ACSTSK

Adaptive Space-Time Shift Keying Based Multiple-Input Multiple-Output Systems

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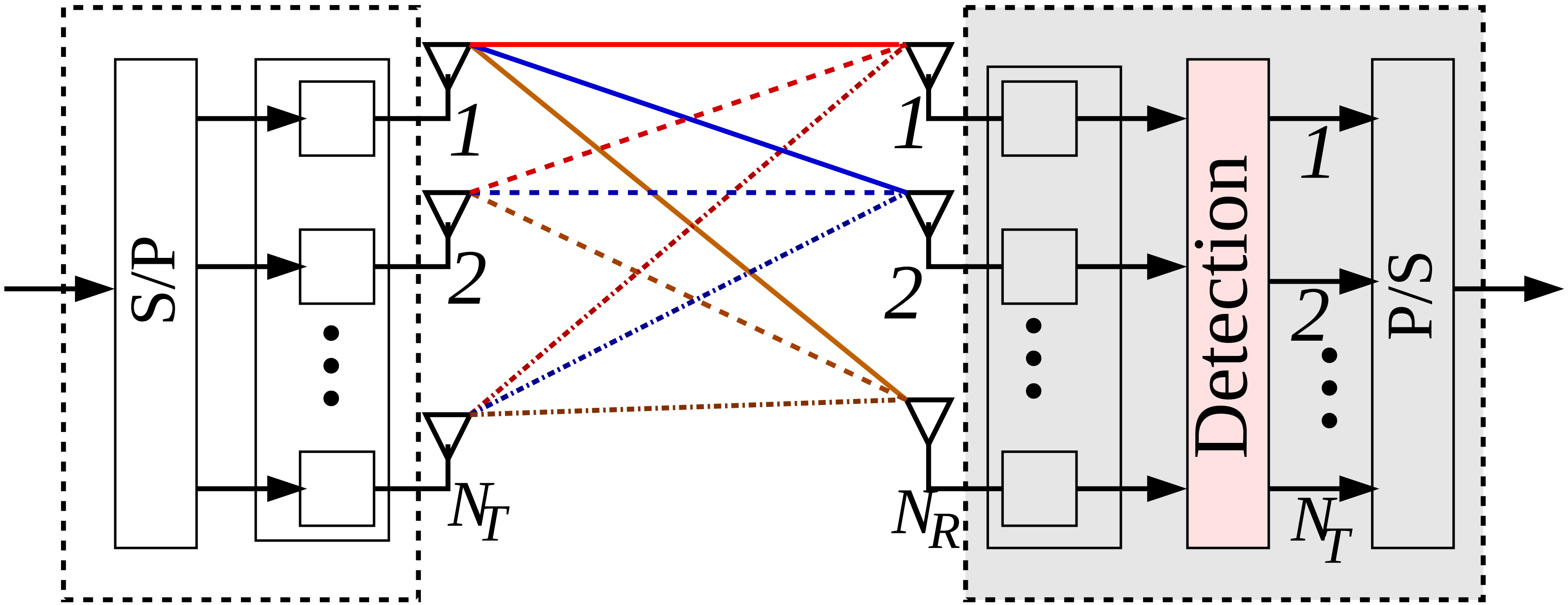
MIMO Landscape

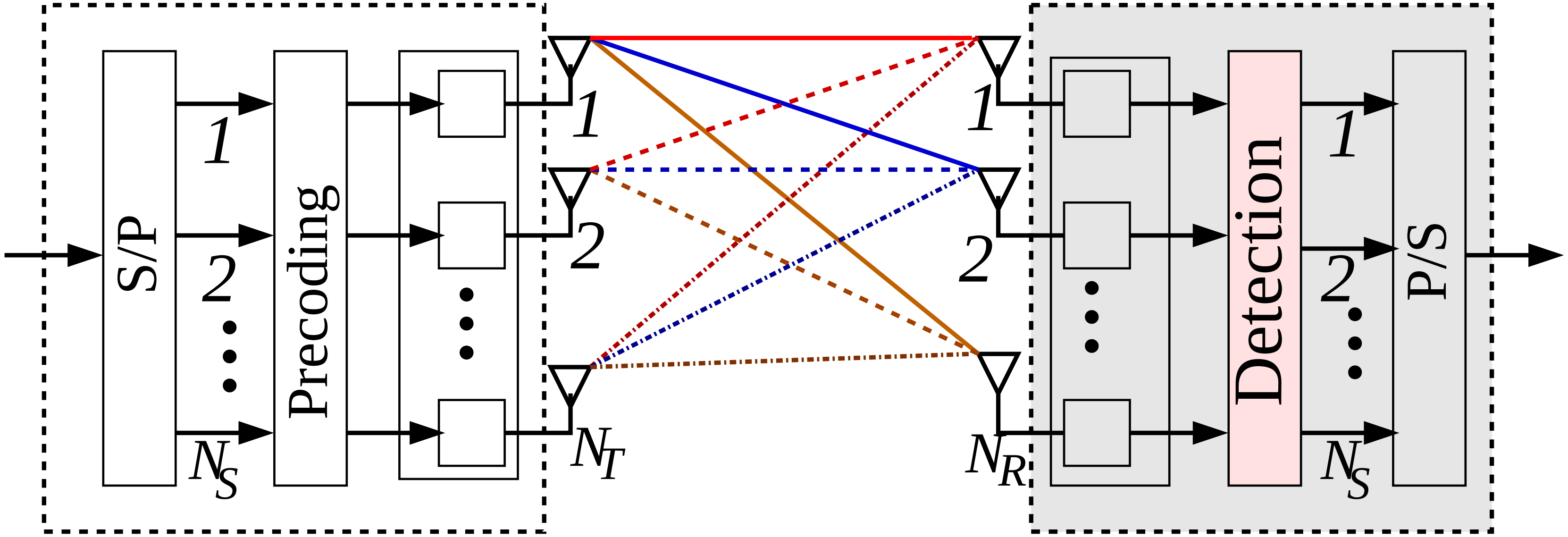
- MIMO: exploits **space** and **time** dimensions $\Rightarrow$ **diversity** and **multiplexing** gains
- **Vertical Bell Lab layered space-time** (V-BLAST)
  - Offers high multiplexing gain at high decoding complexity owing to inter-channel interference (ICI)
- **Orthogonal space-time block codes** (OSTBCs)
  - 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

V-BLAST

- BLAST-type architecture: exploits **spatial dimension** for **multiplexing gain** ⇒ high rate
- Inter-antenna interference or **inter-channel interference** ⇒ prohibitively high complexity for ML detection
- Assuming $N_R \geq N_T$, N_T symbols are mapped to N_T transmit antennas for transmission in $t_n = 1$ time slot



V-BLAST (2)



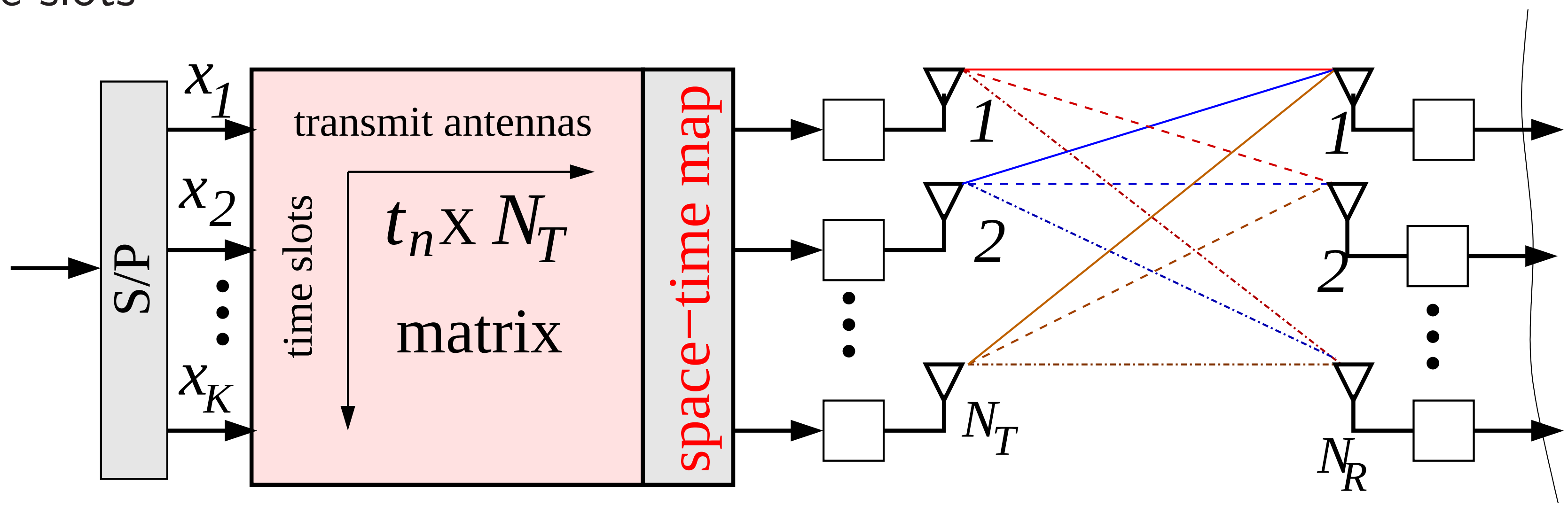
- In general, maximum **spatial multiplexing order**: $N_S = \min\{N_T, N_R\}$
- N_S symbols are mapped to N_T transmit antennas by **precoding** for transmission in $t_n = 1$ time slot
- For L-PSK or L-QAM, normalised **throughput** per time slot

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

OSTBCs

- Space-time block codes exploit space and time dimensions $\Rightarrow$ **maximum diversity gain**, at expense of bandwidth efficiency

- Block of K symbols are mapped to N_T transmit antennas for transmission in t_n time slots



- Thus, STBC is defined by $t_n \times N_T$ complex-valued matrix $\mathbf{S} \in \mathbb{C}^{t_n \times N_T}$

- **Orthogonal** STBCs: advantage of **low-complexity** ML detection

OSTBCs (2)

- For L-PSK or L-QAM, normalised **throughput** per time slot

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

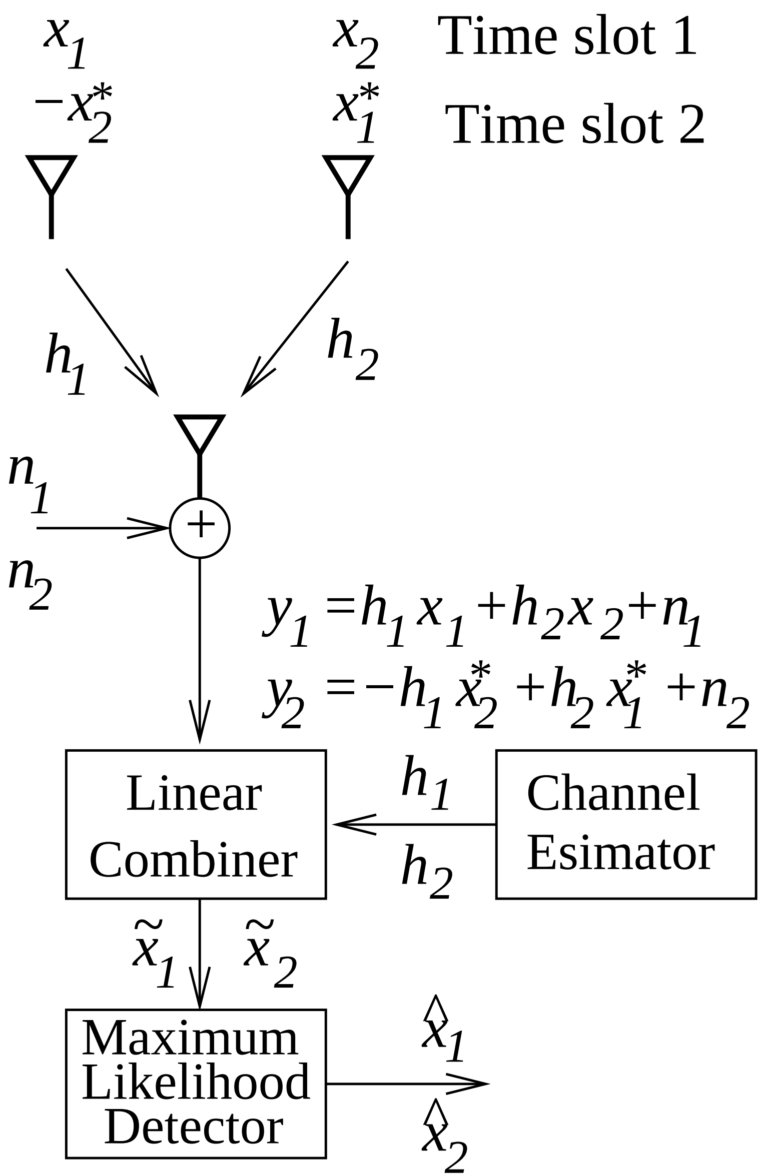
- Generally, $\frac{K}{t_n} < 1$

- Only one OSTBC, **Alamouti** code

$$t_n \times N_T = 2 \times 2 : G_2 = \left[\begin{array}{cc} x_1 & x_2 \\ -x_2^* & x_1^* \end{array} \right]$$

achieves $\frac{K}{t_n} = 1$

- STBCs cannot offer multiplexing gain



LDCs

- LDCs: "between V-BLAST and STBCs", more **flexible** tradeoff between **diversity** and **multiplexing** gains

- Q symbols, $\{s_q = \alpha_q + j\beta_q \in \mathbb{C}\}_{q=1}^{Q}$, are mapped to N_T transmit antennas for transmission in t_n time slots

- The $t_n \times N_T$ LDC matrix, $\mathbf{S} \in \mathbb{C}^{t_n \times N_T}$, is defined by

$$\mathbf{S} = \sum_{q=1}^{Q} \left(\alpha_q \mathbf{A}_q + j\beta_q \mathbf{B}_q \right)$$

  $\mathbf{A}_q, \mathbf{B}_q \in \mathbb{C}^{t_n \times N_T}$ are set of dispersion matrices

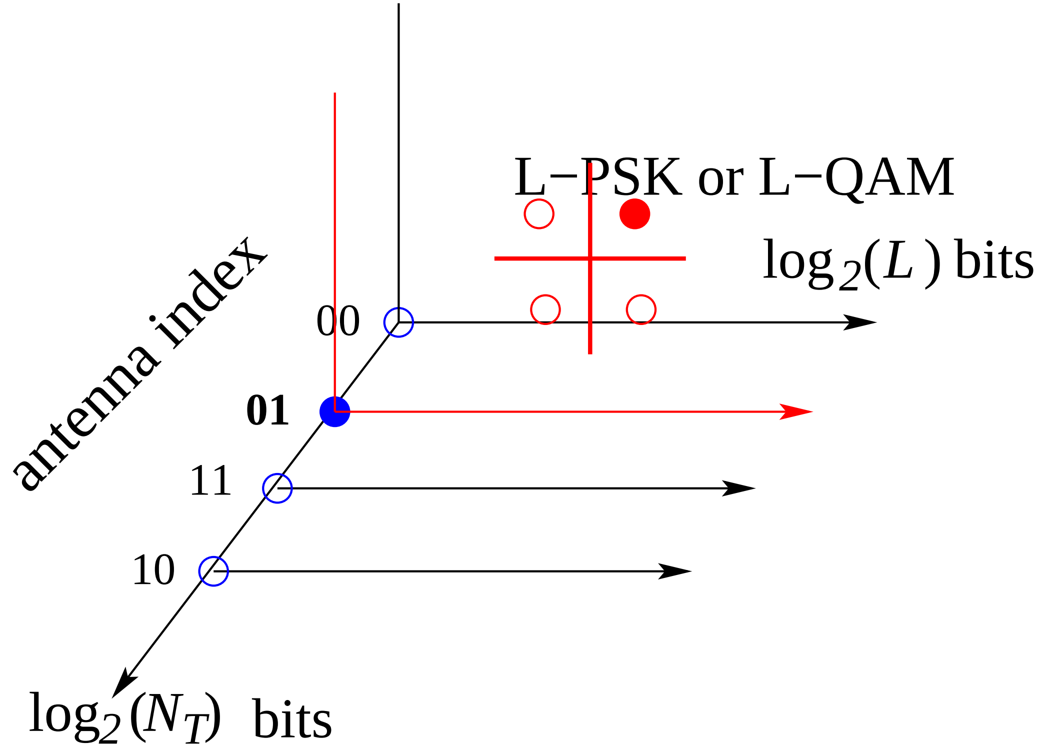
- For L-PSK or L-QAM, normalised **throughput** per time slot

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

- Inter-antenna interference or **inter-channel interference** $\Rightarrow$ prohibitively high complexity for ML detection

SM and SSK

- **Antenna index** conveys bits
- For L-PSK or L-QAM, $\log_2(L)$ bits: select the symbol to transmit
- Another $\log_2(N_T)$ bits: select the transmit antenna to send the symbol in $t_n = 1$ time slot
- Mainly for **multiplexing gain**

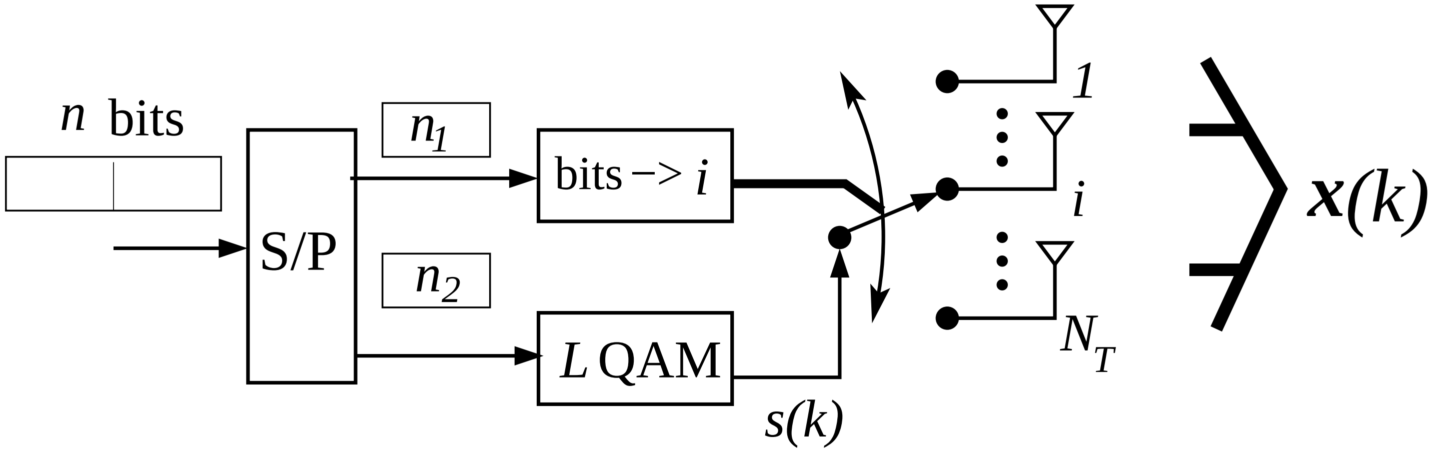


- Normalised **throughput** per time slot

$$R = \log_2\left(N_T \cdot L\right) \text{ [bits/symbol]}$$

- No inter-antenna interference or **inter-channel interference** ⇒ **low complexity** “single-antenna” ML detection

Spatial Modulation Transmitter



- SM (N_T, N_R) with L-PSK/QAM, transmitter block diagram:
  - N_T: number of transmitter antennas, $n_1 = \log_2(N_T)$
  - N_R: number of receiver antennas
  - L: size of modulation constellation, $n_2 = \log_2(L)$
  - $n = n_1 + n_2$: number of transmit bits per time slot
  - k: time slot index
- $n_1 = \log_2(N_T)$ bits select which transmit antenna to activate: n_1 bits $\longrightarrow i$ antenna
- $n_2 = \log_2(L)$ bits decide symbol $s(k)$ from L-PSK/QAM modulation scheme

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

SM Receiver

- With MIMO channel matrix $\boldsymbol{H} \in \mathbb{C}^{N_R \times N_T}$ and AWGN vector $\boldsymbol{v}(k) \in \mathbb{C}^{N_R}$, received signal model

$$\boldsymbol{y}(k) = \boldsymbol{H}\, \boldsymbol{x}(k) + \boldsymbol{v}(k)$$

  - Transmitted signal vector

$$\boldsymbol{x}(k) = [\underbrace{0 \ \cdots \ 0}_{i-1} \ \underbrace{s(k)}_{i} \ \underbrace{0 \ \cdots \ 0}_{N_T-i}]^{\mathrm{T}} \in \mathbb{C}^{N_T}$$

  - $\boldsymbol{x}(k)$ takes values from set

$$\boldsymbol{x}(k) \in \mathcal{S} = \left\{ \boldsymbol{s}_{i,l} \in \mathbb{C}^{N_T}, 1 \le i \le N_T, 1 \le l \le L \right\}$$

    with

$$\boldsymbol{s}_{i,l} = [\underbrace{0 \ \cdots \ 0}_{i-1} \ \underbrace{s_l}_{i} \ \underbrace{0 \ \cdots \ 0}_{N_T-i}]^{\mathrm{T}} \in \mathbb{C}^{N_T}$$

- ML estimates $(\widehat{i}, \widehat{l})$ of (i, l) are given by

$$\left(\widehat{i}, \widehat{l}\right) = \arg \min_{\substack{1 \le i \le N_T \\ 1 \le l \le L}} \left\| \boldsymbol{y}(k) - \boldsymbol{H}\, \boldsymbol{s}_{i,l} \right\|^2$$

- Then de-map $\widehat{i}$ to the n_1 bits, and de-map $\widehat{l}$ to the n_2 bits.

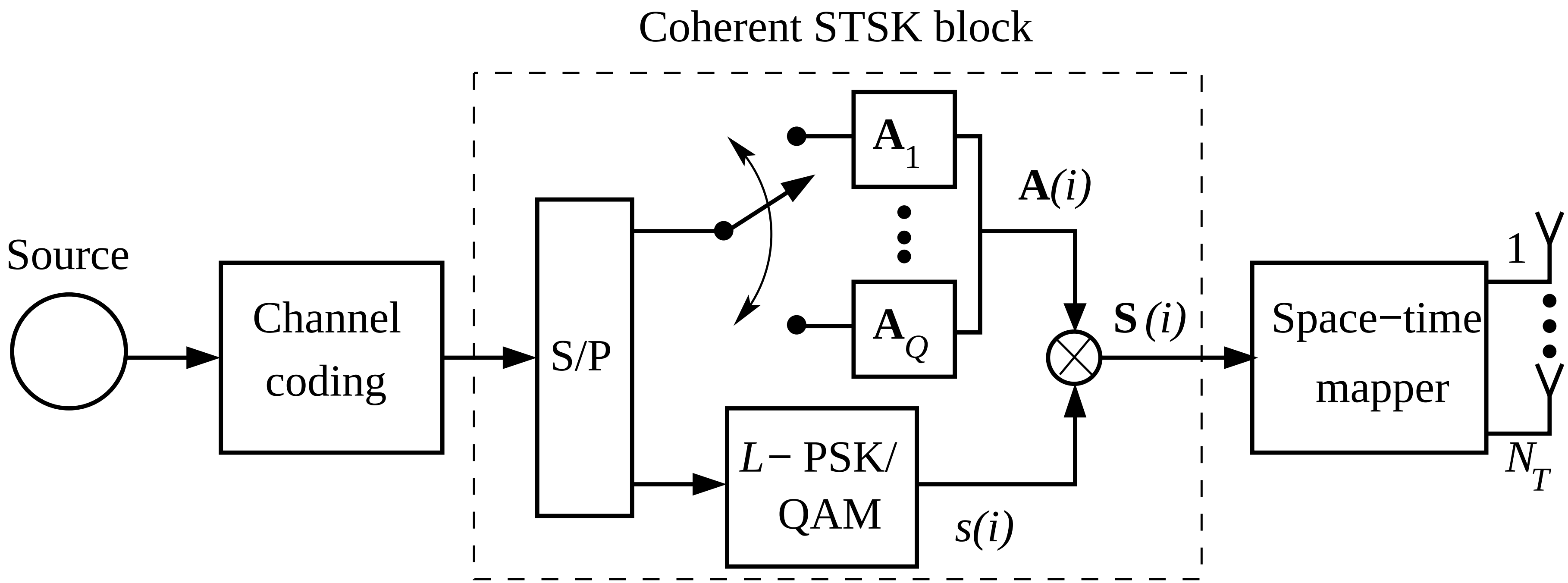
Unified MIMO Architecture

- **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 ⇒ 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 ⇒ efficient semi-blind iterative channel estimation and data detection**

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

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

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

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

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

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

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

Design

- CSTSK (N_T, N_R, T_n, Q) with L-PSK/QAM: high degree of design freedom
  - Similar to LDCs, strike **flexible** diversity versus multiplexing gain trade off
  - Unlike LDCs, we will show STSK imposes **no ICI**
  - Optimisation: number of transmit and receive antennas as well as the set of dispersion matrices $\Rightarrow$ desired diversity and multiplexing gains

- Unlike SM and SSK, STSK fully exploits both spatial and time dimensions
  - SM and SSK can be viewed as special case of STSK
  - Set $t_n = 1$, $Q = N_T$ and choose

$$\mathbf{A}_1 = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \mathbf{A}_2 = \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}, \cdots, \mathbf{A}_Q = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} \Rightarrow \text{SM}$$

CSTSK Receiver Model

- 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 $\mathcal{CN}(0, N_{\rm o})$
- Signal to noise ratio (SNR) is defined as

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

$E_{\rm s}$ 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

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

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

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: $\overline{\mathbf{y}}(i) = \overline{\mathbf{H}}\,\mathbf{\Theta}\,\mathbf{k}(i) + \overline{\mathbf{v}}(i)$

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

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

  where $\big(\overline{\mathbf{H}}\,\mathbf{\Theta}\big)_q$ denotes qth column of the matrix $\overline{\mathbf{H}}\,\mathbf{\Theta}$

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

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

Complexity Comparison

- For STSK, optimal ML detection of $\tau \times \log_2(Q \cdot L)$ bits
  - only requires search for a total of $\tau \times (Q \cdot L)$ points
- For simplicity, assuming $N_T = N_R$, full optimal ML detection for conventional MIMO with the same rate R
  - requires search for a total of $\tau \times N_R^{L \cdot Q}$ points, which may become prohibitive
- K-best sphere decoding approximates ML performance with K set to $K = L \cdot Q$ for conventional MIMO
  - requires search for a total of $\tau \times \big(L \cdot Q + \big(N_R - 1\big)\big(L \cdot Q\big)^2\big)$ points
  - while imposing some additional complexity necessitated by Cholesky factorisation

Training Based Adaptive CSTSK

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

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

- **Least square channel estimate** (LSCE) based on $(\mathbf{Y}_{\mathrm{t}M}, \mathbf{S}_{\mathrm{t}M})$ is given by

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

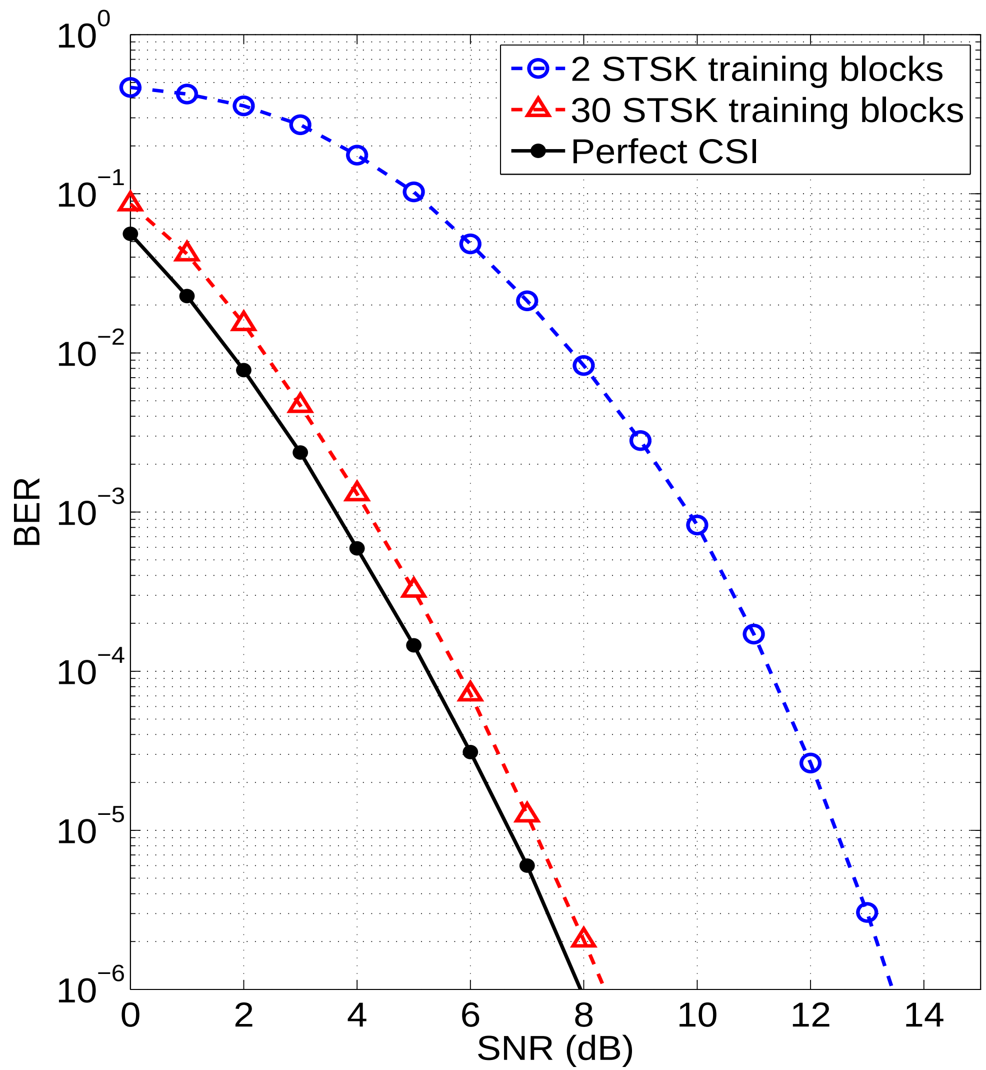
- In order for $\mathbf{S}_{\mathrm{t}M}\mathbf{S}_{\mathrm{t}M}^H$ to have full rank of N_T, it is necessary that $M \cdot T_n \geq N_T$ and this requires a minimum of

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

- 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



Semi-Blind Iterative Algorithm

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

1. Set iteration index $t = 0$ and channel estimate $\tilde{\mathbf{H}}^{(t)} = \hat{\mathbf{H}}_{\mathrm{LSCE}}$;
2. Given $\tilde{\mathbf{H}}^{(t)}$, perform ML detection on $\mathbf{Y}_{\mathrm{d}\tau}$ and carry out channel decoding on detected bits. Corresponding detected information bits, after passing through channel coder again, are re-modulated to yield
$$\hat{\mathbf{S}}_{\mathrm{e}\tau}^{(t)} = \left[\hat{\mathbf{S}}^{(t)}(1)\ \hat{\mathbf{S}}^{(t)}(2)\ \cdots\ \hat{\mathbf{S}}^{(t)}(\tau) \right];$$
3. Update channel estimate with decision-directed LSCE
$$\tilde{\mathbf{H}}^{(t+1)} = \mathbf{Y}_{\mathrm{d}\tau} \left(\hat{\mathbf{S}}_{\mathrm{e}\tau}^{(t)} \right)^H \left(\hat{\mathbf{S}}_{\mathrm{e}\tau}^{(t)} \left(\hat{\mathbf{S}}_{\mathrm{e}\tau}^{(t)} \right)^H \right)^{-1};$$
4. Set $t = t + 1$: If $t < I_{\max}$, 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

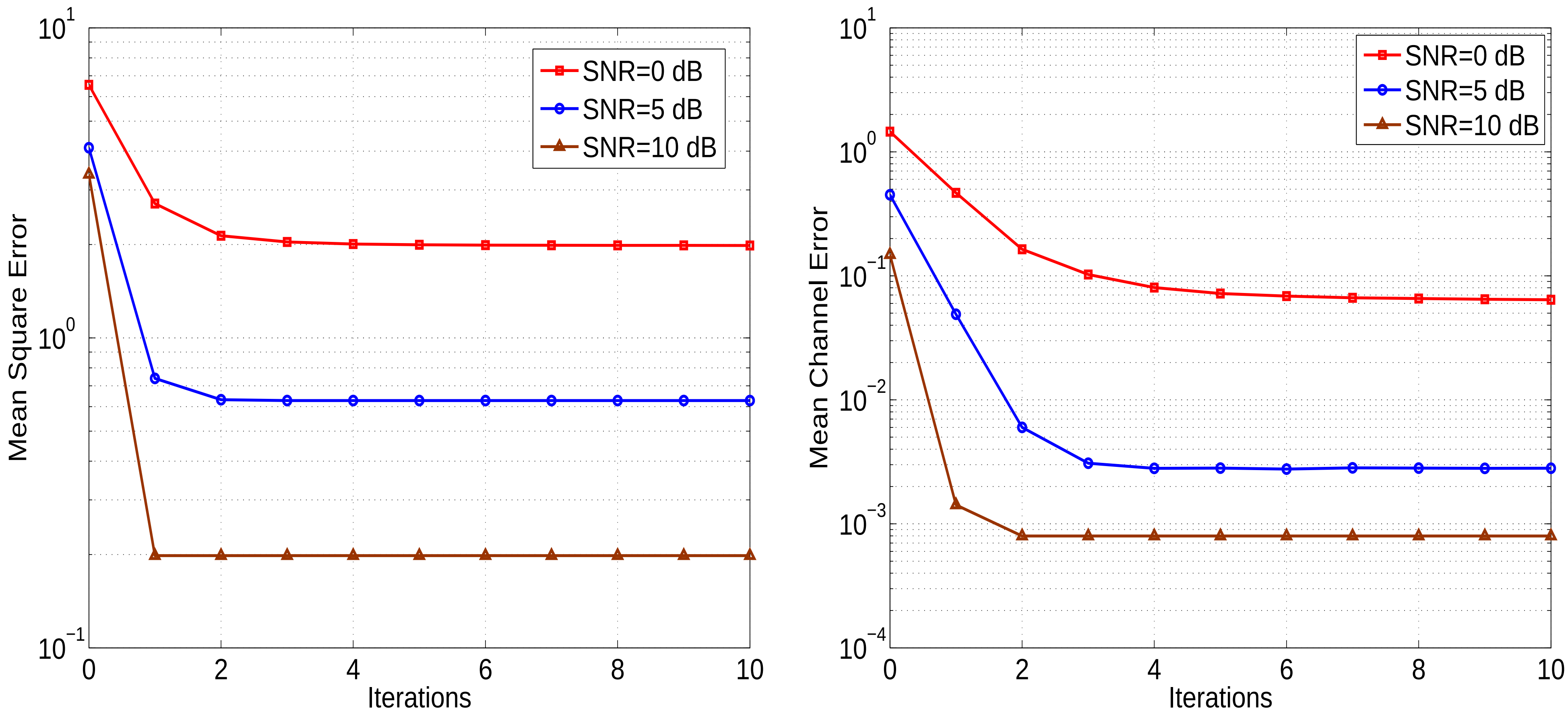
- Performance averaged over 100 channel realisations

- 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

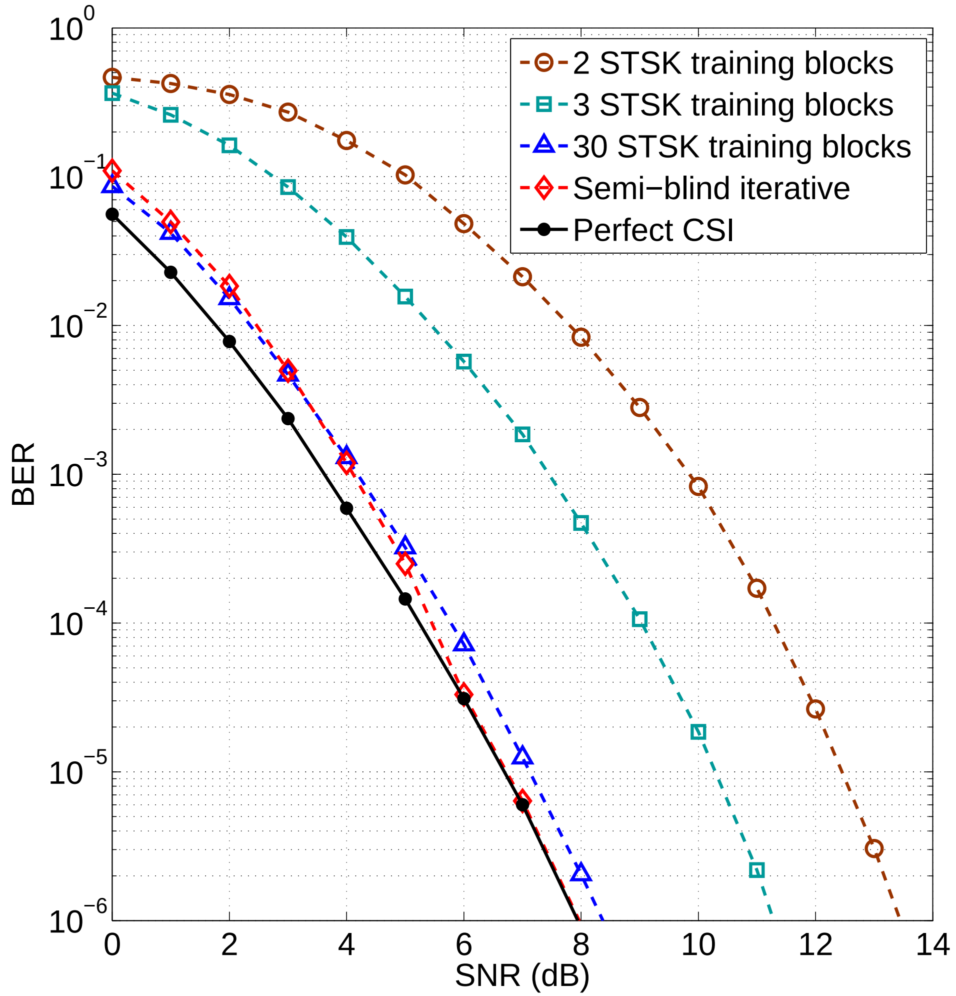
$(4, 4, 2, 4)$ QPSK (Convergence)

- $(N_T = 4, N_R = 4, T_n = 2, Q = 4)$ 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

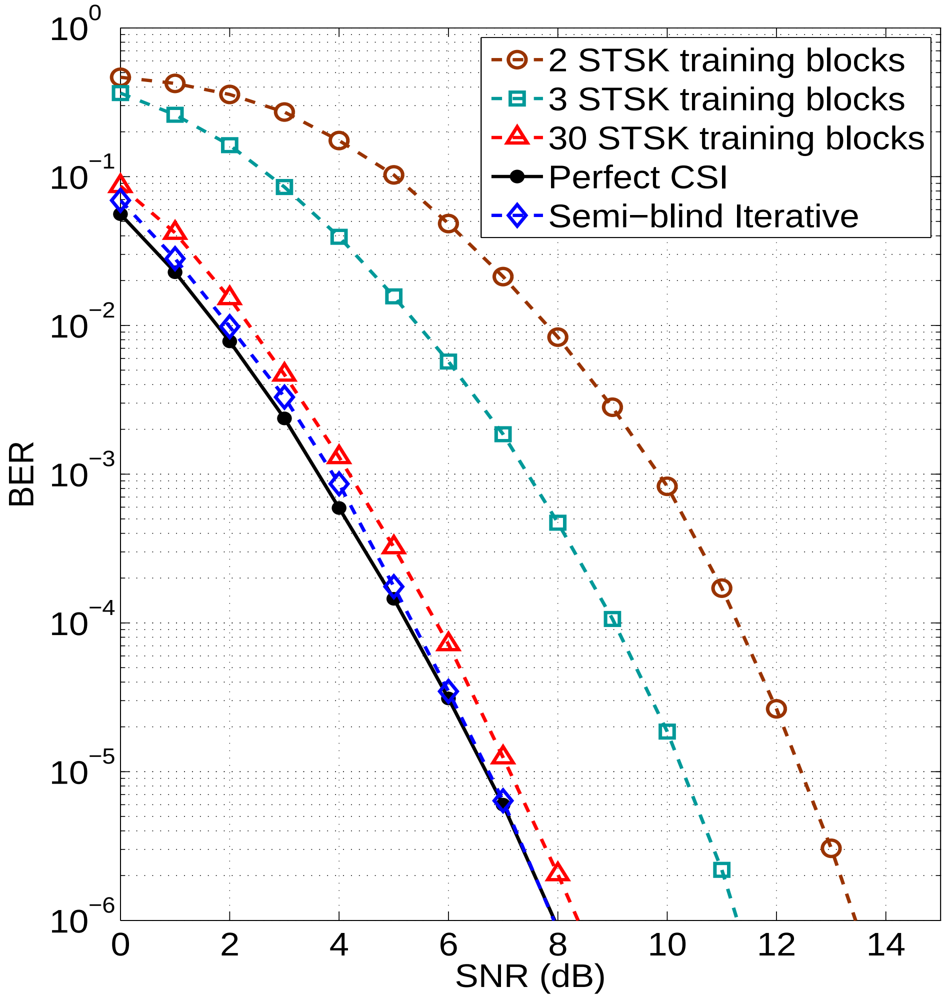


$(4, 4, 2, 4)$ QPSK (Bit Error Rate)

(a) semi-blind with $M = 2$ training

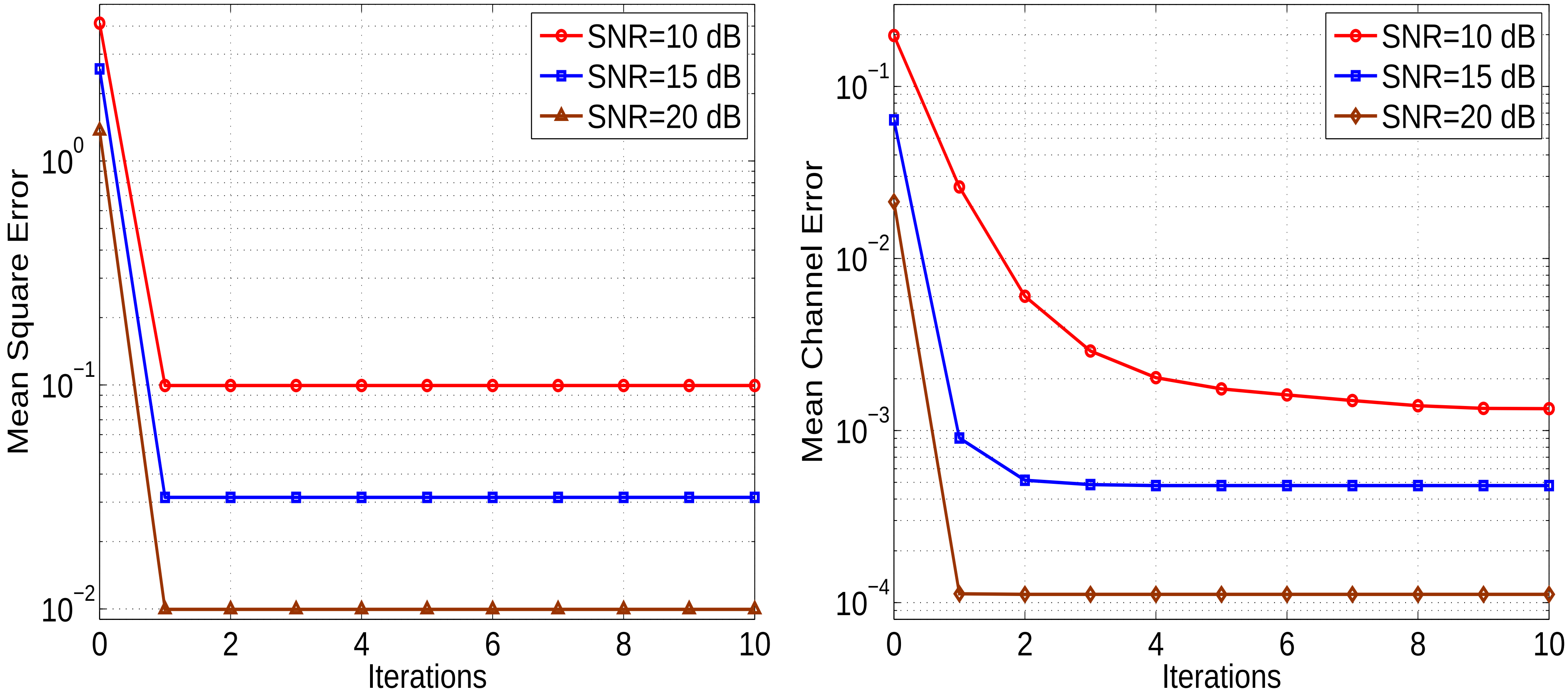


(b) semi-blind with $M = 3$ training



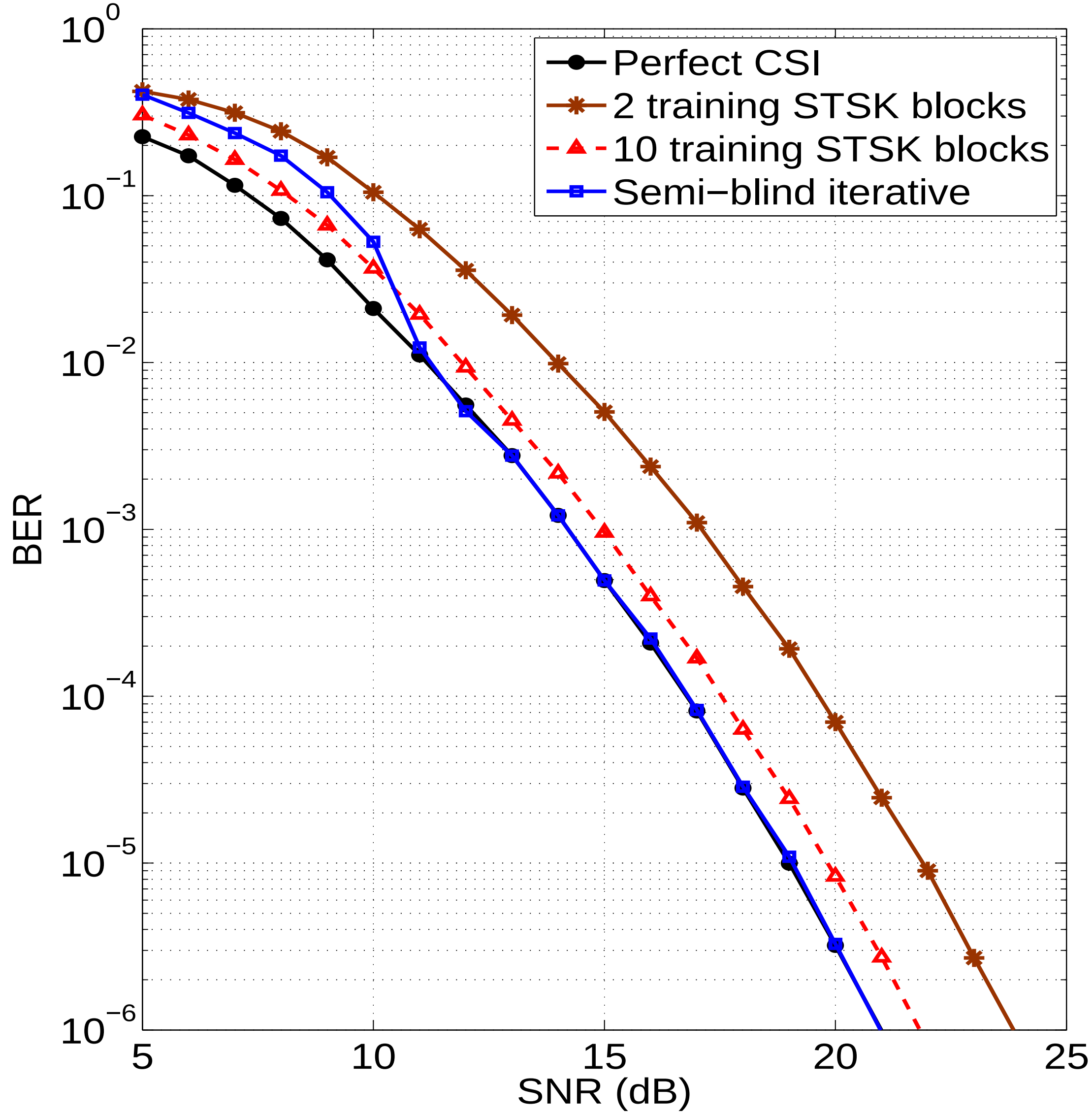
$(4,2,2,4)$ 16QAM (Convergence)

- $(N_T = 4, N_R = 2, T_n = 2, Q = 4)$ 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

- Space-time shift keying offers a unified MIMO architecture
  1. V-BLAST, OSTBCs, LDCs, SM and SSK are special cases
  2. Flexible diversity versus multiplexing gain trade off
  3. No ICI and low-complexity single-antenna ML detection

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

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