Space Time Block Coding for Wireless Communication Systems

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Graduate Students

C. Budakoglu	M.A.Sc.	Key Management for Mobile Ad-Hoc Networks
N. Carson	Ph.D.	Wavelets and Space-Time Coding for OFDM
R. Chen	M.A.Sc.	Security in Local Area Networks
W. Chow	M.A.Sc.	STBC and TC for Unstructured Interference
K. Farrahi	M.A.Sc.	Error Control Coding for Video Transmission
M. Khabbazian	M.A.Sc.	Software Elliptic Curve Cryptography
O. Farooq	M.A.Sc.	Turbo Equalization
M. Khosravifard	Ph.D.	Coding for Monotone Sources
W. Li	Ph.D.	STBC Applications in Wireless Communications
C. Perez	M.A.Sc.	Wireless LANs and Cellular Data Systems
U. Sethakaset	Ph.D.	Indoor Infrared Wireless Communication Systems
Y. Shi	M.A.Sc.	Energy Efficient Wireless Ad-Hoc Networks
J. Swarts	Ph.D.	Self-Dual Codes over Finite Rings
H. Zhang	Ph.D.	STBC and Ultrawideband Communications
Y. Zhang	M.A.Sc.	Improved Routing for Ad-Hoc Networks

Recently Completed Students

Y. Abdel-Hamid	M.A.Sc.	Oct. 2003
On Accessing Multiple Mirror Sites in Parallel		
Z. Blazek	Ph.D.	Oct. 2003
On Lowering the Error-Floor of Low-Complexity Turbo-Codes		
M. Ghassemi	M.A.Sc.	Aug. 2003
Efficient Implementation of Turbo Decoders for Software Defined Radio		
N. Carson	M.A.Sc.	May 2003
Peak-to-Average Power Ratio Reduction of OFDM Symbols		
J. Wong	M.A.Sc.	Dec. 2002
Classification of Small Optimal Codes over Z_4		

Motivation

- By the year 2005, it is projected that the number of wireless subscribers will exceed that of wire-line subscribers:
  - Explosive Growth in wireless services
  - Rapid Convergence with the Internet

Wireless Applications

- Mobile Telephony/data/multimedia (3G)
- Wireless LANs (IEEE 802.11)
- Digital Broadcasting (DAB, DVB)
- Bluetooth
- Wireless Internet/m-commerce

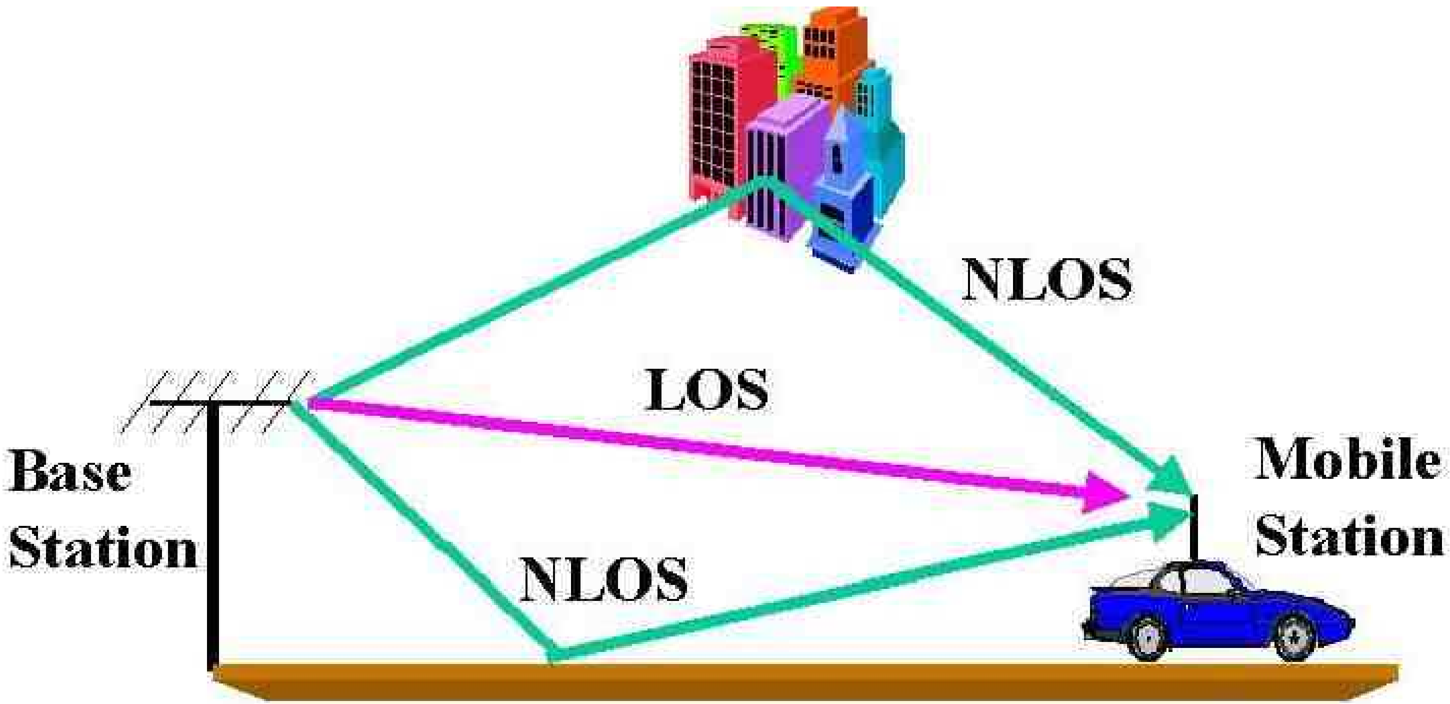
Wireless Challenges

- High Data Rate (multimedia traffic)
- Networking (seamless connectivity)
- Resource Allocation (quality of service-QOS)
- Mobility (rapidly changing physical channel)
- Portability (battery life)
- Privacy/Security (encryption)

Wireless Channel Impairments

- Fading (data rates depend on time, frequency and space)
- Limited Bandwidth
- Dynamism (random access, mobility)
- Limited Power (at the mobile)
- Interference

Multipath Fading



The Current Situation

- Spectrum is limited
- Battery power is growing at a slow rate
- Terminal size is decreasing
- Processor performance is growing exponentially
- Consumers like (demand) wire-line quality
- Wire-line data rates are growing rapidly making expectations much higher

Conclusion

Providing high speed, high quality wireless services given the quality of wireless channels is a challenging task.

Diversity

- Deep fade $\Rightarrow$ A replica of the transmitted signal must be sent to the receiver $\Rightarrow$ Diversity
- Diversity:
  - Temporal Diversity (well understood)
  - Frequency Diversity (well understood)
  - Spatial (Antenna) Diversity
    - receive antenna diversity (well understood)
    - transmit antenna diversity (subject of current research)

Wireless Channel: Diversity

- In many cases the wireless channel is
  - Rayleigh: requires diversity
  - slowly time-varying: no temporal diversity
  - non-frequency selective: no frequency diversity
- $\Rightarrow$ Spatial Diversity is needed

Multiple Antenna Systems

- N transmit and M receive antennas
- At each time, N signals are transmitted simultaneously each from a different antenna.
- Signals transmitted from different antennas undergo independent fading.
- The signal at each receive antenna is a linear superposition of the transmitted signals perturbed by noise (and interference).

Capacity of MIMO Systems

- Telatar, and independently Foschini and Gans, determined that for a multiple antenna system with N transmit and $M = N$ receive antennas

The Capacity Increases Linearly as a function of N as $N \longrightarrow \infty$.

- How to exploit this capacity?

Space-Time Codes!

Notation

- Codewords are written as a matrix:

$$\mathbf{S} = \begin{pmatrix} s_{1,1} & s_{1,2} & s_{1,3} & \cdots & \cdots & s_{1,N} \\ s_{2,1} & s_{2,2} & s_{2,3} & \cdots & \cdots & s_{2,N} \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ s_{L,1} & s_{L,2} & s_{L,3} & \cdots & \cdots & s_{L,N} \end{pmatrix}$$

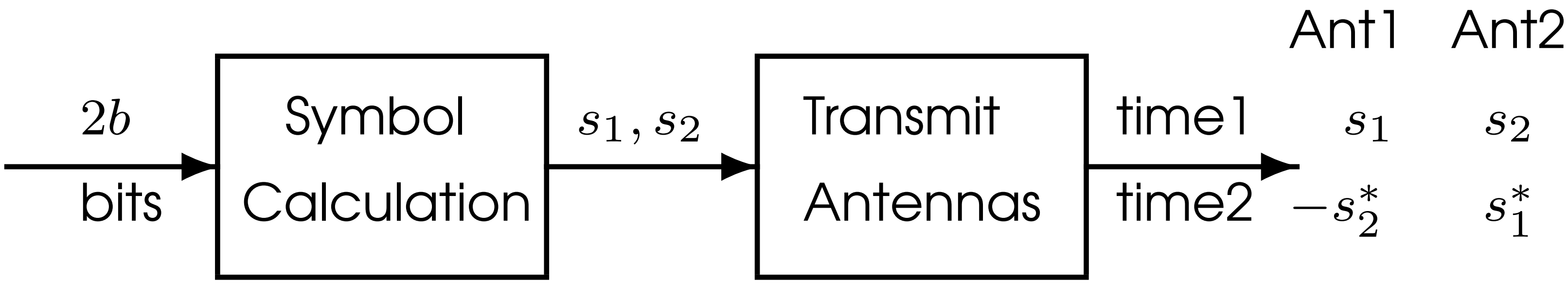
- To send codeword $\mathbf{S}$, at time $t = 1, 2, \cdots, L$, we send $s_{t,1}, s_{t,2}, \cdots s_{t,N}$ simultaneously from transmit antennas $1, 2, \cdots, N$, respectively.

Space-Time Block Codes

- A simple example for two transmit antennas:
  - Suppose the signal constellation has 2^b elements, i.e. BPSK, QPSK, 8-PSK, 16-QAM
  - At time t_1, $2b$ bits arrive at the encoder and pick up constellation symbols s_1 and s_2
  - The transmission matrix is then:

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

Space Time Block Code Example (2x2)



Transmitter Block Diagram

Capacity of STBC over Fading Channels

- Rayleigh/Ricean/Nakagami-m fading with PAM/PSK/QAM modulation
- Closed form expressions for Shannon Capacity

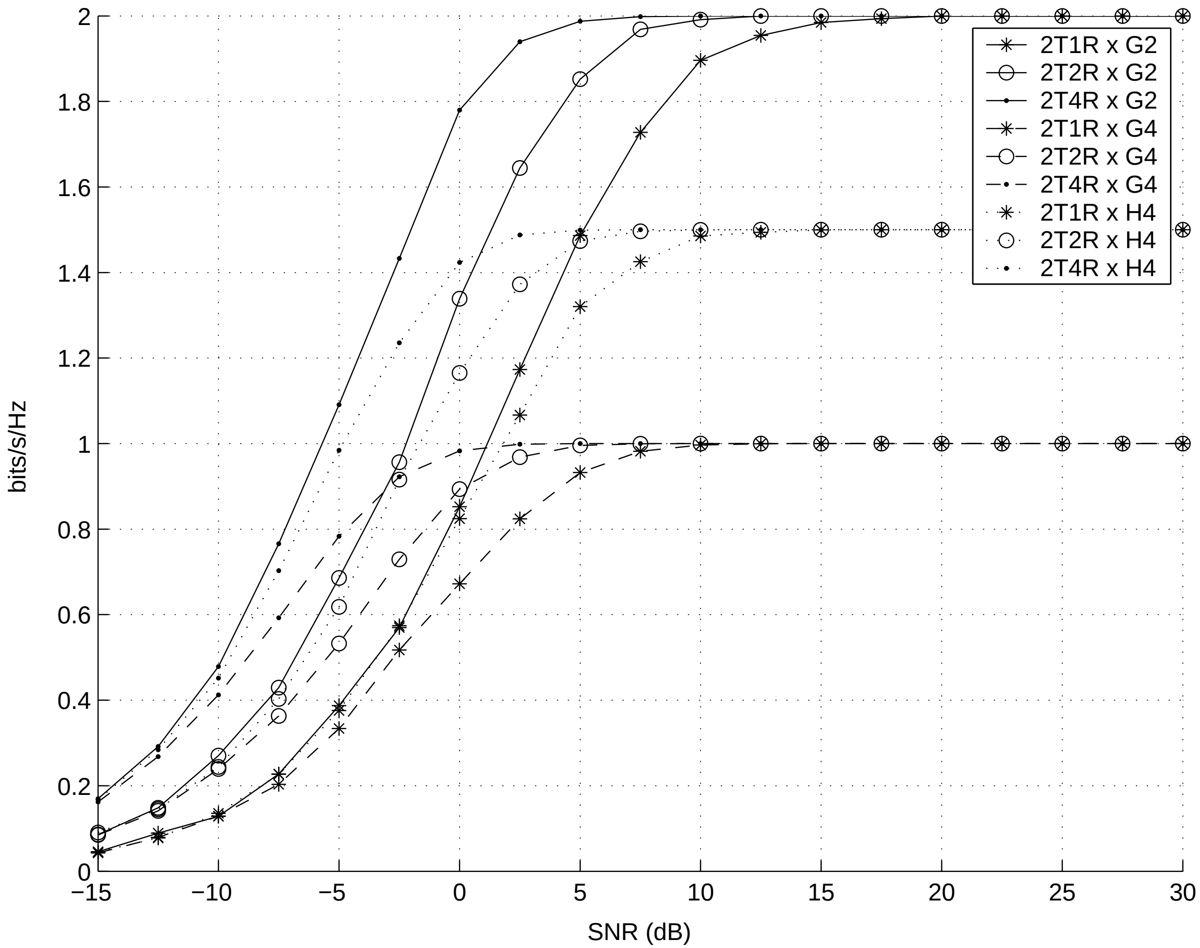
$$C = \log_2(1 + \text{SNR}) \quad \text{bits/s/Hz}$$

For a Ricean channel

$$\begin{aligned}\overline{C} &= R\int_0^\infty \log_2(1+\gamma_s)p(\gamma_s)d\gamma_s \quad \text{bits/s/Hz} \\ &= \sum_{i=0}^\infty \frac{R\log_2 e (MN\beta)^i e^{-MN\beta}}{\Gamma(i+1)\Gamma(MN+i)\overline{\gamma}_c^{MN+i}} f(\overline{\gamma}_c, MN+i-1)\end{aligned}$$

First closed form expressions for STBC Shannon Capacity with PAM/PSK/QAM and fading

Capacity of STBC with QPSK in Rayleigh Fading



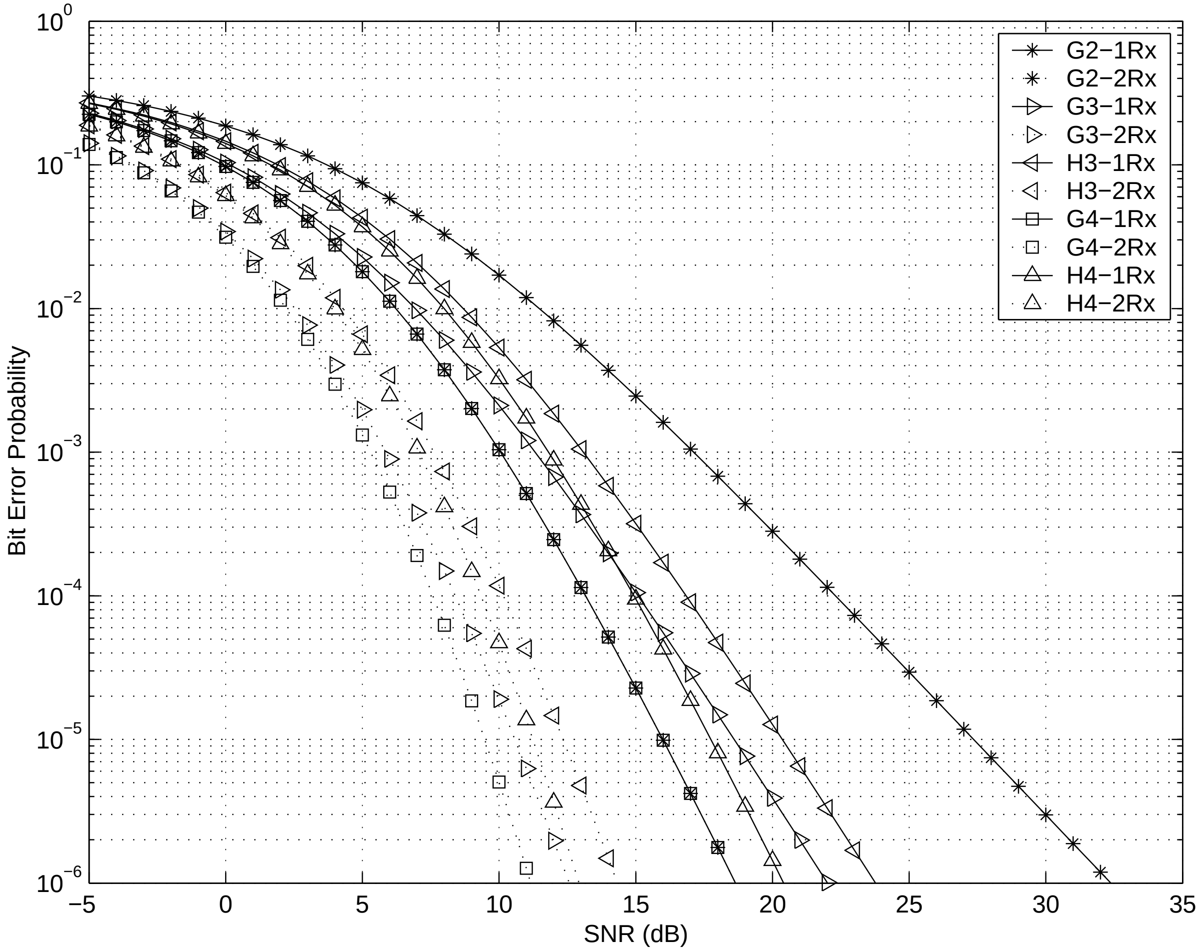
Probability of Error Analysis for STBC

- SER of STBC over Rayleigh/Ricean/Nakagami-m fading channels (given below for Ricean)

$$
\begin{aligned}
P &= \int_0^\infty P_q(\gamma_s) p(\gamma_s) d\gamma_s \\
&= \sum_{n=0}^{\infty} \frac{(MN\beta)^n e^{-MN\beta}}{\Gamma(n+1)} \\
&\quad \times \lambda \left[1 - \sum_{i=0}^{MN+n-1} \mu \left(\frac{1-\mu^2}{4} \right)^i \binom{2i}{i} \right]
\end{aligned}
$$

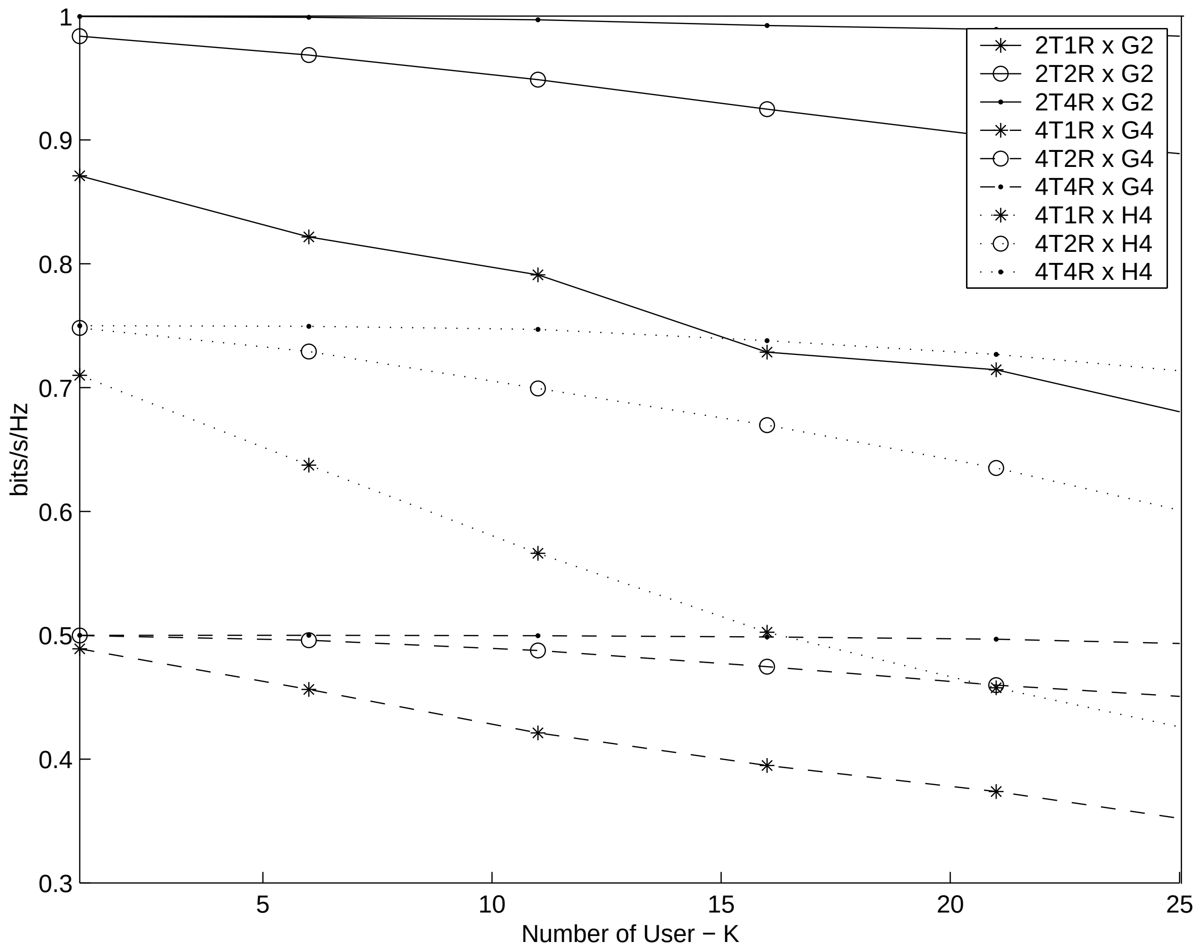
- First exact closed form probability of error expressions for STBC over fading channels

BER of STBC with QPSK in Rayleigh Fading

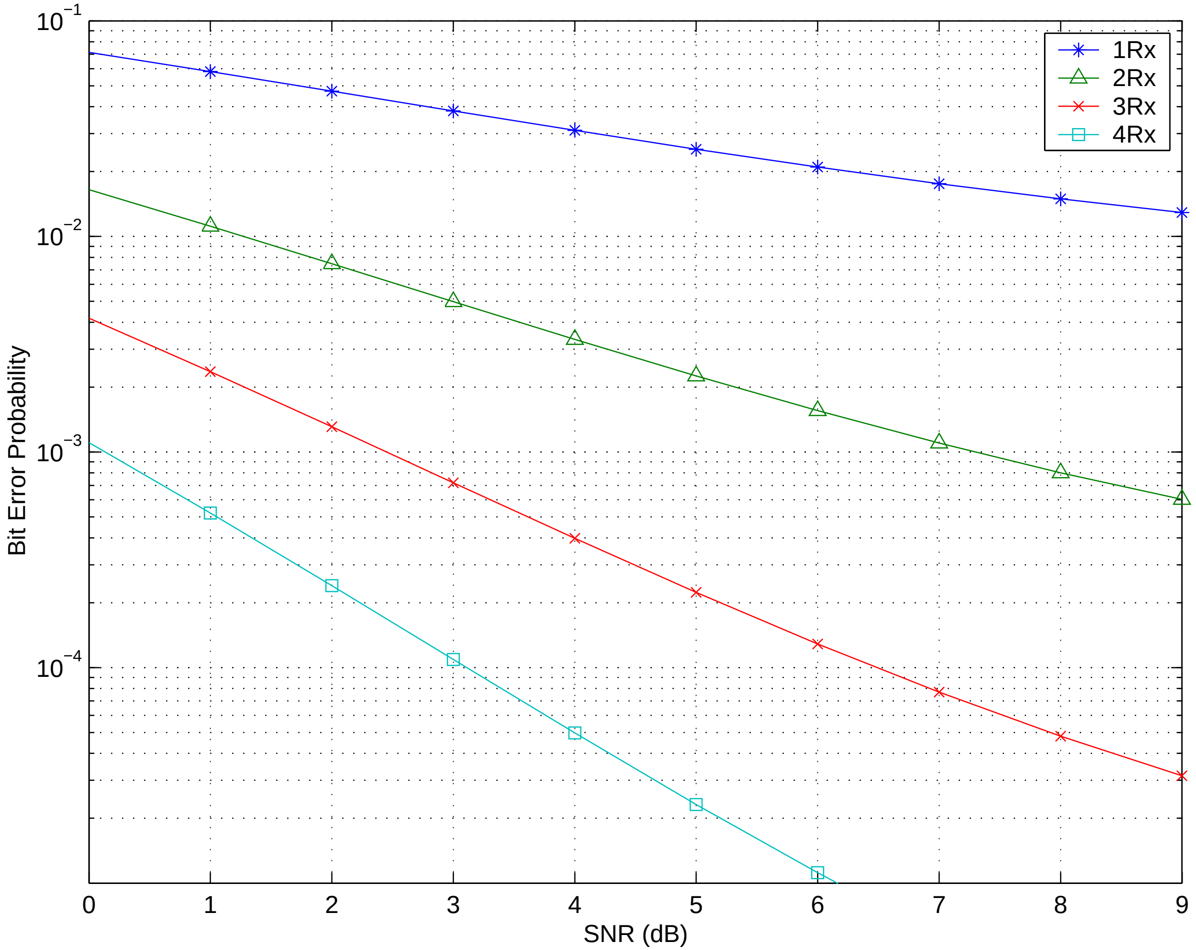


STBC in a DS-CDMA System

Capacity of DS-CDMA with BPSK and STBC in Rayleigh Fading



Performance of DS-CDMA wth BPSK and G_2 in Rayleigh Fading $(PG = 64, K = 20)$



Correlated Channels

- Channel correlation occurs when antennas are not separated sufficiently
- On small wireless devices, receive antennas must be close together
- This correlation results in a diversity loss and performance degradation

BER of STBC over Correlated Channels

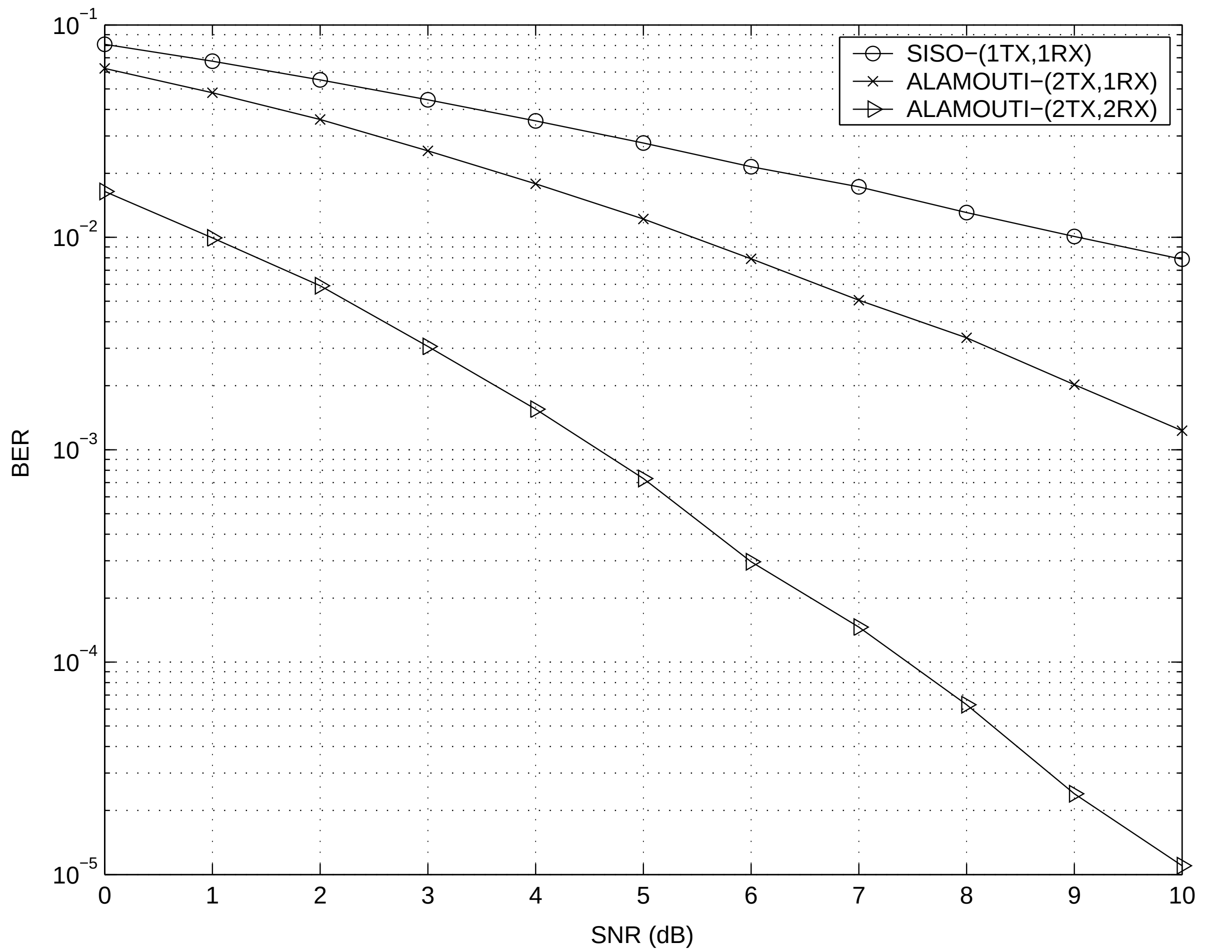
- BER for Correlated Rayleigh Channels

$$P = \lambda \frac{\Gamma_1}{2(\Gamma_1 - \Gamma 2)}[1 - \mu_1] - \lambda \frac{\Gamma_2}{2(\Gamma_1 - \Gamma 2)}[1 - \mu_2]$$

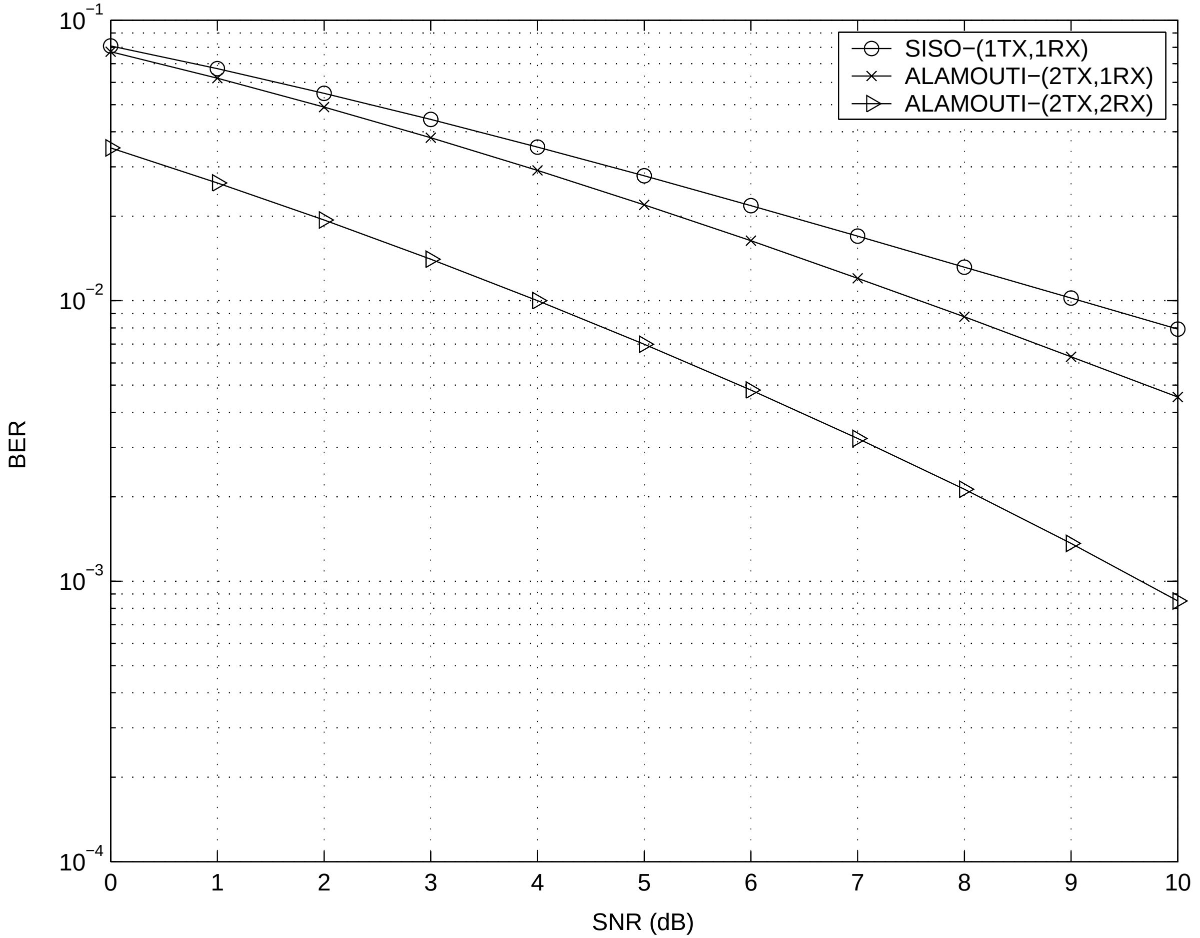
- BER for Correlated Ricean and Nakagami fading channels

$$P = \frac{\lambda}{\pi} \int_0^{\frac{\pi}{2}} \Phi_{\gamma_s} \left(\frac{a\gamma_s}{2sin^2\phi} \right) d\phi$$

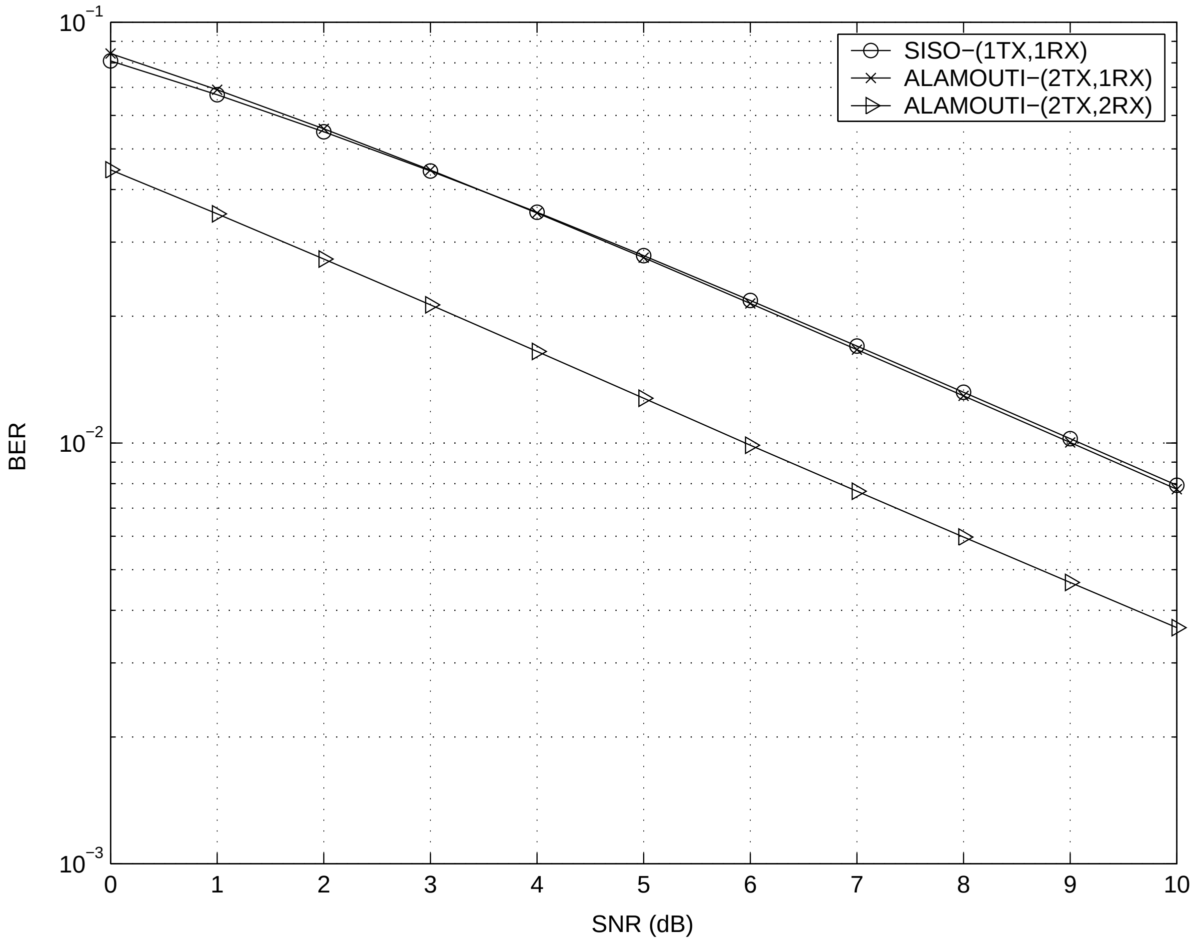
BER of STBC with BPSK in Uncorrelated Ricean Fading $(\beta = 1, \rho = 0)$



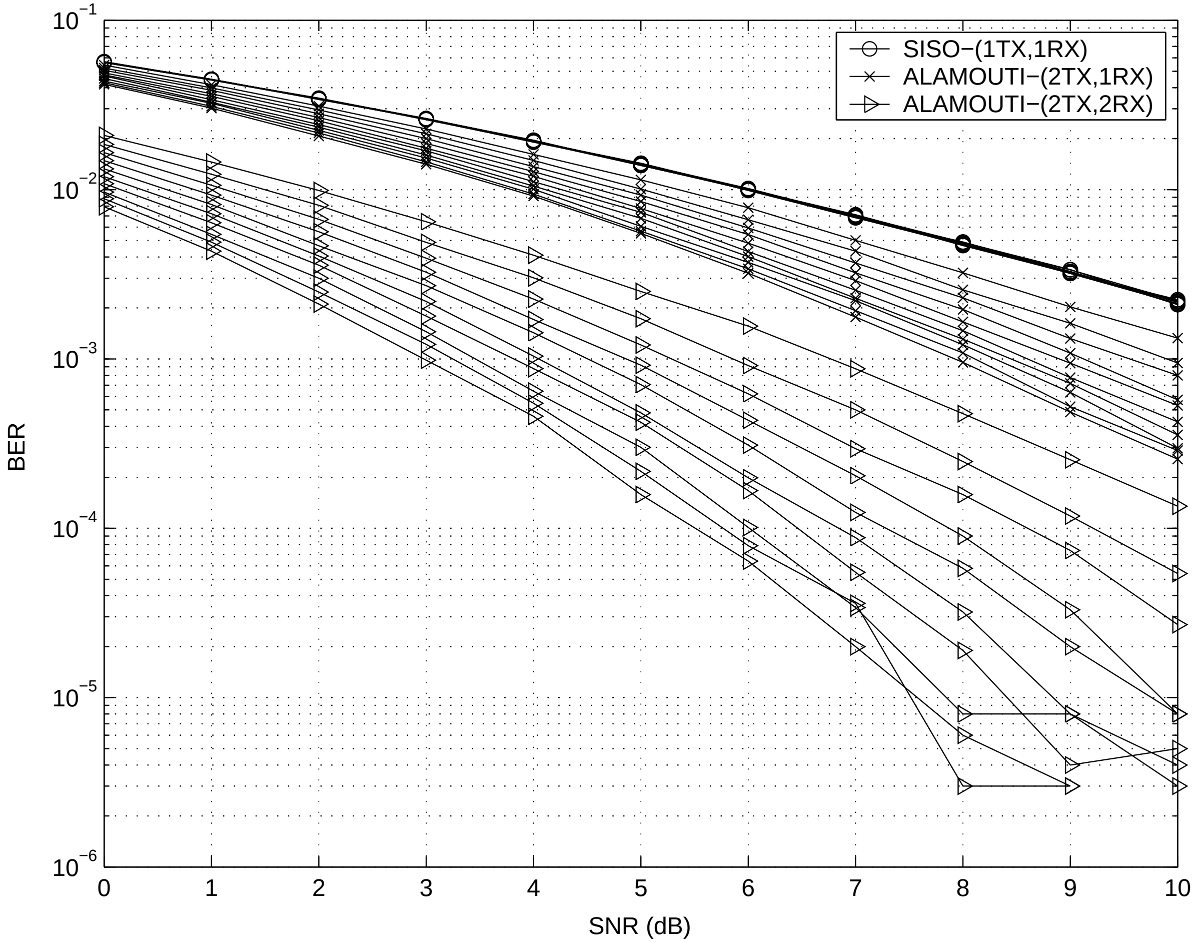
BER of STBC with BPSK in Correlated Ricean Fading $(\beta = 1, \rho = 0.8)$



BER of STBC with BPSK in Correlated Ricean Fading $(\beta = 1, \rho = 1.0)$



BER of STBC with BPSK in Correlated Nakagami Fading $(m = 1, \rho = 0 - .9)$



STBC with Turbo Codes in Unstructured Interference

- STBC and Turbo Codes (TC) are used for high data-rate wireless communications (3G, 4G)
- Industry measurements show that surrounding electronics cause noise in STBC receivers leading to poor performance
- Solution: use a robust STBC receiver for unknown interference suppression

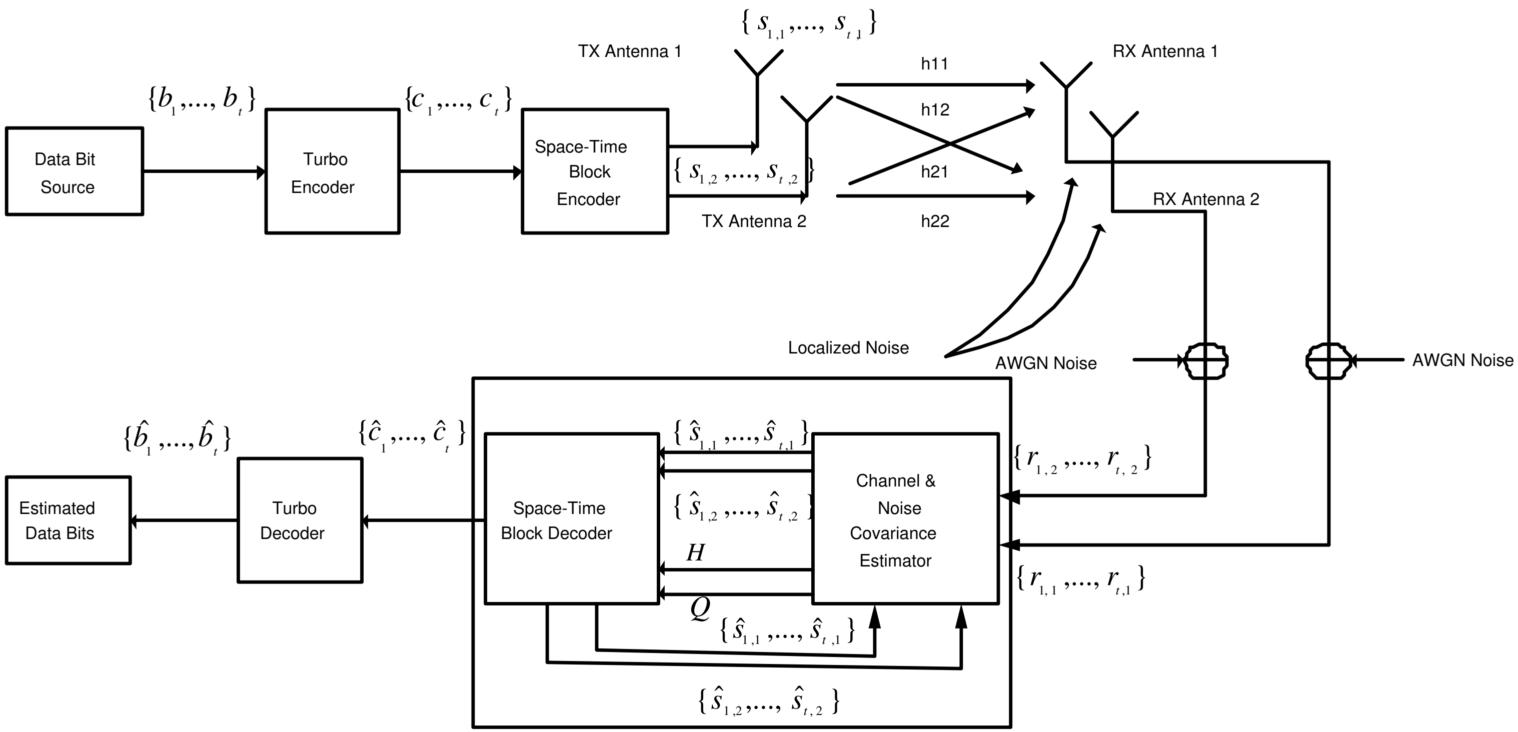
Space-Time Block Coding with Cyclic Maximum-Likelihood Detection

- Received signal in matrix form

$$\mathbf{R} = \sqrt{\frac{\rho}{M}}\mathbf{HX} + \mathbf{N} + \mathbf{I}$$

- $\sqrt{\frac{\rho}{M}}$ = Transmit energy ρ normalized by M
- $\mathbf{H}$ = Channel between each transmit-receive antenna pair
- $\mathbf{X}$ = Transmitted signal matrix
- $\mathbf{N}$ = AWGN noise at the receiver
- $\mathbf{I}$ = External localized interference

Concatenated STBC and TC System Model



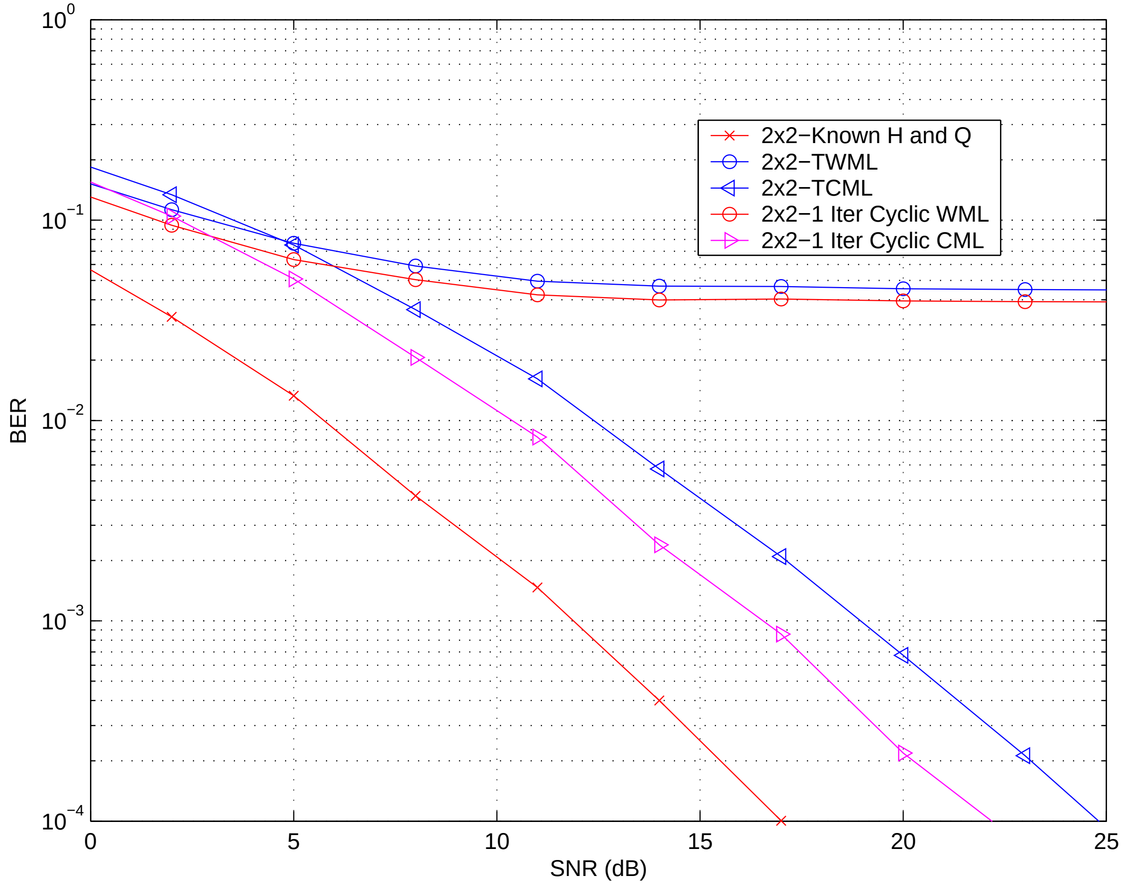
Maximum-Likelihood Detection and CML

- Detection of received frame of codeword matrices incorporating noise statistics $\mathbf{R} = [\mathbf{R}_{1_{tr}} \mathbf{R}_{K_{tr}} \mathbf{R}_1 \ldots \mathbf{R}_L]$

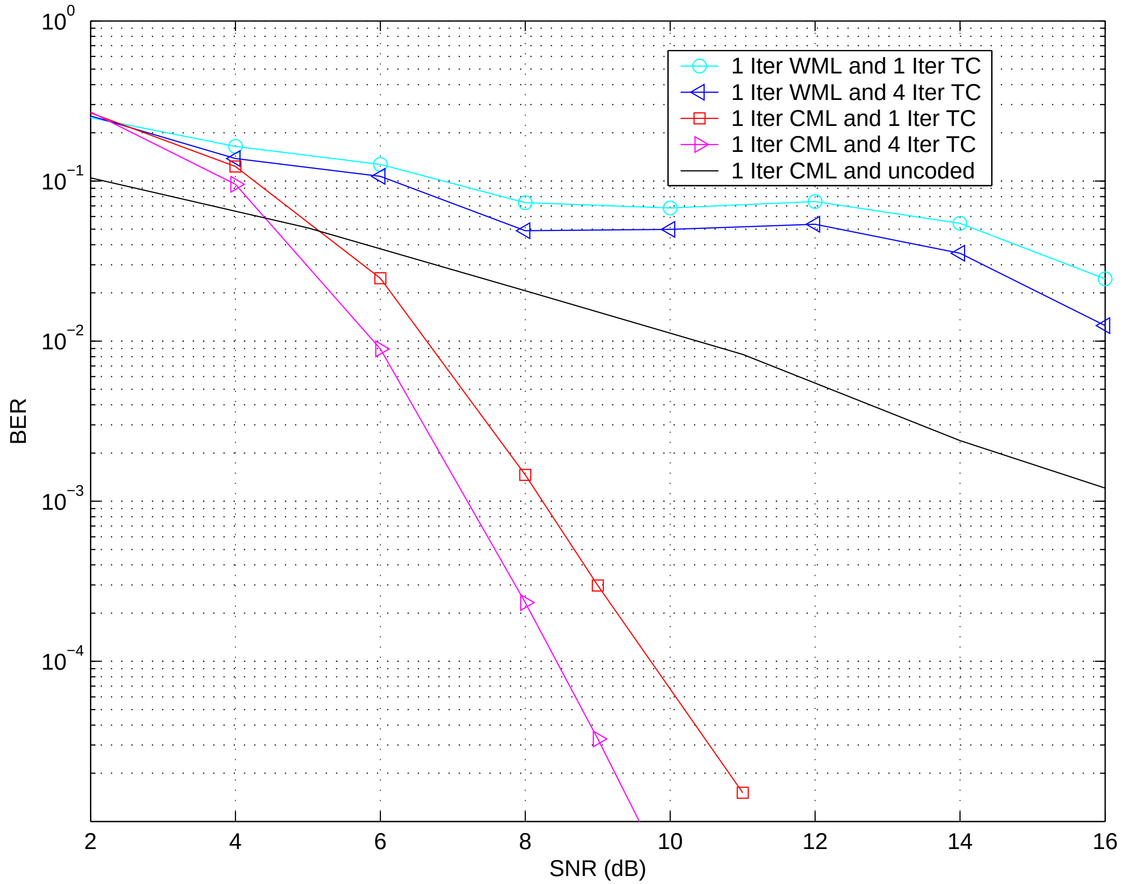
$$\hat{c}_{t,l} = \underset{c}{argmax} \sum_{l=1}^{L} \sum_{t=1}^{2} Re((Re(Tr\{\mathbf{R}_l^* \mathbf{Q}^{-1} \mathbf{H} \mathbf{A}_t\}) + iIm(Tr\{\mathbf{R}_l^* \mathbf{Q}^{-1} \mathbf{H} \mathbf{B}_t\}))c_t^{(l)})$$

- CML obtains and refines initial channel $\mathbf{H}$ and noise $\mathbf{Q}$ estimates based on training data

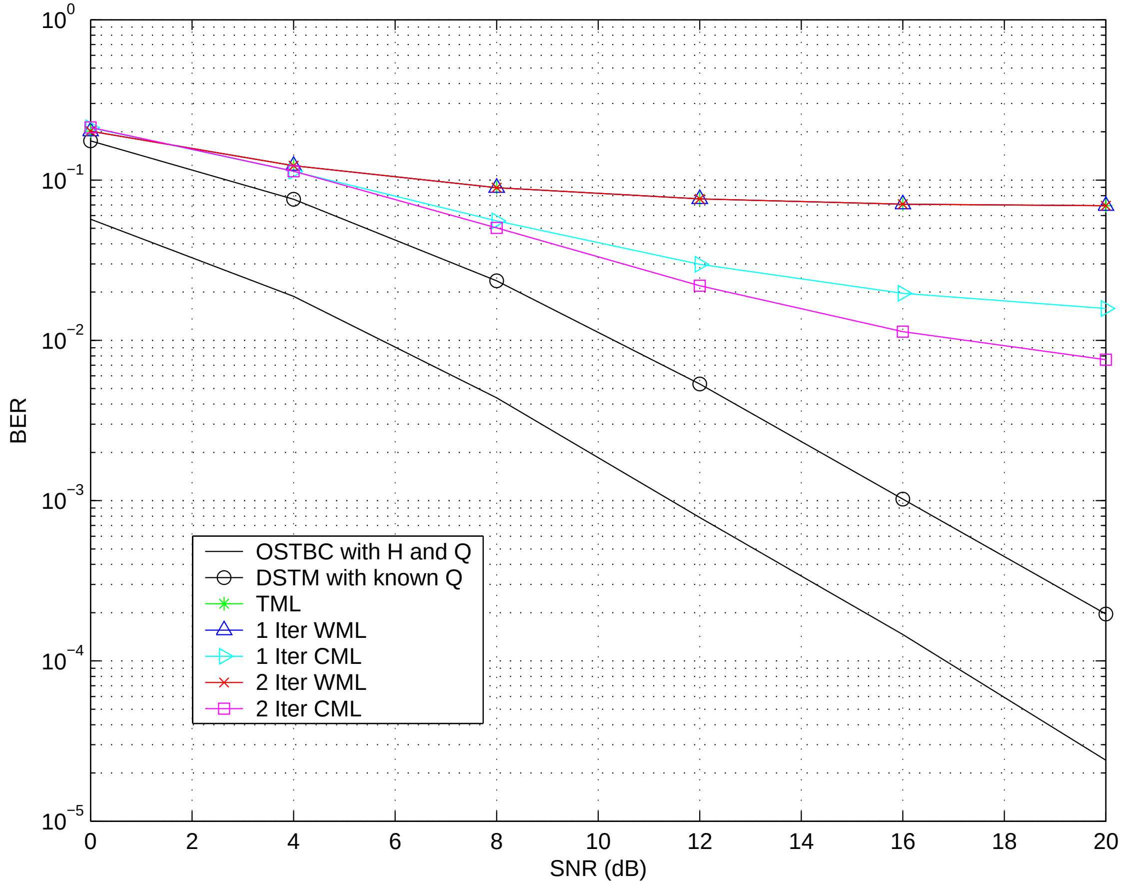
Interference Suppression



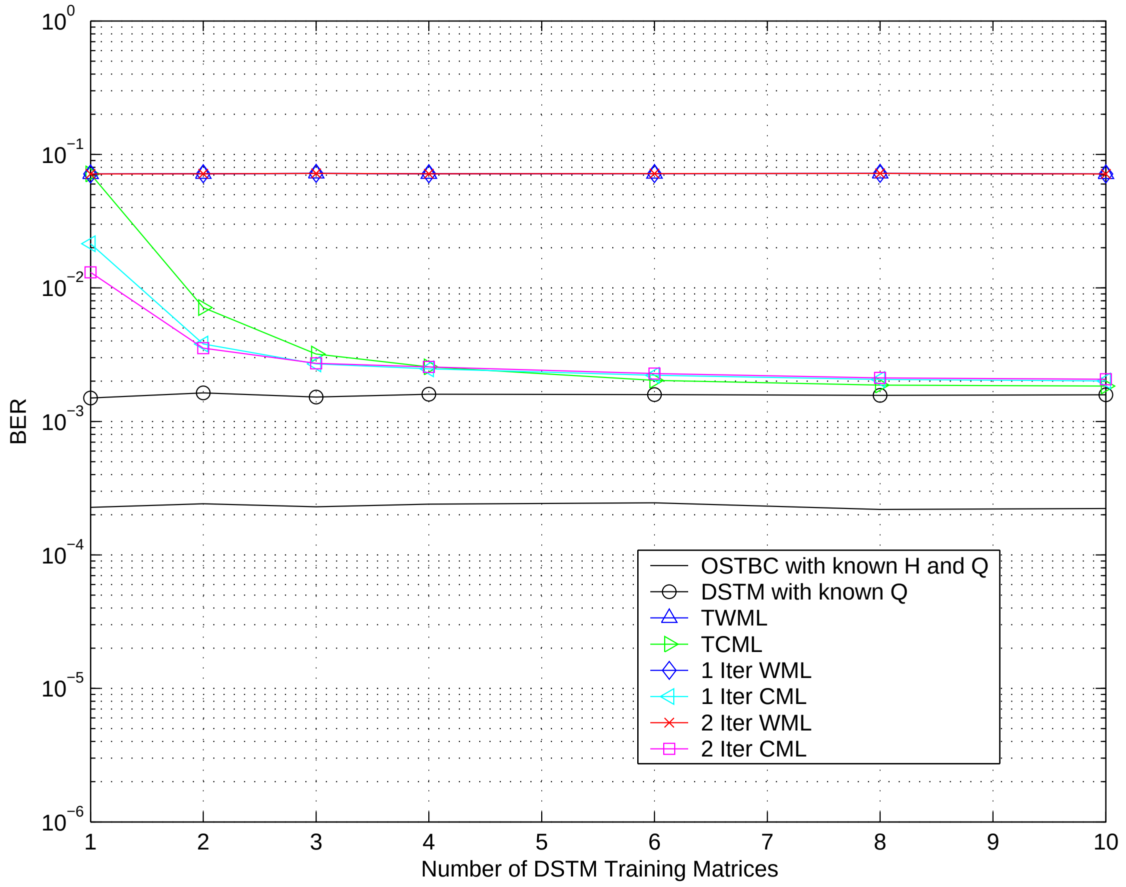
Interference Suppression with Coding



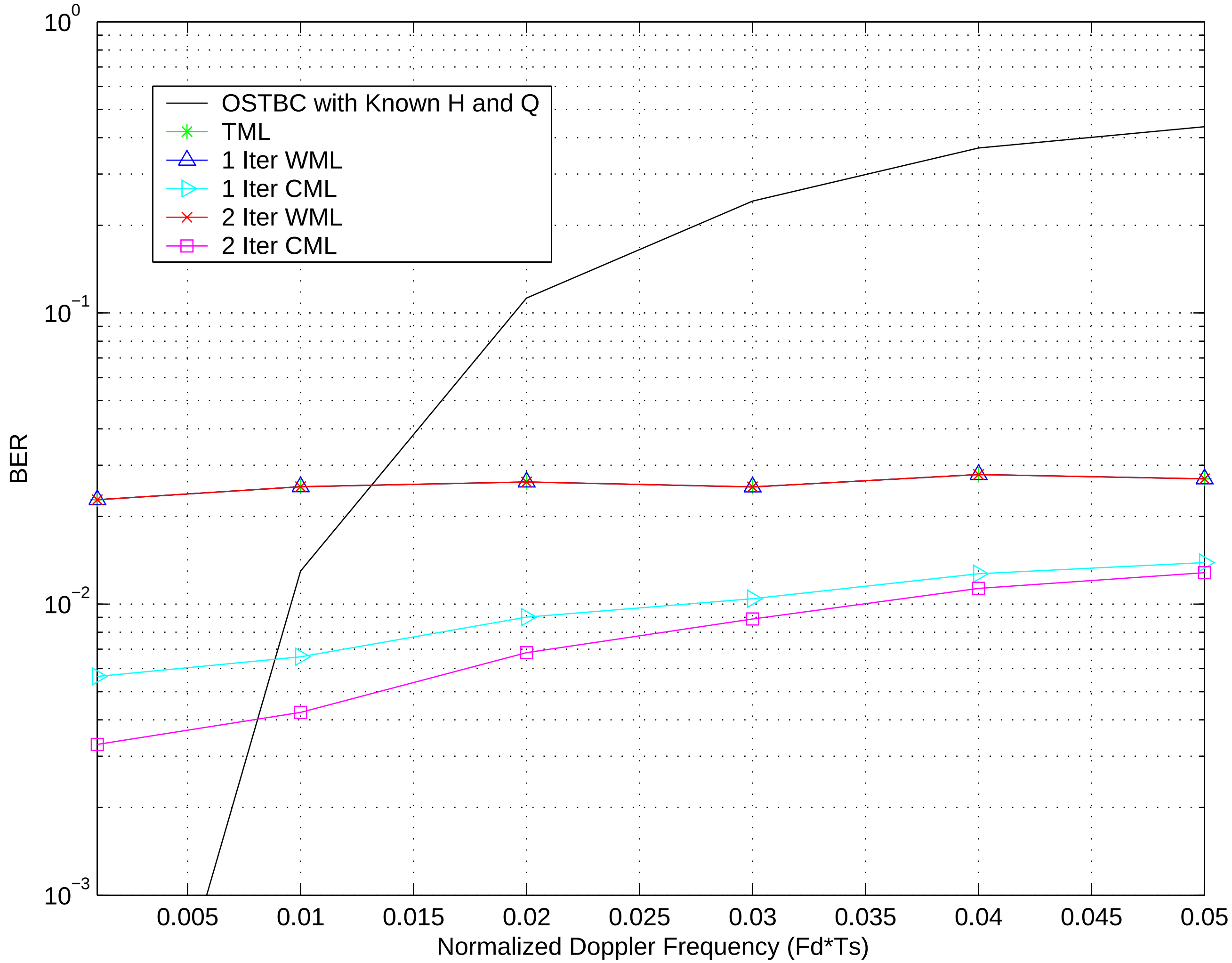
Differential Space Time Modulation



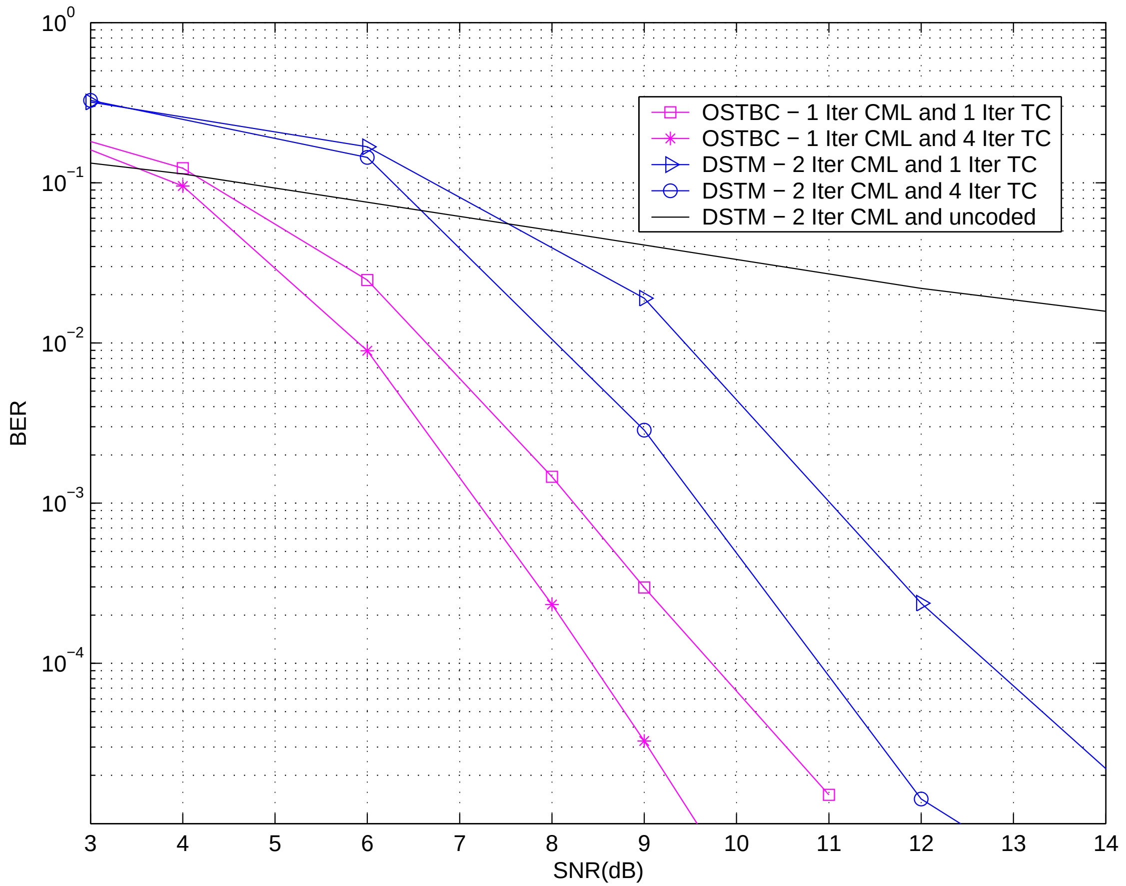
Performance versus Training



Impact of Doppler Fading



Coherent versus Noncoherent



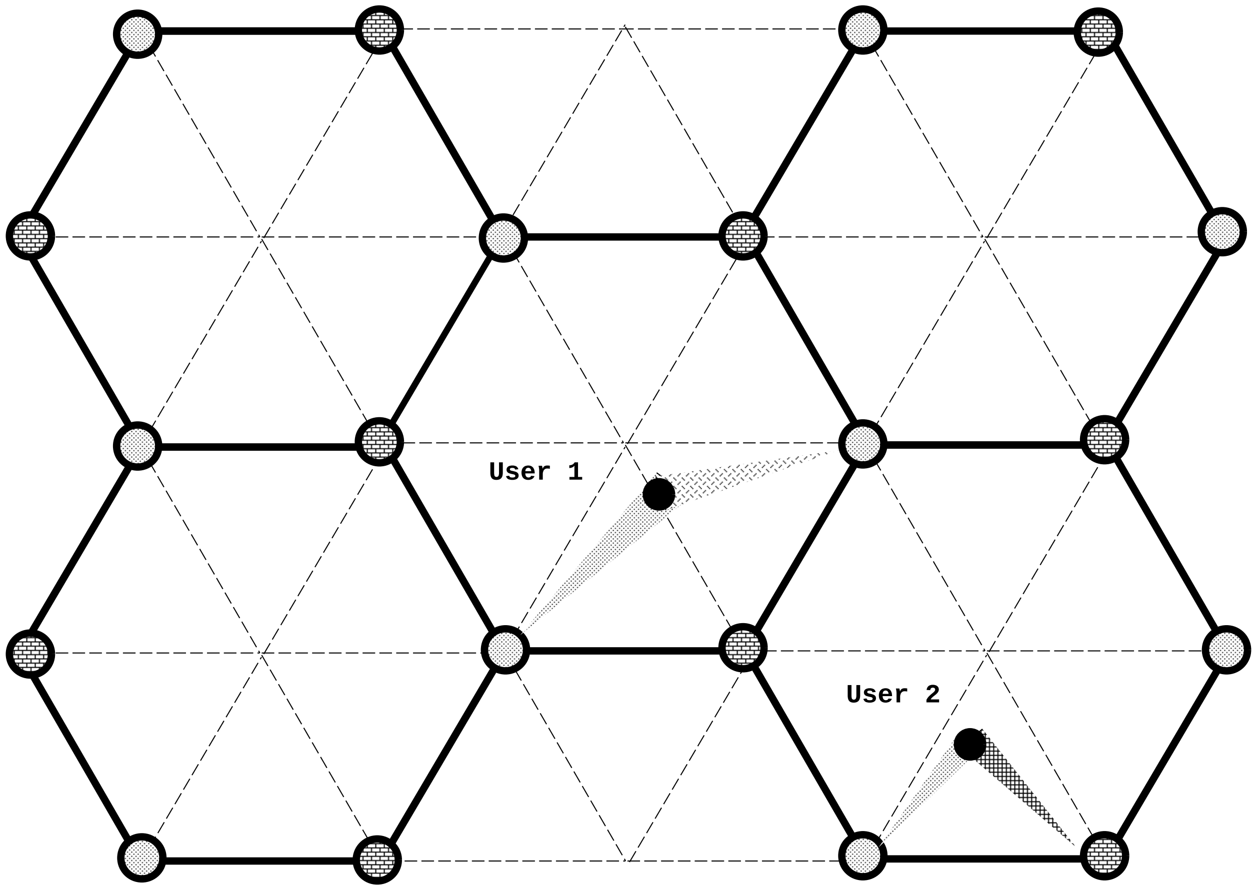
Future Work

- Successive Interference Cancellation with STBC
- Space Time Multilevel Codes
- Space Time Turbo Codes
- Performance and Capacity of MC-CDMA and OFDM systems with STBC
- Wavelet OFDM (Multicarrier Modulation)
- STC for PAPR reduction in OFDM
- PAPR estimation and reduction techniques for OFDM

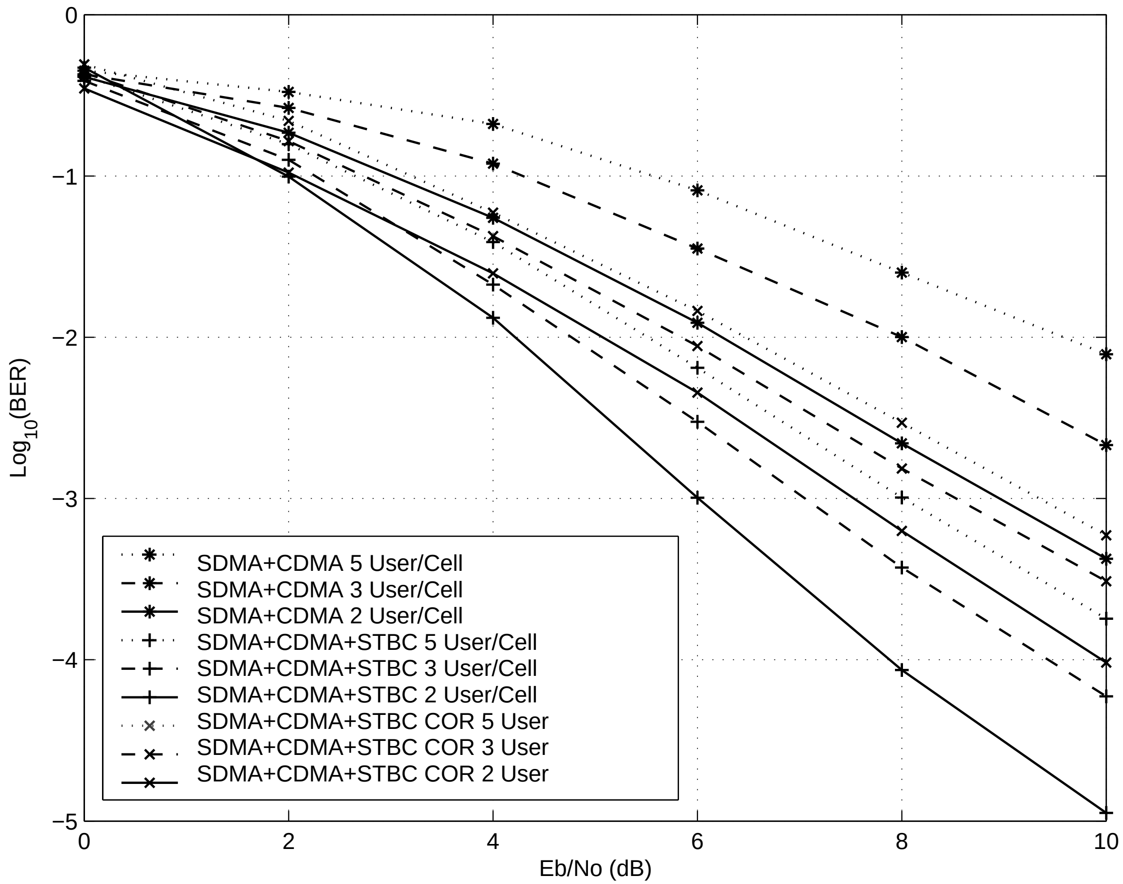
A New STBC Cellular System Structure - 1

- This Structure consists of edge-excited cells
- Each base station covers part of the cells with SDMA
- Eliminates channel correlation
- Reduces interference between users

A New STBC Cellular System Structure - 2



A New STBC Cellular System Structure - 3

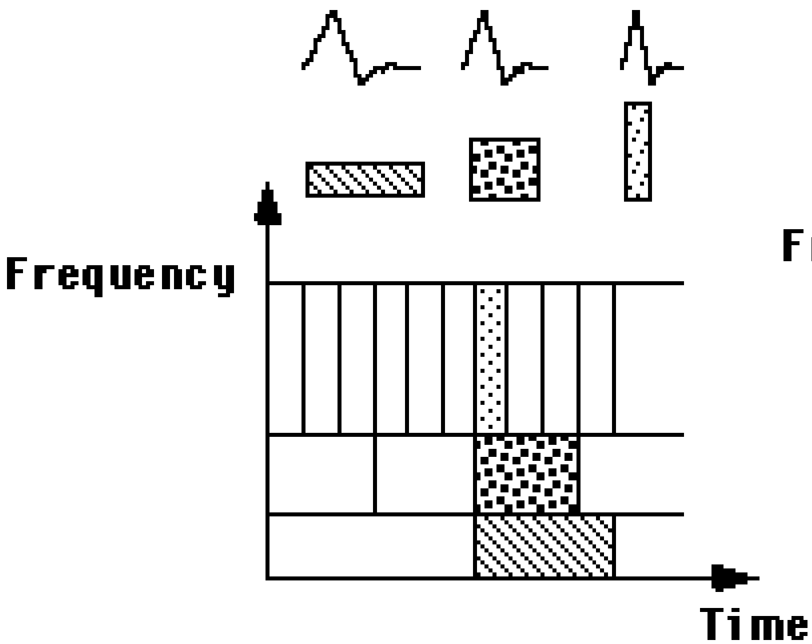


Wavelets

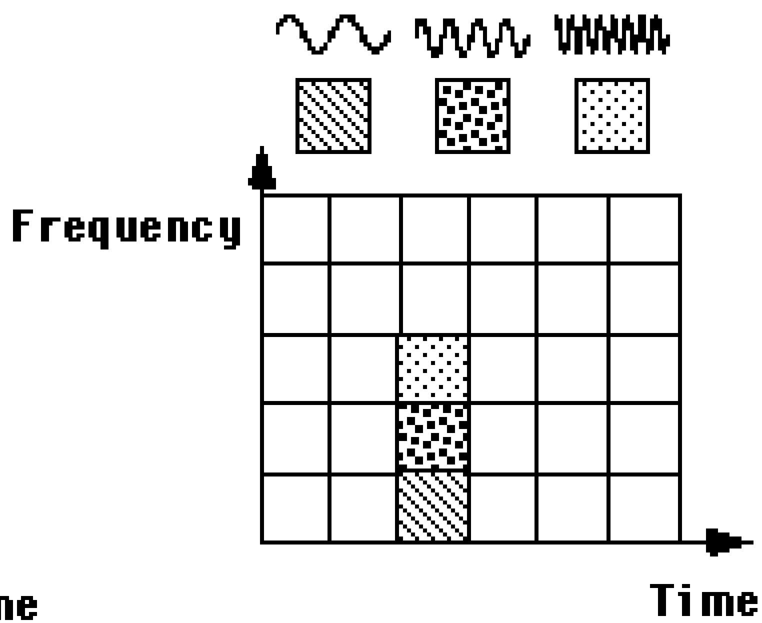
- DSP tool used for analysis of signals
- Wavelets are simultaneously scalable in time and frequency
- Lower complexity than FFT
- Provides high temporal and frequency resolution
- Can be used for partial removal of AWGN

Wavelets

Wavelet transform



Fourier transform



M

Space Time

The Error Matrix

For two distinct codewords

$$\mathbf{C} = \begin{pmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{pmatrix}$$

and

$$\mathbf{D} = \begin{pmatrix} d_1 & d_2 \\ -d_2^* & d_1^* \end{pmatrix}$$

the error matrix

$$\mathbf{C} - \mathbf{D} = \begin{pmatrix} c_1 - d_1 & c_2 - d_2 \\ -c_2^* + d_2^* & c_1^* - d_1^* \end{pmatrix}$$

has full rank $\longrightarrow$ diversity!

Properties

- **Simple decoding:** Each symbol is decoded separately using only linear processing.
- **Maximum diversity:** Same performance as two-level maximum ratio combining.

Is it possible to design similar codes for more number of transmit antennas?

Orthogonal Designs

- What is the reason for these properties?

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

- The columns of $\mathbf{S}$ are orthogonal

$$\mathbf{S}^*\mathbf{S} = (|s_1|^2 + |s_2|^2)I.$$

- We call such an $\mathbf{S}$ an orthogonal design.

Existence of Real Orthogonal Designs

A real orthogonal design exists if and only if $n = 2, 4, 8.$

$$\begin{pmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{pmatrix}$$

$$\begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{pmatrix}$$

Example

$$\begin{pmatrix} s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 & s_8 \\ -s_2 & s_1 & s_4 & -s_3 & s_6 & -s_5 & -s_8 & s_7 \\ -s_3 & -s_4 & s_1 & s_2 & s_7 & s_8 & -s_5 & -s_6 \\ -s_4 & s_3 & -s_2 & s_1 & s_8 & -s_7 & s_6 & -s_5 \\ -s_5 & -s_6 & -s_7 & -s_8 & s_1 & s_2 & s_3 & s_4 \\ -s_6 & s_5 & -s_8 & s_7 & -s_2 & s_1 & -s_4 & s_3 \\ -s_7 & s_8 & s_5 & -s_6 & -s_3 & s_4 & s_1 & -s_2 \\ -s_8 & -s_7 & s_6 & s_5 & -s_4 & -s_3 & s_2 & s_1 \end{pmatrix}$$

Existence of Complex Orthogonal Designs

Given a complex orthogonal design of size n, we replace each complex variable $s_i = s_i^1 + s_i^2 j,\ 1 \le i \le n$ by the 2×2 real matrix

$$\begin{pmatrix} s_i^1 & s_i^2 \\ -s_i^2 & s_i^1 \end{pmatrix}.$$

In this way s_i^* is represented by

$$\begin{pmatrix} s_i^1 & -s_i^2 \\ s_i^2 & s_i^1 \end{pmatrix}.$$

Existence of Complex Orthogonal Designs

- The $2n \times 2n$ matrix formed in this way is a real orthogonal design of size $2n$.
- **Result:** A complex orthogonal design of size n exists only if $n = 2$.

How can we design space-time block codes for higher number of transmit antennas?

Generalized Orthogonal Designs

- Instead of orthogonal designs that are square matrices, we construct generalized orthogonal designs that are rectangular matrices.
- We only allow linear combinations of symbols (linear processing at the transmitter).
- This leads to space-time block coding.

Example

- $K = 3$, $L = 8$, $N = 4$, $R = 0.5$

$$\begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{pmatrix}$$

Example

- $K = 4, L = 8, N = 3, R = 0.5$

$$\begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{pmatrix}$$

Example

- $K = 3, L = 4, N = 4, R = 0.75$

$$\begin{pmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ s_3^* & 0 & -s_1^* & s_2 \\ 0 & s_3^* & -s_2^* & -s_1 \end{pmatrix}$$

STBC for MIMO wireless channels

- Space-time block codes from orthogonal designs can provide maximum diversity.
- Real space-time block codes can provide maximum diversity and rate for any number of transmit antennas, N.
- Rate half complex space-time block codes can provide maximum diversity for any number of transmit antennas, N.
- Rate 3/4 complex space-time block codes can provide maximum diversity for $N = 3, 4$, and rate one code for $N = 2$.