SPACE-TIME CODING AND SIGNAL PROCESSING FOR HIGH DATA RATE WIRELESS COMMUNCATIONS

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Tutorial Overview

- **PART 1: Preliminaries.**
- **PART 2: Space-Time Coding.**
- **PART 3: Applications of Space-Time Coding.**
- **Summary.**

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PART 1: Preliminaries

- ✷ Wireless channels.
- ◆ Outage capacity of fading channels.
- ◆ Diversity Options: time, frequency, and space.
  - ➪ Receive and transmit diversity techniques.

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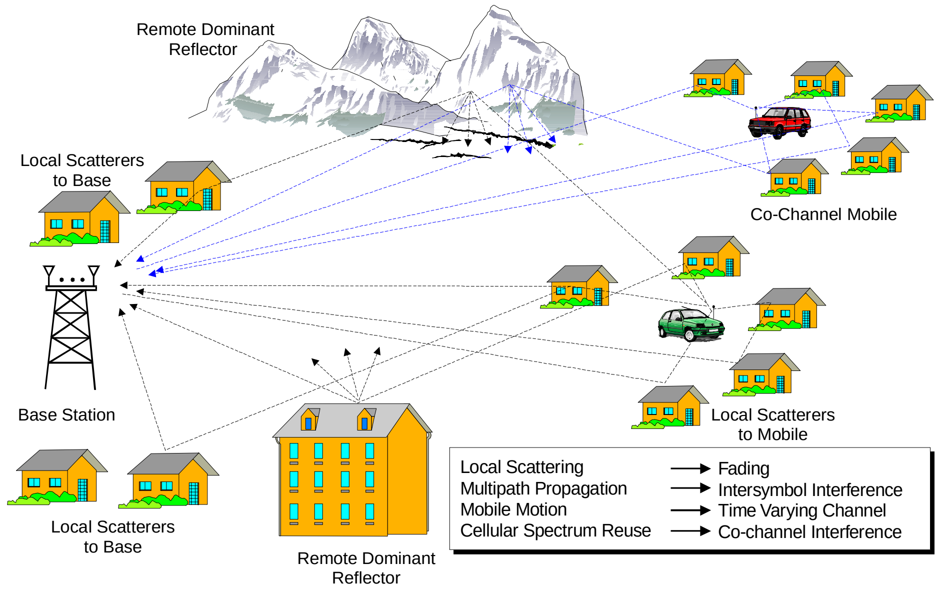
Wireless Channels



Local Scattering → Fading
Multipath Propagation → Intersymbol Interference
Mobile Motion → Time Varying Channel
Cellular Spectrum Reuse → Co-channel Interference

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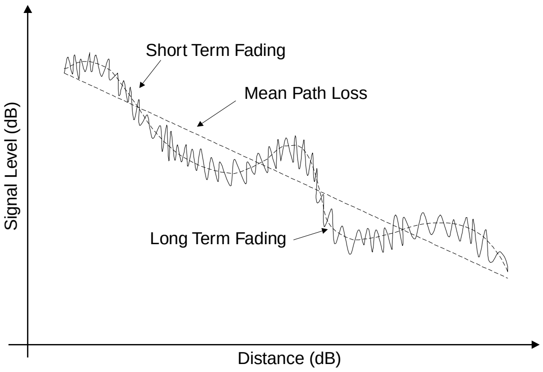
Signal Level in Wireless Channels



- Slow fading (shadowing) is caused by large obstructions between transmitter and receiver.
- Fast fading is due to scattering of the signal by object near transmitter.
- Path loss is proportional to $1/r^{\alpha}$, α is between 2.5 and 5.

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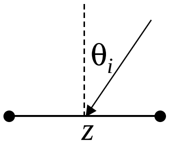
Classification of Wireless Channels

- The multipath channel:

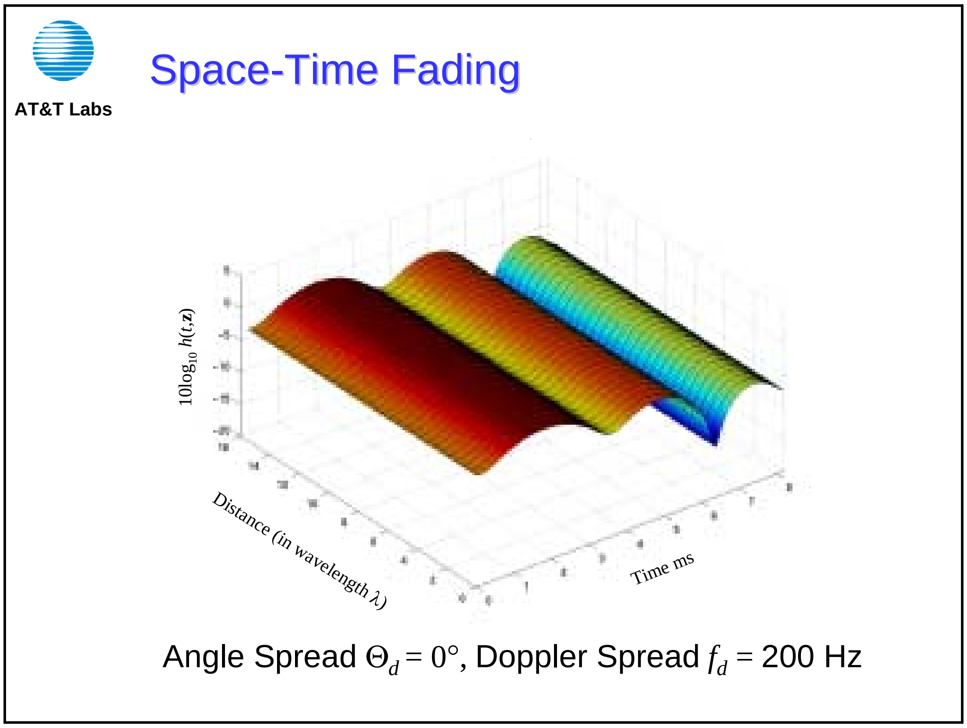
$$h(t,\tau,\mathbf{z}) = \sum_i \alpha_i(t)\cdot e^{-j\varphi_i(t,\tau_i,\mathbf{z})}\cdot\delta(t-\tau_i)$$

$$\varphi_i(t,\tau_i,\mathbf{z}) = 2\pi\cdot\left\{ f_c\tau_i(t) - f_{d,i}t + (z/\lambda)\cdot\sin\theta_i \right\}$$



- The three spreads:

Channel Spread	Channel Selectivity	Measure of Selectivity
Delay Spread	Frequency Selective	Coherence Bandwidth
Doppler Spread	Time Selective	Coherence Time
Angle Spread	Space Selective	Coherence Distance



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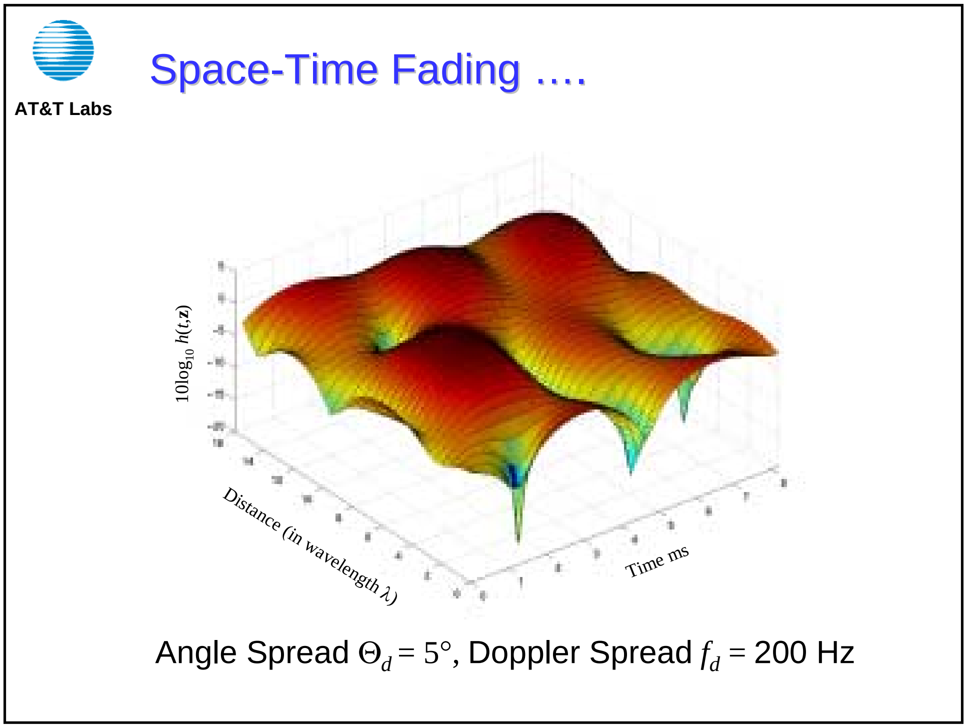
Space-Time Fading

Angle Spread $\Theta_d = 0°$, Doppler Spread f_d = 200 Hz



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Space-Time Fading ….

Angle Spread $\Theta_d = 5°$, Doppler Spread f_d = 200 Hz

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PART 1: Preliminaries

- Wireless channels.
- **Outage capacity of fading channels.**
- Diversity Options: time, frequency, and space.
  - Receive and transmit diversity techniques.

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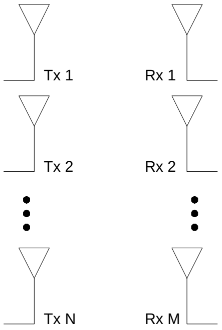
Fundamental Limits: Outage Capacity



$$\mathbf{H} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MN} \end{pmatrix}$$

- Multiple input multiple output (MIMO) channel: N transmitters, M receiver
- α_{ij} is the complex channel gain from i-th transmit antenna to j-th receive antenna.
- $\mathbf{H}$ is the $N \times M$ channel matrix.

Fundamental Limits: Outage Capacity

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- Channel capacity for SISO channel:

$$C = \log_2(1+\rho) \quad \text{bits/sec/use, } \rho \text{ is the SNR}$$

- Channel capacity for MIMO channel:

$$C = \log_2 \det\left(\mathbf{I} + \frac{\rho}{n}\mathbf{H}\mathbf{H}^*\right) \quad \text{bits/sec/use}$$

$\mathbf{H}$ is the $n \times m$ channel matrix

- Outage capacity C_x :

$$\Pr\{C > C_x\} = \int_{\mathbf{H}:C(\mathbf{H})=C_x}^{\infty} C(\mathbf{H})\, f_{\mathbf{H}}(\mathbf{H})\, d\mathbf{H} = x$$

Fundamental Limits: Outage Capacity

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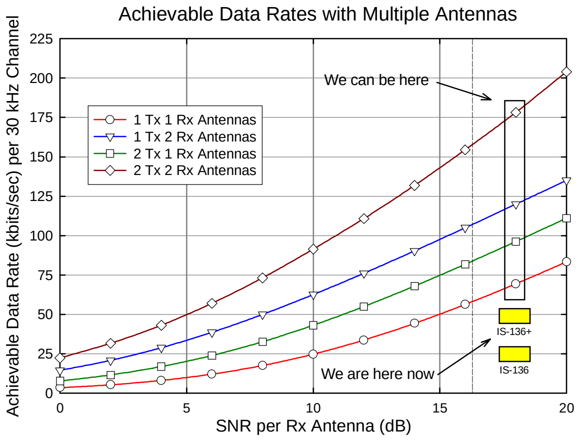

"It is dangerous to put limit on wireless"

Guglielmo Marconi (1932)

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PART 1: Preliminaries

- Wireless channels.
- Outage capacity of fading channels.
- **Diversity Options: time, frequency, and space.**
  - **Receive and transmit diversity techniques.**

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Diversity in Wireless Radio

- Receive the signal via independently fading channels.
- Improves the performance in a fading environment.
  - Space diversity: Multiple antennas are used to receive the signal. Antenna spacing must be such that the fading at each antenna is independent (coherence distance).
  - Frequency diversity: Signal is transmitted in several frequency bands (coherence BW). Not effective on flat (non-frequency selective) channels. Techniques that exploit frequency diversity include: RAKE Receivers, OFDM, equalization.
  - Time diversity: Signal is transmitted in different time slots (coherence time). Channel coding plus interleaving is used to provide time diversity. Not effective over slow fading channels.
  - Polarization diversity: use two antennas with different polarization for reception and/or transmission.

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Receive Diversity

- Make use of a number of receive antennas that are well separated (> coherence distance) to generate independent receptions of the transmitted signal.
    - Selection diversity: choose received signal with largest received power, S/N, etc.
    - Switched diversity: choose alternate antenna if signal falls below a certain threshold.
    - Linear combining: linearly combine a weighted replica of all received signals.
- There is a dramatic improvement even with two branch selection diversity.
- The outage with MRC improves linearly with the number of diversity branches M, but complexity becomes prohibitive.

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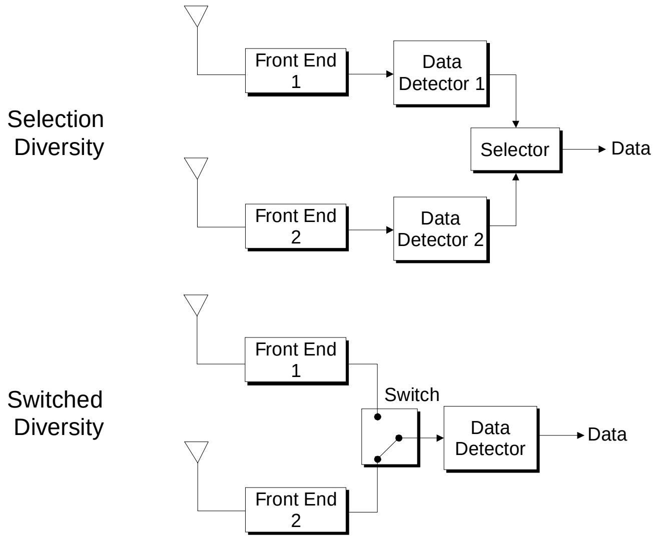
Rx: Selection and Switched Diversity



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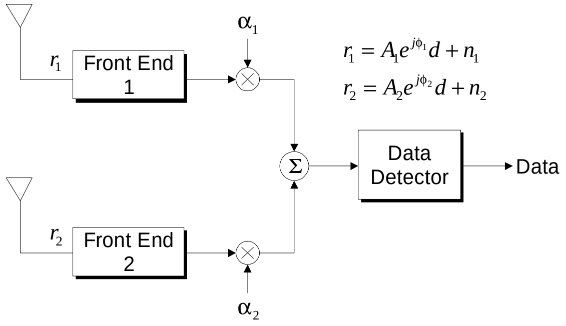
Receive Diversity: Linear Combining



$$r_1 = A_1 e^{j\phi_1} d + n_1$$
$$r_2 = A_2 e^{j\phi_2} d + n_2$$

Equal gain: $\alpha_1 = e^{-j\phi_1}$, $\alpha_2 = e^{-j\phi_2}$

Maximal ratio: $\alpha_1 = A_1 e^{-j\phi_1}$, $\alpha_2 = A_2 e^{-j\phi_2}$

MMSE: training $\left(\alpha_1^*, \alpha_2^*\right) = \arg\min\limits_{\alpha_1,\alpha_2} \left|\alpha_1 r_1 + \alpha_2 r_2 - d\right|^2$

decoding $d = S\left(\alpha_1^* r_1 + \alpha_2^* r_2\right)$

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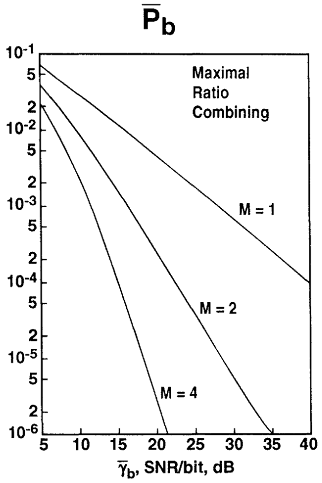
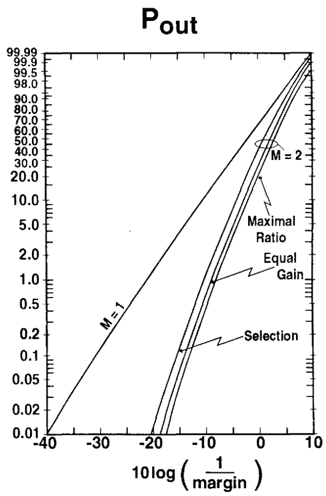
Receive Diversity Performance

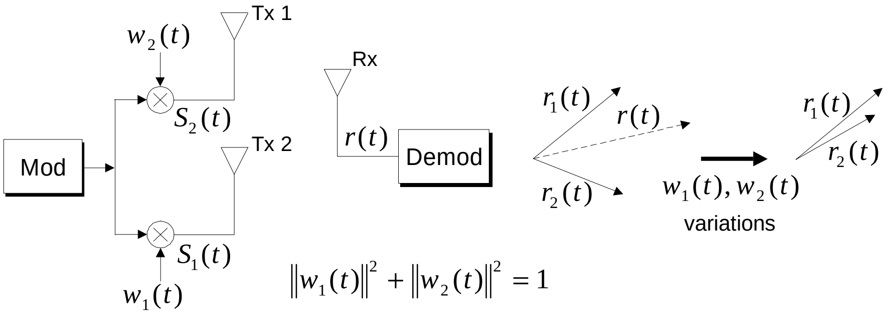




Transmit Diversity

- Provide diversity benefit to a mobile using base station antenna array for frequency division duplexing (FDD) schemes. Cost is shared among different users.
- Order of diversity can be increased when used with other conventional forms of diversity.
- Two kinds of transmit diversity techniques:
  - Transmit diversity with feedback from receiver
  - Transmit diversity without feedback from receiver:
    - No training.
    - Feedforward information.

Transmit Diversity with Feedback



$$\|w_1(t)\|^2 + \|w_2(t)\|^2 = 1$$

- $w_1(t)$ and $w_2(t)$ are varied such that $|r(t)|^2$ is maximized.
- $w_1(t)$ and $w_2(t)$ are adapted with feedback information from the receiver.

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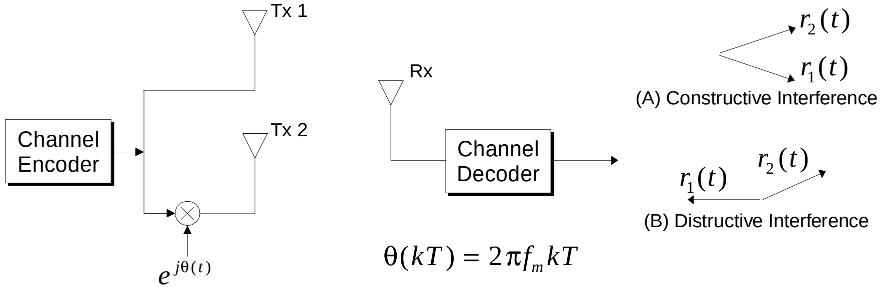
Tx Diversity with Frequency Weighting



$$\theta(kT) = 2\pi f_m kT$$

- Use frequency weighting to mitigate the harm of scenario B.
- Simulate fast fading → can use conventional channel coding and interleaving techniques.

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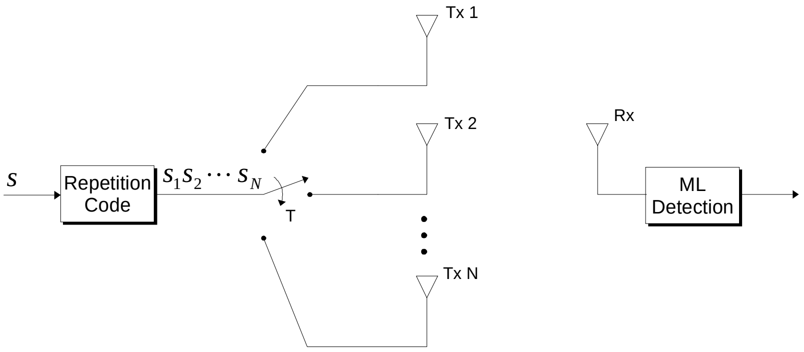
Tx Diversity with Antenna Hopping



- At time i, $1 \leq i \leq N$, transmit s from antenna i.
- Achieves a diversity order of N using ML detection or MRC at the receiver.
- Bandwidth efficiency is $1/N$.

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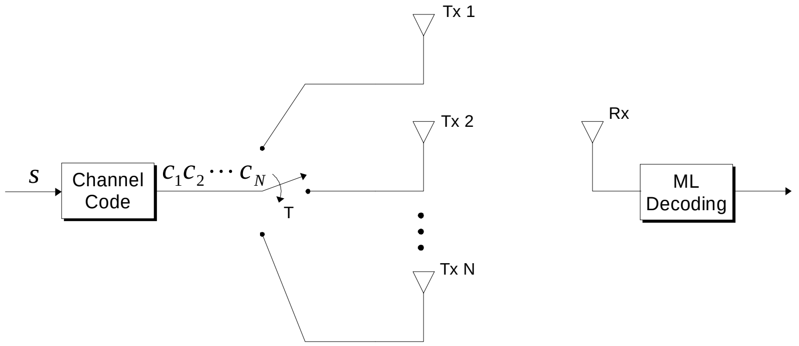
Tx Diversity with Channel Coding



- The channel code has a minimum Hamming distance $d_{\min} \le N$.
- Transmit code symbol i from antenna i.
- After receiving the N symbols, the decoder performs ML decoding to decode the received codeword.

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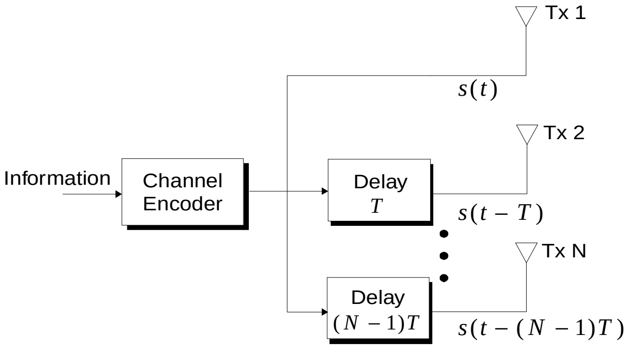
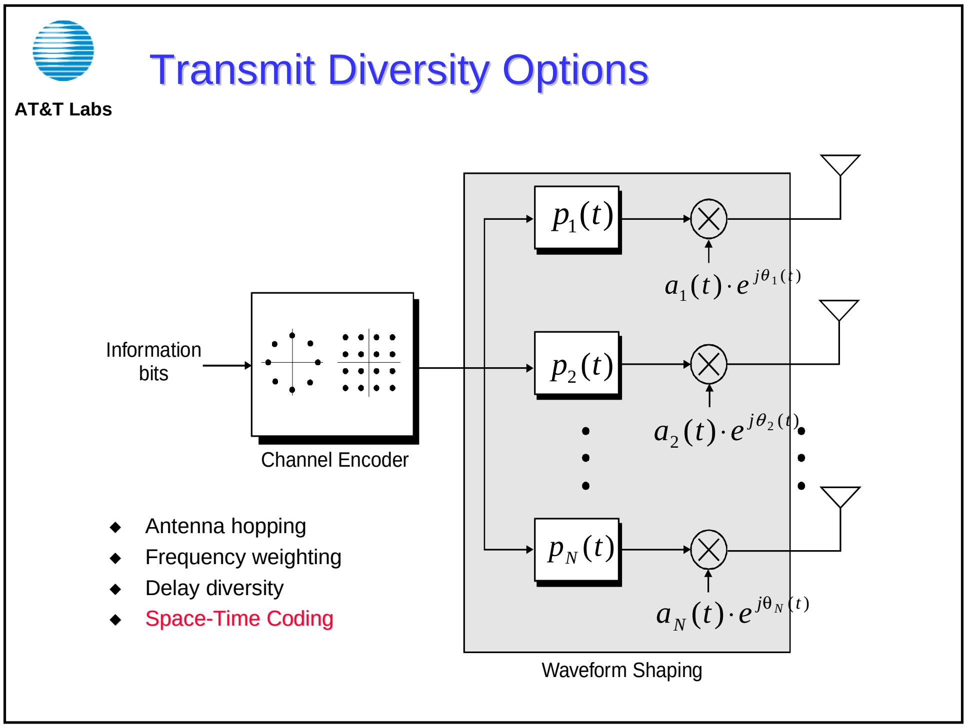
Transmit Diversity via Delay Diversity



- Provide diversity benefit by introducing intentional multipath.
- Receiver uses an equalizer or MLSE for detection.
- Provides a diversity order of N. No loss of BW efficiency.



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Transmit Diversity Options

- Antenna hopping
- Frequency weighting
- Delay diversity
- Space-Time Coding

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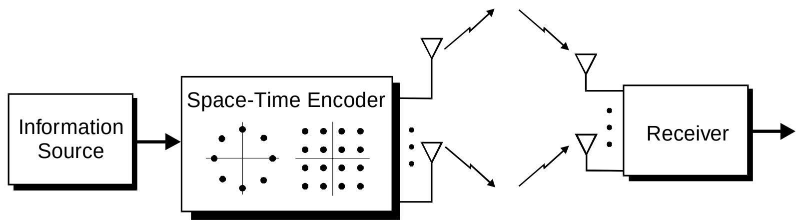
Part 2: Space-Time Coding

- **Space-Time coded modulation (STCM):**
  - **Probability of error analysis and design criterion.**
  - **Space-time trellis codes examples.**
  - **Decoding of space-time trellis codes.**
  - **Comparison with delay-diversity.**
- Space-Time block codes (STBC):
  - Basic idea and decoding of STBC.
  - Incoherent detection of STBC.
  - STBC for more than 2 transmit antennas.
- Interference suppression with STBC:
  - Zero forcing IC and ML decoding of STBC.
  - MMSE IC and ML decoding of STBC.
  - Iterative IC and ML decoding of STBC.

Space-Time Coded Modulation



- For each input symbol, the space-time encoder chooses the constellation points to simultaneously transmit from each antenna so that coding and diversity gains are maximized.
  - ➪ Space-Time trellis codes: coding and diversity gain.
  - ➪ Space-Time block codes: diversity gain + some coding gain (depending on the rate of the code).

Space-Time Coding: The Model

- N transmit and M receive antennas.
- The overall channel is made up of $N \times M$ slowly varying sub-channels.
- Each sub-channel is Rayleigh fading (same analysis applies to Rician fading too).
- At any time interval, N signals are transmitted simultaneously, one from each transmit antenna.
- The sub-channels undergo independent fading.
- The fade coefficients are assumed to be fixed during a slot and independent from slot to another.

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STC: The Model ….

- Transmitted Code Vector:

$$\mathbf{c}_l = [\ c_1(l),\ c_2(l),\ \cdots,\ c_N(l)\ ]^T$$

- Channel Matrix:

$$\mathbf{H} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MN} \end{bmatrix}$$

- Received Signal Vector:

$$\mathbf{r}(l) = \mathbf{H} \cdot \mathbf{c}_l + \mathbf{n}(l)$$

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STC: Probability of Error Analysis

- Transmitted code vector sequence: $\mathbf{C} = \{\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_L\}$.
- Probability of error: assuming perfect knowledge of CSI,

$$\Pr\left(\mathbf{C} \to \tilde{\mathbf{C}} \,|\, \mathbf{H}\right) \le \exp\left(-d^2(\mathbf{C}, \tilde{\mathbf{C}})\right)$$

$$d^2(\mathbf{C}, \tilde{\mathbf{C}}) = \sum_{j=1}^{M} \sum_{l=1}^{L} \left| \alpha_{j1}[c_1(l) - \tilde{c}_1(l)] + \cdots\cdots + \alpha_{jN}[c_N(l) - \tilde{c}_N(l)] \right|^2$$

$$= \Gamma_s \cdot \sum_{j=1}^{M} \mathbf{h}_j\, \mathbf{A}(\mathbf{C}, \tilde{\mathbf{C}})\, \mathbf{h}_j^*, \quad \text{where}$$

$$\Gamma_s = E_s / 4N_o \quad \text{and} \quad \mathbf{h}_j = [\ \alpha_{j1}\ \ \alpha_{j2}\ \cdots\ \ \alpha_{jN}\ ]^T$$

$$\mathbf{A}(\mathbf{C}, \tilde{\mathbf{C}}) = \mathbf{B}(\mathbf{C}, \tilde{\mathbf{C}})\mathbf{B}^*(\mathbf{C}, \tilde{\mathbf{C}})$$

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STC: Probability of Error Analysis ….

- The matrix $\mathbf{B}$ is the error matrix between the transmitted code vector sequence $\mathbf{C}$ and the decoded code vector $\tilde{\mathbf{C}}$ sequence .

$$\mathbf{B} = \begin{pmatrix} c_1(1)-\tilde{c}_1(1) & c_1(2)-\tilde{c}_1(2) & \cdots & c_1(L)-\tilde{c}_1(L) \\ c_2(1)-\tilde{c}_2(1) & c_2(2)-\tilde{c}_2(2) & \cdots & c_2(L)-\tilde{c}_2(L) \\ \vdots & \vdots & \ddots & \vdots \\ c_N(1)-\tilde{c}_N(1) & c_N(2)-\tilde{c}_N(2) & \cdots & c_N(L)-\tilde{c}_N(L) \end{pmatrix}$$

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STC: Probability of Error Analysis ….

- The matrix $\mathbf{A}=\mathbf{B}\mathbf{B}^*$ is Hermitain → $\mathbf{A}$ can be written as $\mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^*$, where $\boldsymbol{\Lambda}$ = diag$\{\lambda_1,\lambda_2,\ldots,\lambda_N\}$ and $\mathbf{U}$ is orthonormal, $\mathbf{U}^*\,\mathbf{U}=\mathbf{I}$, and its columns are the eigenvectors of $\mathbf{A}$.
- Let $\boldsymbol{\beta}_j = \mathbf{U}^*\mathbf{h}_j^*$, then we will have

$$d^2(\mathbf{C},\tilde{\mathbf{C}}) \;=\Gamma_s \cdot \sum_{j=1}^{M} \boldsymbol{\beta}_j^* \boldsymbol{\Lambda} \boldsymbol{\beta}_j \;=\; \Gamma_s \cdot \sum_{j=1}^{M}\sum_{i=1}^{N} \lambda_i |\beta_{ij}|^2$$

- The random variables $\nu_{ij} = |\beta_{ij}|^2$ are i.i.d. , each has a χ^2 distribution with 2 degrees of freedom, that is

$$\nu_{ij} \sim f_\nu(\nu) = e^{-\nu} \quad \text{for} \quad \nu > 0 \quad \text{and} \quad 0 \quad \text{otherwise}$$

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STC: Probability of Error Analysis ….

- Probability of error: average over all $|\beta_{ij}|^2$

$$\Pr\left(\mathbf{C} \to \tilde{\mathbf{C}}\right) \le \left(\prod_{i=1}^{N} \frac{1}{1+\lambda_i \cdot \Gamma_s}\right)^{M}$$

- Let r be the rank of the matrix $\mathbf{A}$ and $\lambda_1,\lambda_2,\ldots,\lambda_r$ be the nonzero eigenvalues of $\mathbf{A}$. Then

$$\Pr\left(\mathbf{C} \to \tilde{\mathbf{C}}\right) \le \left(\prod_{i=1}^{r} \lambda_i\right)^{-M} \cdot \left(\frac{1}{\Gamma_s}\right)^{rM}$$

- Thus a diversity gain of rM and a coding gain of $(\lambda_1\lambda_2\ldots\lambda_r)^{1/r}$ are achieved.

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STC: Design Criteria

- Rank Criterion: In order to achieve the maximum diversity NM, the matrix $\mathbf{B}(\mathbf{C}_1,\mathbf{C}_2)$ has to be full rank for any two code vector sequences $\mathbf{C}_1$ and $\mathbf{C}_2$. If $\mathbf{B}(\mathbf{C}_1,\mathbf{C}_2)$ has a minimum rank r over the set of two tuples of distinct code vector sequences, then a diversity rM is achieved.
- Determinant Criterion: The minimum of the r-th roots of the sum of determinants of all $r\times r$ principal cofactors of $\mathbf{A}(\mathbf{C}_1,\mathbf{C}_2)$ taken over all pairs of distinct code vector sequences $\mathbf{C}_1$ and $\mathbf{C}_2$ corresponds to coding gain, r being the rank of $\mathbf{A}(\mathbf{C}_1,\mathbf{C}_2)$. The target of code design is making this sum as large as possible. If a code is designed to give a diversity gain of NM, for a better coding gain, the minimum of the determinant of $\mathbf{A}(\mathbf{C}_1,\mathbf{C}_2)$ taken over all pairs of distinct code vector sequences $\mathbf{C}_1$ and $\mathbf{C}_2$ must be maximized.

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STC: Design Criteria ....

- Space-time trellis codes were designed using this criteria.
- The trade-off between diversity, rate, and trellis complexity has also been studied.
- It is proved that our designs are optimal in terms of the trade-off between complexity, constellation size, diversity, and rate.
- It is not known whether our codes provide the optimum coding gains at a given complexity, diversity, and rate.

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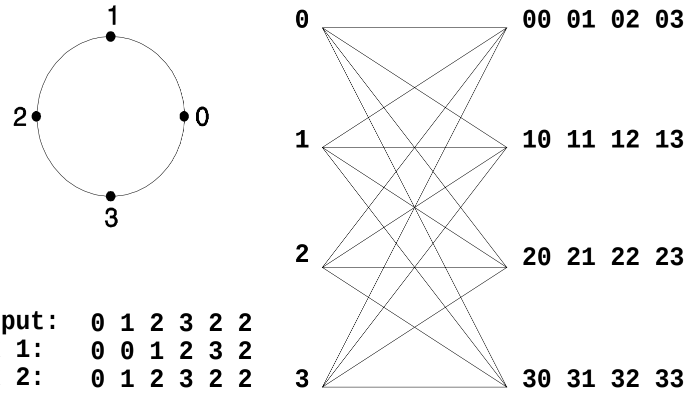
STC: 4-PSK Example



Input:	0	1	2	3	2	2
Tx 1:	0	0	1	2	3	2
Tx 2:	0	1	2	3	2	2

4-PSK 4-State Space-Time Code with 2 Tx Antennas

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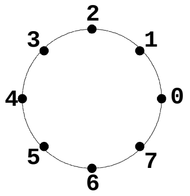
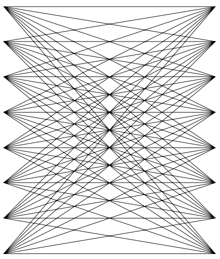
STC: 8-PSK Example 1

Input:	0	1	5	7	6	4
Tx 1:	0	0	5	1	3	6
Tx 2:	0	1	5	7	6	4





0	00,01,02,03,04,05,06,07
1	50,51,52,53,54,55,56,57
2	20,21,22,23,24,25,26,27
3	70,71,72,73,74,75,76,77
4	40,41,42,43,44,45,46,47
5	10,11,12,13,14,15,16,17
6	60,61,62,63,64,65,66,67
7	30,31,32,33,34,35,36,37

8-PSK 8-State Space-Time Code with 2 Tx Antennas

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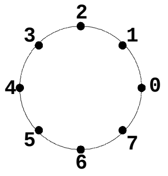
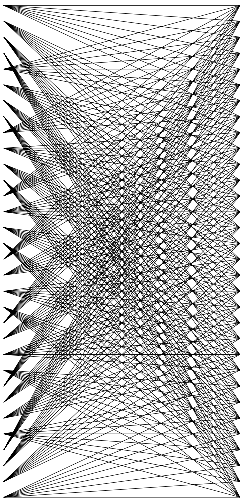
STC: 8-PSK Example 2

Input:	0	1	5	7	6	4
Tx 1:	0	0	5	4	6	3
Tx 2:	0	1	6	3	4	3



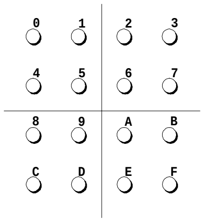


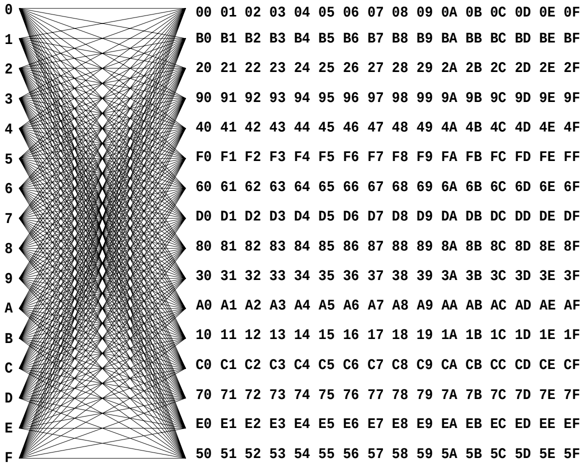
0	00	01	02	03	04	05	06	07
1	51	52	53	54	55	56	57	50
2	22	23	24	25	26	27	20	21
3	73	74	75	76	77	70	71	72
4	44	45	46	47	40	41	42	43
5	15	16	17	10	11	12	13	14
6	66	67	60	61	62	63	64	65
7	37	30	31	32	33	34	35	36
8	37	30	31	32	33	34	35	36
9	00	01	02	03	04	05	06	07
10	51	52	53	54	55	56	57	50
11	22	23	24	25	26	27	20	21
12	73	74	75	76	77	70	71	72
13	44	45	46	47	40	41	42	43
14	15	16	17	10	11	12	13	14
15	66	67	60	61	62	63	64	65
16	22	23	24	25	26	27	20	21
17	73	74	75	76	77	70	71	72
18	44	45	46	47	40	41	42	43
19	15	16	17	10	11	12	13	14
20	66	67	60	61	62	63	64	65
21	37	30	31	32	33	34	35	36
22	00	01	02	03	04	05	06	07
23	51	52	53	54	55	56	57	50
24	51	52	53	54	55	56	57	50
25	22	23	24	25	26	27	20	21
26	73	74	75	76	77	70	71	72
27	44	45	46	47	40	41	42	43
28	15	16	17	10	11	12	13	14
29	66	67	60	61	62	63	64	65
30	37	30	31	32	33	34	35	36
31	00	01	02	03	04	05	06	07

8-PSK 32-State Space-Time Code with 2 Tx Antennas

STC: 16-QAM Example

Input: 0 1 A C 5 7
Tx 1: 0 0 B A C F
Tx 2: 0 1 A C 5 7





0	00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F
1	B0 B1 B2 B3 B4 B5 B6 B7 B8 B9 BA BB BC BD BE BF
2	20 21 22 23 24 25 26 27 28 29 2A 2B 2C 2D 2E 2F
3	90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F
4	40 41 42 43 44 45 46 47 48 49 4A 4B 4C 4D 4E 4F
5	F0 F1 F2 F3 F4 F5 F6 F7 F8 F9 FA FB FC FD FE FF
6	60 61 62 63 64 65 66 67 68 69 6A 6B 6C 6D 6E 6F
7	D0 D1 D2 D3 D4 D5 D6 D7 D8 D9 DA DB DC DD DE DF
8	80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F
9	30 31 32 33 34 35 36 37 38 39 3A 3B 3C 3D 3E 3F
A	A0 A1 A2 A3 A4 A5 A6 A7 A8 A9 AA AB AC AD AE AF
B	10 11 12 13 14 15 16 17 18 19 1A 1B 1C 1D 1E 1F
C	C0 C1 C2 C3 C4 C5 C6 C7 C8 C9 CA CB CC CD CE CF
D	70 71 72 73 74 75 76 77 78 79 7A 7B 7C 7D 7E 7F
E	E0 E1 E2 E3 E4 E5 E6 E7 E8 E9 EA EB EC ED EE EF
F	50 51 52 53 54 55 56 57 58 59 5A 5B 5C 5D 5E 5F

16-QAM 16-State Space-Time Code with 2 Tx Antennas

STC: Maximum Likelihood Decoder

- Given the received vector sequence $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_L\}$, the receiver chooses the code vector sequence $\tilde{\mathbf{C}}$ as the one that was transmitted such that the a posteriori probability

$$\Pr\left(\tilde{\mathbf{C}} \mid \mathbf{R}, \mathbf{H}(l), \; l = 1, \cdots, L\right)$$

is maximized.

- The space-time maximum likelihood decoder (STMLD):

$$\tilde{\mathbf{C}} = \arg\min_{\tilde{\mathbf{C}}} \sum_{l=1}^{L} \left\| \mathbf{r}(l) - \sqrt{E_s} \cdot \mathbf{H}(l) \cdot \tilde{\mathbf{c}}_l \right\|^2$$

- The STMLD is implemented as a vector Viterbi algorithm (v-VA) where the trellis path with the smallest accumulated metric is chosen.

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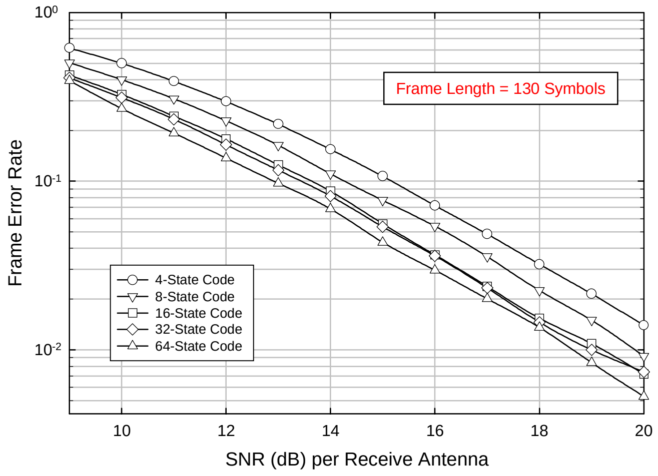
STC: Performance with Perfect CSI

Performance of 4-PSK Space-Time Codes with 2 Transmit and 1 Receive Antennas



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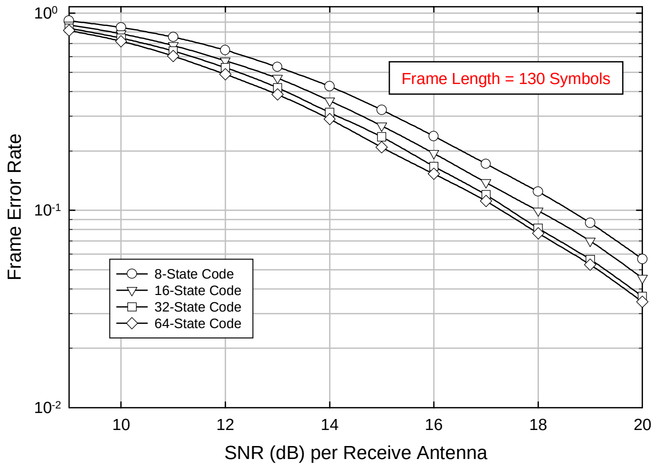
STC: Performance with Perfect CSI ….

Performance of 8-PSK Space-Time Codes with 2 Transmit and 1 Receive Antennas



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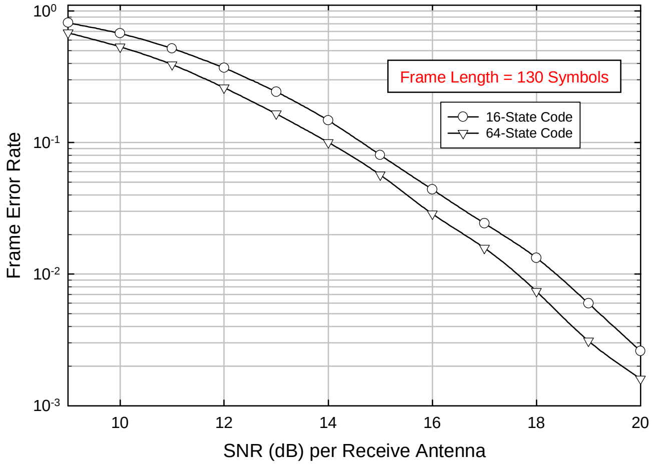
STC: Performance with Perfect CSI ….

Performance of 16-QAM Space-Time Codes with 2 Transmit and 2 Receive Antennas



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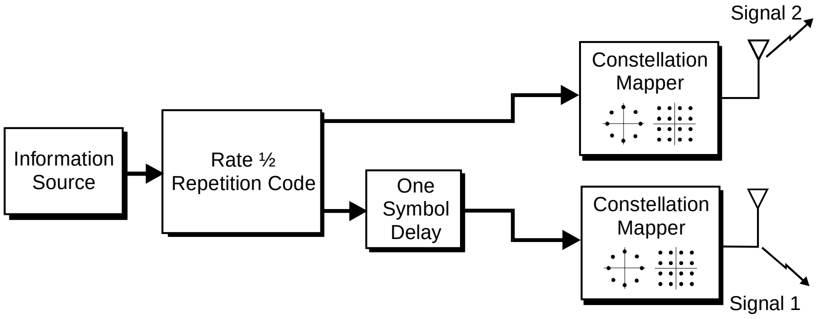
Delay Diversity


Signal 2

Constellation Mapper

Information Source

Rate ½ Repetition Code

One Symbol Delay

Constellation Mapper

Signal 1

Delay Diversity

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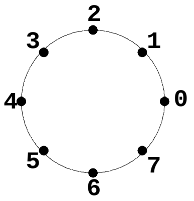
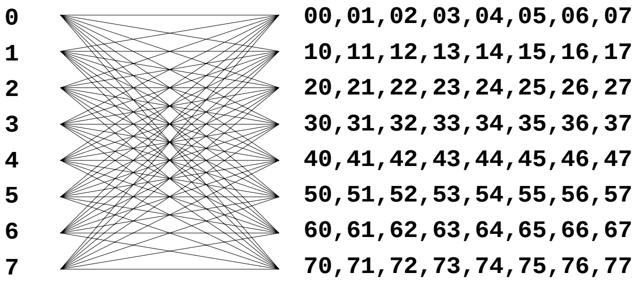
Delay-Diversity as a ST Code

```
Input:   0 1 5 7 6 4
Tx 1:    0 0 1 5 7 6
Tx 2:    0 1 5 7 6 4
```





State	Outputs
0	00,01,02,03,04,05,06,07
1	10,11,12,13,14,15,16,17
2	20,21,22,23,24,25,26,27
3	30,31,32,33,34,35,36,37
4	40,41,42,43,44,45,46,47
5	50,51,52,53,54,55,56,57
6	60,61,62,63,64,65,66,67
7	70,71,72,73,74,75,76,77

8-PSK 8-State Delay Diversity Code with 2 Tx Antennas

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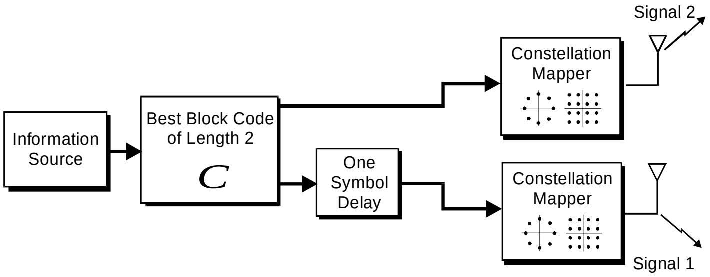
ST Code as a Delay-Diversity



Signal 2

Constellation Mapper

Information Source

Best Block Code of Length 2

C

One Symbol Delay

Constellation Mapper

Signal 1

Space-Time Coding as a Delay Diversity

- For the 8-PSK 8-state ST code:

$$\mathbf{C} = \{00,15,22,37,44,51,66,73\}$$

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Part 2: Space-Time Coding

- Space-Time coded modulation (STCM):
  - Probability of error analysis and design criterion.
  - Space-time trellis codes examples.
  - Decoding of space-time trellis codes.
  - Comparison with delay-diversity.
- **Space-Time block codes (STBC):**
  - **Basic idea and decoding of STBC.**
  - **Incoherent detection of STBC.**
  - **STBC for more than 2 transmit antennas.**
- Interference suppression with STBC:
  - Zero forcing IC and ML decoding of STBC.
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  - Iterative IC and ML decoding of STBC.

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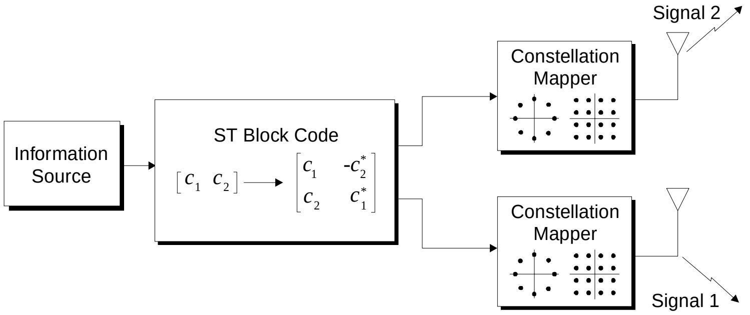
Space-Time Block Codes



- Idea:

$$[c_1 \quad c_2] \rightarrow \begin{pmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{pmatrix}$$

- Assumption: channel is quasi-static.

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Decoding of STBC

- Received Signal:

$$r_1 = h_1 c_1 + h_2 c_2 + n_1$$

$$r_2 = -h_1 c_2^* + h_2 c_1^* + n_2$$

$$\mathbf{r} = \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} = \mathbf{H} \cdot \mathbf{c} + \mathbf{n}$$

- $\mathbf{H}$ is orthogonal:

$$\mathbf{H}^* \mathbf{H} = \left(|h_1|^2 + |h_2|^2 \right) \cdot \mathbf{I} = \|\mathbf{h}\|^2 \cdot \mathbf{I}$$

$$\Rightarrow \tilde{\mathbf{r}} = \mathbf{H}^* \mathbf{r} = \|\mathbf{h}\|^2 \cdot \mathbf{c} + \tilde{\mathbf{n}}$$

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Decoding of STBC ….

- The noise term $\tilde{\mathbf{n}}$ is still white $\Rightarrow$ c_1 and c_2 are detected independently $\Rightarrow$ lower complexity.
- With M receive antennas:

$$\tilde{\mathbf{r}} = \sum_{i=1}^{M} \mathbf{H}_i^* \mathbf{r}_i = \left[\sum_{i=1}^{M} \|\mathbf{h}_i\|^2 \right] \cdot \mathbf{c} + \tilde{\mathbf{n}}$$

- With M receive antennas, a diversity order of $2M$ is achieved.
- Only simple linear processing at the receiver is required.
- Complete CSI is required at the receiver. In practice channel estimation is used to obtain CSI.

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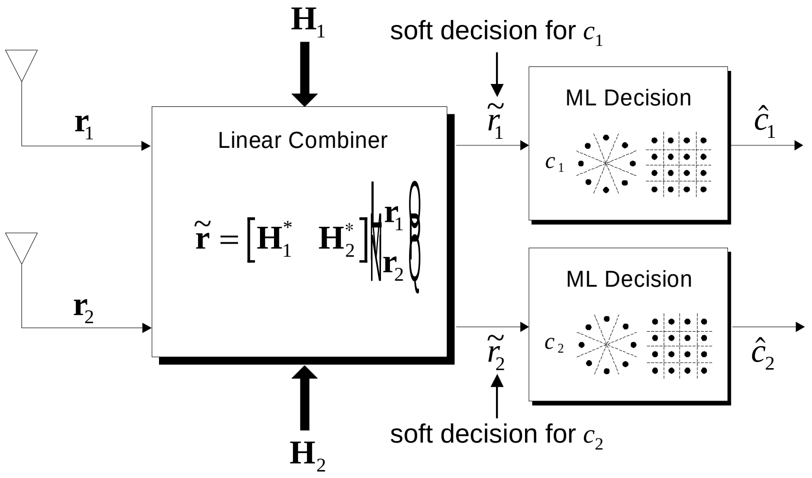
Decoding of STBC ....



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STBC: Incoherent Detection

- Received Signal:

$$\tilde{\mathbf{r}} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \\ c_2^* & -c_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \mathbf{C} \cdot \mathbf{h} + \mathbf{n}$$

- Given c_1 and c_2, h_1 and h_2 can be estimated as

$$\tilde{\mathbf{h}} = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{bmatrix} = \frac{1}{|c_1|^2 + |c_2|^2} \cdot \mathbf{C}^* \cdot \mathbf{r} = \begin{bmatrix} h_1 + \eta_1 \\ h_2 + \eta_2 \end{bmatrix}$$

$$\eta_1 = \frac{c_1^* n_1 + c_2 n_2}{|c_1|^2 + |c_2|^2} \quad \text{and} \quad \eta_2 = \frac{c_2^* n_1 + c_1 n_2}{|c_1|^2 + |c_2|^2}$$

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STBC: Incoherent Detection ….

- If the channel is quasi-static, then the received signal for the next code symbol is:

$$r_3 = h_1 c_3 + h_2 c_4 + n_3$$

$$r_4 = -h_1 c_4^* + h_2 c_3^* + n_4$$

- Use the channel estimate $\tilde{\mathbf{h}}$ for detecting c_3 and c_4.
- Need to transmit two known symbols at the beginning of each time slot.
- If the channel variation is very slow, then at each time we average the channel estimate ⇒ less noisy estimates.
- This scheme will perform within 3 dB of the case when ideal CSI is available at the receiver.

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Space-Time Block Codes for N > 2

- Is there a rate 1 STBC with simple linear processing for more than two antennas (N >2) ?
- Answer: theory of generalized orthogonal designs.
  - Complex constellation: **NO.**
  - Real constellation: **YES.**
- Rate 1 codes with simple linear processing for arbitrary number of transmit antennas and real constellation.
- Rate 1/2 codes with simple linear processing for arbitrary number of transmit antennas and complex constellation.
- Rate 3/4 codes with simple linear processing for N=3 and N=4 transmit antennas and complex constellation.

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Space-Time Block Codes for N > 2 ….

- Example 1: Complex constellation, rate=1/2, 4 transmit antennas (N=4)

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} \rightarrow \begin{pmatrix} c_1 & -c_2 & -c_3 & -c_4 & c_1^* & -c_2^* & -c_3^* & -c_4^* \\ c_2 & c_1 & c_4 & -c_3 & c_2^* & c_1^* & c_4^* & -c_3^* \\ c_3 & -c_4 & c_1 & c_2 & c_3^* & -c_4^* & c_1^* & c_2^* \\ c_4 & c_3 & -c_2 & c_1 & c_4^* & c_3^* & -c_2^* & c_1^* \end{pmatrix}$$

- Will provide 4 branch diversity performance + 3 dB coding gain.

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Space-Time Block Codes for N > 2 ….

- Example 2: Complex constellation, rate=3/4, 4 transmit antennas (N=4)

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} \rightarrow \begin{pmatrix} c_1 & -c_2^* & \frac{c_3^*}{\sqrt{2}} & \frac{c_3^*}{\sqrt{2}} \\ c_2 & c_1^* & \frac{c_3^*}{\sqrt{2}} & -\frac{c_3^*}{\sqrt{2}} \\ \frac{c_3}{\sqrt{2}} & \frac{c_3}{\sqrt{2}} & -\frac{c_1+c_1^*-c_2+c_2^*}{\sqrt{2}} & \frac{c_2+c_2^*+c_1-c_1^*}{\sqrt{2}} \\ \frac{c_3}{\sqrt{2}} & -\frac{c_3}{\sqrt{2}} & -\frac{c_2+c_2^*-c_1+c_1^*}{\sqrt{2}} & -\frac{c_1+c_1^*+c_2-c_2^*}{\sqrt{2}} \end{pmatrix}$$

- Will provide 4 branch diversity performance + 1.25 dB coding gain.

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Space-Time Block Codes for N > 2 ….

- Example 3: Real constellation, rate=1, 4 transmit antennas (N=4)

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} \rightarrow \begin{pmatrix} c_1 & -c_2 & -c_3 & -c_4 \\ c_2 & c_1 & c_4 & -c_3 \\ c_3 & -c_4 & c_1 & c_2 \\ c_4 & c_3 & -c_2 & c_1 \end{pmatrix}$$

- Will provide 4 branch diversity performance and no coding gain.

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Part 2: Space-Time Coding

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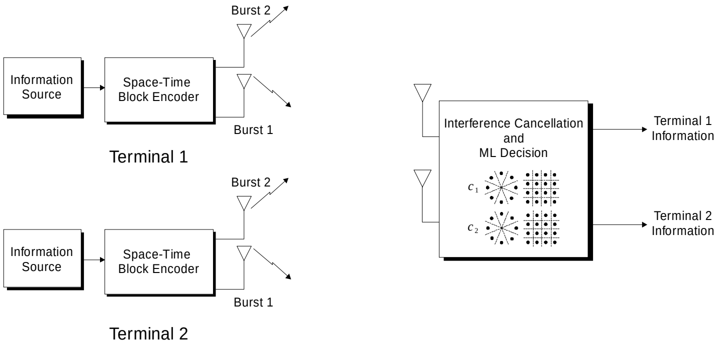
Interference Cancellation with STBC



- *K* users, *N* transmit antennas per user. Classical IC techniques need *N*(*K*-1) +1 receive antennas to suppress interference from *K*-1 co-channel users.
- Exploit code structure to suppress interference ⇒ only *K* receive antennas are required. Assumption: full synchronization between terminals.
- Can be implemented using adaptive LMS or RLS.
- Can be used for increasing system capacity or increasing data rate.

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Zero Forcing IC with STBC

- Received Signal:

$$\begin{aligned}\mathbf{r}_1 &= \mathbf{H}_1 \cdot \mathbf{c} + \mathbf{G}_1 \cdot \mathbf{s} + \mathbf{n}_1\\ \mathbf{r}_2 &= \mathbf{H}_2 \cdot \mathbf{c} + \mathbf{G}_2 \cdot \mathbf{s} + \mathbf{n}_2\end{aligned} \Rightarrow \begin{bmatrix}\mathbf{r}_1\\ \mathbf{r}_2\end{bmatrix} = \begin{bmatrix}\mathbf{H}_1 & \mathbf{G}_1\\ \mathbf{H}_2 & \mathbf{G}_2\end{bmatrix} \cdot \begin{bmatrix}\mathbf{c}\\ \mathbf{s}\end{bmatrix} + \begin{bmatrix}\mathbf{n}_1\\ \mathbf{n}_2\end{bmatrix}$$

$$\mathbf{r} = \mathbf{H} \cdot \tilde{\mathbf{c}} + \boldsymbol{\eta}$$

- Zero forcing solution:

$$\begin{bmatrix}\mathbf{H}_1 & \mathbf{G}_1\\ \mathbf{H}_2 & \mathbf{G}_2\end{bmatrix}^{-1} \cdot \begin{bmatrix}\mathbf{r}_1\\ \mathbf{r}_2\end{bmatrix} = \begin{bmatrix}\hat{\mathbf{r}}_1\\ \hat{\mathbf{r}}_2\end{bmatrix} = \begin{bmatrix}\mathbf{c}\\ \mathbf{s}\end{bmatrix} + \begin{bmatrix}\hat{\mathbf{n}}_1\\ \hat{\mathbf{n}}_2\end{bmatrix}$$

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Zero Forcing IC with STBC ….

$$\begin{bmatrix} \mathbf{H}_1 & \mathbf{G}_1 \\ \mathbf{H}_2 & \mathbf{G}_2 \end{bmatrix}^{-1} = \begin{bmatrix} \tilde{\mathbf{H}}^{-1} & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{G}}^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{I} & -\mathbf{G}_1\mathbf{G}_2^{-1} \\ -\mathbf{H}_2\mathbf{H}_1^{-1} & \mathbf{I} \end{bmatrix}$$

$$\tilde{\mathbf{H}} = \mathbf{H}_1 - \mathbf{G}_1\mathbf{G}_2^{-1}\mathbf{H}_2 \ , \ \tilde{\mathbf{G}} = \mathbf{G}_2 - \mathbf{H}_2\mathbf{H}_1^{-1}\mathbf{G}_1$$

$$\begin{bmatrix} \mathbf{I} & -\mathbf{G}_1\mathbf{G}_2^{-1} \\ -\mathbf{H}_2\mathbf{H}_1^{-1} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{r}}_1 \\ \tilde{\mathbf{r}}_2 \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{H}} & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{G}} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{c} \\ \mathbf{s} \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{n}}_1 \\ \tilde{\mathbf{n}}_2 \end{bmatrix}$$

★ $\tilde{\mathbf{H}}$ and $\tilde{\mathbf{G}}$ are orthogonal and have the same structure and noise $\tilde{\mathbf{n}}_1$ and $\tilde{\mathbf{n}}_2$ are still white ⇒ can detect $\mathbf{c}$ and $\mathbf{s}$ as before.

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Zero Forcing Interference Cancellation ….

◆ ZF Interference Cancellation:

```
$(\mathbf{c}, \Delta_c) = \mathrm{ZFIC}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{H}_1, \mathbf{H}_2, \mathbf{G}_1, \mathbf{G}_2)$
{
    $\tilde{\mathbf{r}} = \mathbf{r}_1 - \mathbf{G}_1\mathbf{G}_2^{-1}\mathbf{r}_2$
    $\tilde{\mathbf{H}} = \mathbf{H}_1 - \mathbf{G}_1\mathbf{G}_2^{-1}\mathbf{H}_2$
    $\hat{\mathbf{c}} = \arg\min_{\mathbf{c}\in\mathbf{C}} \left\| \tilde{\mathbf{r}} - \tilde{\mathbf{H}} \cdot \mathbf{c} \right\|^2$
    $\Delta_c = \left\| \tilde{\mathbf{r}} - \tilde{\mathbf{H}} \cdot \hat{\mathbf{c}} \right\|^2$
}
```

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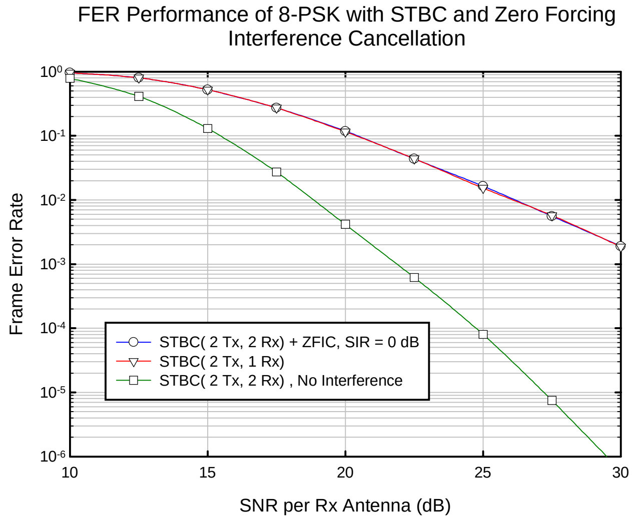
ZFIC Performance


FER Performance of 8-PSK with STBC and Zero Forcing Interference Cancellation

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MMSE Interference Cancellation

- Error Criteria:

$$\Delta(\mathbf{w},\beta_1,\beta_2)=\left\|\mathbf{w}^*\mathbf{r}-\beta_1 c_1-\beta_2 c_2\right\|^2$$

- MMSE IC: find a linear combiner $\boldsymbol{w}$, β_1, and β_2 such that $E\{\Delta(\boldsymbol{w}, \beta_1, \beta_2)\}$is minimized.

★ β_1 or β_2 should be set equal to 1 or else we will get a zero solution.

$$\beta_1=1 \quad\Rightarrow\quad \Delta_1(\mathbf{w}_1,\beta_2)=\left\|\mathbf{w}_1^*\mathbf{r}-c_1-\beta_2 c_2\right\|^2=\left\|\tilde{\mathbf{w}}_1^*\tilde{\mathbf{r}}-c_1\right\|^2$$

$$\beta_2=1 \quad\Rightarrow\quad \Delta_2(\mathbf{w}_2,\beta_1)=\left\|\mathbf{w}_2^*\mathbf{r}-c_2-\beta_1 c_1\right\|^2=\left\|\tilde{\mathbf{w}}_2^*\tilde{\mathbf{r}}-c_2\right\|^2$$

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MMSE Interference Cancellation ….

- MMSE IC solution:

$$\tilde{w}_1 = \begin{bmatrix} \mathbf{M} & \mathbf{h}_2 \\ \mathbf{h}_2^* & 1 \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{h}_1 \\ 0 \end{bmatrix} \ , \ \tilde{w}_2 = \begin{bmatrix} \mathbf{M} & \mathbf{h}_1 \\ \mathbf{h}_1^* & 1 \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{h}_2 \\ 0 \end{bmatrix}$$

$$\mathbf{M} = \mathbf{H}\mathbf{H}^* + \tfrac{1}{\text{SNR}}\mathbf{I}$$

$\mathbf{h}_1 =$ first column of $\mathbf{H}$

$\mathbf{h}_2 =$ second column of $\mathbf{H}$

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MMSE Interference Cancellation ….

- MMSE solution:

$$w_1 = \left(\mathbf{M} - \mathbf{h}_2\mathbf{h}_2^*\right)^{-1}\mathbf{h}_1 \ , \ \beta_2^* = \frac{\mathbf{h}_2^*\mathbf{M}^{-1}\mathbf{h}_1}{1 - \mathbf{h}_2^*\mathbf{M}^{-1}\mathbf{h}_1}$$

$$w_2 = \left(\mathbf{M} - \mathbf{h}_1\mathbf{h}_1^*\right)^{-1}\mathbf{h}_2 \ , \ \beta_1^* = \frac{\mathbf{h}_1^*\mathbf{M}^{-1}\mathbf{h}_2}{1 - \mathbf{h}_1^*\mathbf{M}^{-1}\mathbf{h}_2}$$

- Using the structure of $\mathbf{M}$ and the fact that $\mathbf{h}_1$ and $\mathbf{h}_2$ are orthogonal, we can show that either $\beta_1=0$ and $\beta_2=1$ or $\beta_1=1$ and $\beta_2=0$.

➡ Two different combiners w_1 and w_2 for c_1 and c_2, respectively.

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MMSE Interference Cancellation ….

$$(\mathbf{c},\Delta_c) = \text{MMSE\_IC}\left(\mathbf{r}_1,\mathbf{r}_2,\mathbf{H}_1,\mathbf{H}_2,\mathbf{G}_1,\mathbf{G}_2,\Gamma\right)$$

{

$$\tilde{\mathbf{r}} = \begin{bmatrix}\mathbf{r}_1^T & \mathbf{r}_1^T\end{bmatrix}^T$$

$$\tilde{\mathbf{H}} = \begin{bmatrix}\mathbf{H}_1 & \mathbf{G}_1 \\ \mathbf{H}_2 & \mathbf{G}_2\end{bmatrix}$$

$$\mathbf{M} = \mathbf{H}\mathbf{H}^* + \frac{1}{\Gamma}\mathbf{I}$$

$$\mathbf{h}_1 = \begin{bmatrix}\mathbf{h}_{11}^T & \mathbf{h}_{21}^T\end{bmatrix}^T \ , \ \mathbf{h}_2 = \begin{bmatrix}\mathbf{h}_{12}^T & \mathbf{h}_{22}^T\end{bmatrix}^T$$

$$\boldsymbol{\alpha}_1^* = \mathbf{M}^{-1}\mathbf{h}_1 \ , \ \boldsymbol{\alpha}_2^* = \mathbf{M}^{-1}\mathbf{h}_2$$

$$c_1 = \arg\min_{\hat{c}_1 \in C} \left\|\boldsymbol{\alpha}_1^*\tilde{\mathbf{r}} - \hat{c}_1\right\|^2 \ , \ c_2 = \arg\min_{\hat{c}_2 \in C} \left\|\boldsymbol{\alpha}_1^*\tilde{\mathbf{r}} - \hat{c}_2\right\|^2$$

$$\Delta_c = \left\|\boldsymbol{\alpha}_1^*\tilde{\mathbf{r}} - \hat{c}_1\right\|^2 + \left\|\boldsymbol{\alpha}_1^*\tilde{\mathbf{r}} - \hat{c}_2\right\|^2$$

}

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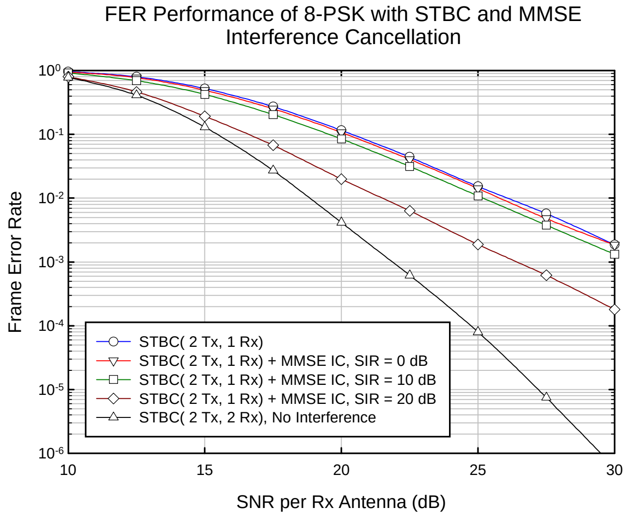
MMSE IC Performance



FER Performance of 8-PSK with STBC and MMSE Interference Cancellation

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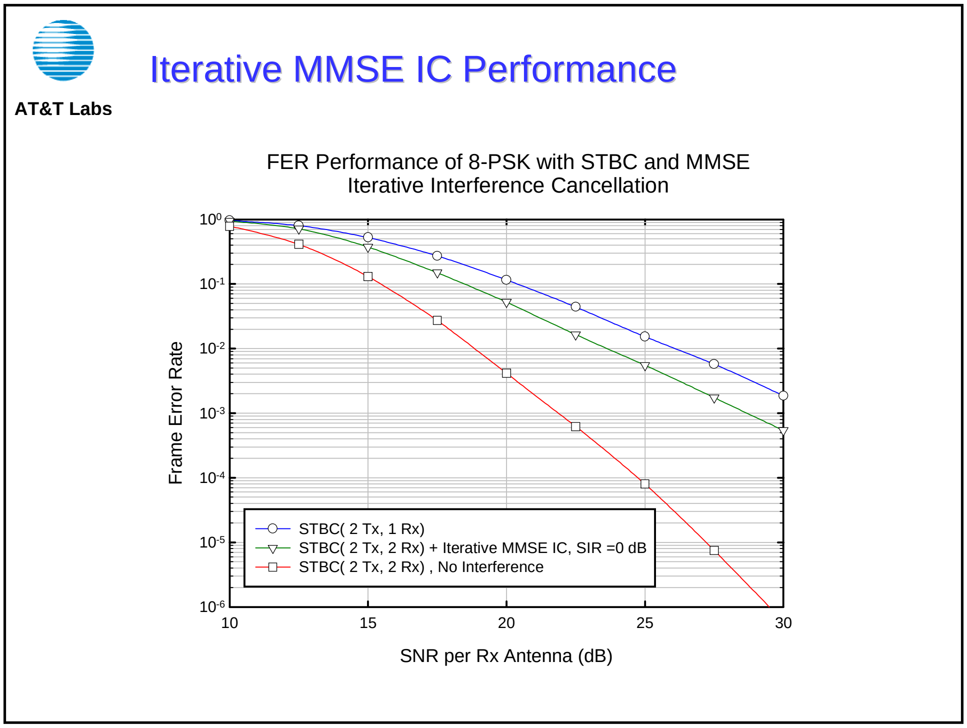
Iterative Interference Cancellation

```
$(\hat{\mathbf{c}}, \hat{\mathbf{s}}) = \text{IT\_IC\_STDEC}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{H}_1, \mathbf{H}_2, \mathbf{G}_1, \mathbf{G}_2)$
{
    $(\hat{\mathbf{c}}_0, \Delta_{c,o}) = \text{IC\_STDEC}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{H}_1, \mathbf{H}_2, \mathbf{G}_1, \mathbf{G}_2)$
        $\mathbf{x}_1 = \mathbf{r}_1 - \mathbf{H}_1 \cdot \hat{\mathbf{c}}_o \quad , \quad \mathbf{x}_2 = \mathbf{r}_2 - \mathbf{H}_2 \cdot \hat{\mathbf{c}}_o$
        $\hat{\mathbf{s}}_o = \arg\min_{s \in \mathbf{S}} \{ \|\mathbf{x}_1 - \mathbf{G}_1 \cdot \mathbf{s}\|^2 + \|\mathbf{x}_2 - \mathbf{G}_2 \cdot \mathbf{s}\|^2 \}$
      $\Delta_{s,o} = \|\mathbf{x}_1 - \mathbf{G}_1 \cdot \mathbf{s}\|^2 + \|\mathbf{x}_2 - \mathbf{G}_2 \cdot \mathbf{s}\|^2$
    $(\hat{\mathbf{s}}_1, \Delta_{s,1}) = \text{IC\_STDEC}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{G}_1, \mathbf{G}_2, \mathbf{H}_1, \mathbf{H}_2)$
        $\mathbf{y}_1 = \mathbf{r}_1 - \mathbf{G}_1 \cdot \hat{\mathbf{s}}_1 \quad , \quad \hat{\mathbf{y}}_2 = \mathbf{r}_2 - \mathbf{G}_2 \cdot \hat{\mathbf{s}}_1$
        $\hat{\mathbf{c}}_1 = \arg\min_{c \in \mathbf{C}} \{ \|\mathbf{y}_1 - \mathbf{H}_1 \cdot \mathbf{c}\|^2 + \|\mathbf{y}_2 - \mathbf{H}_2 \cdot \mathbf{c}\|^2 \}$
      $\Delta_{c,1} = \|\mathbf{y}_1 - \mathbf{H}_1 \cdot \mathbf{c}\|^2 + \|\mathbf{y}_2 - \mathbf{H}_2 \cdot \mathbf{c}\|^2$

    If $(\Delta_{c,o} + \Delta_{s,o}) < (\Delta_{c,1} + \Delta_{s,1}) \Rightarrow (\hat{\mathbf{c}}, \hat{\mathbf{s}}) = (\hat{\mathbf{c}}_o, \hat{\mathbf{s}}_o)$
    Else $(\hat{\mathbf{c}}, \hat{\mathbf{s}}) = (\hat{\mathbf{c}}_1, \hat{\mathbf{s}}_1)$
}
```



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Iterative MMSE IC Performance

FER Performance of 8-PSK with STBC and MMSE
Iterative Interference Cancellation

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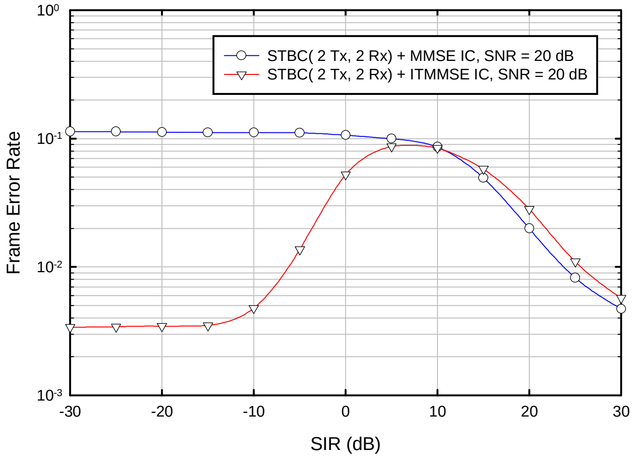
Iterative MMSE IC Performance ….

FER Performance of 8-PSK with STBC and MMSE
Iterative Interference Cancellation



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Part 3: Space-Time Coding Applications

- ✷ **Narrowband TDMA Cellular.**
- ◆ Broadband Wireless OFDM.
- ◆ Applications of STBC with Interference Suppression.

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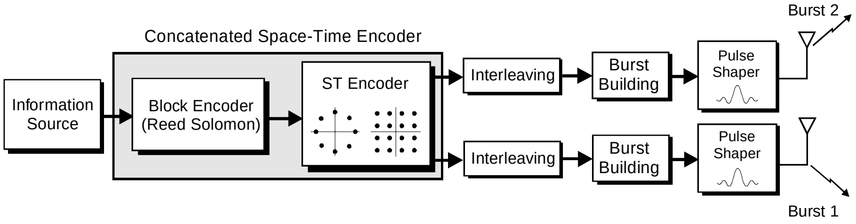
Base-Station Transmitter


Concatenated Space-Time Encoder

Information Source

Block Encoder (Reed Solomon)

ST Encoder

Interleaving

Burst Building

Pulse Shaper

Interleaving

Burst Building

Pulse Shaper

Burst 2

Burst 1

- High rate outer block code will clean up burst errors of the ST code and will provide an error detection mechanism.
- Same interleaving for both bursts.
- Synchronization and pilot sequences are inserted in both bursts for timing and frequency synchronization as well as channel estimation at the receiver.

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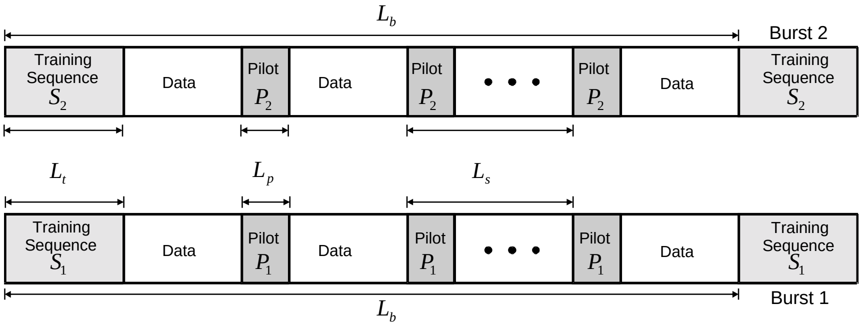
Slot Structure


L_b

Burst 2

Training Sequence S_2 | Data | Pilot P_2 | Data | Pilot P_2 | • • • | Pilot P_2 | Data | Training Sequence S_2

L_t

L_p

L_s

Training Sequence S_1 | Data | Pilot P_1 | Data | Pilot P_1 | • • • | Pilot P_1 | Data | Training Sequence S_1

Burst 1

L_b

- Training sequences S_1 and S_2 as well as pilot sequences P_1 and P_2 are orthogonal sequences. In addition these sequences are constant energy sequences, i.e. from M-PSK constellation (this will give best MSE performance).

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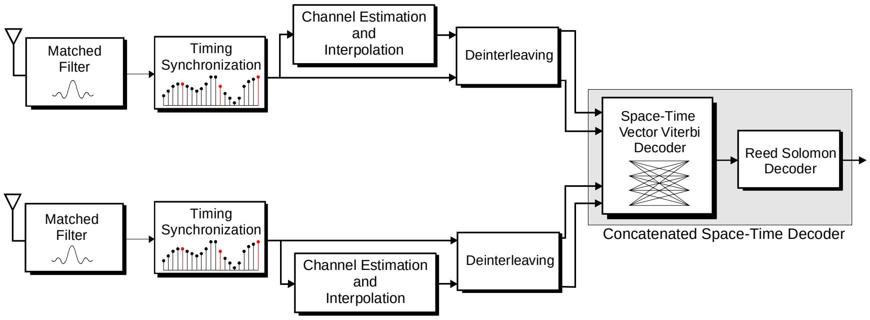
Mobile Receiver



- Design assumes flat fading channel.
- Frequency offset is compensated for as part of the channel estimation.
- Channel estimates at the pilot and training symbol positions are interpolated to obtain CSI for the whole slot.

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Channel Estimation

- Complex channel gain:

$$\tilde{\alpha}_{ij}(t) = \alpha_{ij}(t)e^{-j2\pi f_o t}, \quad f_o \text{ is the frequency offset}$$

$$R_\alpha(\tau) = E\{\tilde{\alpha}^*_{ij}(t)\tilde{\alpha}_{ij}(t+\tau)\} = J_o(2\pi f_d \tau)e^{-j2\pi f_o \tau}$$

- Pilots and synch sequences should be positioned in the slot such that the channel sampling frequency f_s satisfies $2(f_d + f_o) \leq f_s = L_s T_s$.
- Channel Estimation:

$$\mathbf{Y}_j(l) = A \cdot [\mathbf{P}_1\,\mathbf{P}_2 \cdots \mathbf{P}_N] \cdot \tilde{\boldsymbol{\alpha}}_j(l) + \mathbf{z}_j(l) \qquad j = 1, 2, \cdots, M$$

$$\hat{\alpha}_{ij}(l) = \frac{\mathbf{P}_i^* \mathbf{Y}_j(l)}{A \cdot \|\mathbf{P}_i\|^2} \qquad i = 1, 2, \cdots, N$$

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Channel Interpolation

- Channel estimates are interpolated to obtain complete CSI for the whole time slot.
- Wiener interpolation filter (WIF):
  - Optimum interpolation filter needs the knowledge of f_d , f_o, and SNR.
  - A different filter for each symbol in the burst.
  - Poor performance at low Doppler with worst case design.
- Optimum low-pass time-invariant interpolation filter:
  - Similar to WIF, except that we use same filter for all symbols in the burst.
  - Poor CSI near the ends of the slot when only pilot symbols in that slot are used.
  - Lower complexity than WIF, performance is, however, poorer.

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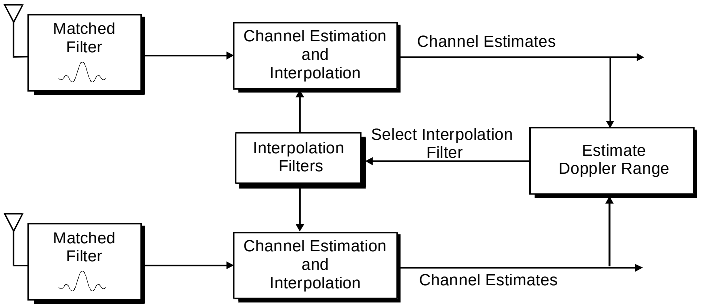
Channel Interpolation ...



Quasi-adaptive interpolation

- Doppler range is divided into different regions and pre-designed WIF is used for each range.
- Receiver selects the filter use based on the quality of the interpolated CSI for the previous slot

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Modem Simulation

- STCM with 16-QAM and 8-PSK.
- Timing and carrier frequency offset synchronization.
- f_c = 1.9 GHz, IS-136 basic channelization and slot structure.
- $\pi/4$-DQPSK modulation for synchronization and pilot symbols.
- Oversampling factor of 8.
- SR raised cosine pulse shaping with 0.35% excess BW.
- FER Performance:
  - FER vs. SNR and Doppler Spread.
  - Space-Time code vs. Delay-Diversity code.
  - Effect of interpolation filter and transmit antenna correlation.
  - Effect of delay spread.

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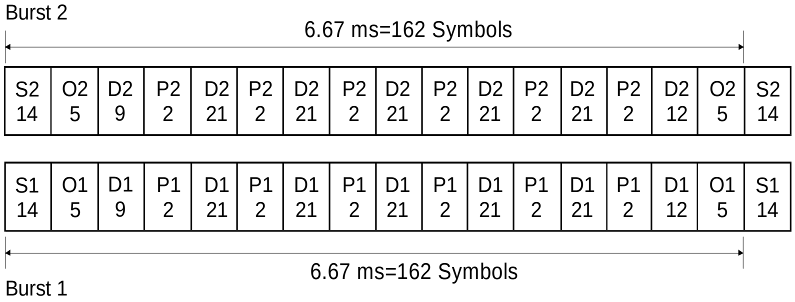
Slot Structure



Burst 2

6.67 ms=162 Symbols

S2	O2	D2	P2	D2	P2	D2	P2	D2	P2	D2	P2	D2	P2	D2	O2	S2
14	5	9	2	21	2	21	2	21	2	21	2	21	2	12	5	14

S1	O1	D1	P1	D1	P1	D1	P1	D1	P1	D1	P1	D1	P1	D1	O1	S1
14	5	9	2	21	2	21	2	21	2	21	2	21	2	12	5	14

6.67 ms=162 Symbols

Burst 1

S1,S2 : Synchronization Sequence (S1 and S2 are orthogonal, S1 as in IS-136)
P1,P2 : Pilot Symbols (P1 and P2 are orthogonal)
D1,D2 : Data
O1,O2 : Overhead Symbols

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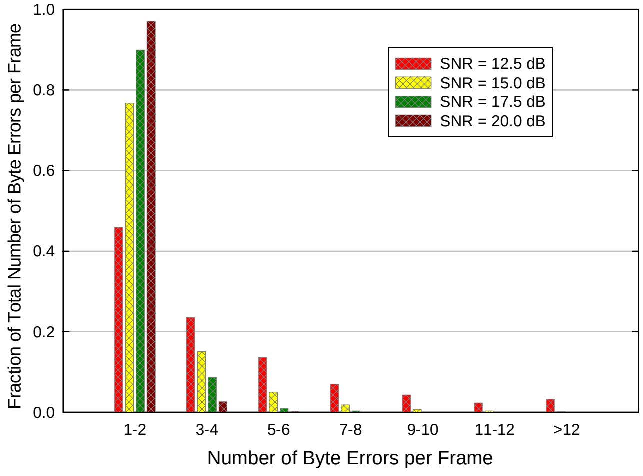
Error Distribution

Error Histogram for the 16-QAM 16-State ST Code with
2 Tx 2 Rx Antennas and Optimized WIF @ f_d = 180 Hz



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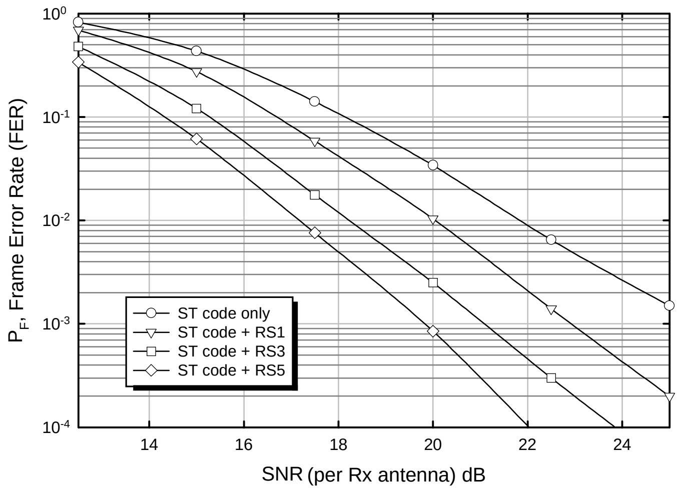
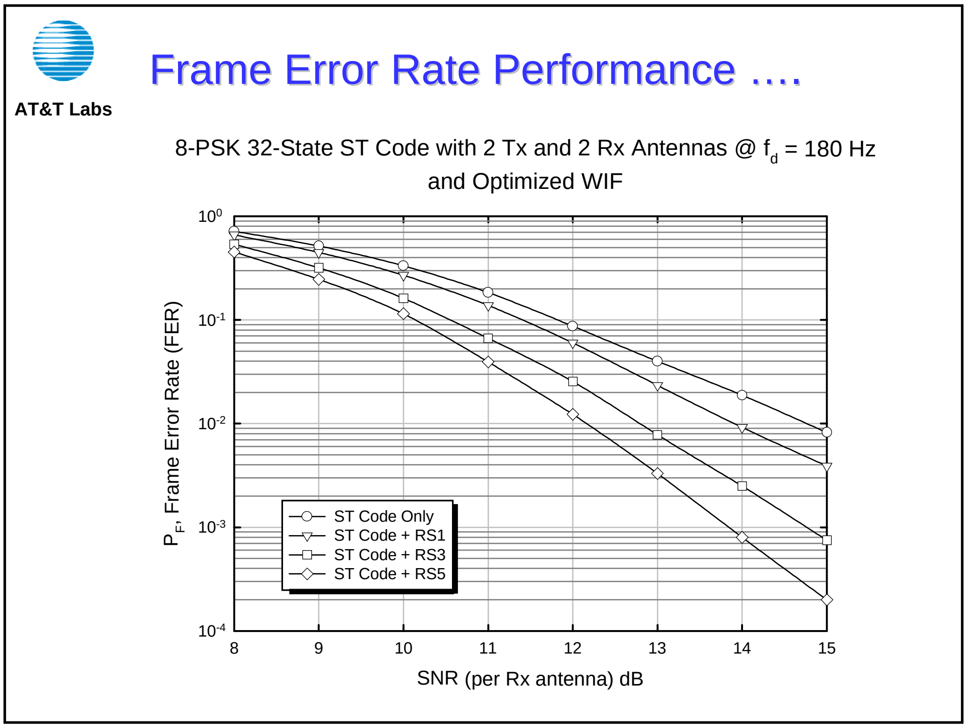
Frame Error Rate Performance

16-QAM 16-State ST Code with 2 Tx and 2 Rx Antennas @ f_d = 180 Hz
with Optimized WIF





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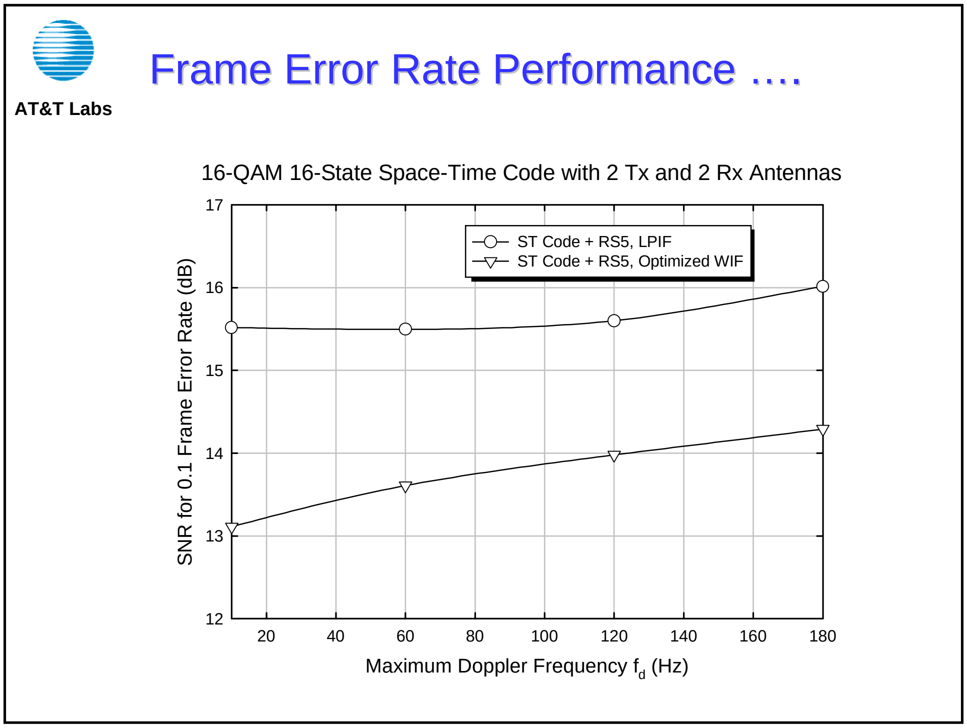
Frame Error Rate Performance ….

8-PSK 32-State ST Code with 2 Tx and 2 Rx Antennas @ f_d = 180 Hz and Optimized WIF



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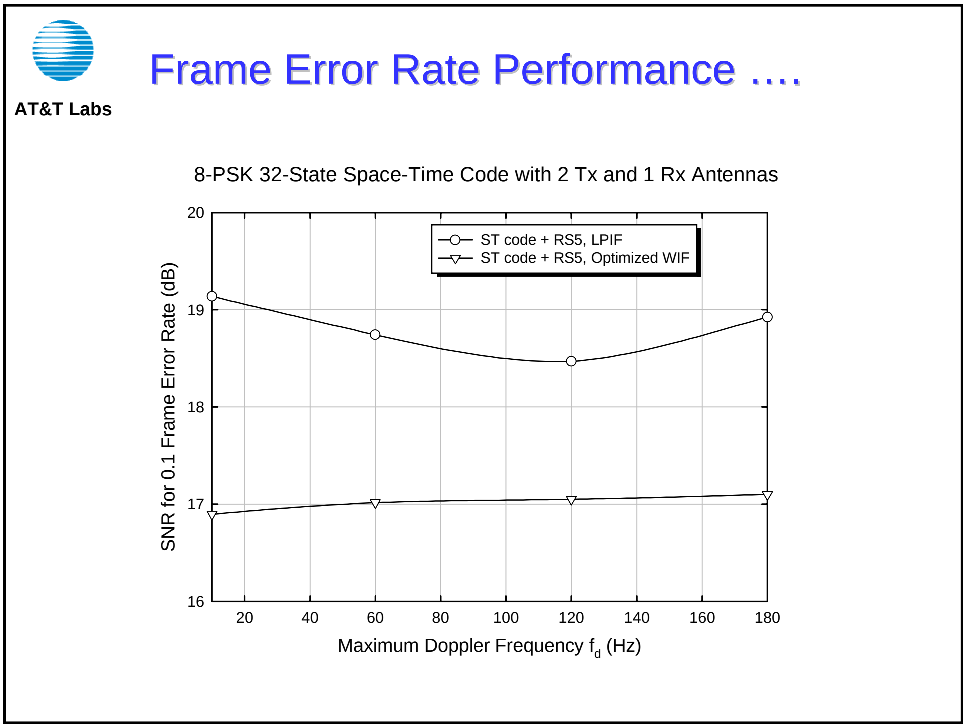
Frame Error Rate Performance ….

16-QAM 16-State Space-Time Code with 2 Tx and 2 Rx Antennas



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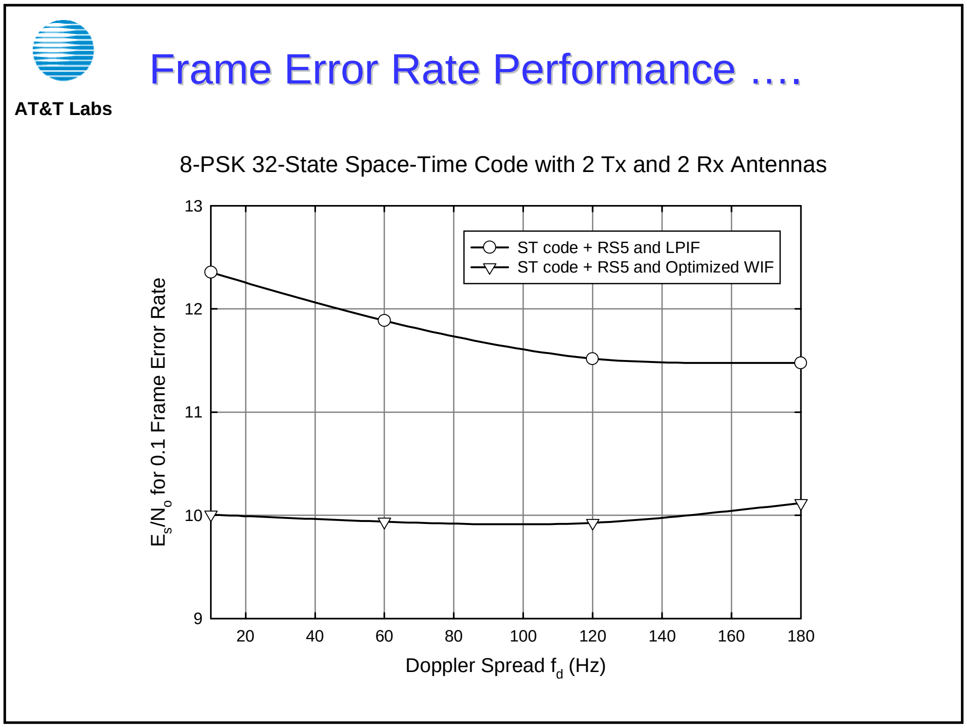
Frame Error Rate Performance ….

8-PSK 32-State Space-Time Code with 2 Tx and 1 Rx Antennas



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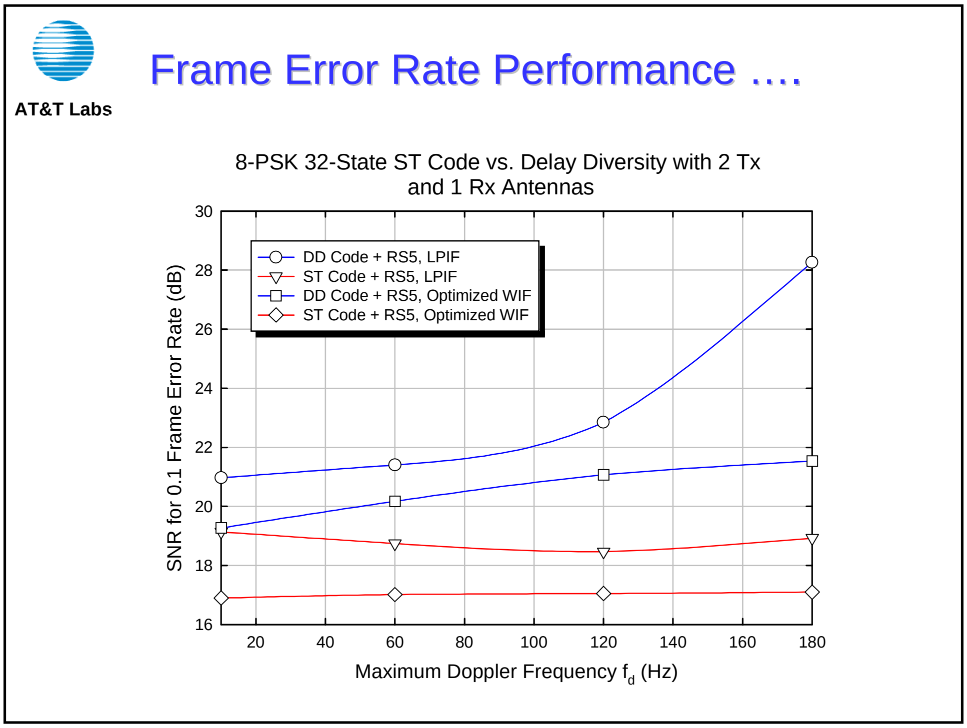
Frame Error Rate Performance ….

8-PSK 32-State Space-Time Code with 2 Tx and 2 Rx Antennas



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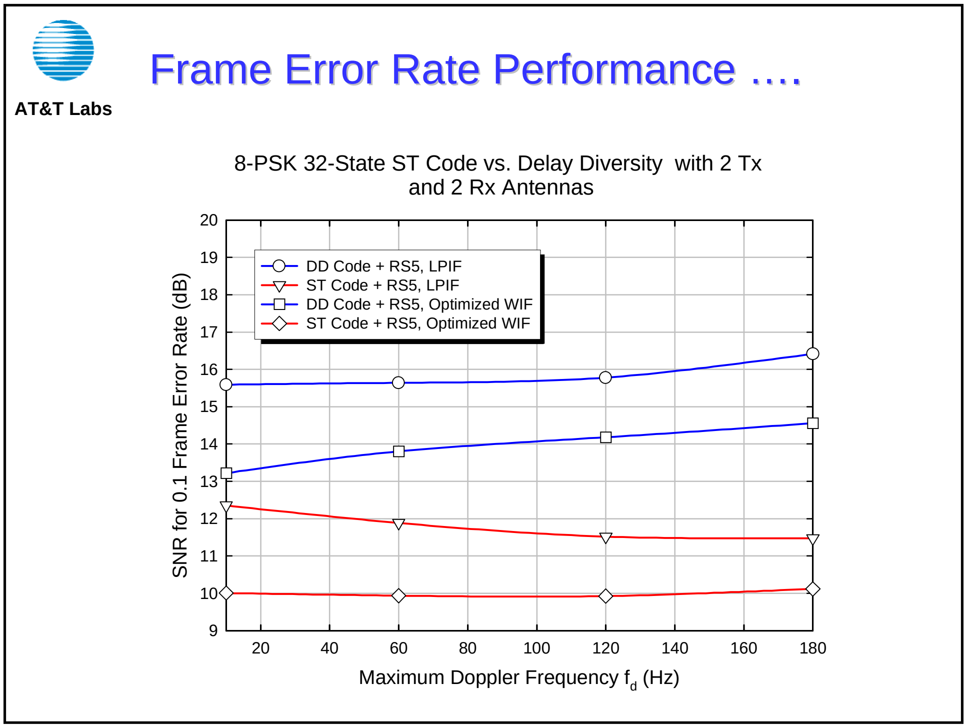
Frame Error Rate Performance ….

8-PSK 32-State ST Code vs. Delay Diversity with 2 Tx and 1 Rx Antennas



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Frame Error Rate Performance ….

8-PSK 32-State ST Code vs. Delay Diversity with 2 Tx and 2 Rx Antennas

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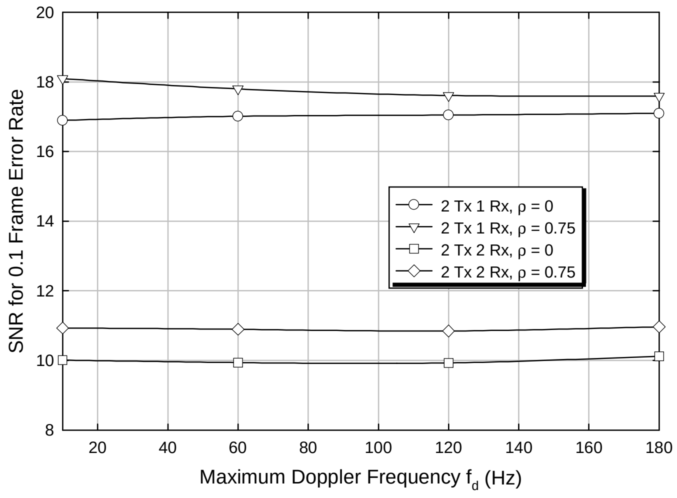
Frame Error Rate Performance ….

8-PSK 32-State Space-Time Code with Optimized WIF



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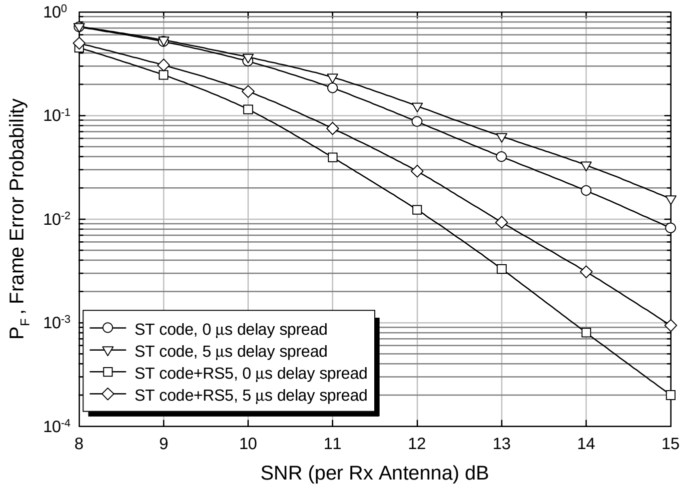
Delay Spread Performance

8-PSK 32-State ST Code with 2 Tx and 2 Rx Antennas and Optimized WIF @ f_d = 180 Hz and 5 µs delay spread (TU model)



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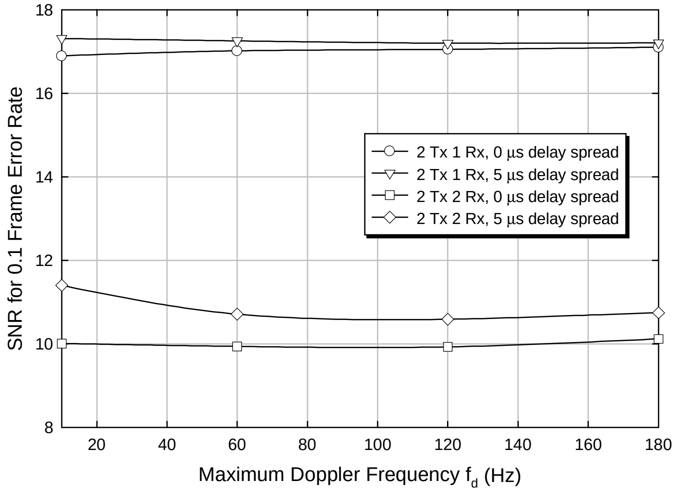
Delay Spread Performance ….



8-PSK 32-State Space-Time Code with Optimized WIF

@ f_d = 180 Hz and 5 µs delay spread (TU model)

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Performance Summary

DIVERSITY	***MODULATION & CODING***	***DOPPLER SPREAD***	***SNR FOR 55.8 KBPS (ST)***	***SNR FOR 50.4 KBPS (ST+RS3)***	***SNR FOR 46.8 KBPS (ST+RS5)***
2Tx 1Rx	8PSK/CST	10 Hz	18.3 dB	17.3 dB	16.9 dB
2Tx 2Rx	8PSK/CST	10 Hz	11.2 dB	10.3 dB	10.1 dB
2Tx 1Rx	8PSK/CST	180 Hz	20.1 dB	17.6 dB	17.1 dB
2Tx 2Rx	8PSK/CST	180 Hz	11.8 dB	10.6 dB	10.2 dB

DIVERSITY	***MODULATION & CODING***	***DOPPLER SPREAD***	***SNR FOR 74.4 KBPS (ST)***	***SNR FOR 67.2 KBPS (ST+RS3)***	***SNR FOR 62.4 KBPS (ST+RS5)***
2Tx 1Rx	16-QAM/CST	10 Hz	22.4 dB	21.1 dB	20.5 dB
2T x 2Rx	16-QAM/CST	10 Hz	15.7 dB	13.8 dB	13.2 dB
2Tx 1Rx	16-QAM/CST	180 Hz	30.6 dB	25 .0 dB	23.0 dB
2T x 2Rx	16-QAM/CST	180 Hz	18.1 dB	15.3 dB	14.3 dB

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Part 3: Space-Time Coding Applications

- Narrowband TDMA Cellular.
- **Broadband Wireless OFDM.**
- Applications of STBC with Interference Suppression.

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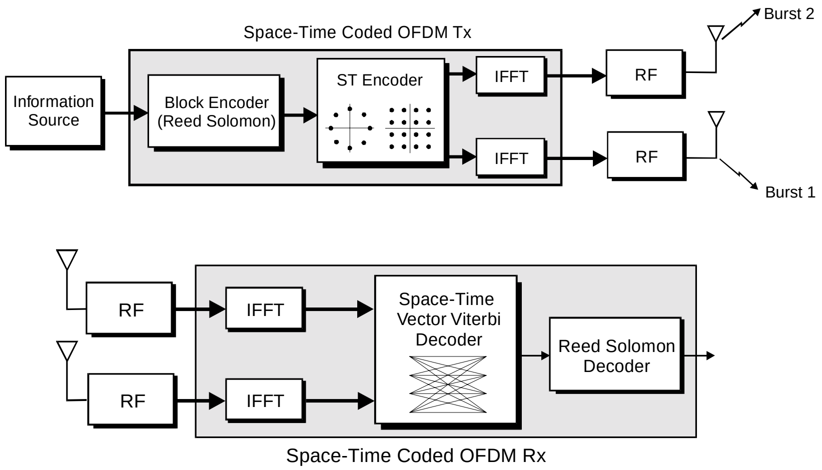
Broadband Wireless OFDM



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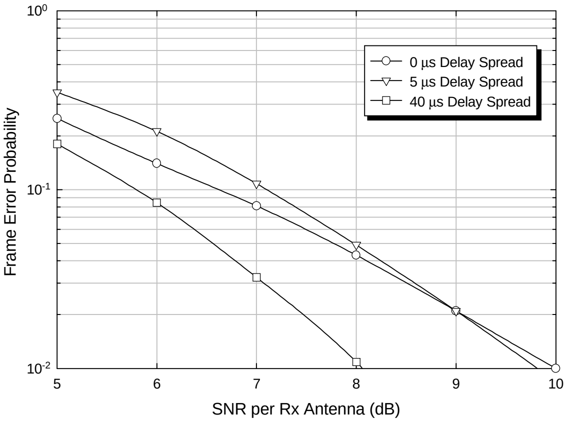
Performance of ST-Coded OFDM

- 1 MHz bandwidth.
- 256 tones.
- QPSK 16-state ST code with 2 transmit antennas.
- 2-Ray fading channel model with equal strength.
- Ideal CSI.
- 1.5 Mbps data rate (1.5 bits/sec/Hz)
- For 10% FER, an E_b/N_o between 2.7-4 dB is required (depending on delay spread).
- With 16-QAM, 4 Tx and 2 Rx antennas, 6 bits/sec /Hz is achievable. Can be used for downlink.

Frame Error Probability for Concatenated Space-Time Coded OFDM with 4-PSK 16-State ST Code and 2 Tx and 2 Rx Antennas



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Part 3: Space-Time Coding Applications

- Narrowband TDMA Cellular.
- Broadband Wireless OFDM.
- **Applications of STBC with Interference Suppression.**

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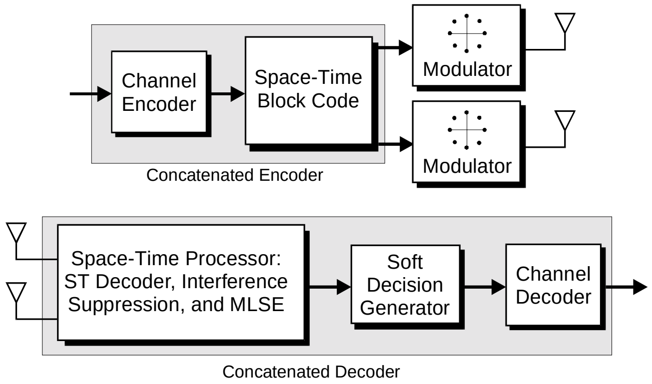
Increase Capacity



- Outer FEC code provides immunity against channel errors. Inner STBC provides interference suppression and fading mitigation through transmit diversity.

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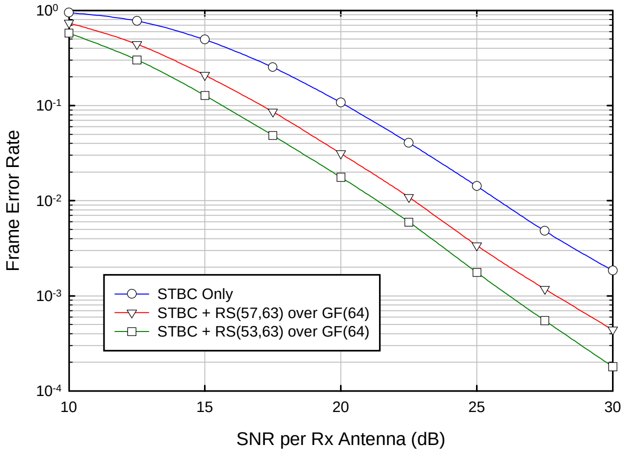
Performance

FER Performance of 8-PSK with FEC + STBC and MMSE Interference Cancellation at 0 dB SIR



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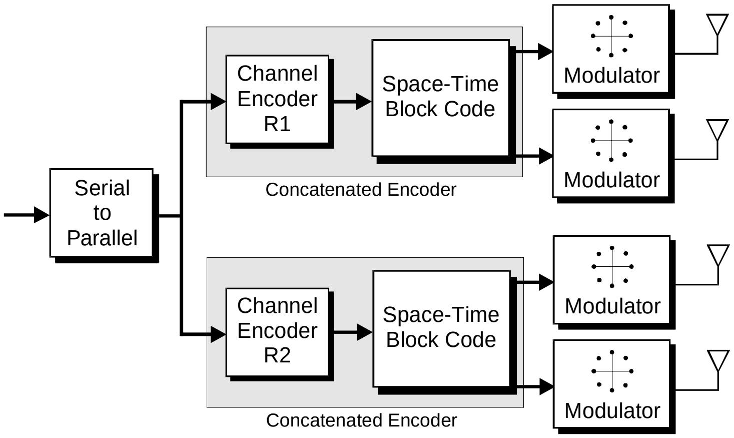
Increase Data Rate


Serial to Parallel

Channel Encoder R1

Space-Time Block Code

Concatenated Encoder

Channel Encoder R2

Space-Time Block Code

Concatenated Encoder

Modulator

Modulator

Modulator

Modulator

➪ Throughput: $\rho = 0.5 \times \left[R_1 \cdot \left(1 - FER_1\right) + R_2 \cdot \left(1 - FER_2\right) \right]$

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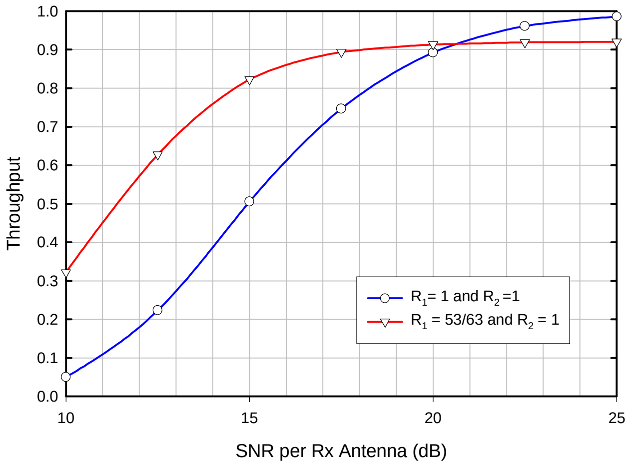
Performance

Throughput Performance of 8-PSK with STBC and Unequal Error Protection with RS(53,63)



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Summary

- Space-Time coding: good idea with great potential.
- Current work in space-time coding:
  - ➪ Systematic design of space-time trellis codes.
  - ➪ Multi-channel equalization for space-time coding.
  - ➪ Applications of space-time coding to WCDMA.