S-72.333 Postgraduate Course in Radio Communications, Autumm 2004

BLAST Architectures

January 25th, 2005 (Updated February 1, 2005)

Eduardo Zacarías B.

ezacaria@wooster.hut.fi

Outline

- Introduction.
- D-BLAST.
- V-BLAST.
- Turbo-BLAST
- Capacity considerations.
- Performance considerations.
- Examples.
- Q&A.

Introduction

- MIMO systems promise explosive growth in capacity for wireless communications.
- Some assumptions required. Practical systems have to solve many engineering issues.
- Suboptimal schemes become very important.

System model described by:

$$\mathbf{y} = \mathbf{HWX} + \text{noise} \tag{1}$$

(output of receive antenna array, beamforming matrix, modulation matrix, i.i.d. white noise)

System model

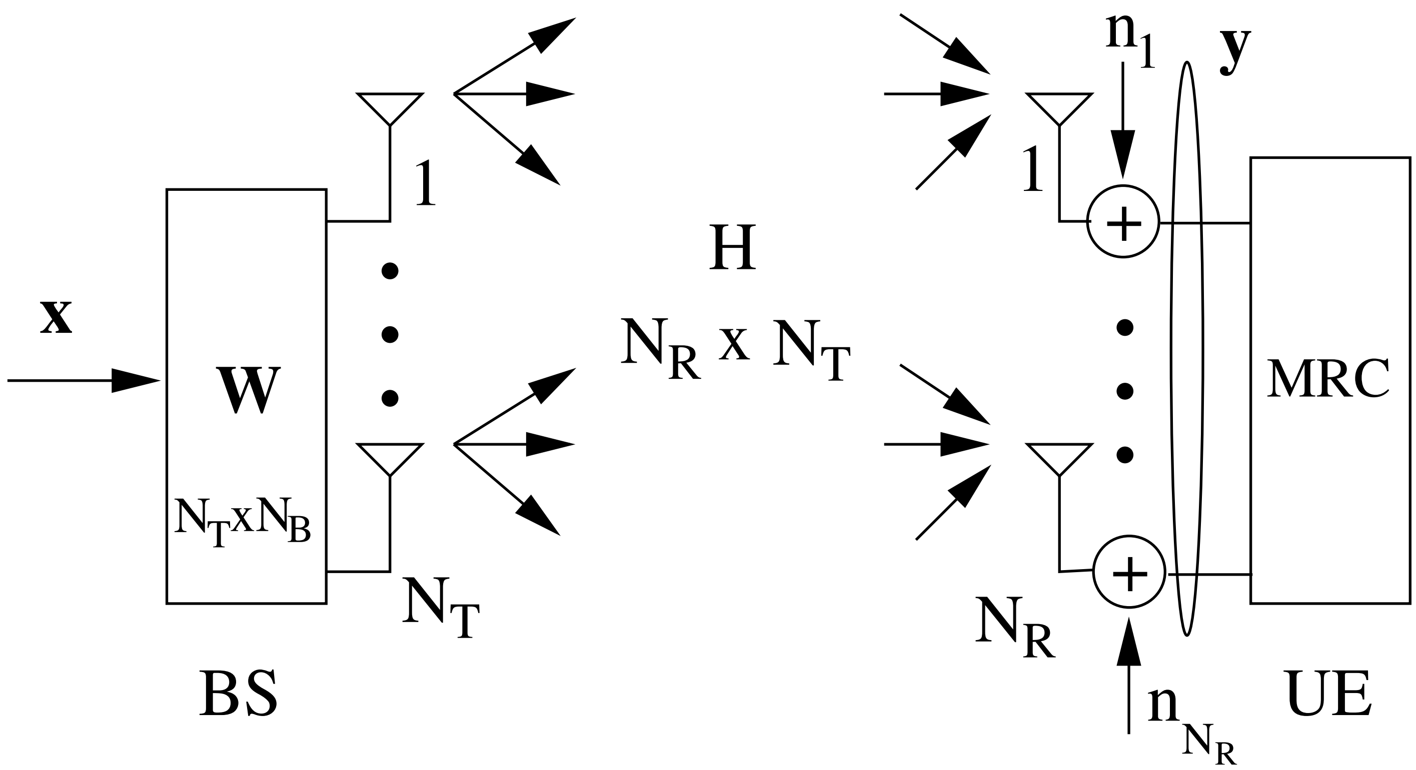

Figure 1: System model.

D-BLAST

- Originally proposed by G.F. Foschini, 1996 [1].
- Information bit stream demultiplexed (serial to parallel) into N_T substreams.
- Substreams coded independently (FEC), mapped to symbols and layered diagonally.

D-BLAST: encoder

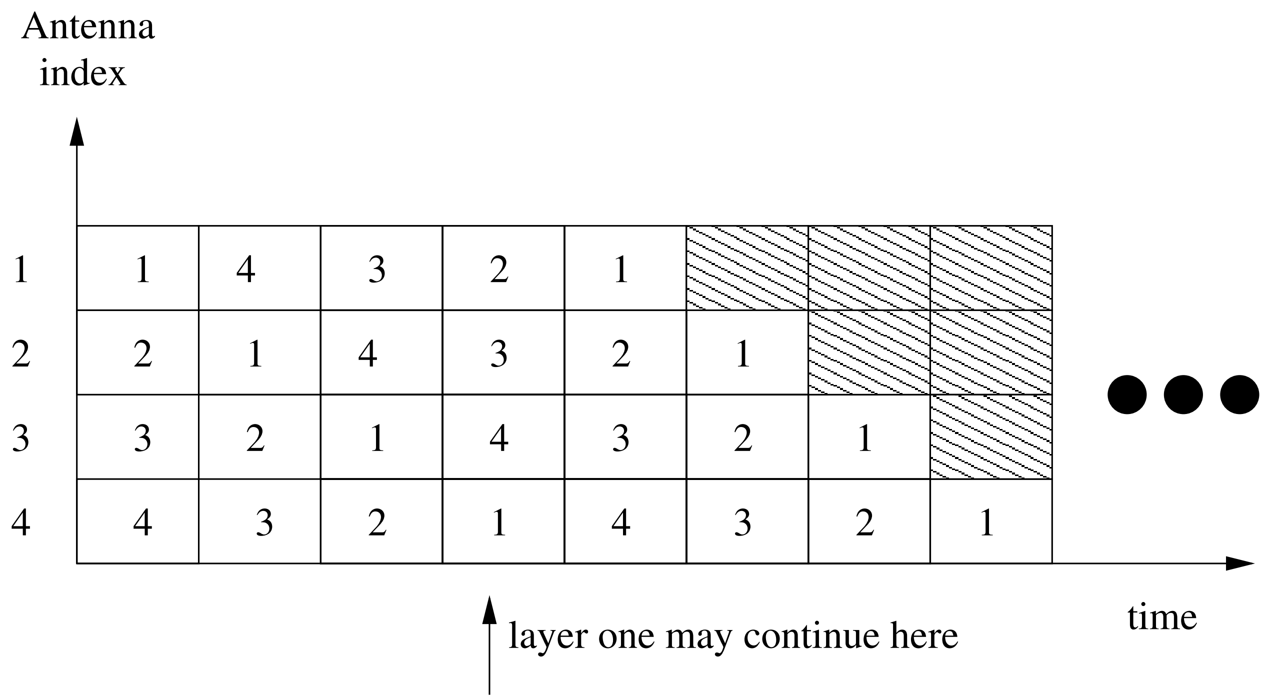

Figure 2: D-BLAST: diagonal layering. Numbers in blocks represent the layer that can transmit its symbols at that antenna and symbol period. Filled blocks represent space time wastage.

D-BLAST: decoder

- First symbol must be demodulated alone, space-time wastage required!
- Based on successive removal of layers.
- Decoding of whole layer (FEC) must be done before subtracting and exposing next one. Requires error free decoding, or suffers from propagation errors.

D-BLAST: decoder

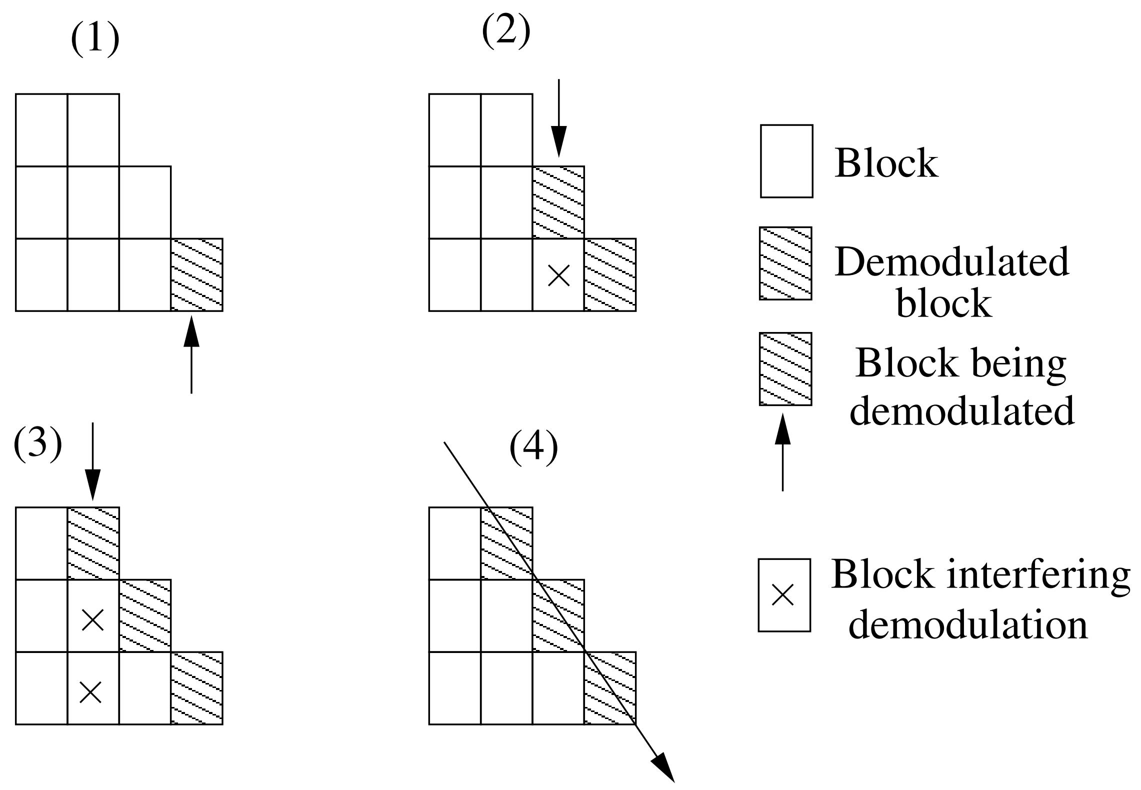

Figure 3: D-BLAST decoder (adapted from [2]).

V-BLAST

- Originally proposed by Wolniansky et al. [3].
- Simplification of D-BLAST, avoids cyclic layer permutation by using *horizontal encoding*.
- Does not exploit transmit diversity, both capacity and diversity are thus reduced.

V-BLAST: encoder

- Information bit stream demultiplexed (serial to parallel) into N_T substreams.
- Substreams coded independently (FEC) and mapped to symbols.
- Up to here, like in D-BLAST.
- Each substream on its own fixed antenna (N_T substreams for N_T antennas). This is “horizontal encoding”.

V-BLAST: decoder

- Recovers symbols for substreams in the received vector(s).
- If FEC in use, need for buffering demodulated symbols, so bit streams can be decoded.
- Several decoders to extract symbols from the output of receive side antenna array.

V-BLAST: decoder

- Maximum Likelihood decoder
  - $\hat{\mathbf{s}} = \underset{\mathbf{s}}{\operatorname{argmin}} \left\| y - \sqrt{\frac{E_s}{N_T}} \mathbf{H}\mathbf{s} \right\|_F^2$
  - Exhaustive seach not practical for high order constellations.
  - Suboptimal algorithms based on sphere decoder [4].
- Linear receivers: slice filtered received vector: $\mathbf{G}\mathbf{y}$
  - Zero Forcing (ZF): $\mathbf{G}_{zf} = \sqrt{\frac{N_T}{E_s}} \mathbf{H}^{\dagger}$. Attempts to invert channel directly, noise amplification.

V-BLAST: decoder

- Linear receivers (cont.)
  - Minimum Mean Square Error (MMSE): $\mathbf{G}_{mmse} = \sqrt{\frac{N_T}{E_s}} \left(\mathbf{H}^H \mathbf{H} + \frac{N_T}{\rho} \mathbf{I}_{N_T} \right)^{-1} \mathbf{H}^H$. attempts to both invert the channel, but keep the noise amplification controlled, in a MMSE sense. See [2] ch. 7 for more details.
  - († denotes Moore-Penrose pseudo inverse and H denotes hermitian transpose)
- Ordered Serial Interference Cancellation (OSIC): classifies substreams according to SNR and iteratively detect and subtract (cancellation). See [3].

Turbo-BLAST

- Sellathurai and Haykin, 2000 (but source for this presentation is [5], 2002).
- Based on bit interleaving coding ideas (Random Layered Space Time scheme, RLST). Mapping to symbols after bit interleaving.
- Decoding based on Turbo principle.
- No claims about capacity, but improvement in Bit Error Rate performance.

Turbo-BLAST: encoder

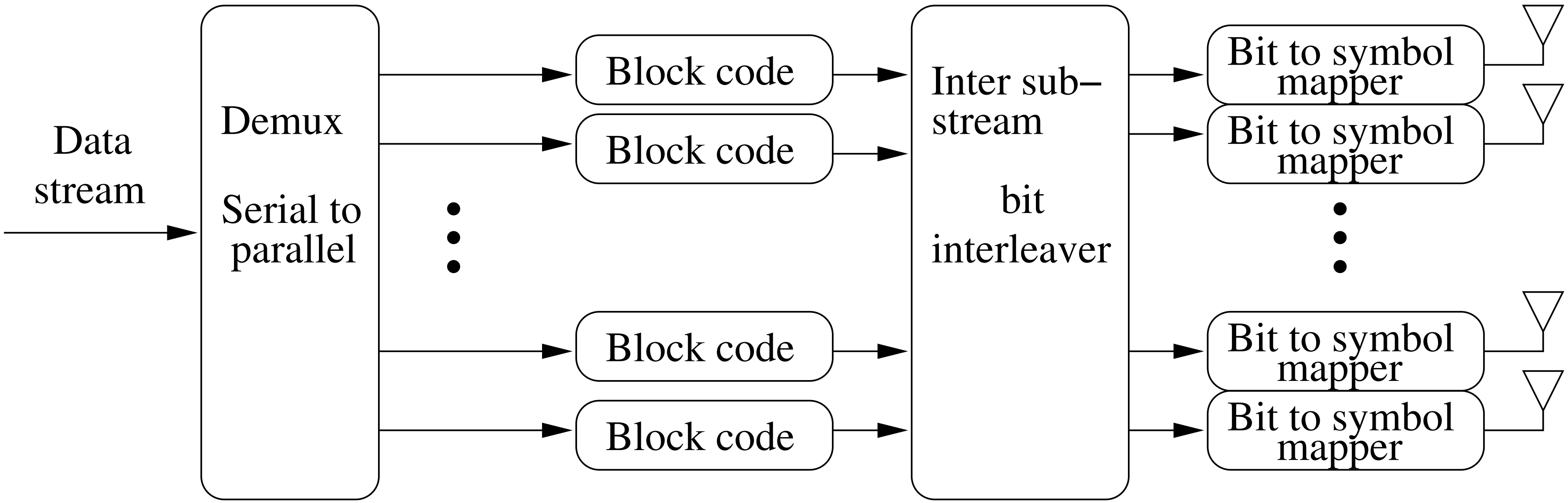

Figure 4: Turbo-BLAST encoder.

Turbo-BLAST: encoder

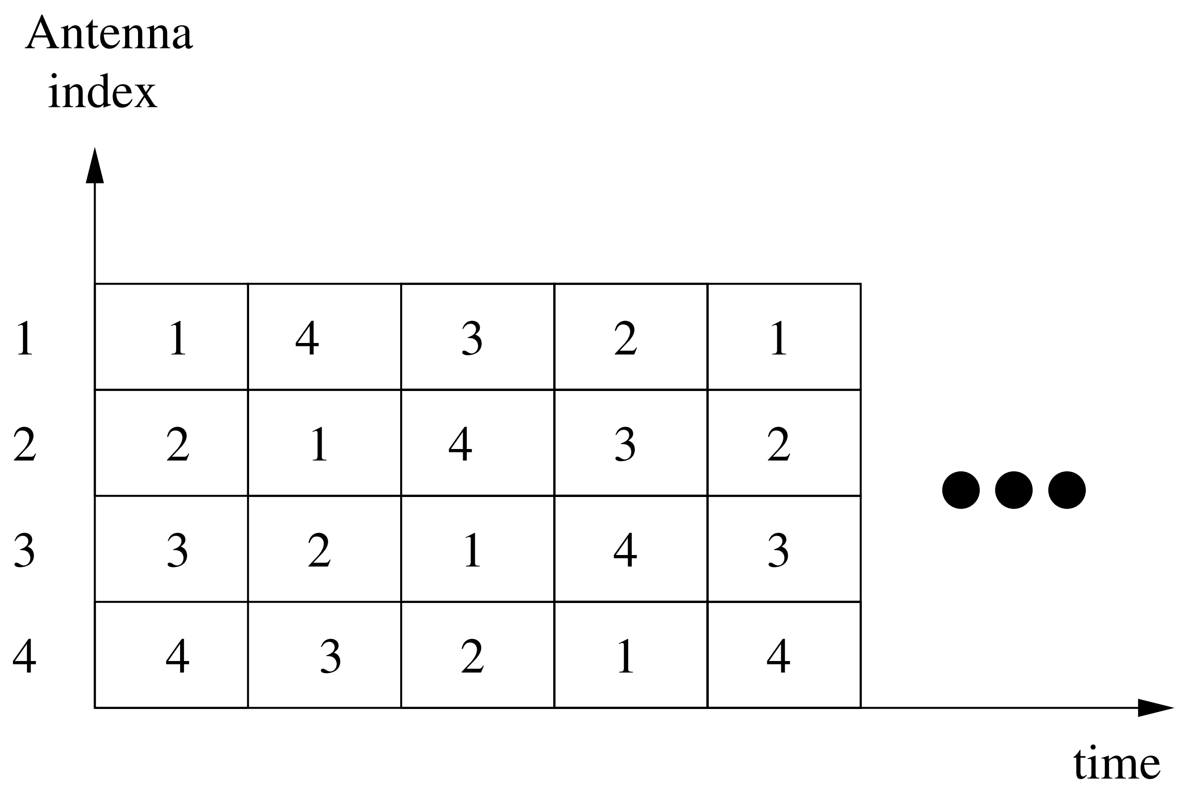

Figure 5: Turbo-BLAST diagonal bit interleaver.

Turbo-BLAST: decoder

- Decoding interweaved streams is very expensive computationally.
- Iterative suboptimal algorithm proposed in [5].
- Based on decoding of serially concatenated turbo codes, interprets the encoder as a group of block codes (“outer coder”) connected with an “inner coder” through parallel interleavers.
- Inner decoder copes with Inter Symbol Interference (ISI) (from multipath)
- Outer decoder corrects distortions due to channel’s first path.
- Both decoders output soft decisions, hard limiters used after required iterations.

Turbo-BLAST: decoder

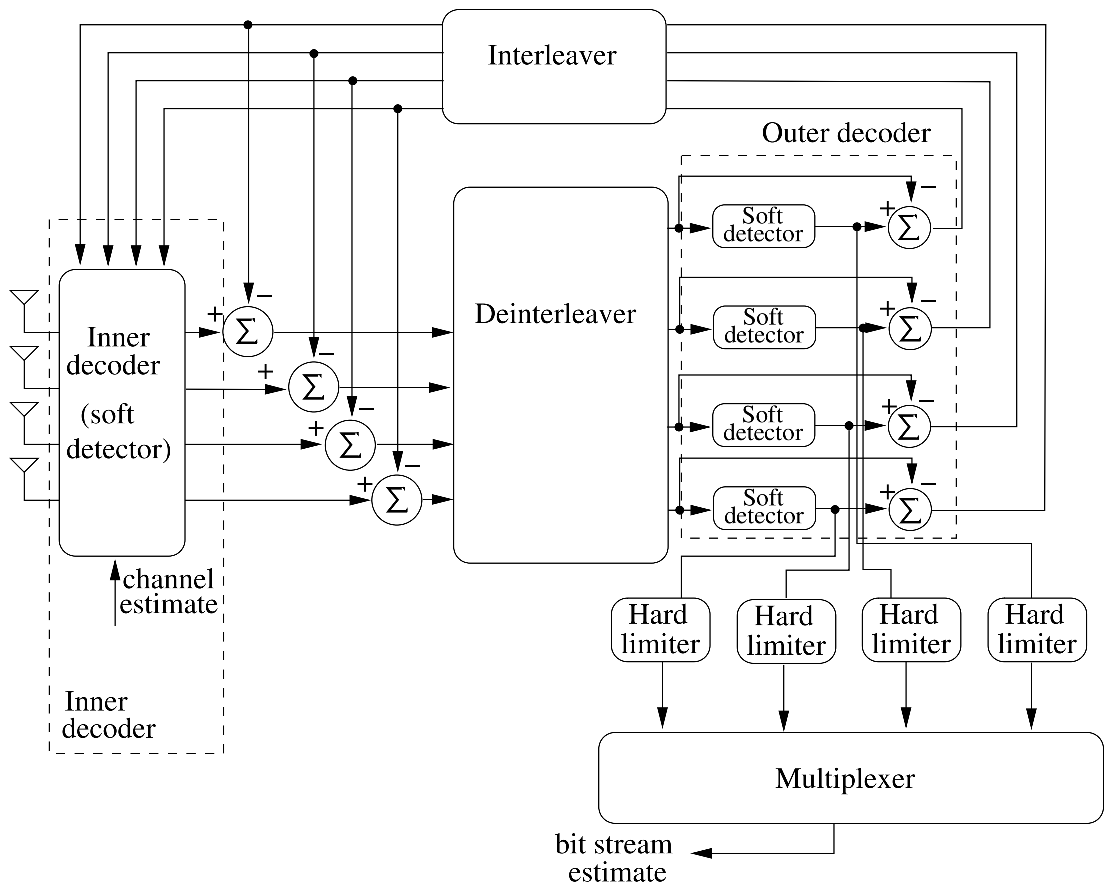

Figure 6: Turbo-BLAST iterative detection and decoding scheme.

Capacity aspects

- *If space time wastage is neglected and the frames are suitably long*, the D-BLAST scheme is able to reach the channel capacity of the fading channel (see [2], sec. 12.4.1). But frames can't be arbitrarily long, due to delay, memory and complexity restrictions.
- V-BLAST loses transmit diversity, possible information rates are reduced. Suboptimal scheme.
- Closed form expression for capacity of Turbo-BLAST architecture does not seem to exist yet. Only claims (based on experiments), about bit error rates. Authors claim that Turbo-BLAST can cope with the asymetric $N_T > N_R$ case.

Complexity issues

- In descending order: D-BLAST, Turbo-BLAST, V-BLAST.
- Choice of suboptimal algorithms also affects.
- Complexity evaluations were not found in the literature review.

Fading environment requirements

Quoting [6]:

1. The system operates in a rich Rayleigh scattering environment.
2. Appropriate coding structures are used.
3. Error-free decisions are available in the interference-cancellation schemes. This condition assumes the combined use of arbitrarily long (and therefore powerful) FEC codes and perfect decoding.

Switching between V-BLAST and OSTBC

- If feedback is available, it can be used to implement Adaptive Modulation and Coding techniques, e.g. in WCDMA's High Speed Downlink Packet Access (HSDPA) [7].
- When is the channel good for V-BLAST: Heath and Paulraj showed when to switch to transmit diversity (OSTBC) [8].
- Criterion is Euclidean distance of the symbol constellations after the channel.

Switching between V-BLAST and OSTBC

- Same data rate for both schemes.
- Constellations for V-BLAST and STC have minimum Euclidean distances d_{BLAST} and d_{STC} (e.g. QPSK and 16QAM for a 2x2 array).
- V-BLAST is preferred whenever the channel satisfies: $\kappa \leq \frac{d_{BLAST}}{d_{STC}}$
- $\kappa := \frac{||\mathbf{H}||_F}{\lambda_{\min}}$ and $\lambda_{\min}$ is the smallest singular value of the channel matrix $\mathbf{H}$.
- Decision can be made at mobile, therefore one bit feedback is required to signal the decision to switch.

Switching between V-BLAST and OSTBC

“Composite” BER curve is better than both the “individual” curves.

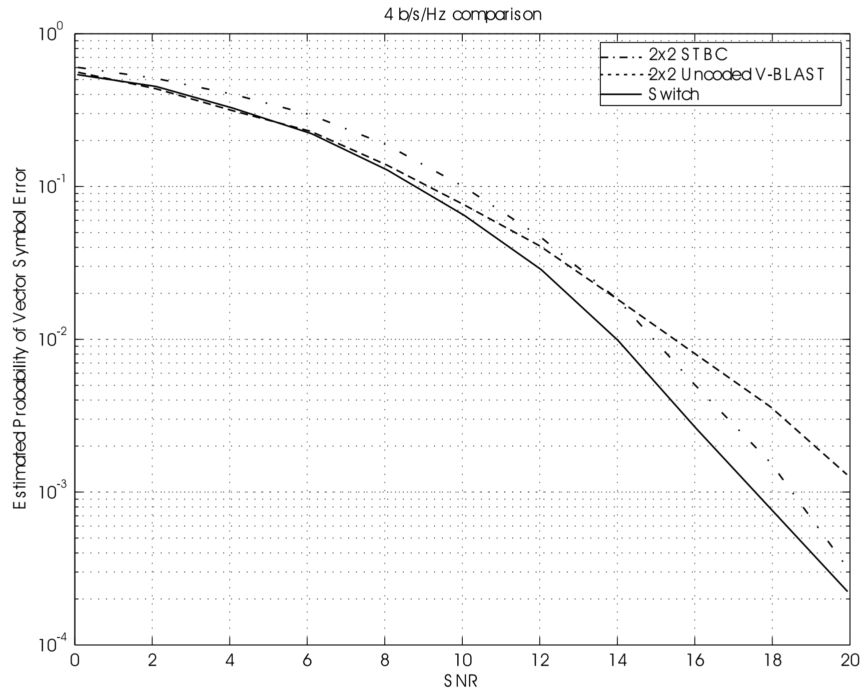

Figure 7: Switching between V-BLAST and STC based on Euclidean distance.

Switching between V-BLAST and OSTBC: probability of choosing V-BLAST

Rate	N	P_{HP}	Uncorrelated	3GPP C2	3GPP C4
4	2	0.216	0.215	0.002	0.056
8	2	0.687	0.688	0.038	0.354
8	4	0.485	0.484	0.000	0.028

Table 1: Measured probability for V-BLAST being preferred over OSTBC for square systems, compared to expression obtained by Heath and Paulraj (P_{HP}) [8]. Rate is given in bits per channel use. 3GPP C2 and C4 refer to 3GPP correlated channel models.

V-BLAST and waterfilling: all the streams?

- Exploiting CSI at Tx, waterfilling is essential.
- Not all the eigenmodes have the same gain.
- Usually minimum gain in eigenmode is too small.
- As the array size increases, there emerges more than one dominant eigenmode. Number of non vanishing eigen-gains is the “practical rank” of the channel matrix.

V-BLAST and waterfilling: effect of the weak beam

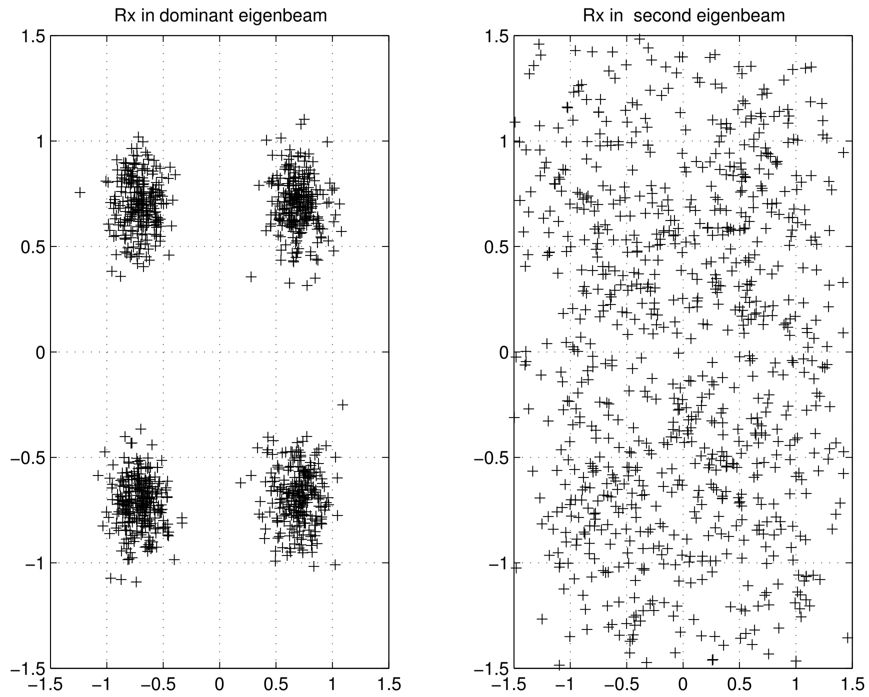

Figure 8: Received symbols (MMSE) in 2x2 uncoded V-BLAST system with full CSI and fixed modulation scheme (no waterfilling).

Statistics for singular values

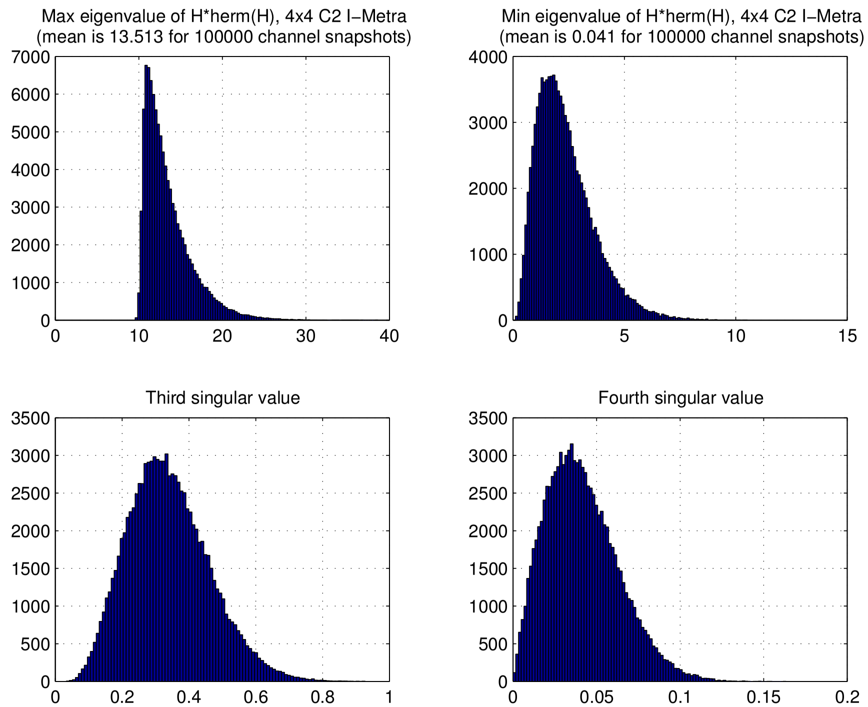

Figure 9: Statistical characterization of singular values of 4x4 strongly correlated channel.

Diversity order and multiplexing gain

- *Diversity order* is defined as the asymptotic rate at which the Frame Error Rate (FER) curve falls as a function of the SNR in a log-log plot [6]: $d_0 = -\lim_{\rho\to\infty} \left\{ \frac{\log(FER(\rho))}{\log(\rho)} \right\}$. Maximal diversity order for the MIMO system is $N_T N_R$.
- *Multiplexing gain* is defined [6] as the asymptotic increase of the ergodic capacity as function of SNR, also in log-log plot: $r = \lim_{\rho\to\infty} \frac{C(\rho)}{\log(\rho)}$ and its maximum is $\min(N_T, N_R)$.

Comparisons between architectures

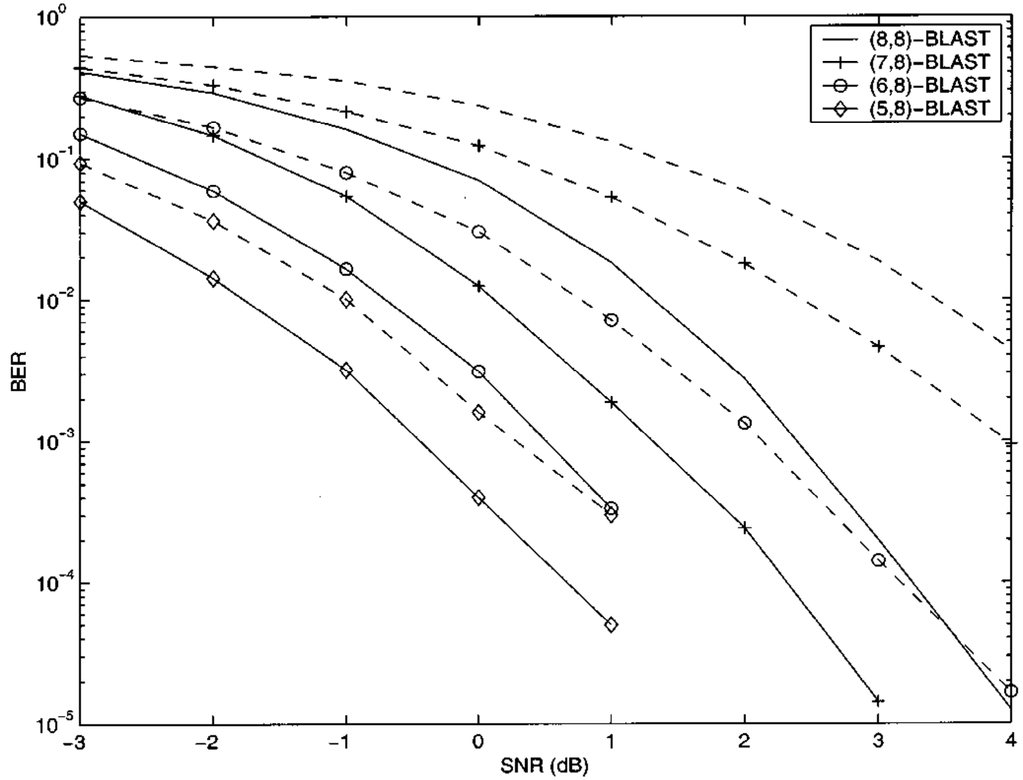

Figure 10: Experimental Turbo-BLAST versus V-BLAST results.

Comparisons between architectures

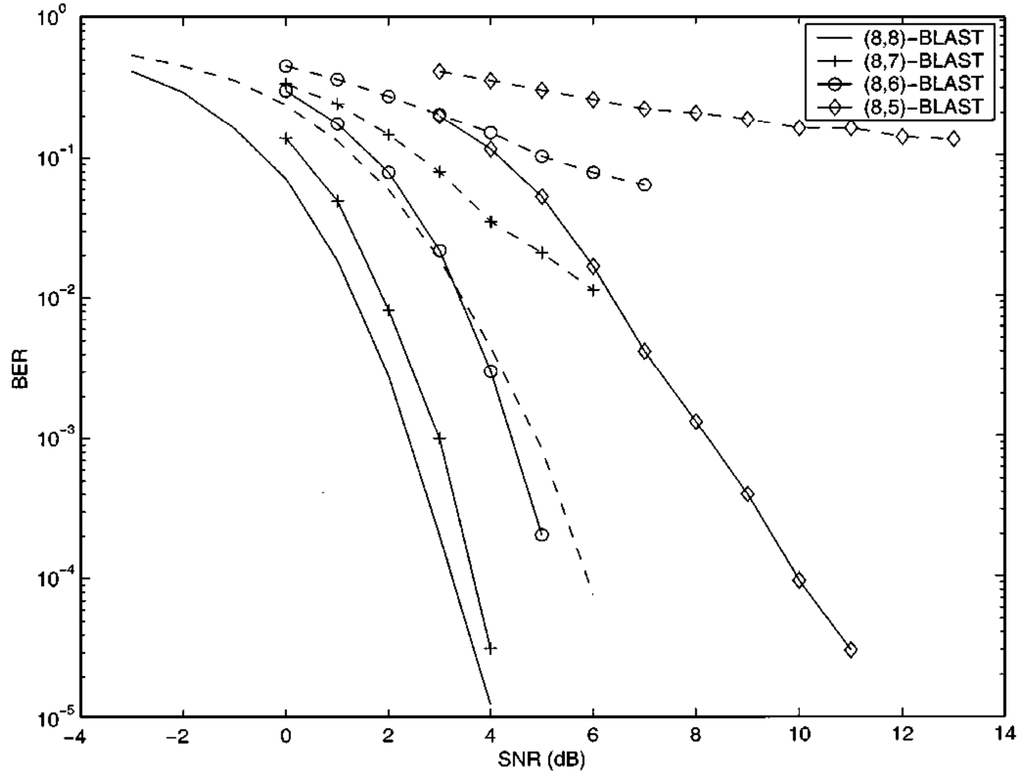

Figure 11: Experimental Turbo-BLAST versus V-BLAST results when $N_T > N_R$.

Conclusions

- Brief review of D-BLAST, V-BLAST and Turbo-BLAST: encoding, decoding, key assumptions.
- BLAST architectures aimed to increased capacity. When more reliability is required, use of transmit diversity might be necessary, or combined AMC arrangement, if feedback is available.
- Some examples given, intended to illustrate some important issues.

Homework

- Describe briefly the main differences between the BLAST architectures.
- What’s the main difference in purpose between transmit diversity and the BLAST architectures?

References

[1] G. Foschini, “Layered space-time architecture for wireless communication in a fading environment when using multiple antennas,” Bell Labs, Technichal Journal 2, 1996, appeared in Volume 1, number 2, pp 41-59.

[2] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge University Press, May 2003.

[3] P. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, “V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel,” *URSI International Symposium on Signals, Systems, and Electronics, 1998. ISSSE 98.*, 1998.

[4] E. Viterbo and J. Boutros, “A universal lattice code decoder for fading channels,” *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1639 – 1642, July 1999.

[5] M. Sellathurai and S. Haykin, “Turbo-BLAST for wireless communications: Theory and experiments,” *IEEE Transactions on Signal Processing*, 2002.

[6] S. Haykin and M. Moher, *Modern Wireless Communications (International Edition)*. Pearson Education, March 2004.

[7] T. 3GPP, “TR 25.858: Physical layer aspects of utra high speed downlink packet access,” 3GPP, Tech. Rep., 2002.

[8] A. Paulraj and R. J. Heath, “Characterization of MIMO channels for spatial multiplexing systems,” *IEEE International Conference on Communications*, vol. 2, no. 11-14, pp. 591 – 595, June 2001.