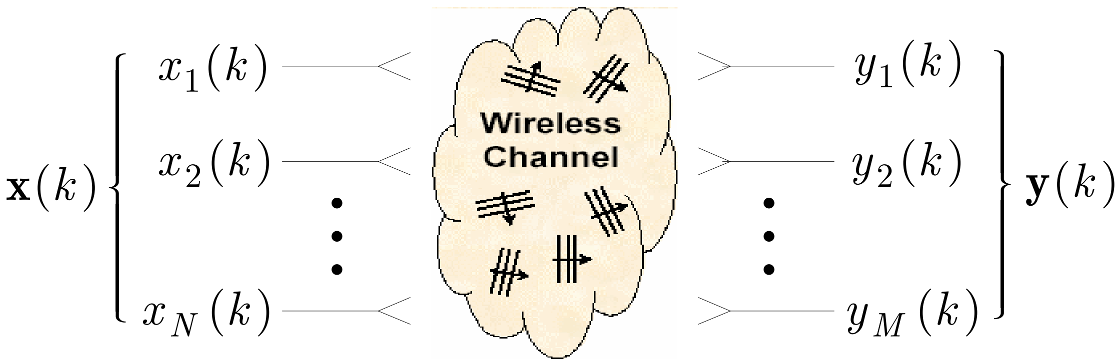
A Flexible Uplink CDMA Space-Time Transceiver with Reduced Complexity V-BLAST Detection

Chung-Lien Ho and Ta-Sung Lee

Department of Communication Engineering
National Chiao Tung University
Hsinchu, Taiwan, R.O.C.
E-mail: margee.cm87g@nctu.edu.tw ; tslee@mail.nctu.edu.tw

Overview

- **Multi-input multi-output (MIMO) concept**



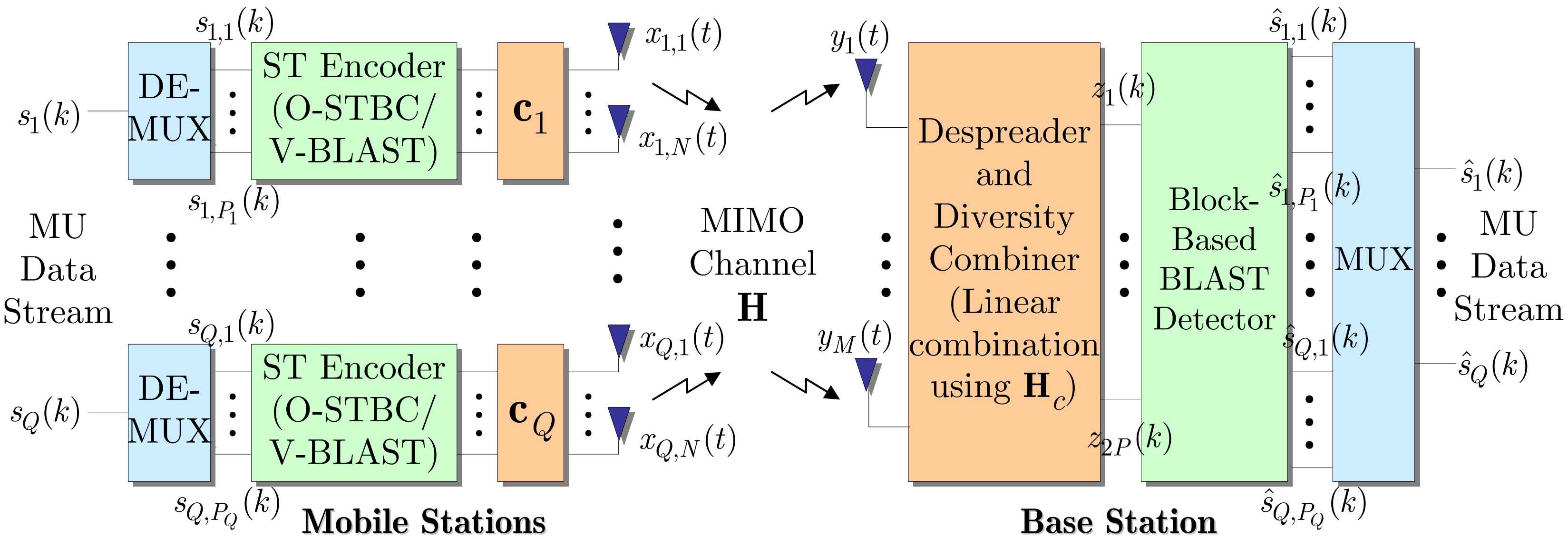
  - Basic idea: use multiple antennas at both sides to improve BER and/or data rate of a communication system
  - Core scheme: space-time coding (STC)
    - Goal: exploits spatial-temporal signature of channel
    - Provisioning: diversity & multiplexing
  - Scenario: most likely a mixture of diversity & multiplexing
  - Applications: 3GPP, 3GPP2, IEEE 802.11n, IEEE 802.16a

- **Space-time coding schemes**
  - Transmit diversity perspective
    - ST block code (STBC)
      - Provides diversity gain but no coding gain
      - Simple detection at receiver
    - ST trellis code (STTC)
      - Provides both diversity and coding gains
      - Complicated detection at receiver
  - Spatial multiplexing perspective
    - Layered ST code (LSTC), aka BLAST
      - Provides some coding gain and diversity gain
      - Provides multiplexing gain for increased bandwidth efficiency

System Model

Uplink MIMO-CDMA system over fading channel

- System description and basic assumption
  - N antennas at each of Q MSs, and M antennas at BS
  - Data stream of MS $s_q(k)$, $1 \leq q \leq Q$, can be
    - Space-time encoded: O-STBC ("orthogonal" STBC)
    - Spatially multiplexed: V-BLAST ("vertical" BLAST)



- Assumptions:
  - $M \geq N$ (so that V-BLAST users can be detected)
  - Q_D O-STBC users and Q_M V-BLAST users
- O-STBC mode: P_D symbols encoded over K symbol periods
- V-BLAST mode: $P_M = NK$ symbols transmitted over K symbol periods

Code matrix

$$s_q(k) = \{s_1(k), s_2(k)\}_{\text{O-STBC}}$$

$P_D = 2,\ K = 2$

O-STBC

$$s_q(k) = \{s_1(k), s_2(k), s_3(k), s_4(k)\}_{\text{V-BLAST}}$$

$$\Rightarrow \begin{bmatrix} x_1(k) & x_1(k+1) \\ x_2(k) & x_2(k+1) \end{bmatrix} \Rightarrow$$

V-BLAST

$P_M = 4,\ K = 2$

$$\mathbf{X}_q(k) = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}_{\text{O-STBC}}$$

$$\mathbf{X}_q(k) = \begin{bmatrix} s_1 & s_3 \\ s_2 & s_4 \end{bmatrix}_{\text{V-BLAST}}$$

- At Rx, chip-sampled ST data matrix over K symbol periods

$$\underbrace{\mathbf{Y}(k) := [\mathbf{y}(k)\cdots\mathbf{y}(k+K-1)]}_{M(G+L-1)\times K} = \sum_{q=1}^{Q}\mathbf{H}_q\mathbf{X}_q(k) + \mathbf{V}(k)$$

where

  - $\mathbf{y}(k) \in \mathbb{C}^{M(G+L-1)\times 1}$: chip-sampled data vector collected at M antennas
  - G: spreading factor ; L: no. of resolvable paths
  - $\mathbf{X}_q(k) \in \mathbb{C}^{N\times K}$: code matrix
  - $\mathbf{H}_q \in \mathbb{C}^{M(G+L-1)\times N}$: MIMO channel matrix that includes effect of spreading code
  - $\mathbf{V}(k) \in \mathbb{C}^{M(G+L-1)\times K}$: channel noise matrix

- Equivalent vectorized data model (real-valued)†

$$\mathbf{y}_c(k) := \begin{bmatrix} \tilde{\mathbf{y}}(k) \\ \vdots \\ \tilde{\mathbf{y}}(k+K-1) \end{bmatrix} = \mathbf{H}_c \mathbf{s}_c(k) + \mathbf{v}_c(k)$$

$2KM(G+L-1) \times 1$

where

- $\tilde{\mathbf{y}}(k) := [\mathrm{Re}\{\mathbf{y}^T(k)\} \;\; \mathrm{Im}\{\mathbf{y}^T(k)\}]^T \in \mathbb{R}^{2M(G+L-1)}$
- $\mathbf{H}_c \in \mathbb{R}^{2KM(G+L-1)\times 2P}$: equivalent MIMO channel matrix
- $\mathbf{s}_c(k) \in \mathbb{R}^{2P}$: total transmitted symbol vector from all MSs,
  - $P = Q_D P_D + Q_M N K$

† New data model facilitates detection and analysis

A Flexible Detection Strategy

- Separation of multiple CDMA users
  - Dictates multi-user detection
  - V-BLAST detector is a candidate
- Detection of O-STBC user data streams
  - Simple decoder is available
- Detection of V-BLAST user data streams
  - Straightforward to use V-BLAST detector
- V-BLAST detector is therefore applied to
  - Separate data streams from different O-STBC users
  - Separate data streams from different antennas of each V-BLAST user

- Sufficient statistics for symbol decision (matched filter output)

$$\mathbf{z}(k) := \underbrace{\mathbf{H}_c^T \mathbf{y}_c(k)}_{2P \times 1} = \mathbf{F}\mathbf{s}_c(k) + \overline{\mathbf{v}}(k)$$

where

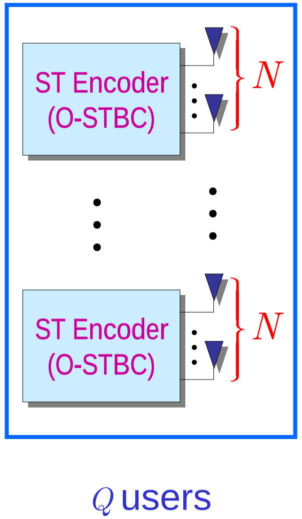
$$\mathbf{F} := \mathbf{H}_c^T \mathbf{H}_c = \begin{bmatrix} \mathbf{F}_{11} & \cdots & \mathbf{F}_{1Q} \\ \vdots & \ddots & \vdots \\ \mathbf{F}_{Q1} & \cdots & \mathbf{F}_{QQ} \end{bmatrix} \in \mathbb{R}^{2P \times 2P}$$

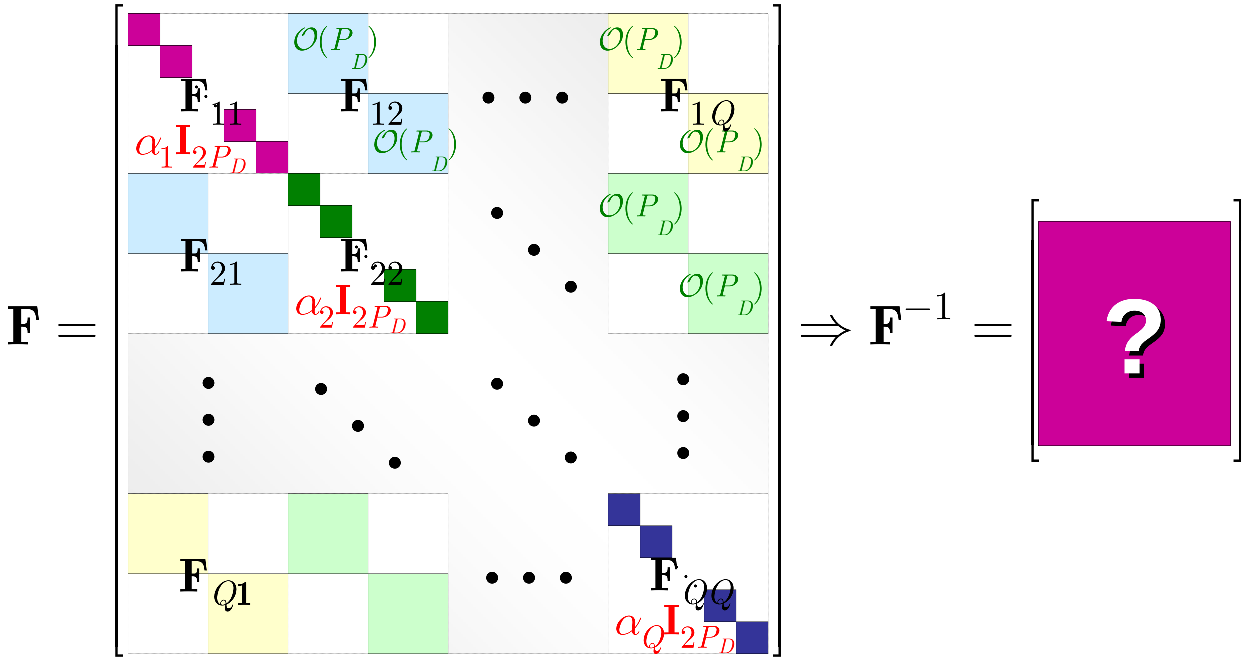
$\mathbf{F}_{pq}$: cross-coupling matrix between pth & qth users

- $\mathbf{F}$ is diagonal for single O-STBC user, but quite involved for general case $\Rightarrow$ use V-BLAST to restore $\mathbf{s}_c(k)$
- Distinctive structure of $\mathbf{F}$ induces block detection advantage

- V-BLAST detection
  - Algorithm:
    - Ordering
    - Nulling
    - Decision and reconstruction
    - Canceling
  - Ordering & nulling require $\mathbf{F}^{-1}$
    - Ordering is determined by diagonal entries of $\mathbf{F}^{-1}$
- Block based V-BLAST detection
  - Distinctive structure of $\mathbf{F}$ leads to block detection
    - Equal diagonal entries of $\mathbf{F}^{-1}$ for each O-STBC user
    - A block of symbols can be jointly detected (same order)
    - Fewer iterations involved

- **Case 1:** Pure O-STBC scenario
  - Structure of $\mathbf{F}$

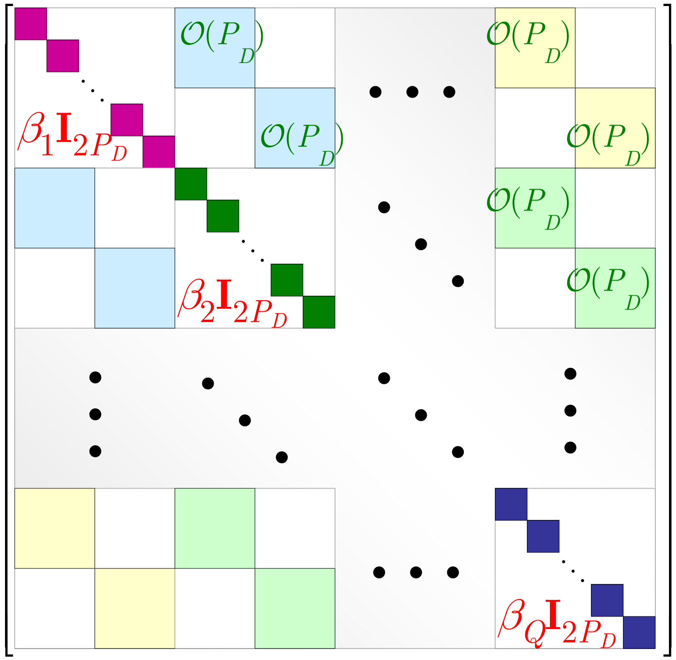




  - Diagonal blocks: diagonal with equal diagonal entries
  - Off-diagonal blocks: orthogonal

- $\mathbf{F}^{-1}$ assumes exactly the same structure as $\mathbf{F}$

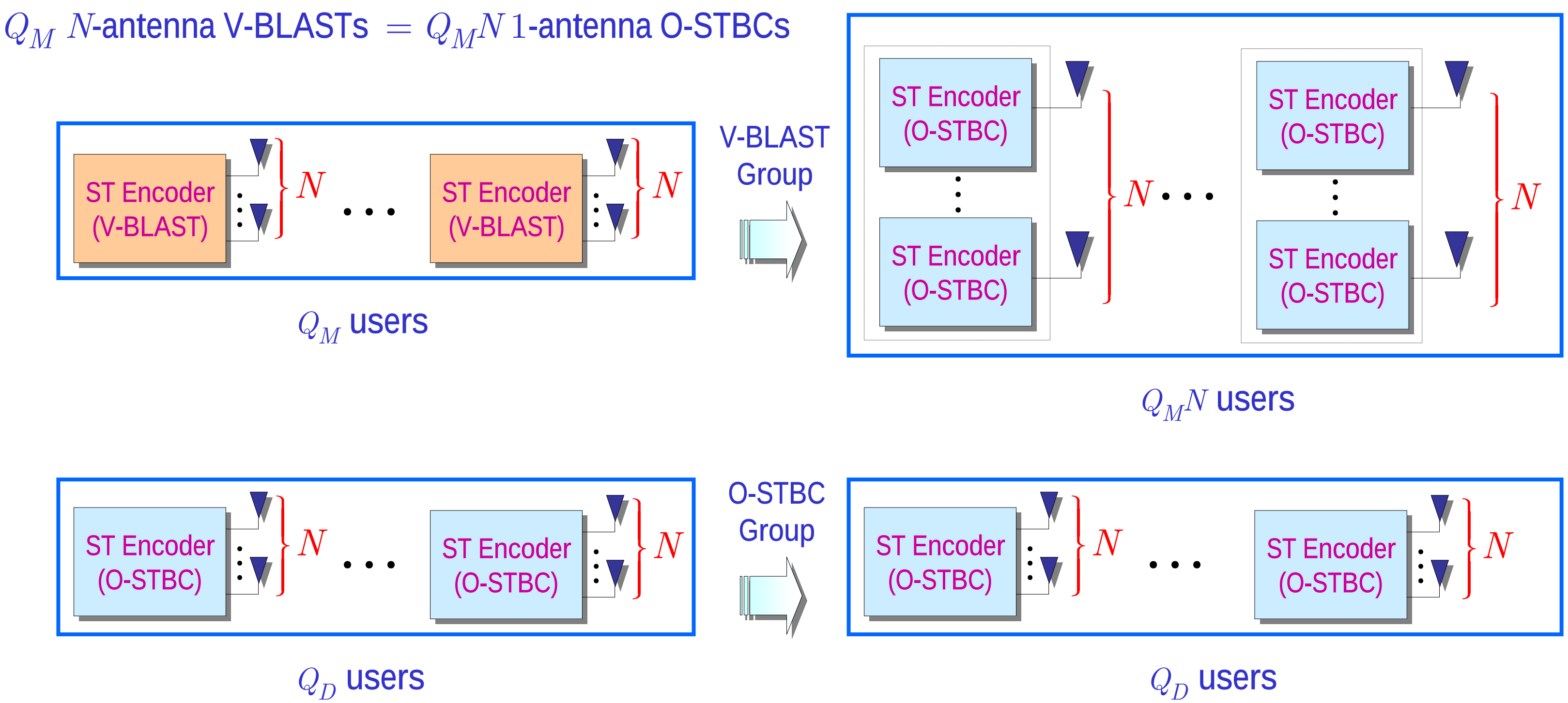
$\mathbf{F}^{-1} =$



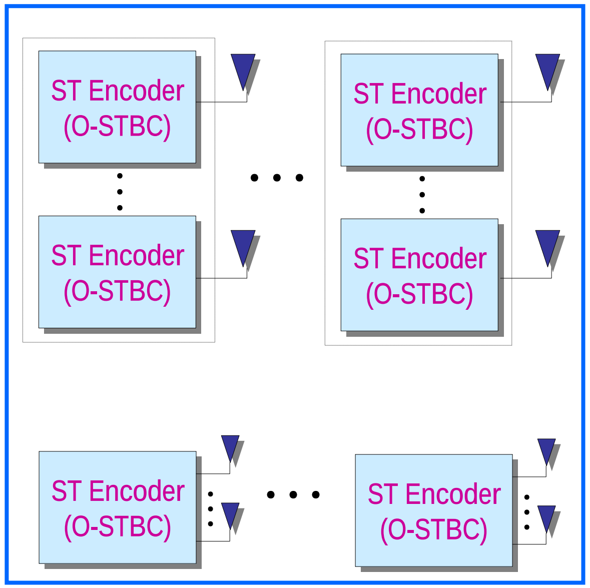
$2QP_D$ diagonal entries assume only Q different levels

- Block based: checks only Q levels and thus performs Q iterations
- Symbol based: checks $2QP_D$ levels and thus performs $2QP_D$ iterations

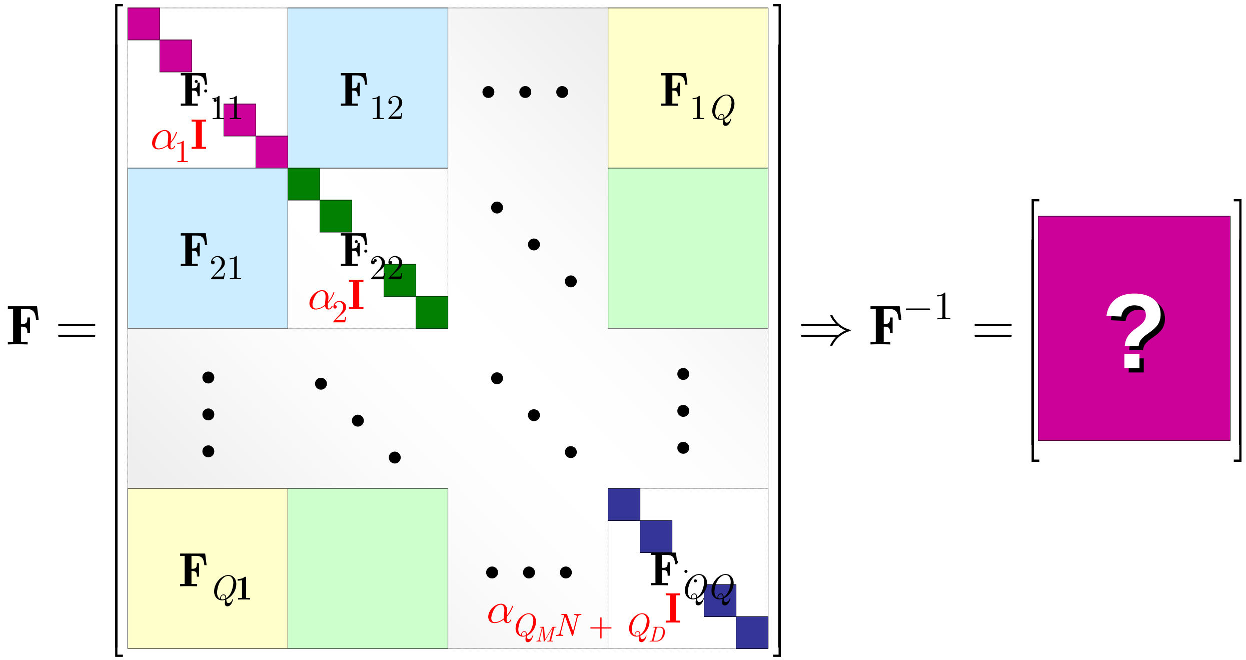
- **Case 2:** Mixed O-STBC & V-BLAST scenario
  - Treat a V-BLAST user as N O-STBC users
  - Totally $Q_M N + Q_D$ equivalent O-STBC users



Structure of $\mathbf{F}$

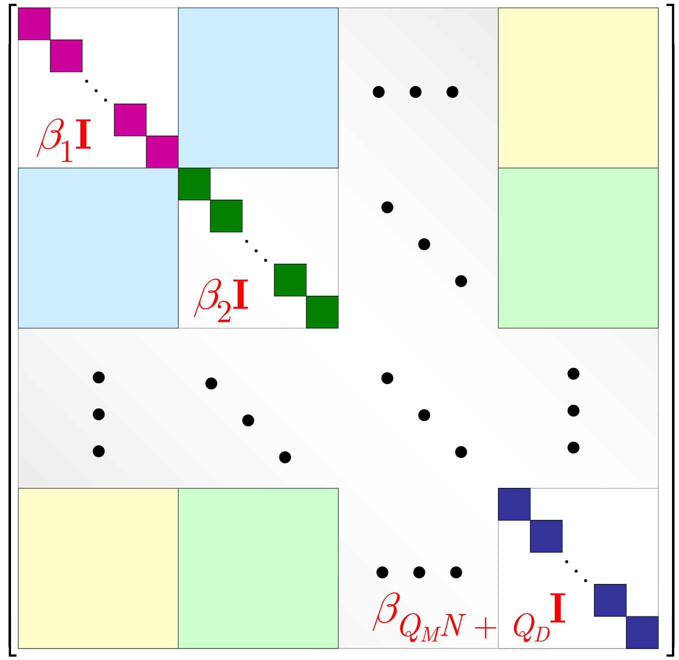


$Q_M N + Q_D$ users



- Diagonal blocks: diagonal with equal diagonal entries
- Off-diagonal blocks: orthogonal

- $\mathbf{F}^{-1}$ assumes exactly the same structure as $\mathbf{F}$

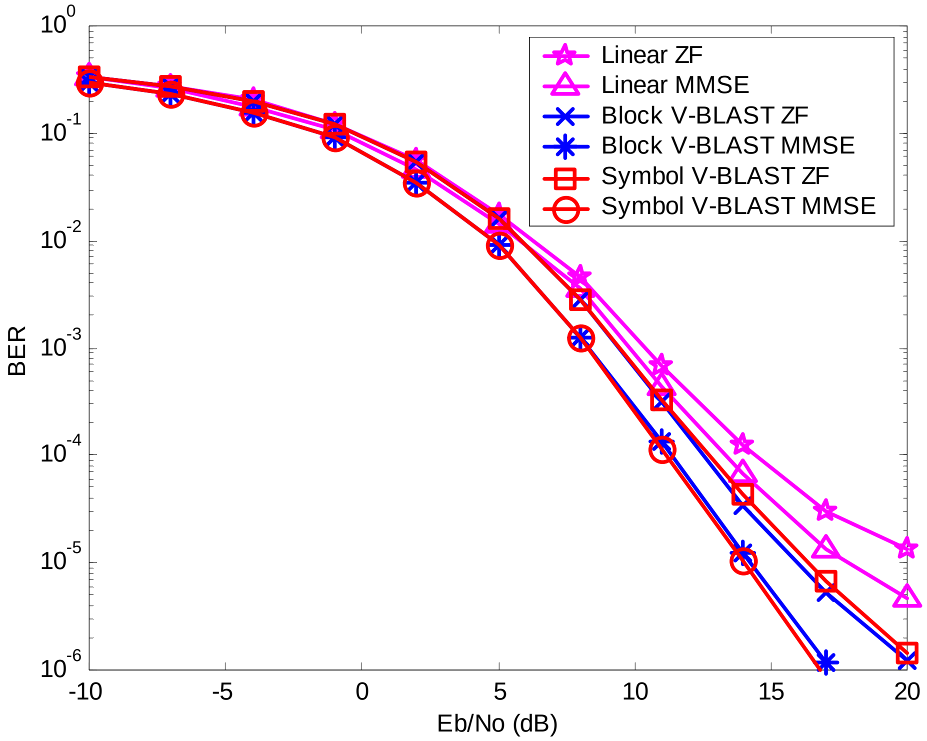
$\mathbf{F}^{-1} =$ 

$2(Q_M NK + Q_D P_D)$ diagonal entries assume only $Q_M N + Q_D$ diff. levels

  - **Block based**: checks only $Q_M N + Q_D$ levels and thus performs $Q_M N + Q_D$ iterations
  - **Symbol based**: checks $2(Q_M NK + Q_D P_D)$ levels and thus performs $2(Q_M NK + Q_D P_D)$ iterations

Simulation Results

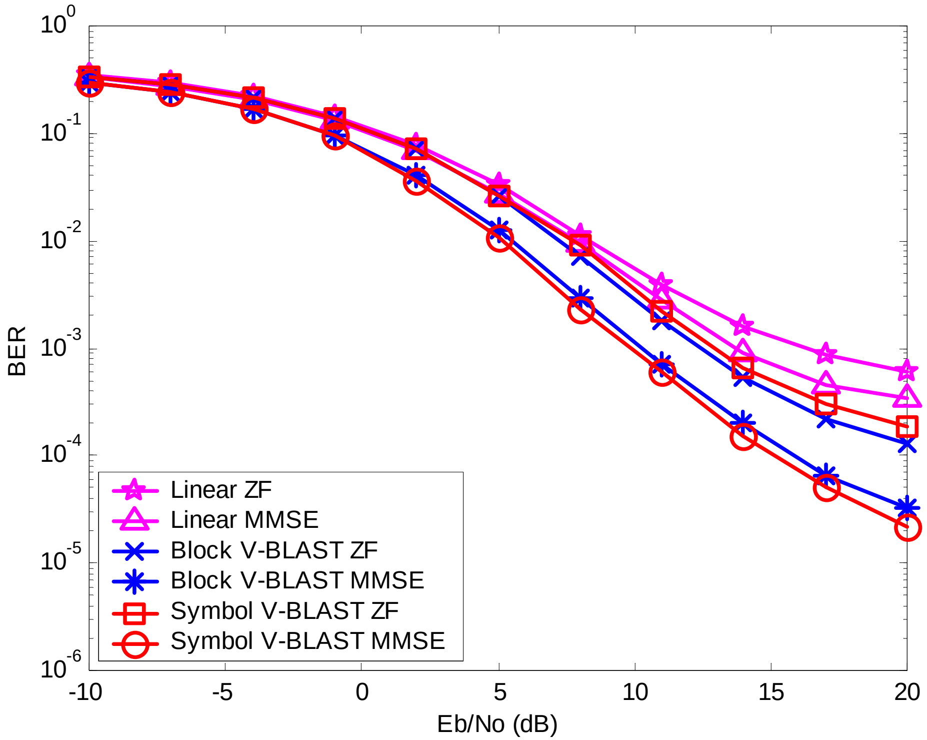
- BER performance vs. SNR
  - Perfect channel knowledge at RX; QPSK modulation
  - 4 O-STBCs $(N = M = 2,\ K = 2,\ G = 8,\ L = 2)$



$\mathbf{F} \in \mathbb{R}^{16\times 16}$

- Symbol based: 16 iterations
- Block based: 4 iterations

- BER performance vs. SNR
  - Perfect channel knowledge at RX; QPSK modulation
  - 2 V-BLASTs & 2 O-STBCs $(N = M = 2,\ K = 2,\ G = 8,\ L = 2)$



$\mathbf{F} \in \mathbb{R}^{24\times 24}$

- Symbol based: 24 iterations
- Block based: 6 iterations

Conclusion

- Flexible MIMO transceiver is proposed
  - Each user's data can be ST block coded or spatial multiplexed
  - User-wise (block based) detection can be adopted at RX
- Block based detection
  - Exploits rich structures embedded in channel matrix
  - Endowed by orthogonal ST block encoders at TX
  - Compared with symbol based transceiver
    - Reduces computational complexity and decision delay
    - Achieves nearly the same performance
- Applications: B3G high speed uplink communications
- Ongoing work: efficient calculation of $\mathbf{F}^{-1}$