Adaptive Space-Time Shift Keying Systems

Peichang Zhang, Shinya Sugiura, Sheng Chen
and Lajos Hanzo

School of Electronics and Computer Science
University of Southampton
Southampton SO17 1BJ, UK
E-mails: {pz3g09, ss07r, sqc, lh}@ecs.soton.ac.uk

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Outline

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MIMO Landscape

MIMO: **Space** and **Time** dimensions; **Diversity** and **Multiplexing** gains

- **Vertical Bell Lab layered space-time** (V-BLAST)
  - Offers high multiplexing gain at high decoding complexity owing to inter-channel interference (ICI)
- **Space-time block codes** (STBCs)
  - Maximum diversity gain at expense of bandwidth efficiency
- **Linear dispersion codes** (LDCs)
  - Flexible tradeoff between diversity and multiplexing gains
- **Spatial modulation** (SM) and **space-shift keying** (SSK)
  - Mainly multiplexing gain, can achieve receive diversity
  - No ICI $\Rightarrow$ low-complexity single-antenna ML detection

Unified MIMO Architecture

- **Space-time shift keying** (STSK): unified MIMO including V-BLAST, STBCs, LDCs, SM and SSK as special cases
  - Fully exploit both spatial and time dimensions
  - Flexible diversity versus multiplexing gain tradeoff
  - **No ICI** with low-complexity single-antenna ML detection
- **Coherent** STSK (CSTSK):
  - Better performance and flexible design
  - Requires channel state information (CSI)
- **Differential** STSK:
  - Doubling noise power, limited design in modulation scheme and choice of linear dispersion matrices
  - **No need for CSI**

Coherent MIMO

- Ability of an MIMO system to approach its **capacity** heavily relies on accuracy of CSI
- **Training** based schemes: capable of accurately estimating MIMO channel at expense of large training overhead $\Rightarrow$ considerable reduction in system throughput
- **Blind** methods: high complexity and slow convergence, also unavoidable estimation and decision ambiguities
- **Semi-blind** methods offer attractive practical means of implementing adaptive MIMO systems
  - Low-complexity ML data detection in STSK $\Rightarrow$ efficient semi-blind iterative channel estimation and data detection

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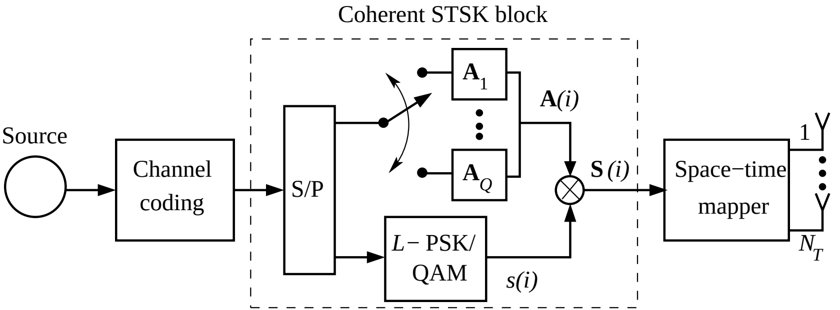
CSTSK Transmitter



- CSTSK (N_T, N_R, T_n, Q) with L-PSK/QAM:
  - N_T: number of transmitter antennas
  - N_R: number of receiver antennas
  - T_n: number of time slots per STSK block, block index i
  - Q: size of linear dispersion matrices
  - L: size of modulation constellation

Transmitted Signal

- Each block $\mathbf{S}(i) \in \mathbb{C}^{N_T \times T_n}$ is generated from $\log_2(L \cdot Q)$ bits by

$$\mathbf{S}(i) = s(i)\mathbf{A}(i)$$

- $\log_2(L)$ bits decides $s(i)$ from L-PSK/QAM modulation scheme

$$s(i) \in \mathcal{S} = \{s_l \in \mathbb{C}, 1 \leq l \leq L\}$$

- $\log_2(Q)$ bits selects $\mathbf{A}(i)$ from set of Q dispersion matrices

$$\mathbf{A}(i) \in \mathcal{A} = \{\mathbf{A}_q \in \mathbb{C}^{N_T \times T_n}, 1 \leq q \leq Q\}$$

  Each dispersion matrix meets power constraint $\mathrm{tr}\left[\mathbf{A}_q^H \mathbf{A}_q\right] = T_n$

- Normalised throughput per time-slot of this CSTSK scheme is

$$R = \frac{\log_2(Q \cdot L)}{T_n} \text{ [bits/symbol]}$$

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Received Signal

- Received signal matrix $\mathbf{Y}(i) \in \mathbb{C}^{N_R \times T_n}$ takes MIMO model

$$\mathbf{Y}(i) = \mathbf{H}\,\mathbf{S}(i) + \mathbf{V}(i)$$

- Channel matrix $\mathbf{H} \in \mathbb{C}^{N_R \times N_T}$: each element obeys $\mathcal{CN}(0, 1)$
- Noise matrix $\mathbf{V}(i) \in \mathbb{C}^{N_R \times T_n}$: each element obeys $\mathcal{CN}(0, N_{\text{o}})$
- Signal to noise ratio (SNR) is defined as

$$\text{SNR} = E_{\text{s}}/N_{\text{o}}$$

E_{s} is average symbol energy of L-PSK/QAM modulation scheme

- Let vec[$\cdot$] be vector stacking operator, $\mathbf{I}_M$ be $M \times M$ identity matrix and $\otimes$ be Kronecker product

Equivalent Signal Model

- Introduce notations

$$\bar{\mathbf{y}}(i) = \text{vec}[\mathbf{Y}(i)] \in \mathbb{C}^{N_R T_n \times 1} \quad \bar{\mathbf{H}} = \mathbf{I}_{T_n} \otimes \mathbf{H} \in \mathbb{C}^{N_R T_n \times N_T T_n}$$
$$\bar{\mathbf{v}}(i) = \text{vec}[\mathbf{V}(i)] \in \mathbb{C}^{N_R T_n \times 1} \quad \mathbf{\Theta} = \left[\text{vec}[\mathbf{A}_1] \cdots \text{vec}[\mathbf{A}_Q]\right] \in \mathbb{C}^{N_T T_n \times Q}$$

$$\mathbf{k}(i) = [\underbrace{0 \ \cdots \ 0}_{q-1} \ s(i) \ \underbrace{0 \ \cdots \ 0}_{Q-q}]^T \in \mathbb{C}^{Q \times 1}$$

where q is index of dispersion matrix $\mathbf{A}_q$ activated

- Equivalent transmitted signal vector $\mathbf{k}(i)$ takes value from set

$$\mathcal{K} = \{\mathbf{k}_{q,l} \in \mathbb{C}^{Q \times 1}, \ 1 \le q \le Q, \ 1 \le l \le L\}$$

which contains $Q \cdot L$ legitimate transmitted signal vectors

$$\mathbf{k}_{q,l} = [\underbrace{0 \ \cdots \ 0}_{q-1} \ s_l \ \underbrace{0 \ \cdots \ 0}_{Q-q}]^T, \ 1 \le q \le Q, 1 \le l \le L$$

where s_l is the lth symbol in the L-point constellation $\mathcal{S}$

- Equivalent received signal model: $\bar{\mathbf{y}}(i) = \bar{\mathbf{H}} \, \mathbf{\Theta} \, \mathbf{k}(i) + \bar{\mathbf{v}}(i)$

Maximum Likelihood Detection

- Free from ICI $\Rightarrow$ low-complexity single-antenna ML detector, only searching $L \cdot Q$ points !
- Let (q, l) correspond to specific input bits of ith STSK block, which are mapped to s_l and $\mathbf{A}_q$
- Then ML estimates $(\hat{q}, \hat{l})$ are given by

$$(\hat{q}, \hat{l}) = \arg \min_{\substack{1 \leq q \leq Q \\ 1 \leq l \leq L}} \|\bar{\mathbf{y}}(i) - \bar{\mathbf{H}}\,\mathbf{\Theta}\,\mathbf{k}_{q,l}\|^2 = \arg \min_{\substack{1 \leq q \leq Q \\ 1 \leq l \leq L}} \|\bar{\mathbf{y}}(i) - s_l \left(\bar{\mathbf{H}}\,\mathbf{\Theta}\right)_q\|^2$$

  where $\left(\bar{\mathbf{H}}\,\mathbf{\Theta}\right)_q$ denotes qth column of the matrix $\bar{\mathbf{H}}\,\mathbf{\Theta}$

- Assume channel's coherence time lasts the duration of τ STSK blocks. Then complexity of detecting $\tau \log_2(Q \cdot L)$ bits is

$$C_{\mathrm{ML}} \approx 4QT_nN_R\left(3\tau L + 2N_T\right) \text{ [Flops]}$$

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Least Square Channel Estimate

- Assume number of available training blocks is M and training data are arranged as

$$\begin{aligned} \mathbf{Y}_{\mathrm{t}M} &= \left[\mathbf{Y}(1)\ \mathbf{Y}(2)\ \cdots\ \mathbf{Y}(M)\right] \\ \mathbf{S}_{\mathrm{t}M} &= \left[\mathbf{S}(1)\ \mathbf{S}(2)\ \cdots\ \mathbf{S}(M)\right] \end{aligned}$$

- Then LSCE based on $(\mathbf{Y}_{\mathrm{t}M}, \mathbf{S}_{\mathrm{t}M})$ is given by

$$\hat{\mathbf{H}}_{\mathrm{LSCE}} = \mathbf{Y}_{\mathrm{t}M}\mathbf{S}_{\mathrm{t}M}^{H}\left(\mathbf{S}_{\mathrm{t}M}\mathbf{S}_{\mathrm{t}M}^{H}\right)^{-1}$$

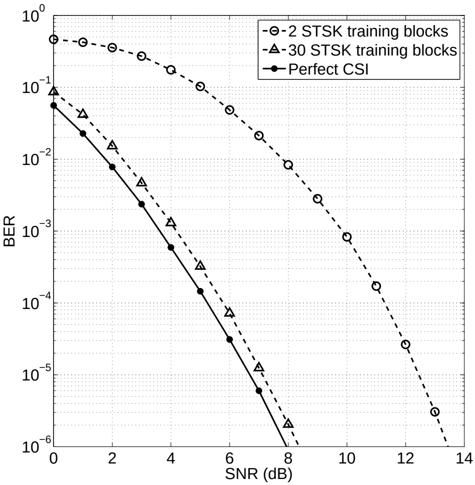
- In order for $\mathbf{S}_{\mathrm{t}M}\mathbf{S}_{\mathrm{t}M}^{H}$ to have full rank of N_T, it is necessary that $M \cdot T_n \geq N_T$ and this requires a minimum of

$$M = \left\lceil \frac{N_T}{T_n} \right\rceil \text{ training blocks}$$

- However, to achieve an accurate channel estimate, large training overhead is required

(4, 4, 2, 4) QPSK Example

- Convolution code with code rate 2/3, octally represented generator polynomials of $G_1 = [23, 35]_8$ and $G_1 = [5, 13]_8$
- Hard-input hard-output Viterbi algorithm decoding
- $(N_T = 4, N_R = 4, T_n = 2, Q = 4)$ with $L = 4$ QPSK modulation
- Frame of 800 information source bits, after channel coding, are mapped to $\tau = 300$ STSK blocks
- Average over 100 channel realisations



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Semi-Blind Iterative algorithm

Use minimum $M = \left\lceil \frac{N_T}{T_n} \right\rceil$ training blocks to obtain initial $\hat{\mathbf{H}}_{\rm LSCE}$, and let observation data for ML detector be $\mathbf{Y}_{{\rm d}\tau} = \left[\mathbf{Y}(1)\ \mathbf{Y}(2)\ \cdots\ \mathbf{Y}(\tau)\right]$

1. Set iteration index $t = 0$ and channel estimate $\tilde{\mathbf{H}}^{(t)} = \hat{\mathbf{H}}_{\rm LSCE}$;
2. Given $\tilde{\mathbf{H}}^{(t)}$, perform ML detection on $\mathbf{Y}_{{\rm d}\tau}$ and carry out channel decoding on detected bits. Corresponding detected information bits, after passing through channel coder again, are re-modulated to yield

$$\hat{\mathbf{S}}_{{\rm e}\tau}^{(t)} = \left[\hat{\mathbf{S}}^{(t)}(1)\ \hat{\mathbf{S}}^{(t)}(2)\ \cdots\ \hat{\mathbf{S}}^{(t)}(\tau)\right];$$

3. Update channel estimate with decision-directed LSCE

$$\tilde{\mathbf{H}}^{(t+1)} = \mathbf{Y}_{{\rm d}\tau}\left(\hat{\mathbf{S}}_{{\rm e}\tau}^{(t)}\right)^H \left(\hat{\mathbf{S}}_{{\rm e}\tau}^{(t)}\left(\hat{\mathbf{S}}_{{\rm e}\tau}^{(t)}\right)^H\right)^{-1};$$

4. Set $t = t + 1$: If $t < I_{\rm max}$, go to Step 2); otherwise, stop.

Simulation Settings

- Performance was assessed using estimated mean square error

$$J_{\text{MSE}}(\tilde{\mathbf{H}}) = \frac{1}{\tau \cdot N_R \cdot T_n} \sum_{i=1}^{\tau} \|\mathbf{Y}(i) - \tilde{\mathbf{H}}\,\hat{\mathbf{S}}(i)\|^2$$

mean channel estimation error

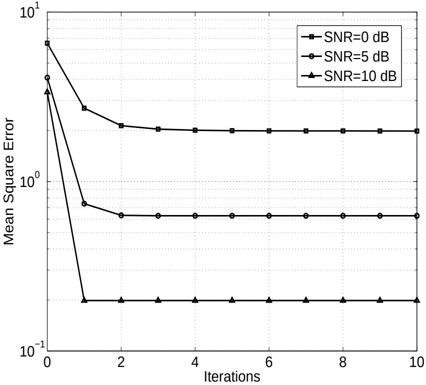
$$J_{\text{MCE}}(\tilde{\mathbf{H}}) = \frac{1}{N_R \cdot N_T} \|\mathbf{H} - \tilde{\mathbf{H}}\|^2$$

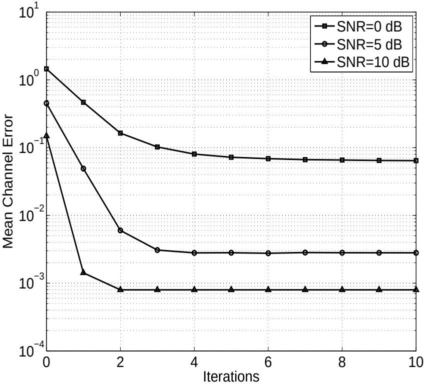
and BER, where $\tilde{\mathbf{H}}$ is channel estimate, $\hat{\mathbf{S}}(i)$ are ML-detected and re-modulated data, and $\mathbf{H}$ is true MIMO channel matrix

- Performance averaged over 100 channel realisations
- Convolution code with code rate $2/3$, octally represented generator polynomials of $G_1 = [23, 35]_8$ and $G_1 = [5, 13]_8$
- Hard-input hard-output Viterbi algorithm for channel decoding

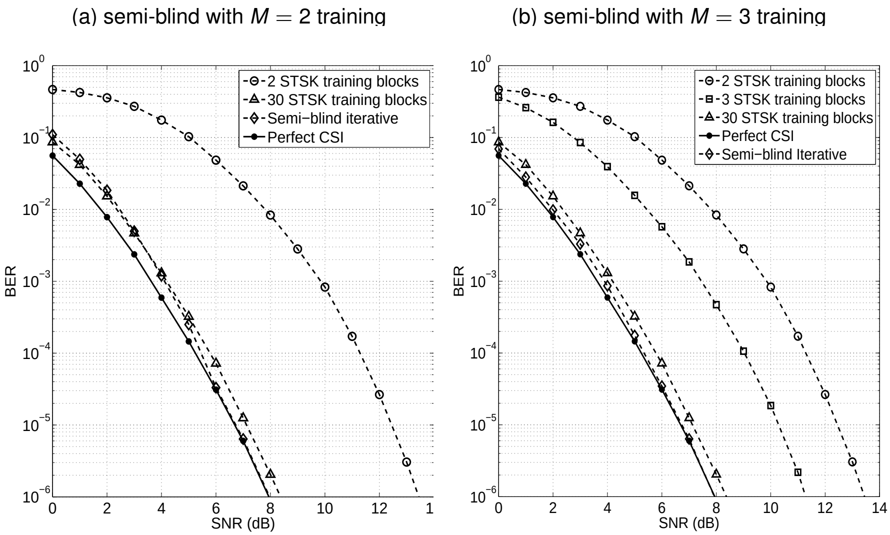
(4, 4, 2, 4) QPSK (Convergence)

- $(N_T = 4, N_R = 4, T_n = 2, Q = 4)$ with $L = 4$ QPSK modulation
- Frame of 800 information source bits, after channel coding, are mapped to $\tau = 300$ STSK blocks
- Semi-blind with $M = 2$ training STSK blocks



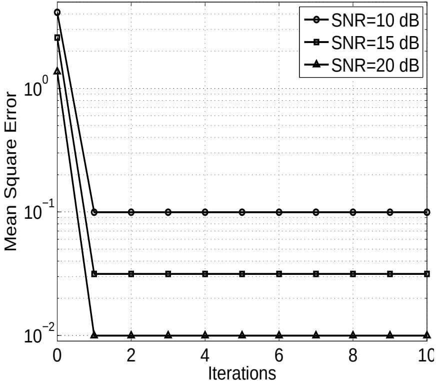


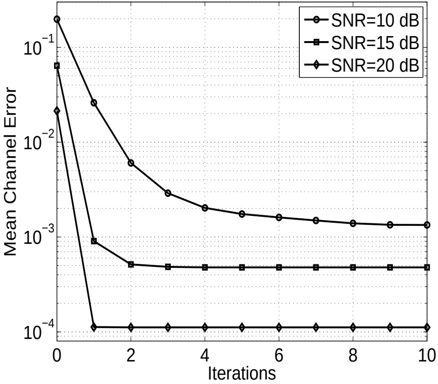
(4, 4, 2, 4) QPSK (Bit Error Rate)



(4, 2, 2, 4) 16QAM (Convergence)

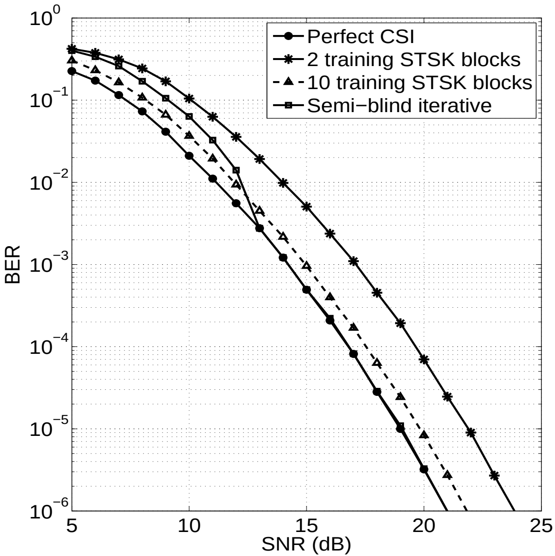
- ($N_T = 4$, $N_R = 2$, $T_n = 2$, $Q = 4$) with $L = 16$ QAM modulation
- Frame of 800 information source bits, after channel coding, are mapped to $\tau = 200$ STSK blocks
- Semi-blind with $M = 2$ training STSK blocks





(4, 2, 2, 4) 16QAM (Bit Error Rate)

Semi-blind with $M = 2$ training



Summary

- A semi-blind iterative channel estimation and data detection scheme for coherent STSK systems
- Use minimum number of training STSK blocks to provide initial LSCE for aiding the iterative procedure
- Proposed semi-blind iterative channel estimation and ML data detection scheme is inherently low-complexity
- Typically no more than five iterations to converge to optimal ML detection performance obtained with perfect CSI

References

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