

Space-Time Codes and Signal Processing for Slow Fading Channels

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Base Document: The presentation provides an overview of recent advances in space-time codes and signal processing. Since space-time techniques have potentially large benefits for MMDS systems, it is recommended that 802.16.3 investigate their applications in the new standard under development.

Purpose: Discussion

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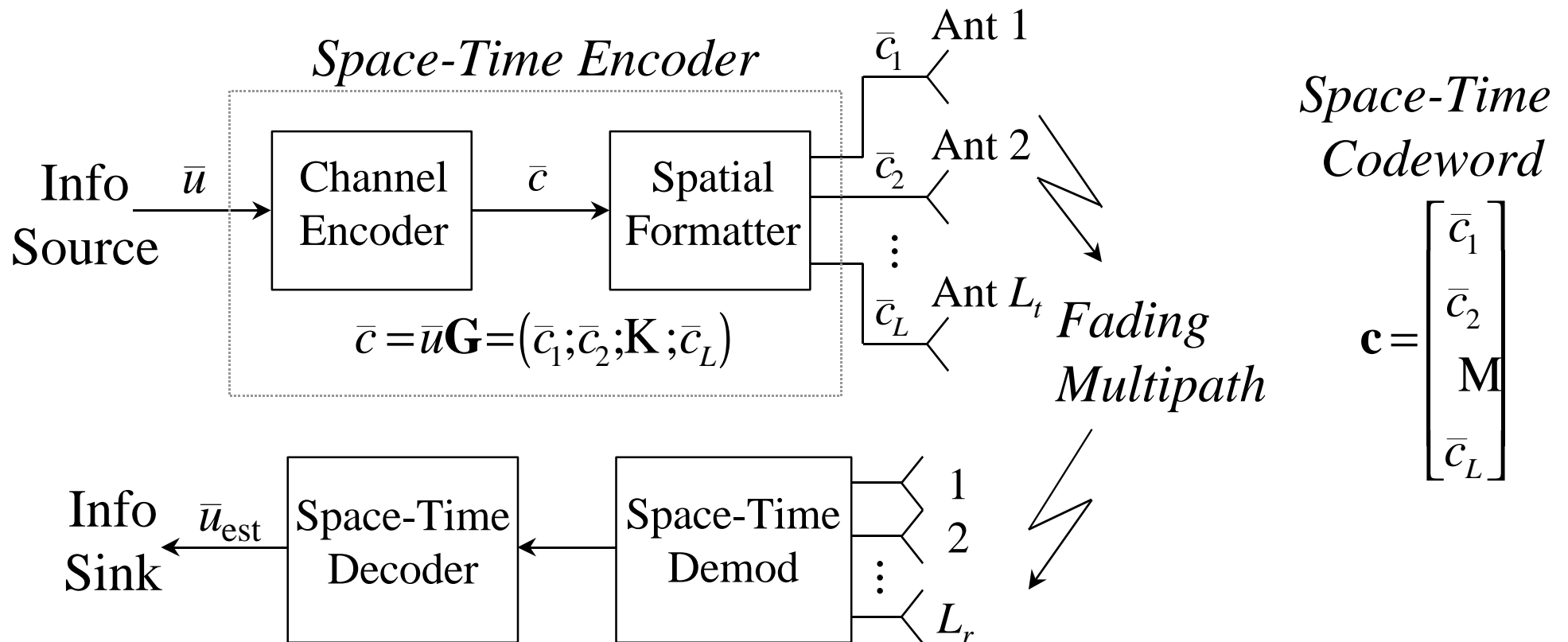
Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <<mailto:r.b.marks@ieee.org>> as early as possible, in written or electronic form, of any patents (granted or under application) that may cover technology that is under consideration by or has been approved by IEEE 802.16. The Chair will disclose this notification via the IEEE 802.16 web site <<http://ieee802.org/16/ipr/patents/letters>>.

Space-Time Codes and Signal Processing for Slow Fading Channels

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Germantown, Maryland USA**

Space-Time Modems Exploit “Hidden” Capacity of the Multipath Channel



- **Space-time codes:** $L_t > L_r$. Seek diversity through code design.
- **BLAST:** $L_r = L_t$. Seek high throughput through signal processing.
- **Hybrid schemes:** Also possible.

Space-Time Technology: Code Design and Signal Processing

AT&T Research has popularized

“Space-Time Channel Codes”

(*Tarokh, Seshadri, Calderbank*)

- **Primary objective:** Increased diversity
- **Method:** Channel coding performed across antennas as well as time

Lucent has popularized

“Layered Space-Time Architecture”

or “BLAST” (*Foschini, Gans*)

- **Primary objective:** Increased throughput
- **Method:** Independent spatial channels via interference avoidance and cancellation



We investigated synergistic approaches that advance the state of the art in both space-time codes and space-time modems.

Design Criteria for Space-Time Codes

Pairwise error probability for Rayleigh fading channel:

$$P(\mathbf{c} \rightarrow \mathbf{e}) \leq \left(\frac{\mathbf{h}E_s}{4N_0} \right)^{-r}$$

where $r = \text{rank}(f(\mathbf{c}) - f(\mathbf{e}))$ ← rank of baseband difference

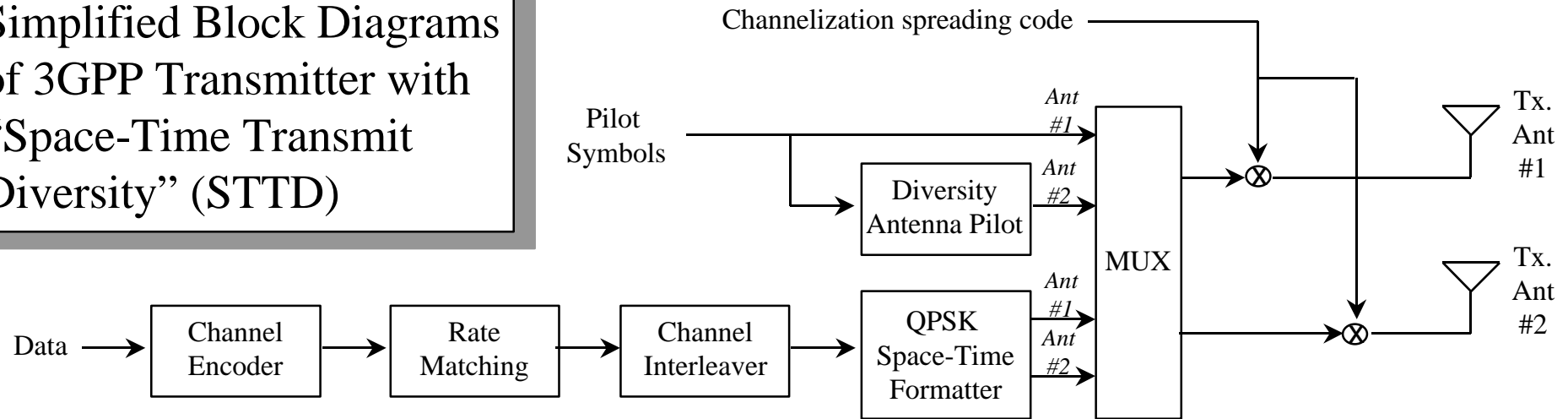
$$\mathbf{h} = (\mathbf{I}_1 \mathbf{I}_2 \Lambda \mathbf{I}_r)^{1/r} \quad \leftarrow \text{geometric mean of eigenvalues}$$

Design Criteria [Fitz (Ohio State Univ.), Tarokh (AT&T)]

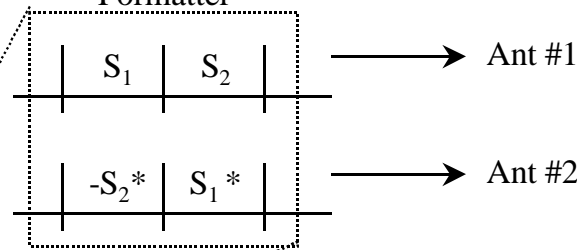
- *Rank Criterion* : Maximize diversity advantage r over all distinct code word pairs \mathbf{c} and \mathbf{e} .
- *Product Distance Criterion* : Maximize coding advantage η over all distinct code word pairs \mathbf{c} and \mathbf{e} .

Space-Time Modulation Format Gives 3GPP “Open Loop” Transmit Diversity

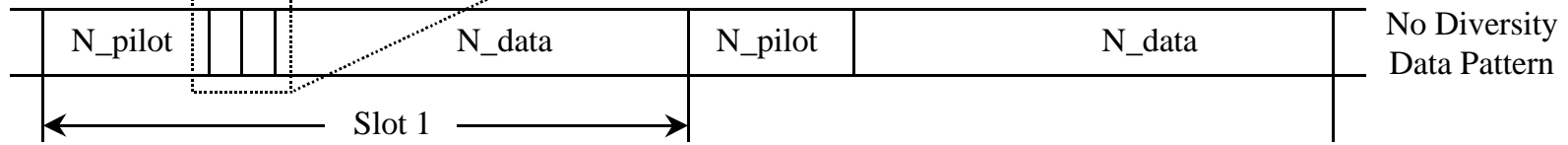
Simplified Block Diagrams of 3GPP Transmitter with “Space-Time Transmit Diversity” (STTD)



QPSK Space-Time Formatter

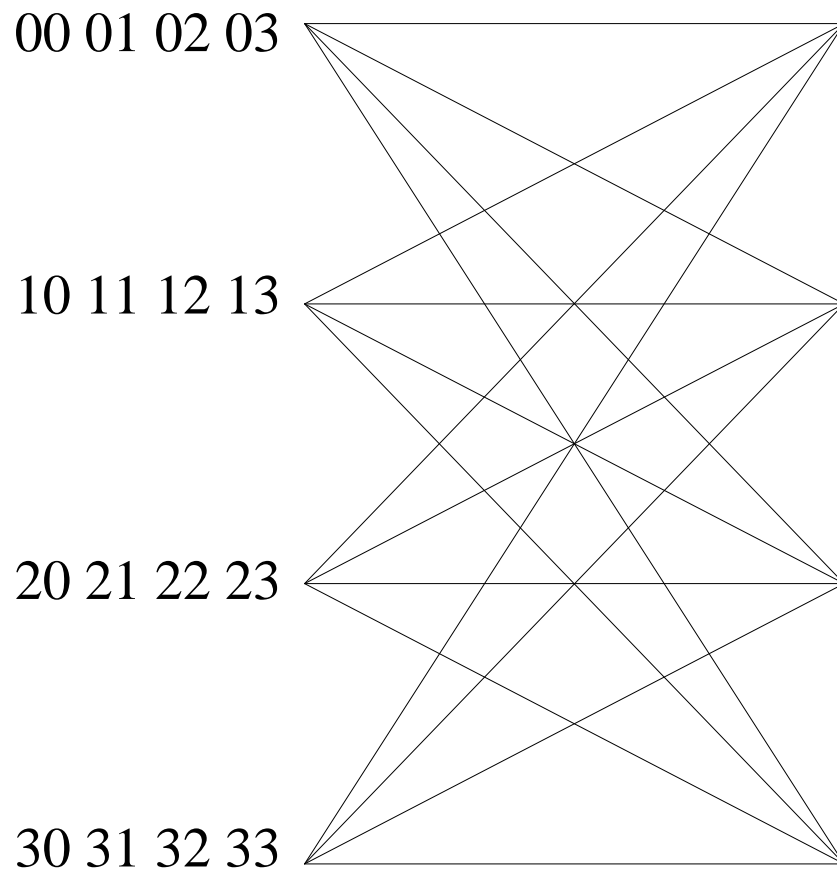


Alamouti space-time “block code”



Handcrafted Trellis Codes Achieving Full Spatial Diversity are Known

Tarokh-Seshadri-Calderbank (TSC) 4-State Trellis Code for QPSK Modulation

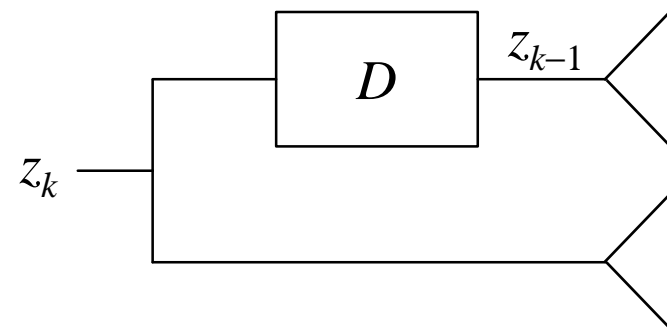


Binary Formulation

$$x_t^{(1)} = 2b_{t-1} + a_{t-1}$$

$$x_t^{(2)} = 2b_t + a_t$$

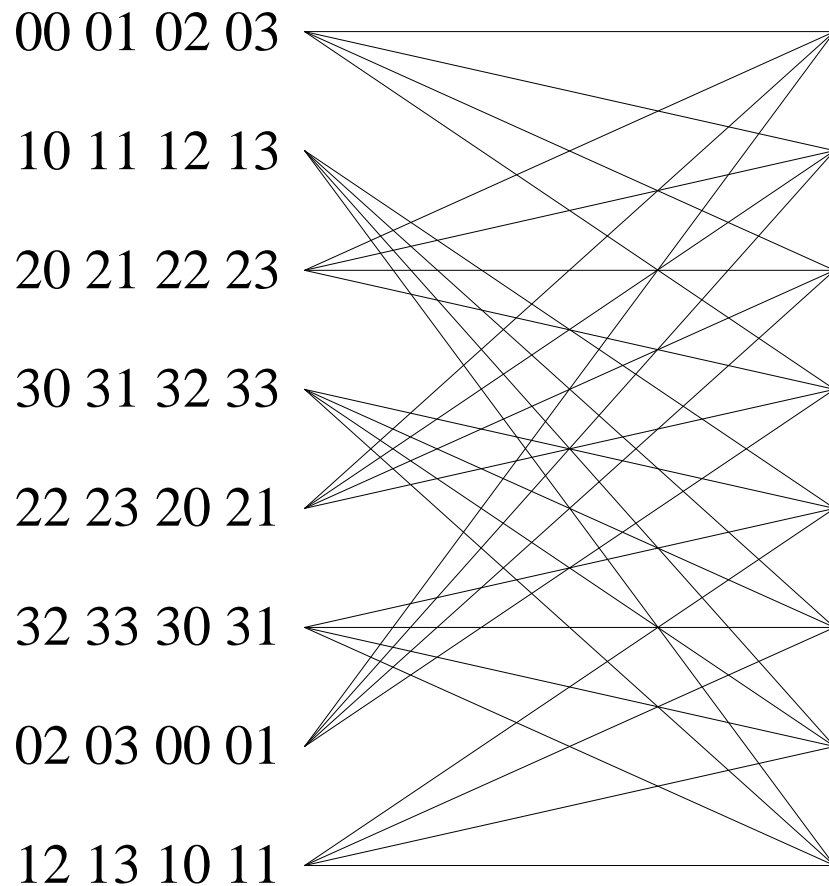
\mathbf{Z}_4 Formulation



Achieves maximum 2-level spatial diversity.

Handcrafted Trellis Codes Achieving Full Spatial Diversity are Known

Tarokh-Seshadri-Calderbank (TSC) 8-State Trellis Code for QPSK Modulation



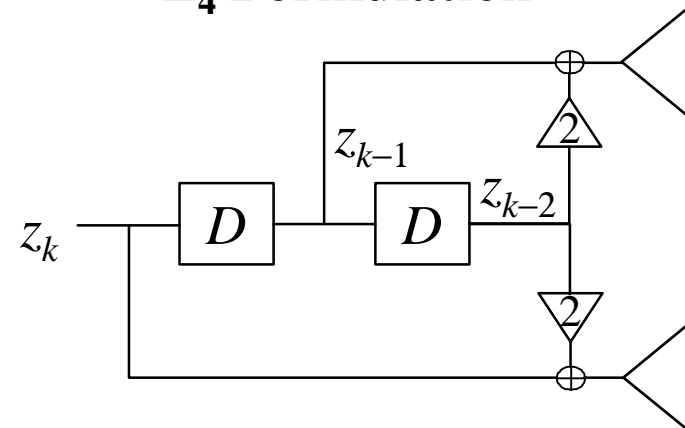
Achieves maximum 2-level spatial diversity.

Binary Formulation

$$x_t^{(1)} = 2a_{t-2} + 2b_{t-1} + a_{t-1}$$

$$x_t^{(2)} = 2a_{t-2} + 2b_t + a_t$$

Z_4 Formulation



Binary Criteria Identify Full-Diversity Space-Time Codes

- **BPSK Binary Rank Criterion:** Let C be a linear $L \times n$ space-time code with $n \geq L$. Suppose that every non-zero binary code word $\mathbf{c} \in C$ is matrix of full rank over the binary field F . Then, for BPSK transmission, the space-time code C satisfies the space-time rank criterion and achieves full spatial diversity L .
- **QPSK Binary Rank Criterion:** Let C be a linear $L \times n$ space-time code over Z_4 with $n \geq L$. Suppose that, for every non-zero binary code word $\mathbf{c} \in C$, the row-based indicant $\Xi(\mathbf{c})$ or the column-based indicant $\Psi(\mathbf{c})$ has full rank L over F . Then, for QPSK transmission, the space-time code C satisfies the space-time rank criterion and achieves full spatial diversity L .
- **Extensions to Higher-Order Modulation:** Use multi-level construction and apply binary rank criteria to the design of the constituent codes at each level.

“Stacking” Constructions Yield New Full-Diversity Space-Time Codes

Stacking Construction

$$\mathbf{c}(\bar{x}) = \begin{bmatrix} T_1(\bar{x}) \\ T_2(\bar{x}) \\ \mathbf{M} \\ T_L(\bar{x}) \end{bmatrix} = \begin{bmatrix} \triangle \triangle \triangle \triangle \Lambda \triangle \\ \diamond \diamond \diamond \diamond \Lambda \diamond \\ \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{O} \mathbf{M} \\ \pentagon \pentagon \pentagon \pentagon \Lambda \pentagon \end{bmatrix} \in \mathbf{C}$$

\mathbf{C} satisfies BPSK binary rank criterion iff $T = a_1 T_1 + a_2 T_2 + \Lambda + a_L T_L$ is non-singular unless $a_1 = a_2 = \Lambda = a_L = 0$.

Multi-Stacking Construction

$$\begin{bmatrix} \triangle \overline{\triangle \diamond \pentagon} \triangle \overline{\triangle \diamond \pentagon} \Lambda \triangle \overline{\triangle \diamond \pentagon} \\ \diamond \overline{\triangle \diamond \pentagon} \diamond \overline{\triangle \diamond \pentagon} \Lambda \diamond \overline{\triangle \diamond \pentagon} \end{bmatrix} \in \mathbf{C}$$

Concatenations of space-time codes satisfying binary rank criterion form full-diversity space-time codes \mathbf{C} .

Transformation Theorem

Full-Diversity Space-Time Code

$$\begin{bmatrix} \bar{c}_1 \\ \bar{c}_2 \\ \mathbf{M} \\ \bar{c}_L \end{bmatrix} = \begin{bmatrix} \triangle \triangle \triangle \triangle \Lambda \triangle \\ \diamond \diamond \diamond \diamond \Lambda \diamond \\ \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{O} \mathbf{M} \\ \pentagon \pentagon \pentagon \pentagon \Lambda \pentagon \end{bmatrix} \in \mathbf{C}$$

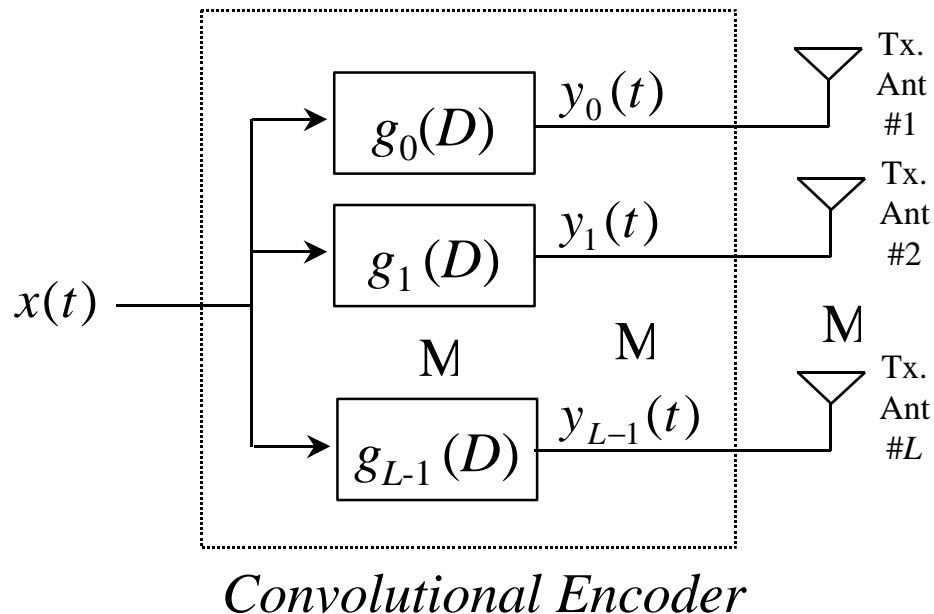
Linear transformation of full-rank



$$\begin{bmatrix} T(\bar{c}_1) \\ T(\bar{c}_2) \\ \mathbf{M} \\ T(\bar{c}_L) \end{bmatrix} = \begin{bmatrix} \overline{\triangle \triangle \triangle \triangle \Lambda \triangle} \\ \overline{\diamond \diamond \diamond \diamond \Lambda \diamond} \\ \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{M} \mathbf{O} \mathbf{M} \\ \overline{\pentagon \pentagon \pentagon \pentagon \Lambda \pentagon} \end{bmatrix} \in T(\mathbf{C})$$

Full-Diversity Space-Time Code

Convolutional Codes with Optimal d_{free} Yield Full-Diversity Space-Time Codes

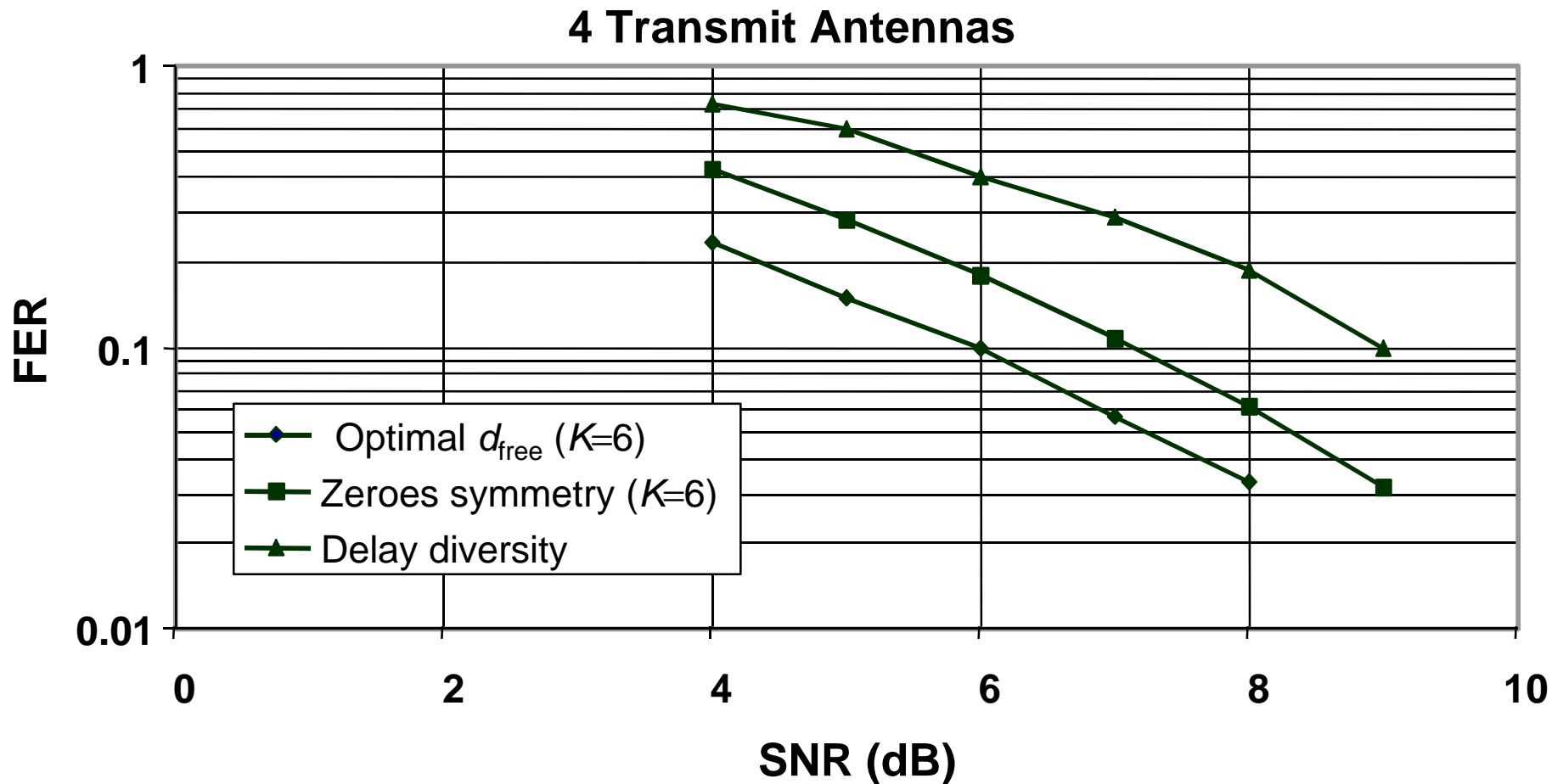


“Natural” space-time code associated with rate $1/L$ convolutional code:
Multiplex L output coded bits in space (among antennas) rather than time.

Practical examples of our general space-time “Stacking Constructions.”

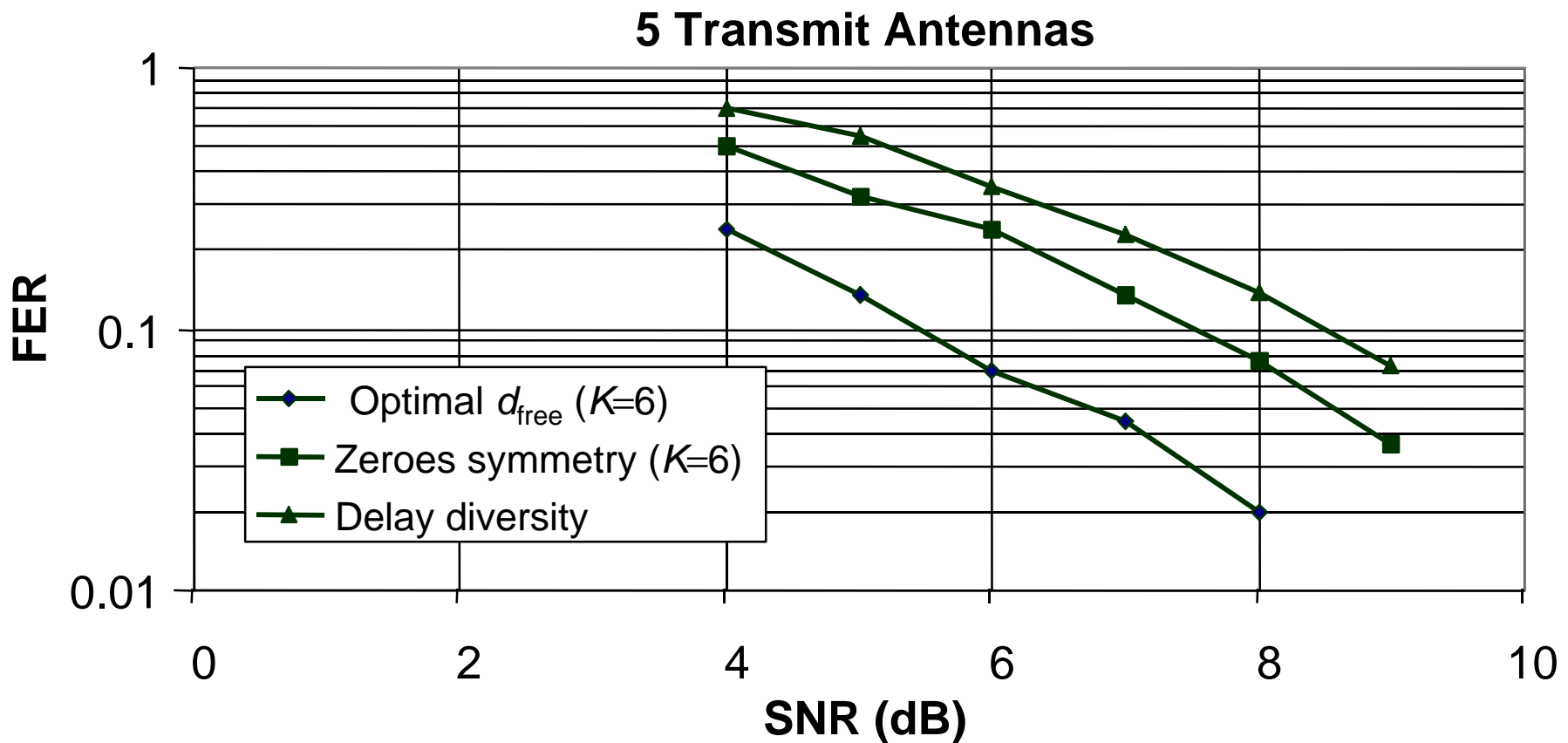
| L | n | Connection Polynomials | d_{free} | |
|-----|-----|-------------------------|-------------------|----|
| 2 | 2 | 5, 7 | 5 | |
| | 3 | 64, 74 | 6 | |
| | 4 | 46, 72 | 7 | |
| | 5 | 65, 57 | 8 | |
| | 6 | 554, 744 | 10 | |
| | 7 | 712, 476 | 10 | |
| | 8 | 561, 753 | 12 | |
| | 3 | 3 | 54, 64, 74 | 10 |
| 4 | | 52, 66, 76 | 12 | |
| 5 | | 47, 53, 75 | 13 | |
| 6 | | 554, 624, 764 | 15 | |
| 7 | | 452, 662, 756 | 16 | |
| 8 | | 557, 663, 711 | 18 | |
| 4 | | 4 | 52, 56, 66, 76 | 16 |
| | | 5 | 53, 67, 71, 75 | 18 |
| | 7 | 472, 572, 626, 736 | 22 | |
| 5 | 8 | 463, 535, 733, 745 | 24 | |
| | 5 | 75, 71, 73, 65, 57 | 22 | |
| | 7 | 536, 466, 646, 562, 736 | 28 | |

Performance of BPSK Space-Time Codes with 4 Transmit Antennas



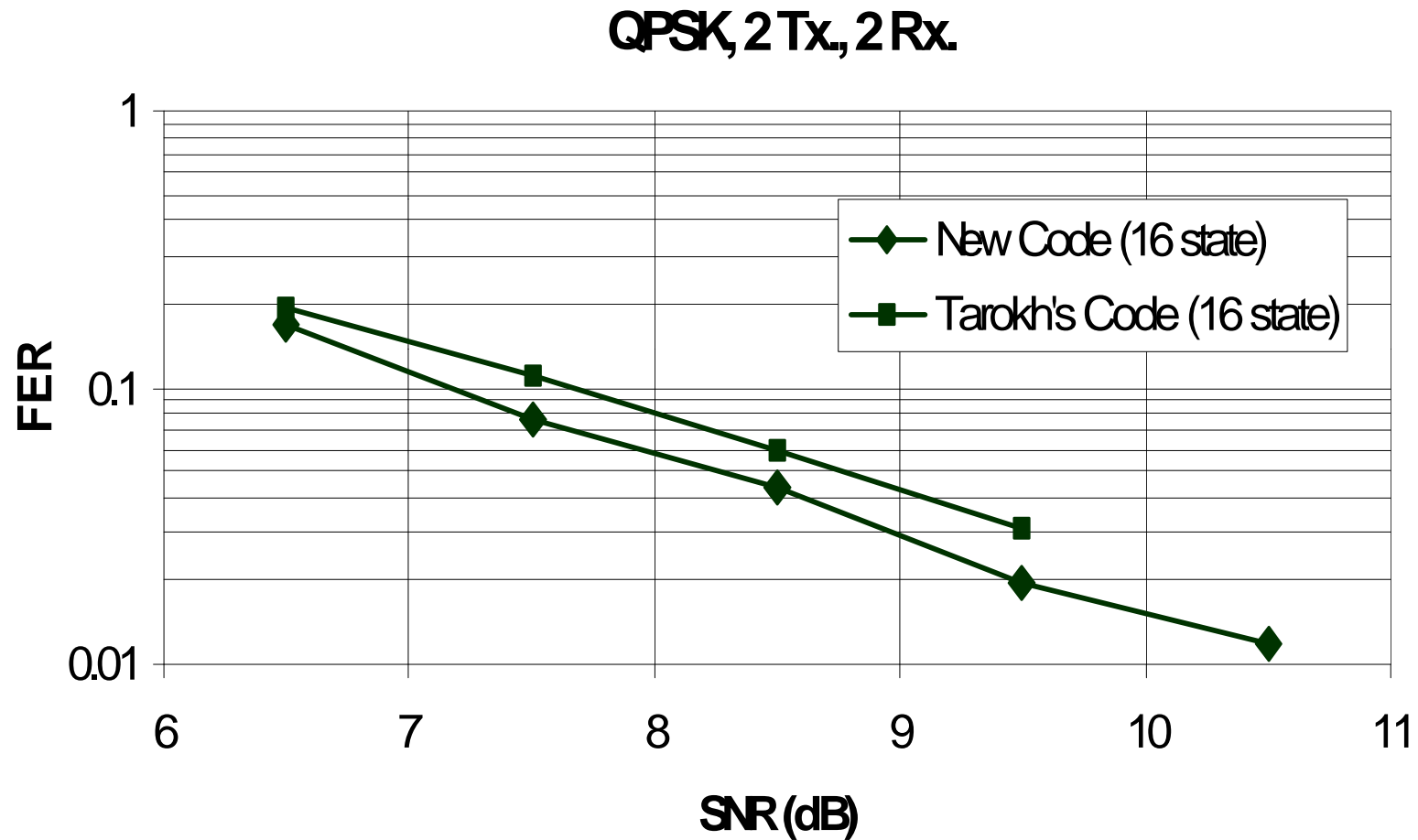
- Optimal d_{free} code is 3 dB better than the delay diversity scheme.
- Optimal d_{free} code is 1 dB better than Fitz-Grimm zeroes symmetry code.

Performance of BPSK Space-Time Codes with 5 Transmit Antennas



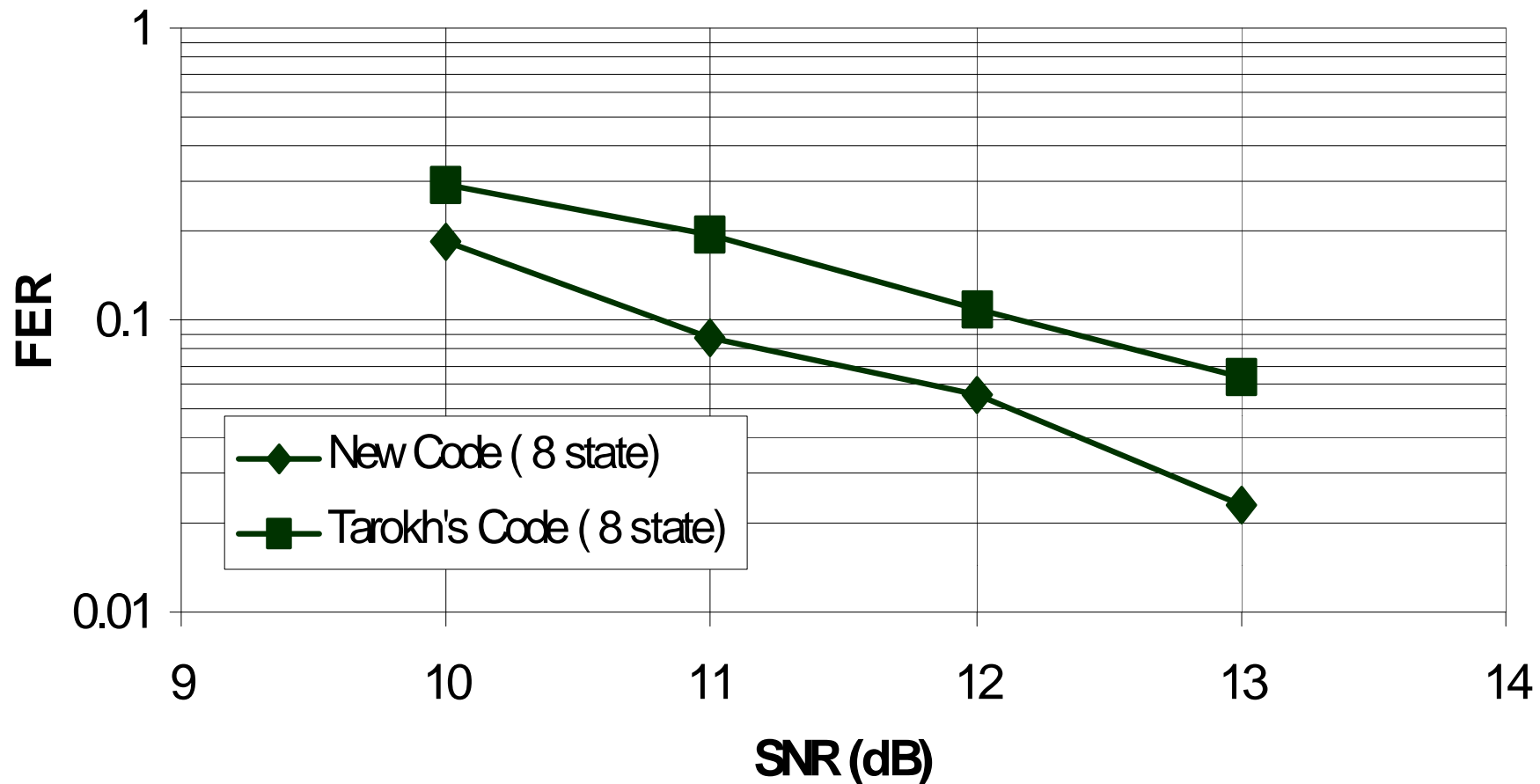
- Optimal d_{free} code is 3 dB better than the delay diversity scheme.
- Optimal d_{free} code is 2 dB better than Fitz-Grimm zeroes symmetry code.

Performance of QPSK Space-Time Codes in Quasi-Static Fading Channels

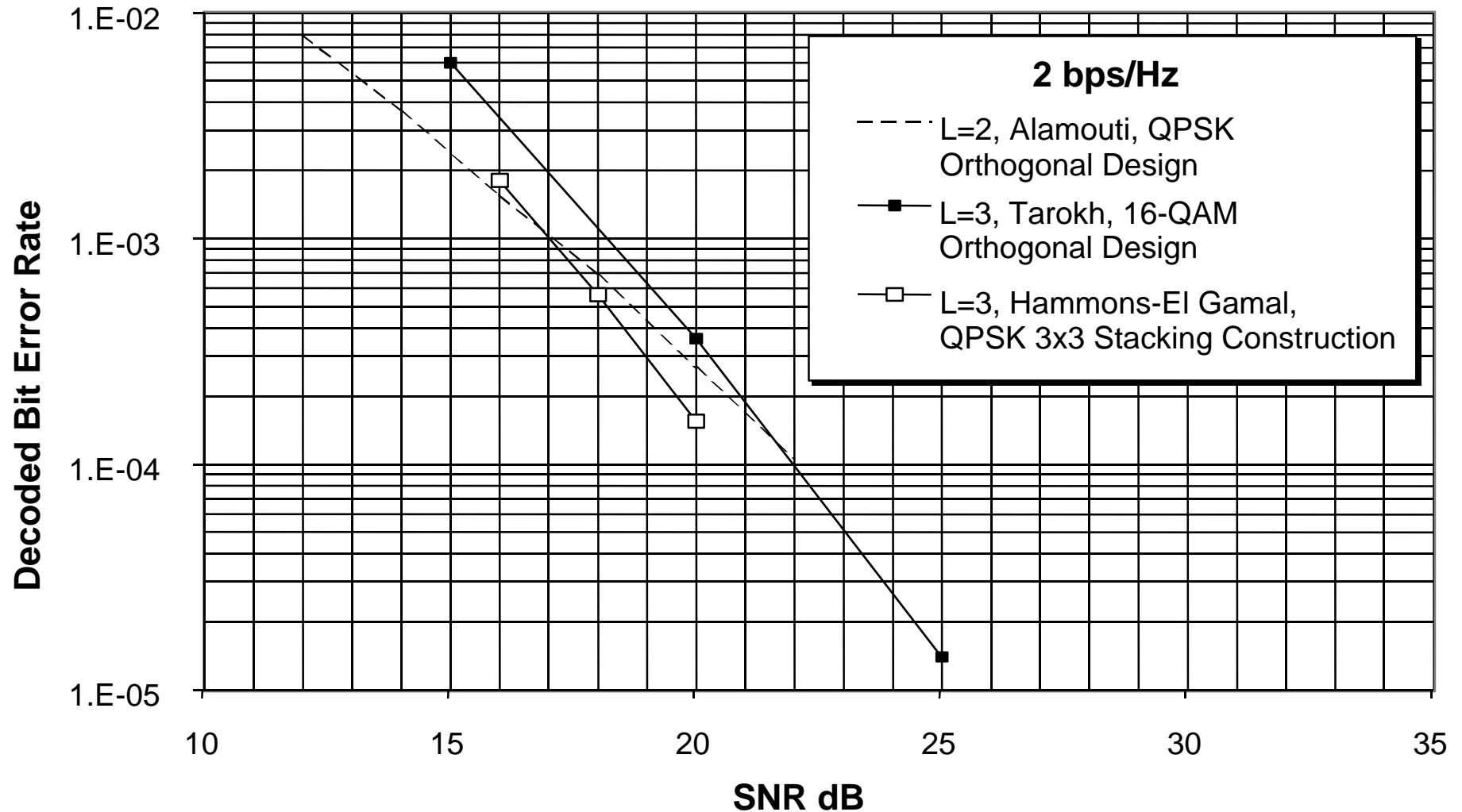


Performance of 8-PSK Space-Time Codes in Quasi-Static Fading Channels

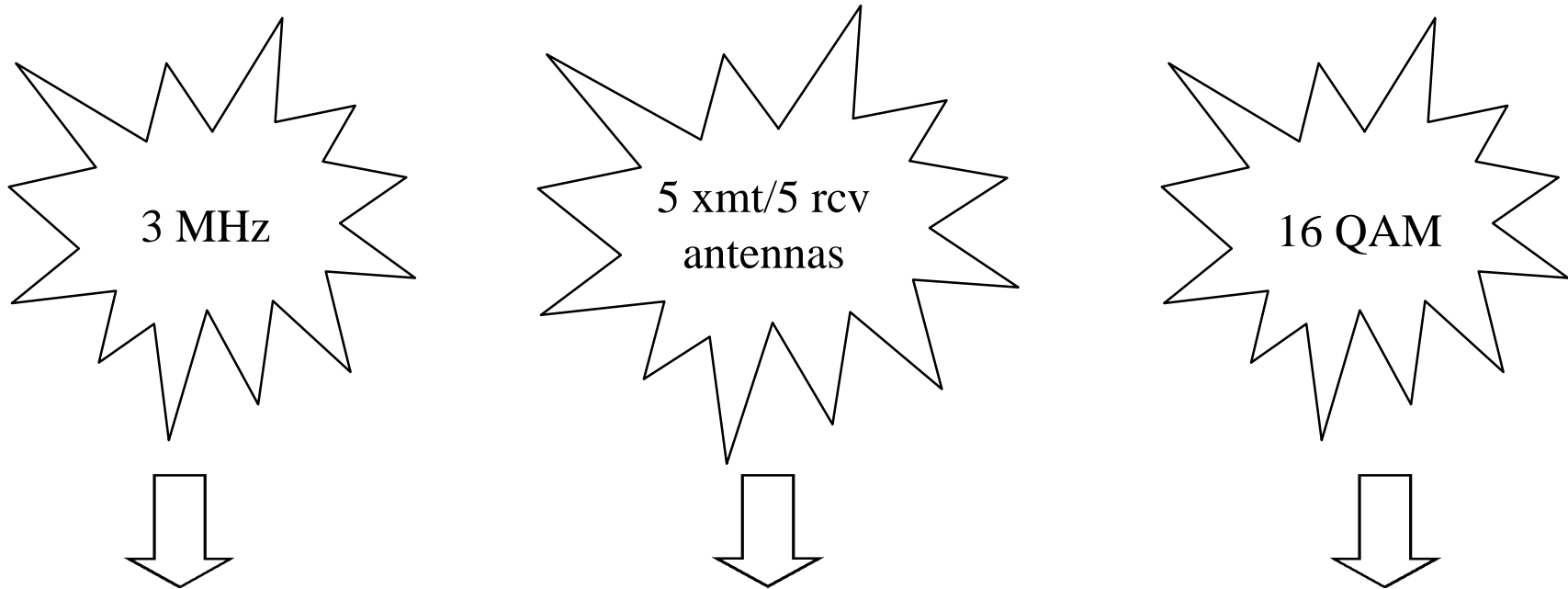
8-PSK, 2 Tx, 2 Rx.



Stacking Construction Yields New Codes for Space-Time Appliques



Foschini Showed that Outage Capacity Increases Linearly When L_r Equals L_t

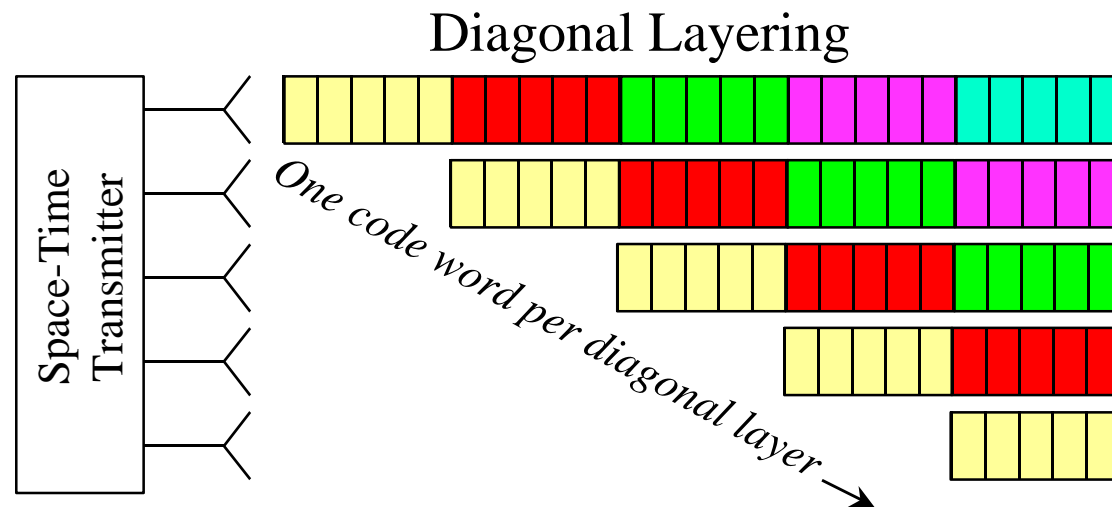
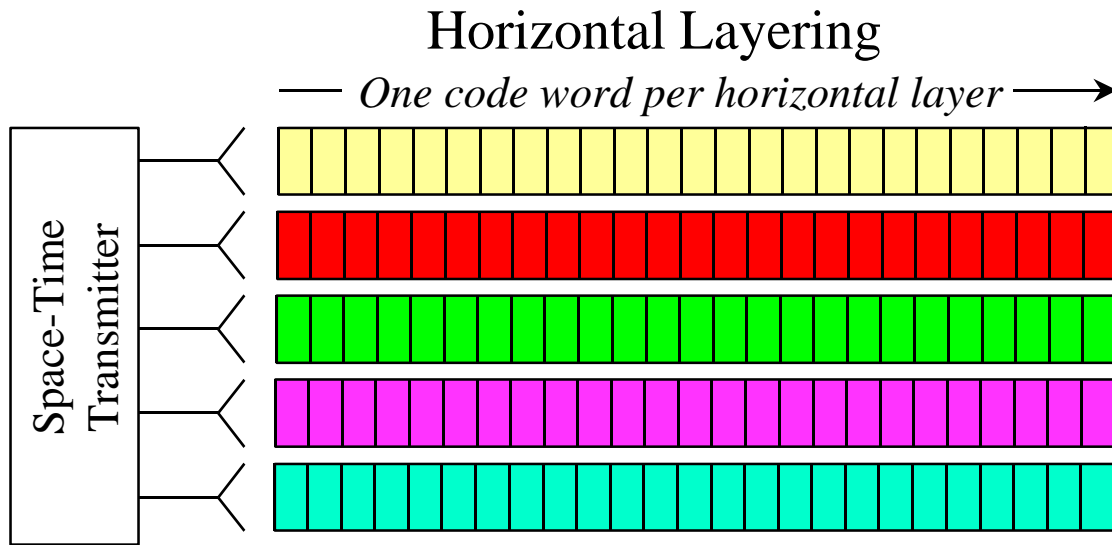


Bit Rate = Bandwidth · Number of antennas · Bit rate/antenna · Coding rate



$$30 \text{ Mbps} = 3 \cdot 5 \cdot 4 \cdot 1/2$$

Layered Space-Time Architectures



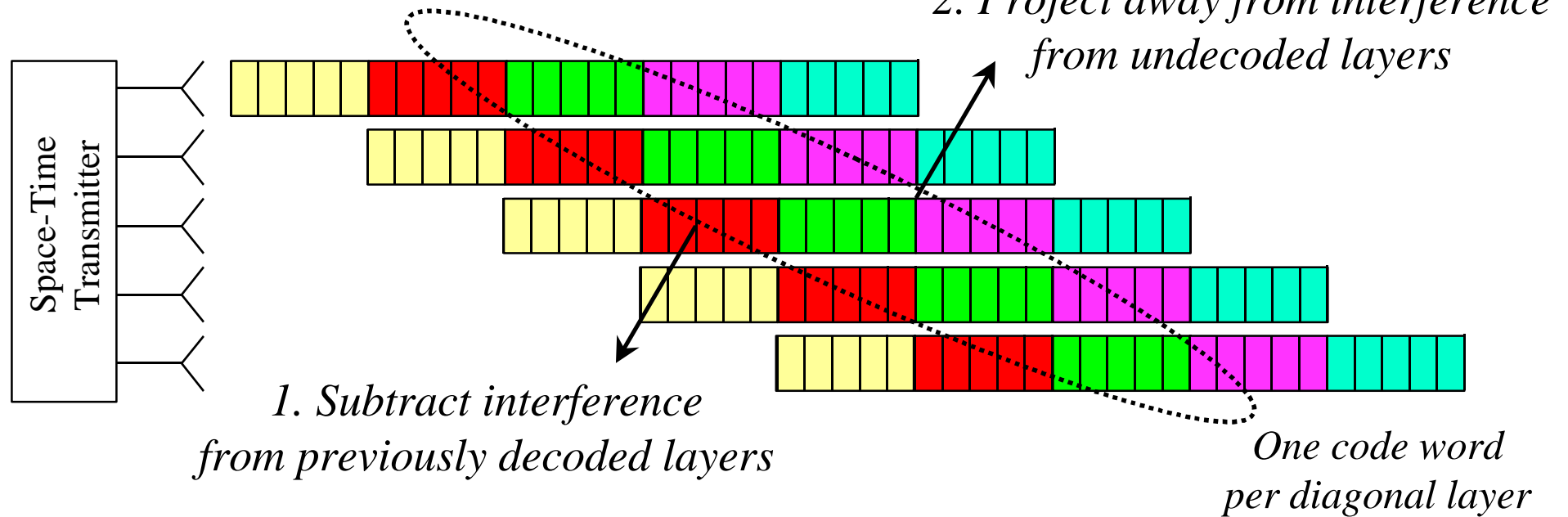
Definition: A layer is an assignment of space-time transmission resources to a component channel encoder in which at most one antenna is available each transmitted symbol interval.

Properties:

- No spatial interference within a layer.
- Decoding is performed layer by layer.
- Conventional channel codes can be used.

Lucent's BLAST Technology

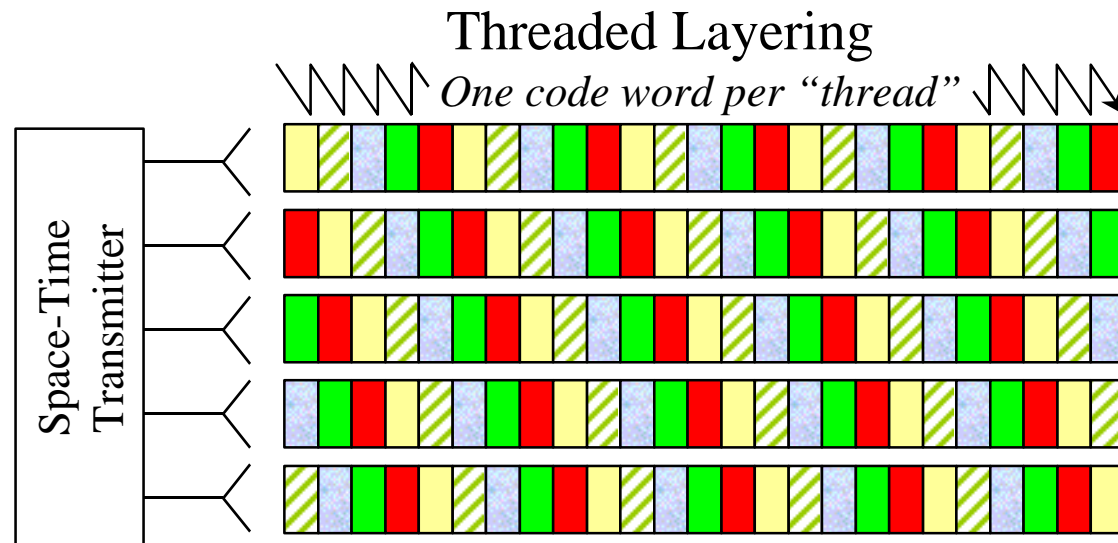
Two steps to decode a given layer :



Potential Limitations of BLAST Signal Processing

- Requires equal number of transmit and receive antennas
- Spatial diversity varies within a code word
- Errors can propagate both spatially and temporally
- Limited ability to interleave for temporal diversity
- Loss in throughput due to diagonal layering

Hughes Offers Threaded Space-Time Architecture

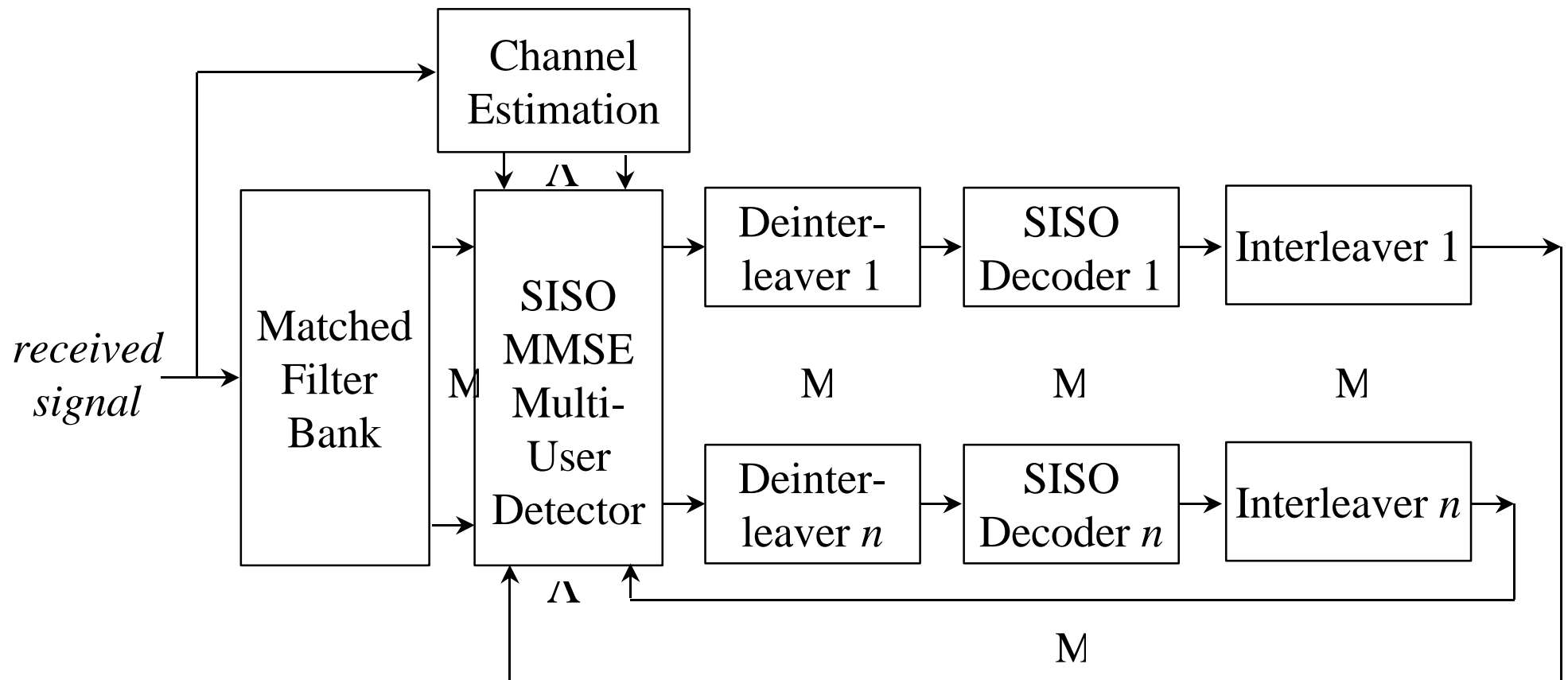


Thread = Layer whose temporal span is maximal for each antenna

Characteristics of Threaded Space-Time Architecture

- Generalized layering exploits spatial and temporal diversity
- Threaded space-time channel codes ensure full-diversity
- Receiver uses new, efficient, multi-user detection techniques
 - Soft-decision feedback reduces spatial error propagation.
 - Iterative MMSE processing results in a symmetrical performance.

Iterative MMSE Space-Time Receiver



- Iterative multi-user detection (MUD) is one key to threaded space-time architecture.
- Threaded channel codes, based on space-time principles, are optimized for MUD.

Threaded Space-Time Code Design for Quasi-static Fading Channels

Theorem (Threaded Stacking Construction):

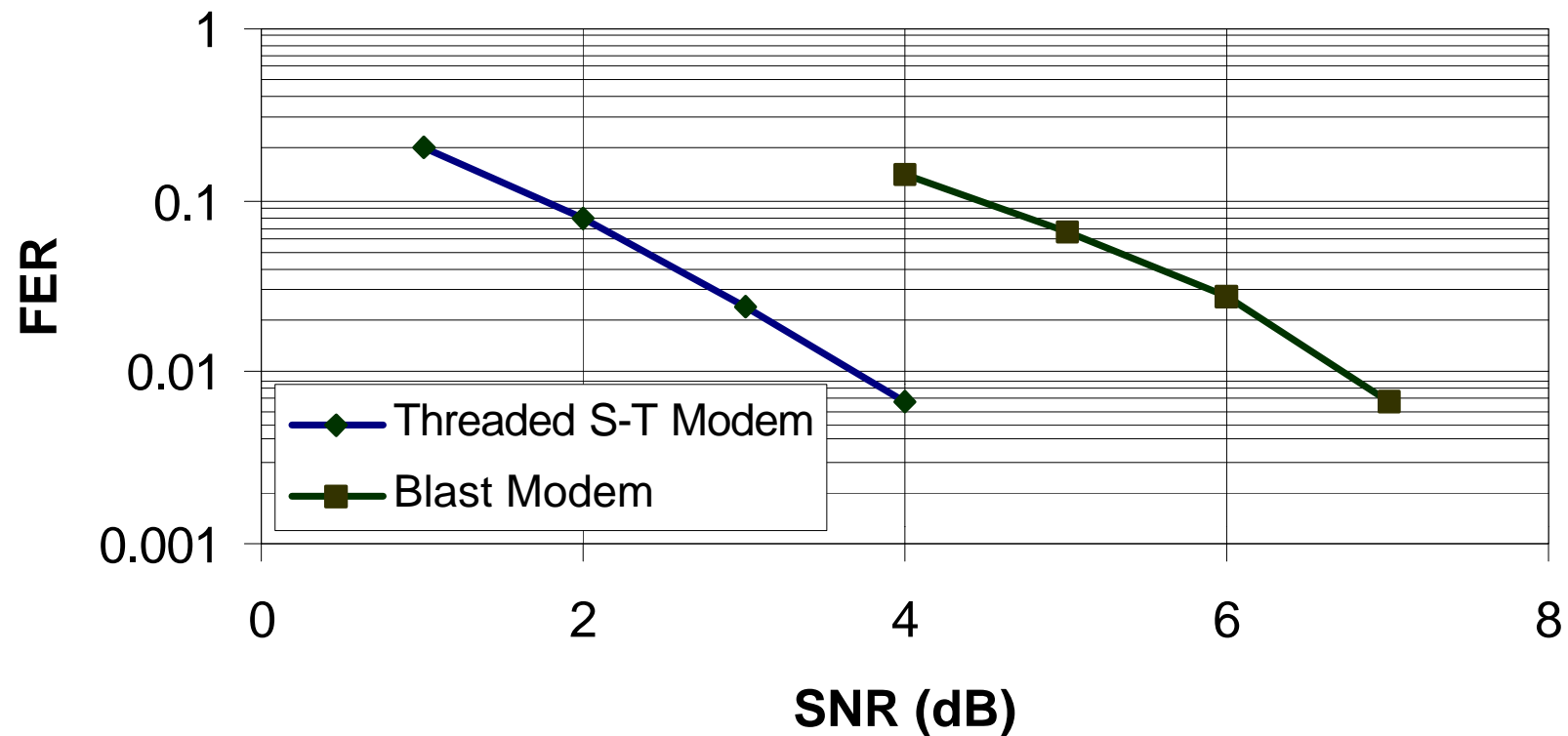
Let L be a layer of spatial span n . Given binary matrices $\mathbf{M}_1, \mathbf{M}_2, \dots, \mathbf{M}_n$ of dimension $k \times \lambda$, let C be the binary code of dimension k consisting of all code words $g(\bar{x}) = \bar{x}\mathbf{M}_1 | \bar{x}\mathbf{M}_2 | \Lambda | \bar{x}\mathbf{M}_n$, where \bar{x} denotes an arbitrary k -tuple of information bits. Let \mathbf{f}_L denote the spatial modulator having the property that the modulated symbols $\mathbf{m}(\bar{x}\mathbf{M}_j)$ are transmitted in the symbol intervals of L that are assigned to antenna j .

Then, as the space-time code in a communication system with n transmit antennas and m receive antennas, the space-time code \mathbf{C} consisting of C and \mathbf{f}_L achieves spatial diversity dm in a quasi-static fading channel if and only if d is the largest integer such that $\mathbf{M}_1, \mathbf{M}_2, \dots, \mathbf{M}_n$ have the property that

$$\forall a_1, a_2, \dots, a_n \in \mathbf{F}, \quad a_1 + a_2 + \Lambda + a_n = n - d + 1:$$
$$\mathbf{M} = [a_1\mathbf{M}_1 \quad a_2\mathbf{M}_2 \quad \Lambda \quad a_n\mathbf{M}_n] \text{ is of rank } k \text{ over } \mathbf{F}.$$

Threaded-STC Yields Bigger Bang than the BLAST Technology

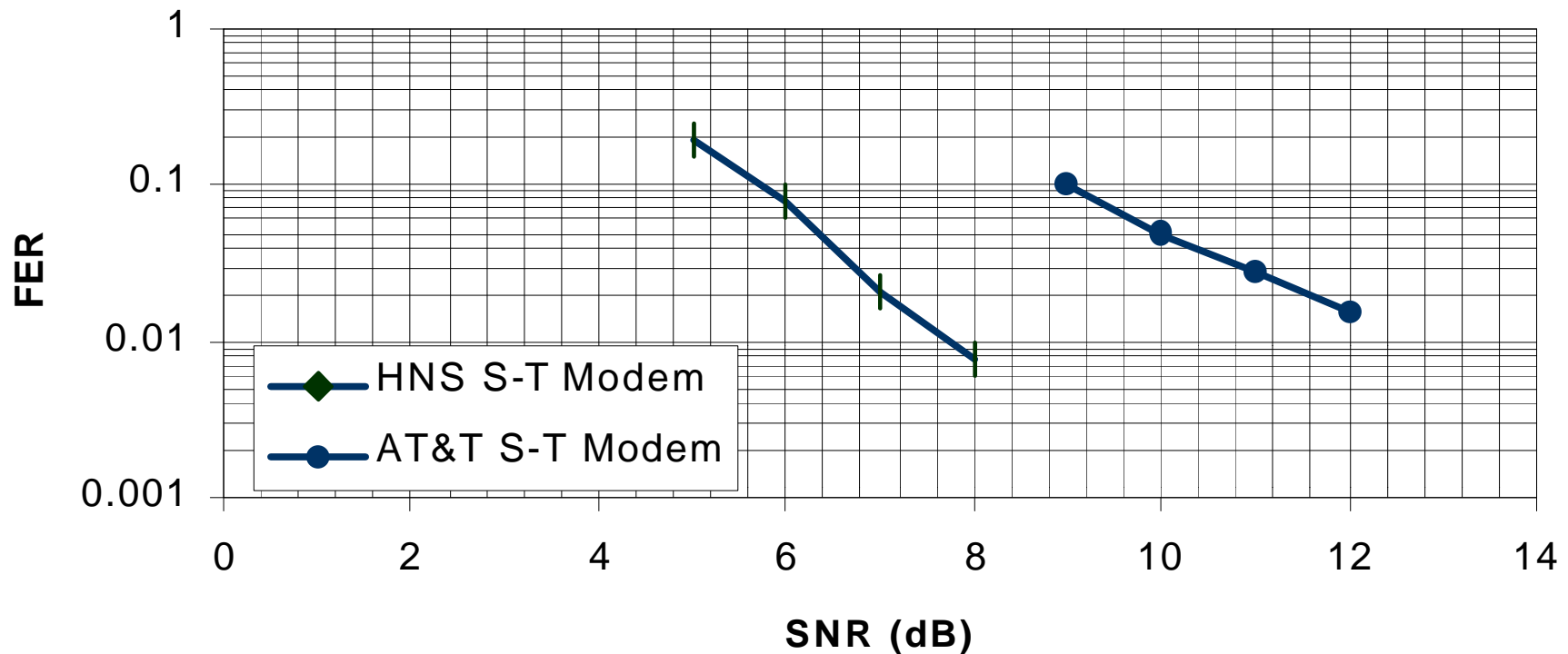
BPSK, 2bits/sec/HZ, 4 Tx., 4 Rx.



At 1% FER, advantage is more than 3 dB.

Threaded Space-Time Outperforms AT&T's Group Suppression Approach

QPSK, 4bits/sec/hz, 4Tx., 4Rx.



At 1% FER, advantage is more than 4 dB.

Conclusions

- MMDS must contend with slow fading channels
- Space-time technology offers potentially large gains in this environment
- 802.16.3 should be aggressive in study and adoption of best space-time solutions

References

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- El Gamal and Hammons, "A new approach to layered space-time signal processing and code design," accepted for publication (pending revision) in *IEEE Transactions on Information Theory*.

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- El Gamal and Hammons, "Binary Design Criteria for Space-Time Codes," In Proceedings of *Thirty-Seventh Annual Allerton Conference on Communication, Control, and Computing*, University of Illinois, Urbana-Champaign, 1999.
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- El Gamal and Hammons, "Space-Time Coding for the Block Fading Channel," In Proceedings of *CISS'2000*, Princeton University.
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