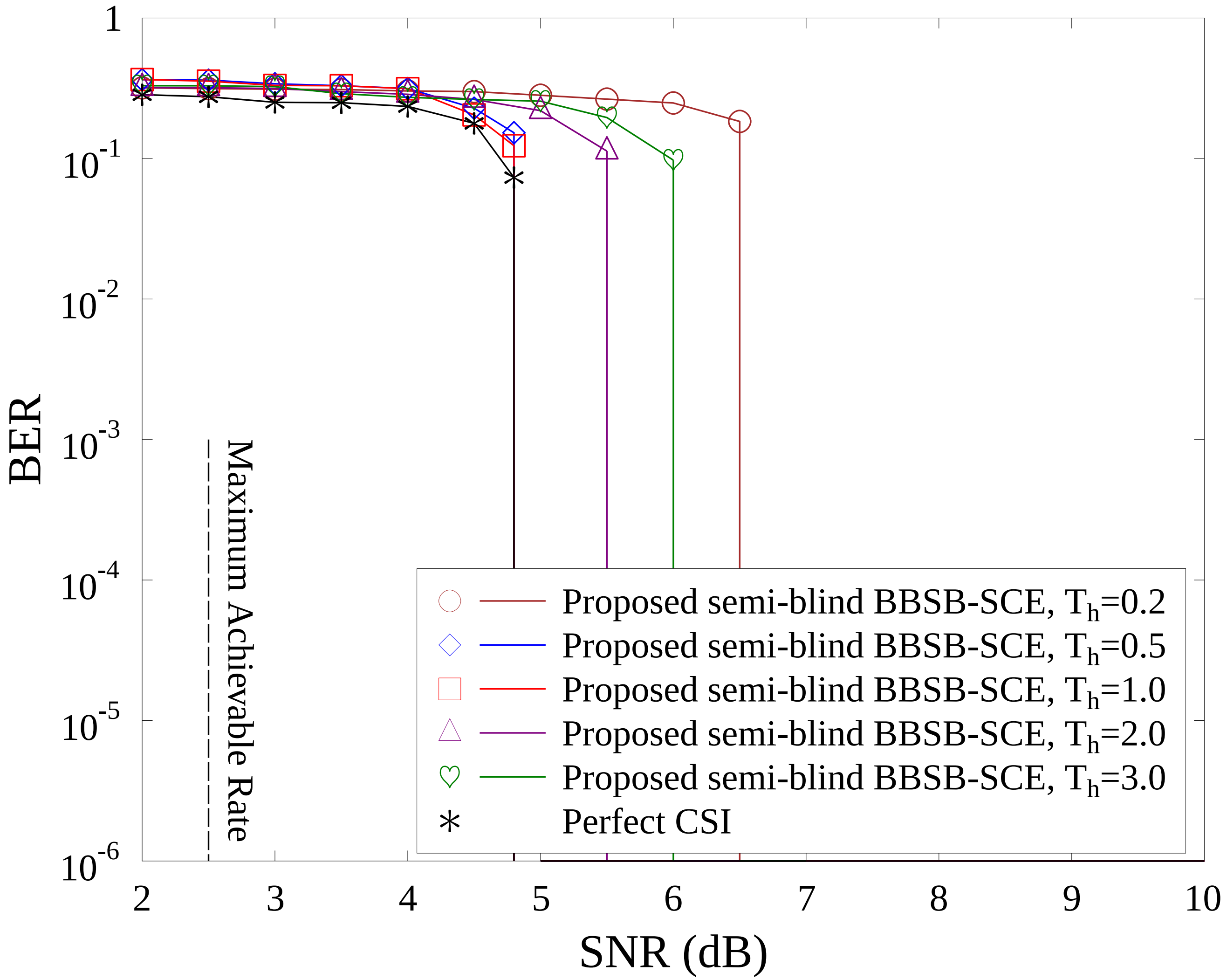
BER Convergence Performance

- BER **convergence** performance versu outer iterations of the proposed joint BBSB-SCE and three-stage turbo receiver with a block-of-bits selection threshold of $T_h = 1.0$, in comparison to the perfect-CSI case



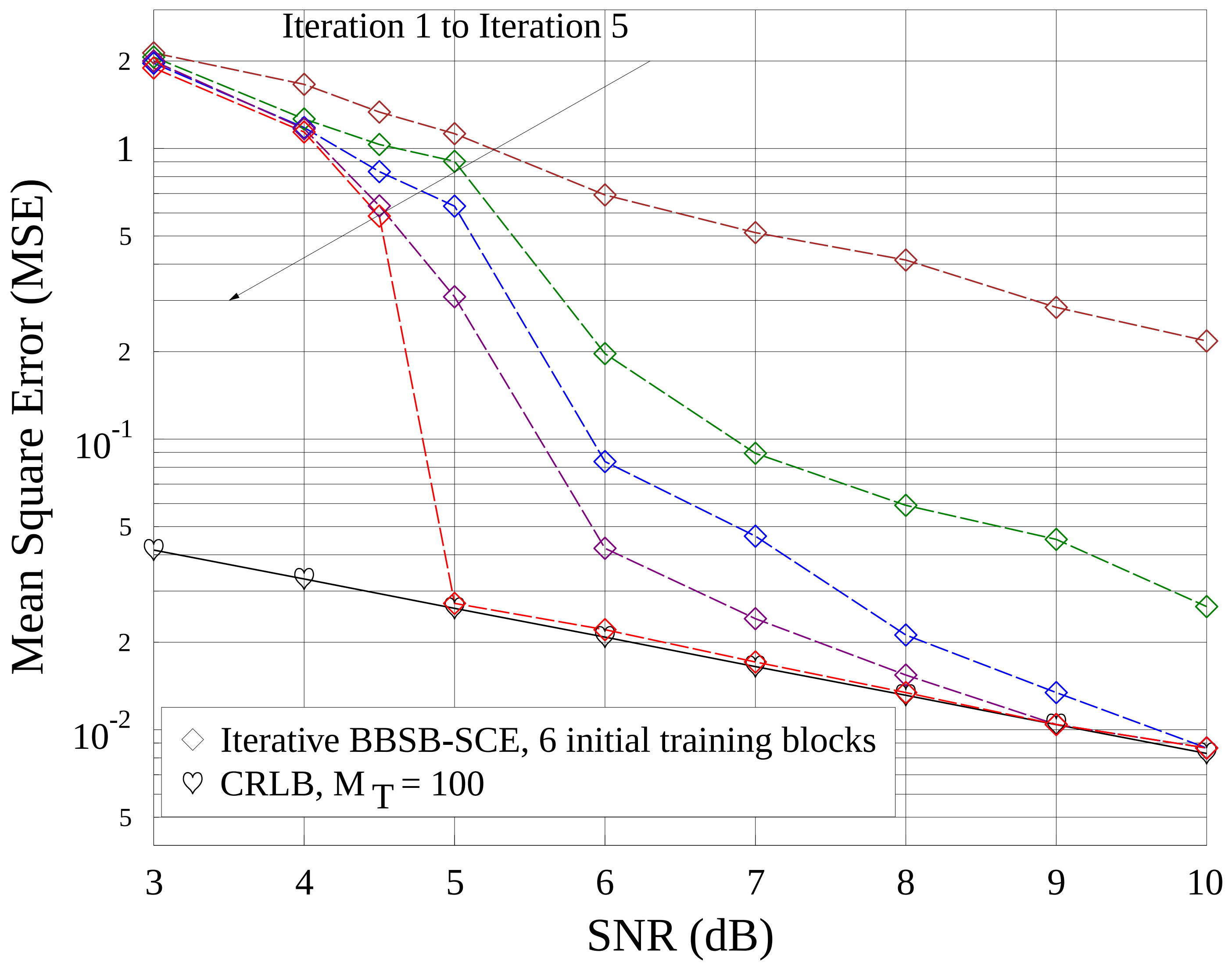
Influence of Selection Threshold

- Effects of the block-of-bits **selection threshold** T_h on the BER performance of our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver
- $T_h \in [0.5,\ 1.0]$ **appropriate** for this example, and as long as the threshold is not chosen to be too small or too large, the scheme is not sensitive to the value of T_h used



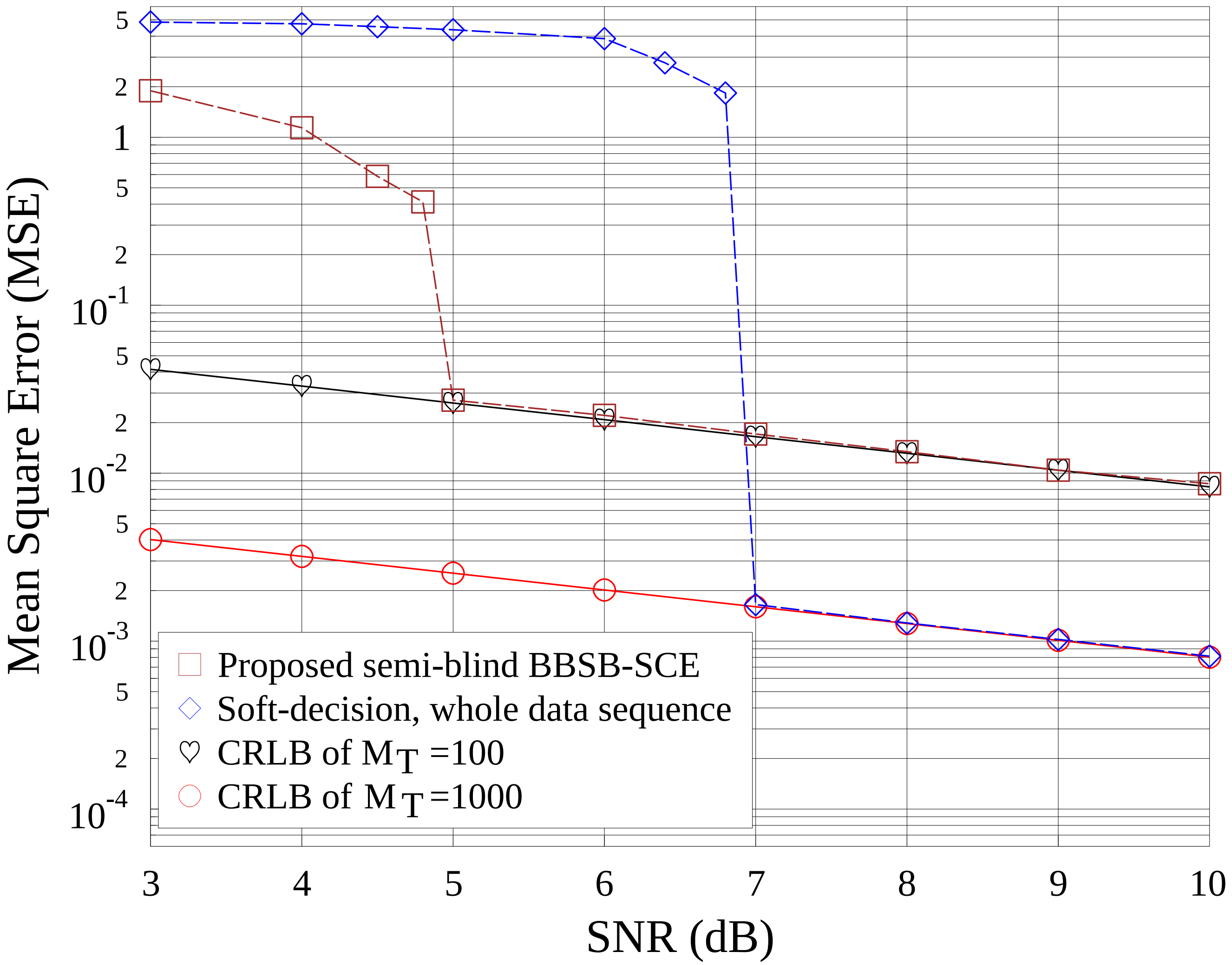
MSE Convergence Performance

- **Mean square error** convergence performance versu outer iterations of the channel estimator in our proposed semi-blind joint BBSB-SCE and three-stage turbo receiver using a block-of-bits selection threshold of $T_h = 1.0$ and $M_s^t \leq 100$



MSE Performance Comparison

- MSE performance comparison: **proposed** joint BBSB-SCE and three-stage turbo receiver, which selects $M_s^t \leq 100$ high-quality soft detected symbol vectors for channel estimator, and **conventional** joint CE and three-stage turbo receiver, which uses all $M_F = 1000$ soft detected symbol vectors for channel estimator

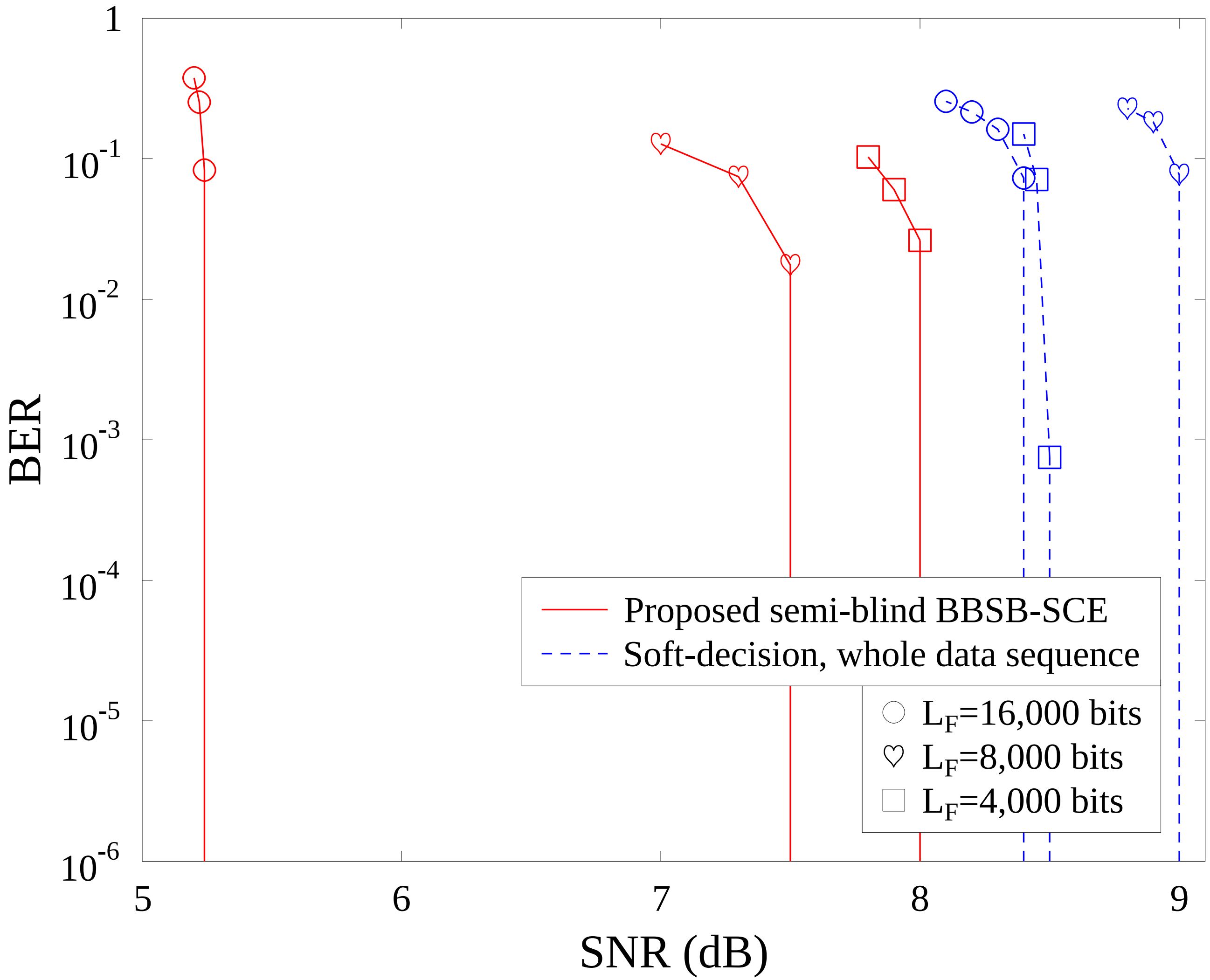


Simulation System (2)

- **Time-varying Rayleigh fading** MIMO: System settings identical to **Simulation System (1)**, except
  - MIMO channels are faded at **symbol rate** with normalised Doppler frequency f_d
- For time-varying MIMO: **trade off** between time-varying channel's estimation (TVCE) performance and turbo channel decoder's performance
  - For turbo channel coding, a **long** interleaver length L_F is preferred for the sake of achieving near-capacity performance
  - A short frame length M_F, i.e. a **short** interleaver length L_F is preferred for the sake of achieving a good TVCE performance.
- We compare our proposed scheme with the existing stat-of-the-art that uses entire soft-decision frame for CE, in terms of **achievable bit error rate**
  - Computational complexity of our scheme is dramatically **lower**

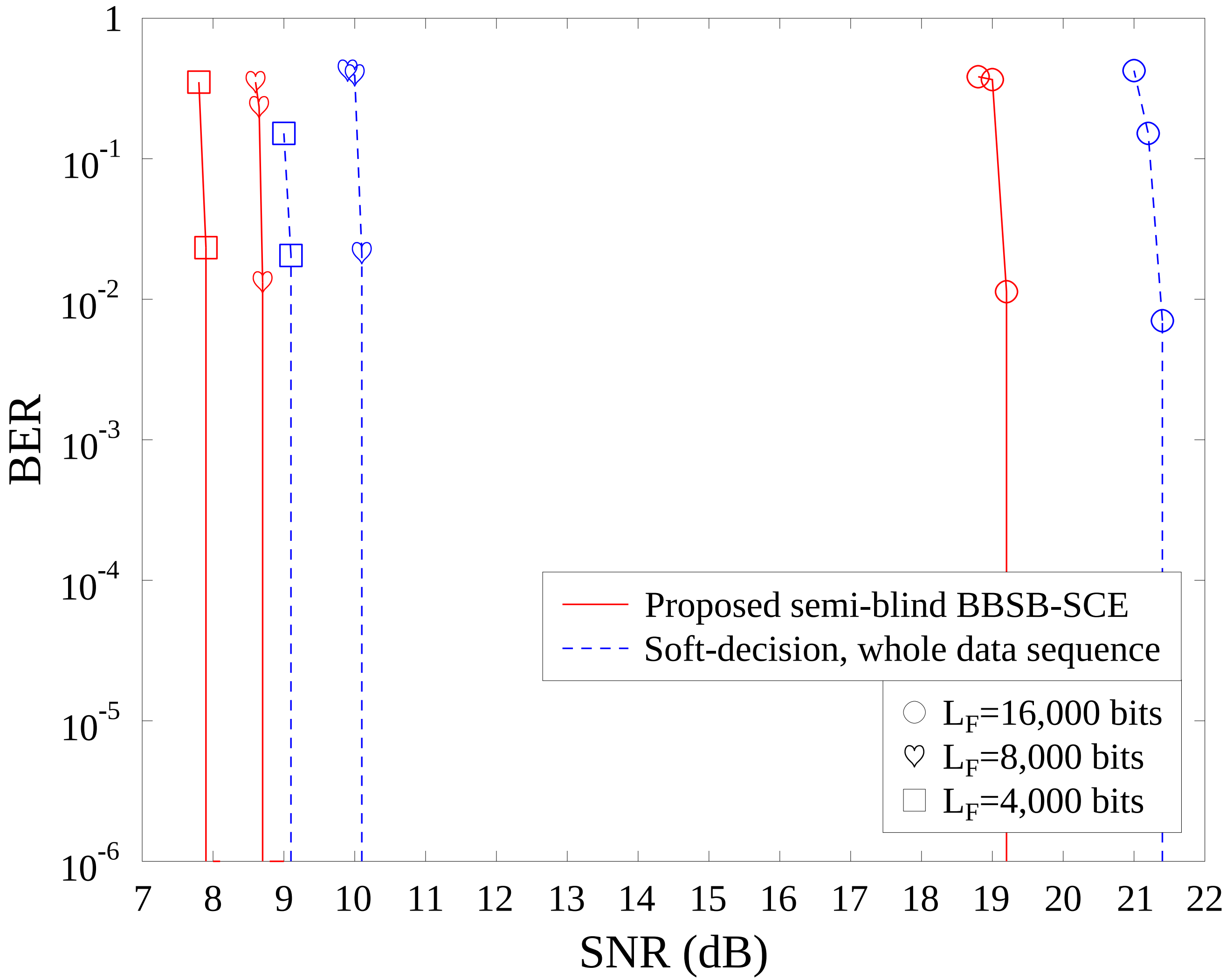
$f_d = 10^{-5}$

- BER performance comparison: a) **proposed** joint BBSB-SCE and three-stage turbo receiver with $T_h = 1.0$, and b) **existing** joint CE and three-stage turbo receiver employing the entire detected data sequence for the soft decision aided channel estimator, for the time-varying MIMO system with the interleaver lengths of $L_F = 16,000$ bits, $8,000$ bits and $4,000$ bits, respectively.



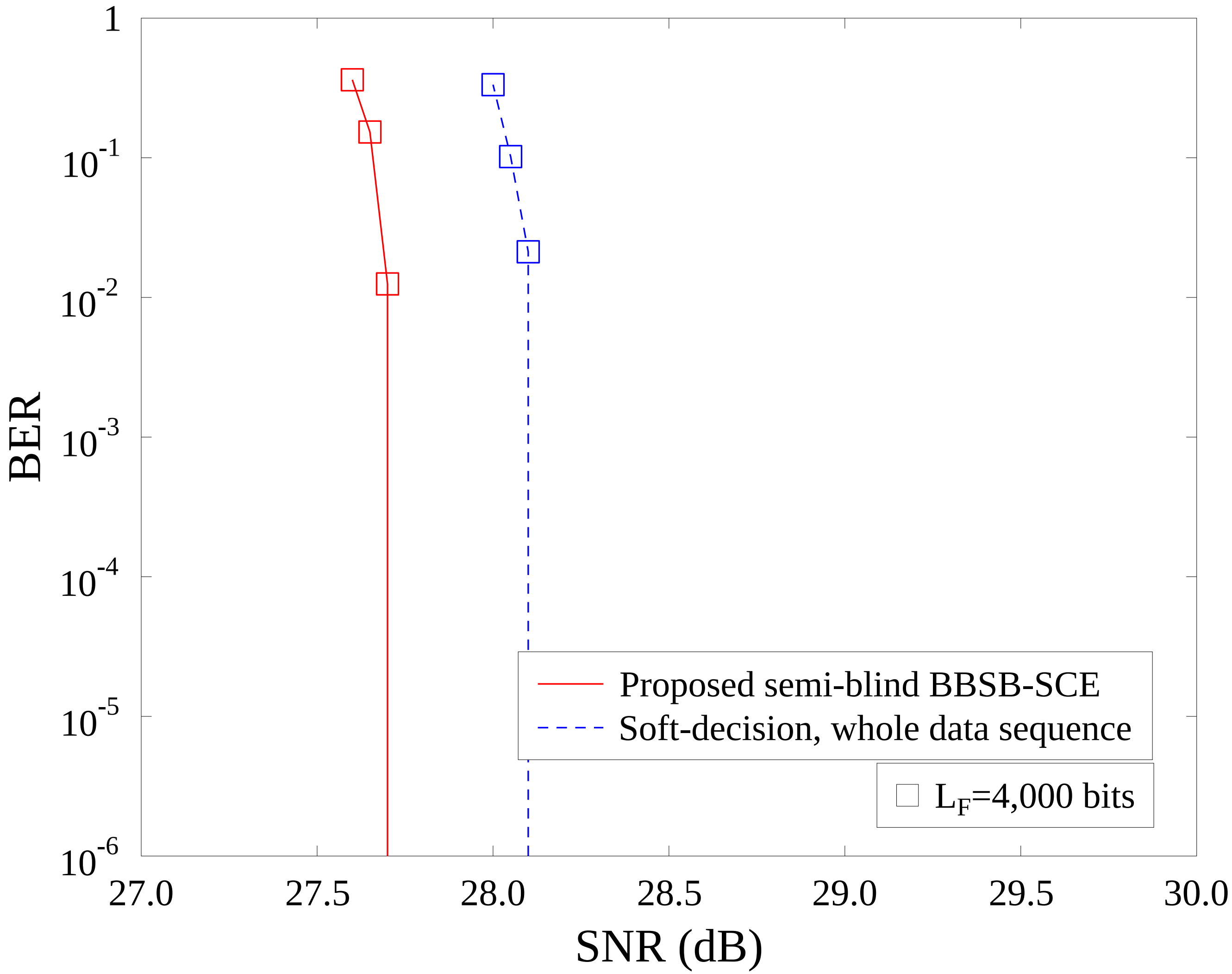
$f_d = 10^{-4}$

- BER performance comparison: a) **proposed** joint BBSB-SCE and three-stage turbo receiver with $T_h = 1.0$, and b) **existing** joint CE and three-stage turbo receiver employing the entire detected data sequence for the soft decision aided channel estimator, for the time-varying MIMO system with the interleaver lengths of $L_F = 16,000$ bits, $8,000$ bits and $4,000$ bits, respectively.



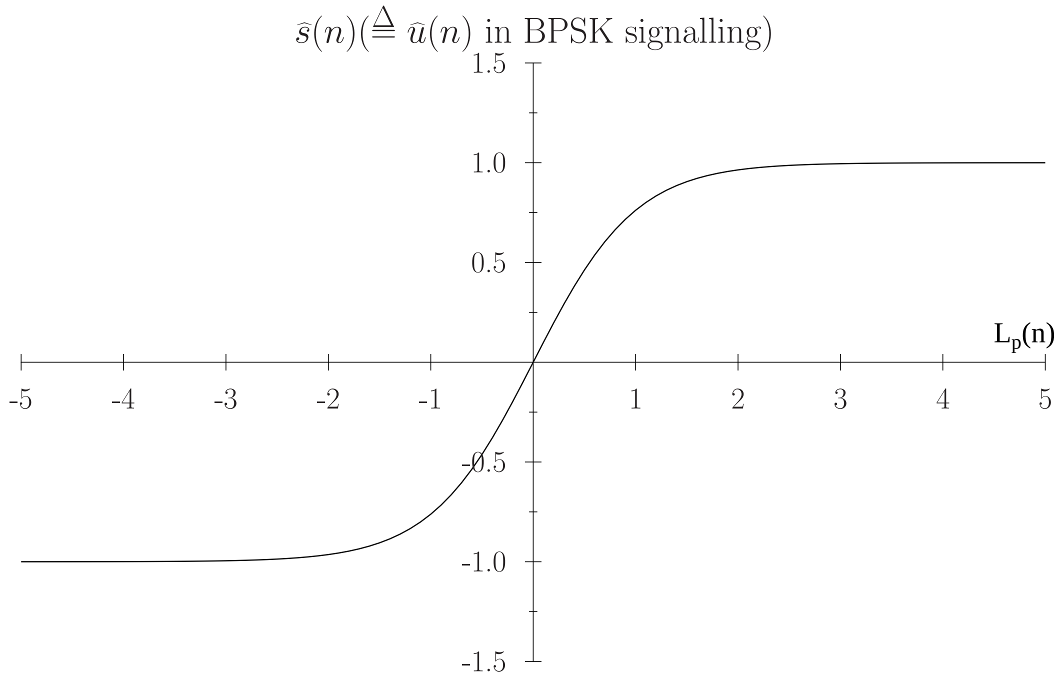
$$f_d = 5 \times 10^{-4}$$

- BER performance comparison: a) **proposed** joint BBSB-SCE and three-stage turbo receiver with $T_h = 1.0$, and b) **existing** joint CE and three-stage turbo receiver employing the entire detected data sequence for the soft decision aided channel estimator, for the time-varying MIMO system with the interleaver length of $L_F = 4,000$ bits.



Simulation System (3)

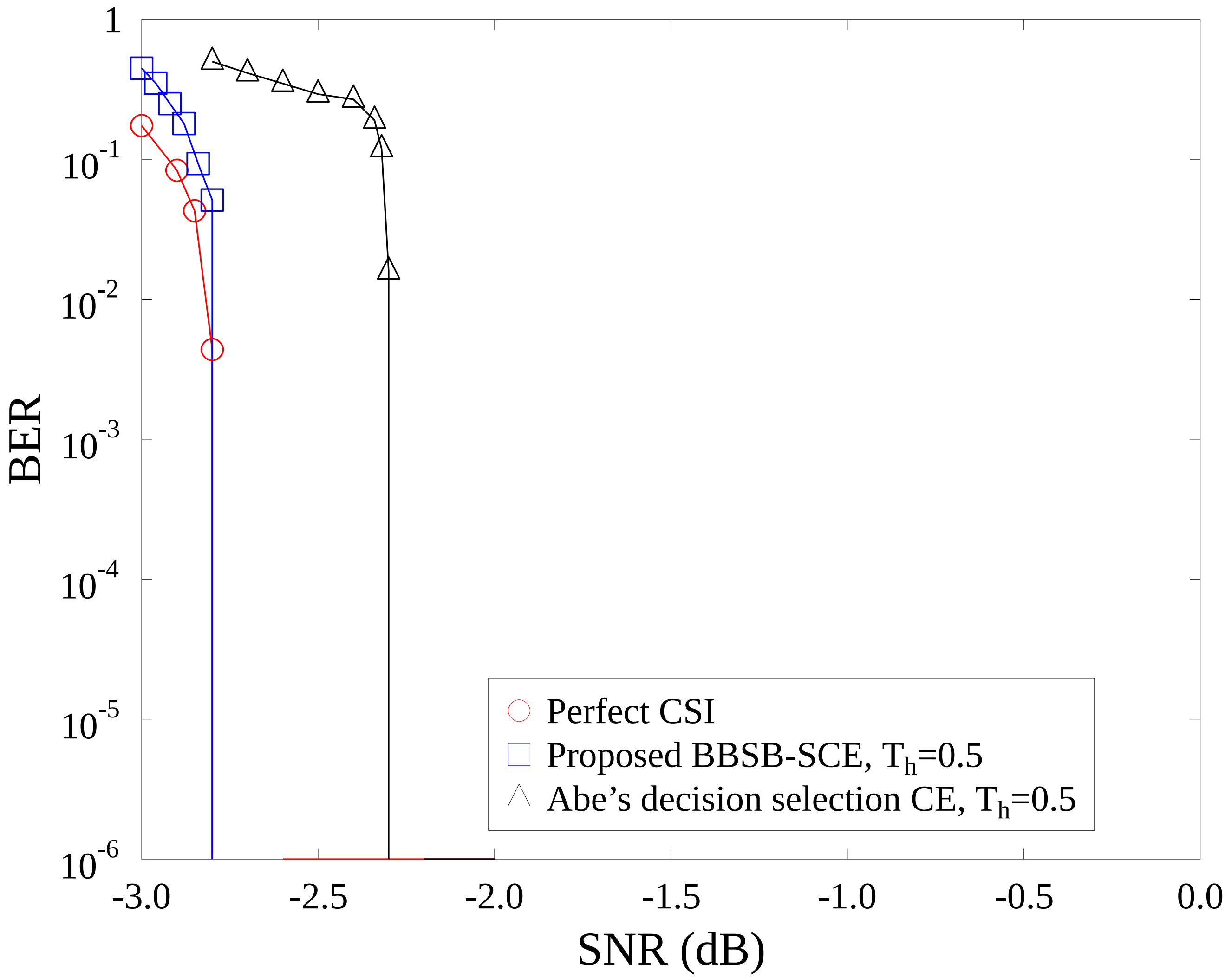
- **Quasi-static Rayleigh fading** MIMO: $N_T = N_R = 2$, BPSK, and $M_T = 6$
  - Other system settings identical to **Simulation System (1)**
- For **BPSK**, there exists a scheme of selecting high-quality bits according to LLRs $L_p^{I_{\rm in}}(n)$
  - T. Abe and T. Matsumoto, "Space-time turbo equalization in frequency-selective MIMO channels," *IEEE Trans. Vehicular Technology*, 52(3), 469–475, 2003



  - Soft symbol (bit) estimate $\widehat{s}(n) = \tanh\left(L_p^{I_{\rm in}}(n)\right)$: magnitude $|\widehat{s}(n)|$ as **estimated probability** of nth bit $\Rightarrow$ decide whether this bit is reliable or not

BER Performance comparison

- BER performance comparison: a) perfect CSI case, b) proposed joint BBSB-SCE and three-stage turbo receiver with $T_h = 0.5$, and c) Abe and Matsumoto's BPSK decision selection scheme based soft CE, for quasi-static **BPSK MIMO** system with $N_T = N_R = 2$.



Summary

- Our challenging objective is to reach **MIMO wonderland**
  - with aid of very modest (minimum) training overhead
  - without significantly increasing associated complexity

- Semi-blind iterative **block-of-bits selection** based soft-decision aided channel estimation and three-stage turbo detection-decoding

  1. Only utilize high-quality or reliable detected symbols $\Rightarrow$ **not entire frame** of detected soft bits for CE, dramatically reducing CE complexity
  2. Channel estimation naturally embedded in original turbo detection-decoding process $\Rightarrow$ **no extra iterative loop** between CE and turbo detector-decoder
  3. Capable of **attaining optimal** ML turbo detector-decoder bound associated with perfect CSI, while imposing similar complexity

- Next big challenge: **pilot contamination** in multi-cell massive MIMO

References

1. Wang, Ng, Wolfgang, Yang, Chen, Hanzo, "Near-capacity three-stage MMSE turbo equalization using irregular convolutional codes," in: *Proc. Turbo-Coding-2006* (Munich, Germany), April 3-7, 2006, 6 pages.

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4. Zhang, Chen, Hanzo, "Embedded iterative semi-blind channel estimation for three-stage-concatenated MIMO-aided QAM turbo-transceivers," *IEEE Trans. Vehicular Technology*, vol.63, no.1, pp.439–446, Jan. 2014

5. Zhang, Zhang, Chen, Mu, El-Hajjar, Hanzo, "Pilot contamination elimination for large-scale multiple-antenna aided OFDM systems," *IEEE J. Selected Topics in Signal Processing*, to appear, 2014