Adaptive Space-Time Shift Keying Systems

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The UC4G 2010 Beijing Workshop
Outline

1. Introduction
   - Motivations

2. CSTSK MIMO System
   - Transmitter Model
   - Receiver Model

3. Adaptive CSTSK MIMO System
   - Training Based Adaptive CSTSK
   - Semi-Blind Iterative Scheme

4. Conclusions
Introduction

Motivations

CSTSK MIMO System

Transmitter Model

Receiver Model

Adaptive CSTSK MIMO System

Training Based Adaptive CSTSK

Semi-Blind Iterative Scheme

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

- $\log_2(Q)$ 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 $\text{tr}[\mathbf{A}_q^H\mathbf{A}_q] = T_n$

- 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 $\mathcal{CN}(0, N_o)$

- Signal to noise ratio (SNR) is defined as
  \[ \text{SNR} = \frac{E_s}{N_o} \]
  $E_s$ is average symbol energy of $L$-PSK/QAM modulation scheme

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

- Introduce notations
  \[
  \bar{y}(i) = \text{vec}[Y(i)] \in \mathbb{C}^{N_R T_n \times 1} \\
  \bar{v}(i) = \text{vec}[V(i)] \in \mathbb{C}^{N_R T_n \times 1} \\
  \bar{H} = I_{T_n} \otimes H \in \mathbb{C}^{N_R T_n \times N_T T_n} \\
  \Theta = [\text{vec}[A_1] \cdots \text{vec}[A_Q]] \in \mathbb{C}^{N_T T_n \times Q}
  \]

- Equivalent transmitted signal vector \( k(i) \) takes value from set
  \[
  \mathcal{K} = \{ k_{q,l} \in \mathbb{C}^{Q \times 1}, \ 1 \leq q \leq Q, \ 1 \leq l \leq L \}
  \]
  which contains \( Q \cdot L \) legitimate transmitted signal vectors
  \[
  k_{q,l} = [0 \cdots 0 \ s_l \ 0 \cdots 0]^T, \ 1 \leq q \leq Q, \ 1 \leq l \leq L
  \]
  where \( s_l \) is the \( l \)th symbol in the \( L \)-point constellation \( S \)

- Equivalent received signal model:
  \[
  \bar{y}(i) = \bar{H} \Theta k(i) + \bar{v}(i)
  \]
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 $i$th STSK block, which are mapped to $s_l$ and $A_q$

- Then ML estimates $(\hat{q}, \hat{l})$ are given by

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

where $(\mathbf{H}_\Theta)_q$ denotes $q$th column of the matrix $\mathbf{H}_\Theta$

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

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

- Assume number of available training blocks is $M$ and training data are arranged as
  \[ Y_{tM} = \begin{bmatrix} Y(1) & Y(2) & \cdots & Y(M) \end{bmatrix} \]
  \[ S_{tM} = \begin{bmatrix} S(1) & S(2) & \cdots & S(M) \end{bmatrix} \]

- Then LSCE based on $(Y_{tM}, S_{tM})$ is given by
  \[ \hat{H}_{LSCE} = Y_{tM}S_{tM}^H(S_{tM}S_{tM}^H)^{-1} \]

- In order for $S_{tM}S_{tM}^H$ to have full rank of $N_T$, it is necessary that
  \[ M \cdot T_n \geq N_T \]
  and this requires a minimum of
  \[ M = \left\lceil \frac{N_T}{T_n} \right\rceil \]
  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 $\hat{H}_{\text{LSCE}}$, and let observation data for ML detector be $Y_{d\tau} = \begin{bmatrix} Y(1) & Y(2) & \cdots & Y(\tau) \end{bmatrix}$.

1. Set iteration index $t = 0$ and channel estimate $\tilde{H}(t) = \hat{H}_{\text{LSCE}}$;

2. Given $\tilde{H}(t)$, perform ML detection on $Y_{d\tau}$ and carry out channel decoding on detected bits. Corresponding detected information bits, after passing through channel coder again, are re-modulated to yield

$$\hat{S}_{e\tau}^{(t)} = \begin{bmatrix} \hat{S}^{(t)}(1) & \hat{S}^{(t)}(2) & \cdots & \hat{S}^{(t)}(\tau) \end{bmatrix};$$

3. Update channel estimate with decision-directed LSCE

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

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

- Performance was assessed using estimated mean square error

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

mean channel estimation error

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

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

- 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

1. S. Sugiura, S. Chen and L. Hanzo, “A unified MIMO architecture subsuming space shift keying, OSTBC, BLAST and LDC,” to be presented at VTC 2010-Fall (Ottawa, Canada), Sept. 6-9, 2010, 5 pages
