V-BLAST: A High Capacity Space-Time Architecture for the Rich-Scattering Wireless Channel

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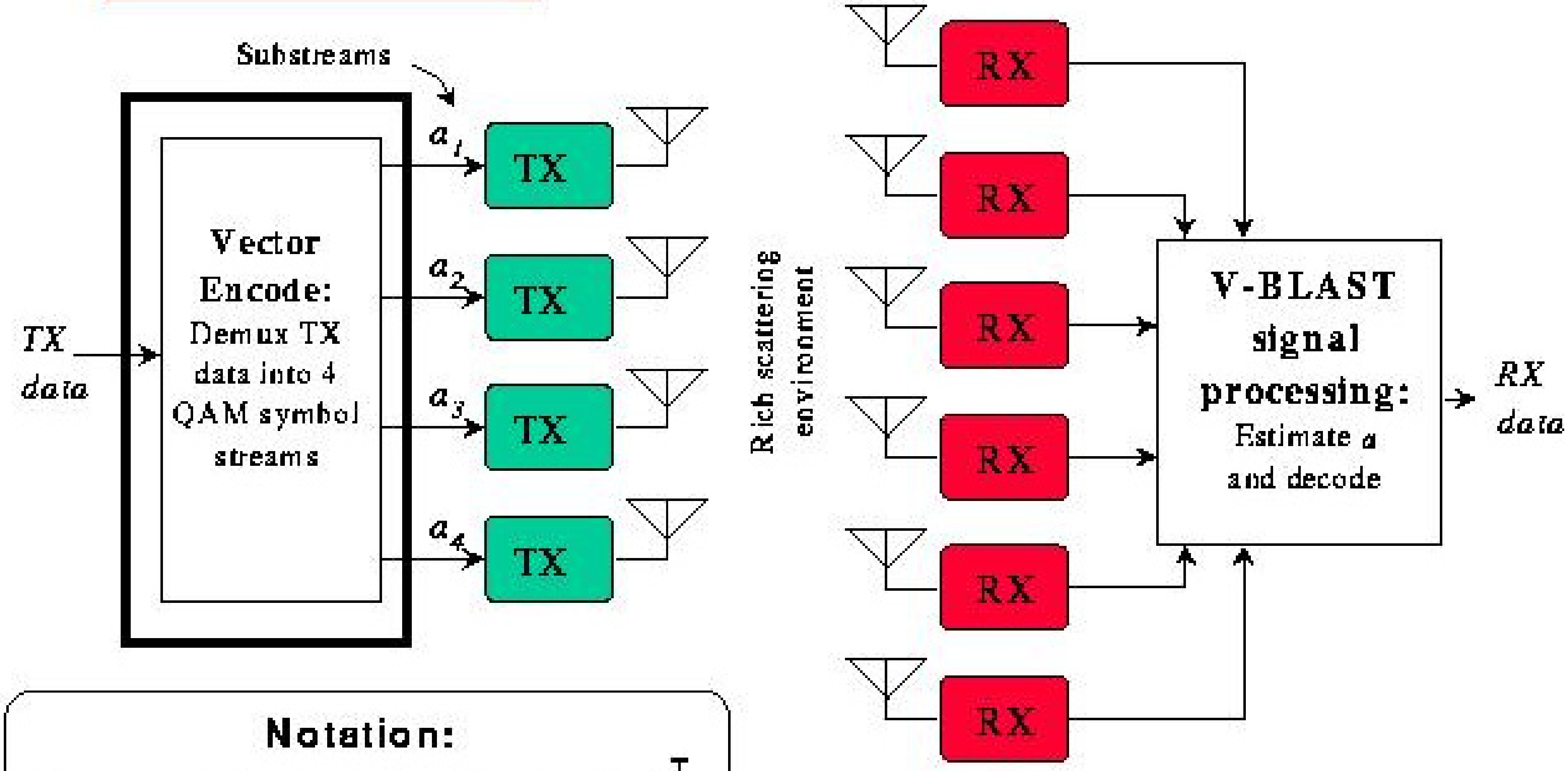
V-BLAST Overview

(***BLAST***: Bell Laboratories Layered Space-Time)

(***V-***: Vertical; related to blocking structure)

- System overview
- Motivation for vector approach
- Brief look at signal processing
- Realtime prototype results

V-BLAST: The Big Picture



Notation:

Vector symbol $\mathbf{a} \equiv (a_1, a_2, a_3, a_4)^T$

Number of xmtrs = M Number of rcvrs = N

An M = 4, N = 6 V-BLAST system

Key points & basic assumptions

- Transmitters operate *co-channel*, *symbol-synchronized*. All use same QAM constellation.
- Transmitted substreams ("subguys") are *independent*; V-BLAST is *not* transmit diversity!
- Individual TX powers scaled by $1/M$ so total radiated power remains *constant*, indep. of M.
- Burst mode operation: Channel estimated during each burst via a training sequence.
- Prop. environment: Flat fading, quasi-stationary.

$N \geq M$

Vector approach: Theoretical Motivation

- The rich-scattering wireless channel is capable of huge theoretical capacities. [1-4]
- Partitioning a single high-SNR channel into many low-SNR overlapping subchannels is key to achieving large spectral efficiencies. [1-4]
- Vector approach (multiple xmtrs and rcvrs) is an inherently practical means for performing this partitioning for the wireless channel. [1-6]
- Even a simple, uncoded vector approach like V-BLAST can do quite well. [6-7]

Hierarchy of vector approaches

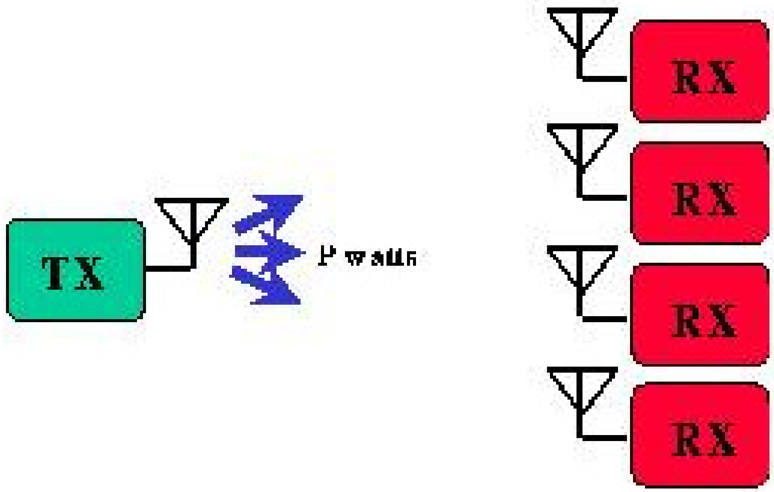
Grouping	Processing	Approach	Description
Nulling + cancellation	Diagonal Processing	D-BLAST	OPC + cancellation + fancy inter-subguy coding.
Nulling + cancellation	Diagonal Processing	D-BLAST	OPC + cancellation + folding + simple per-subguy coding.
Nulling + cancellation	Vertical Processing	V-BLAST	OPC + optimum cancellation + simple per-subguy coding
Nulling + cancellation	Vertical Processing	V-BLAST	OPC + optimally-ordered cancellation
Nulling + cancellation	Vertical Processing	V-BLAST	OPC + fixed-order cancellation
Nulling only	Vertical Processing	Vanilla AAA (vector)	OPC: vector transmitter (M > 1)
Nulling only		Vanilla AAA (scalar)	OPC: scalar transmitter (M = 1)

← Increasing capacity (from bottom to top)

Vector vs. Scalar: The Capacity Argument

Comparison example: Scalar system vs. vector system

Traditional (scalar) system: $M = 1$

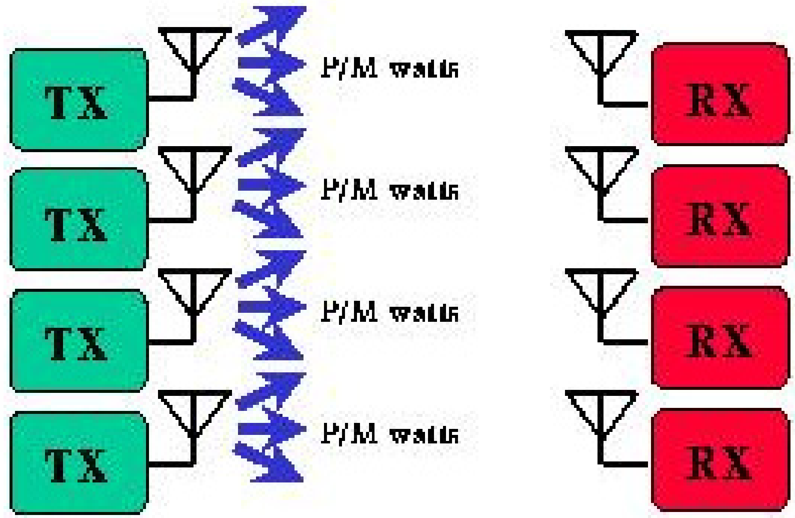


Total TX power = P watts

Each RX SNR = S

Bandwidth = 1/T = W Hz

Vector system: $M > 1, N >= M$



Total TX power = P watts

Each RX SNR = S/M

Bandwidth = 1/T = W Hz

(All transmitters operate *co-channel*)

Capacity argument (cont'd)

Simple view: Ignore fading statistics, account only for antenna gain.
Scalar system capacity and spectral efficiency are

$$C_{scalar} \approx W \log_2 NS$$

$$E_{scalar} \approx \log_2 NS$$

Note that C and E grow only logarithmically with *N*.

Idealized vector case: Assume signals from each transmitter can be separately detected without noise penalty. Then

$$C_{vector} \approx MW \log_2\left(N \cdot \frac{S}{M}\right)$$

$$\geq MW \log_2 S \quad \text{for } N \geq M$$

$$E_{vector} \geq M \log_2 S$$

Here, C and E grow *linearly* with *M*.

Capacity argument (cont'd)

In the real world, separation of subguys incurs a noise penalty which depends on the propagation environment and the receiver signal processing approach. This penalty can be expressed as a loss in SNR relative to the idealized case:

$$C_{vector} \approx \sum_{i=1}^{M} W \log_2 \left(f_i S \right)$$

where the f_i represent the SNR degradation, $0 \le f_i < 1$.

Asympotically, for large M and S, in Rayleigh scattering, $f_i \sim 1/e$

Practical implications

<u>Key point #1:</u>

Even in real-world rich-scattering environment at reasonable SNRs, capacity growth is roughly linear, even for small M.

Example: Typical indoor channel, 24 dB SNR, $\alpha = 0.23$: Measure channel and compute theoretical efficiencies: For an M=1, N=12 scalar system, the theoretical spectral efficiency is about 9 bps/Hz; for an M=8, N=12 vector system it is about 49 bps/Hz. (These are rough 5% outage numbers.)

Practical implications (cont'd)

Key point #2:

Scalar system encodes B bits per symbol using a single constellation of 2^B points. Vector system realizes same rate using M constellations of $2^{B/M}$ points each. Thus, vector system can realize large spectral efficiencies (i.e. large B) in an inherently more practical manner.

Example: To achieve, say, 26 bps/Hz in a system with rolloff of 23% requires 26 * (1.23) = 32 bits/symbol. A vector system with M=8 transmitters realizes this using eight 16-point constellations. A scalar system requires a single constellation with 2^{32} or more than 4 billion points, which is impractical, regardless of SNR.

Receiver signal processing overview

In real world, subguys are not uncoupled, and interfere with each other. Operate jointly on all received signals to extract subguys. Detection desideratum: Maximize the worst f_i.

Basic Idea: Treat each subguy in turn as "desired" signal, rest as "interferers", then use AAA-like techniques to detect each. ("AAA" = linear combinatorial nulling).

- V-BLAST detection does significantly better than simple AAA: Subguy synchronism is exploited, permitting *symbol cancellation with optimal ordering* as well as linear combinatorial nulling. (When cancellation is used, the f_i depend on the detection order.)

- As usual, degree of correlation between "desired" and "interferer" vectors determines noise enhancement, hence ultimate attainable performance. Rich scattering => low correlation => large E.

Notation

$\mathbf{a} \equiv (a_1, a_2, \ldots, a_M)^T$	Symbol vector: components are QAM symbols
$\mathbf{H}^{N \times M}$	Channel matrix: *ij*th element is transfer function from transmitter *j* to receiver *i*.
$\mathbf{v}^{N \times 1}$	Noise vector: components are WSS, IID
$\mathbf{r}_1^{N \times 1} = \mathbf{H}\mathbf{a} + \mathbf{v}$	Initial received signal vector.
$k_1, k_2, \ldots, k_M$	Subguy detection sequence: k_1 first, ... k_M last.
$\mathbf{w}_{k_i}^{N \times 1}$	k_ith zero-forcing (ZF) nulling vector.
y_{k_i}	k_ith decision statistic
$Q(\cdot)$	Constellation quantization (slicing) function.

V-BLAST detection algorithm

(Zero-forcing shown for simplicity; MMSE formulation is similar.)

initialization:

$i = 1$

$\mathbf{G}_1 = \mathbf{H}^+$ — Compute candidate set of nulling vectors

$k_1 = \arg\min_j \|(\mathbf{G}_1)_j\|^2$ — Determine which subguy to detect first

recursion:

$\mathbf{w}_{k_i} = (\mathbf{G}_i)_{k_i}$ — k_i-th nulling vector is k_i-th row of G

$y_{k_i} = \mathbf{w}_{k_i}^T \mathbf{r}_i$ — Compute k_i-th decision statistic

$\hat{a}_{k_i} = Q(y_{k_i})$ — Estimate k_i-th component of a

$\mathbf{r}_{i+1} = \mathbf{r}_i - \hat{a}_{k_i}(\mathbf{H})_{k_i}$ — Cancel detected component (deflate system)

$\mathbf{G}_{i+1} = \mathbf{H}_{\bar{k}_i}^+$ — Candidate nulling vectors for deflated system

$k_{i+1} = \arg\min_{j \notin \{k_1, \ldots, k_i\}} \|(\mathbf{G}_{i+1})_j\|^2$ — Determine which subguy to detect next

$i = i + 1$

Next...

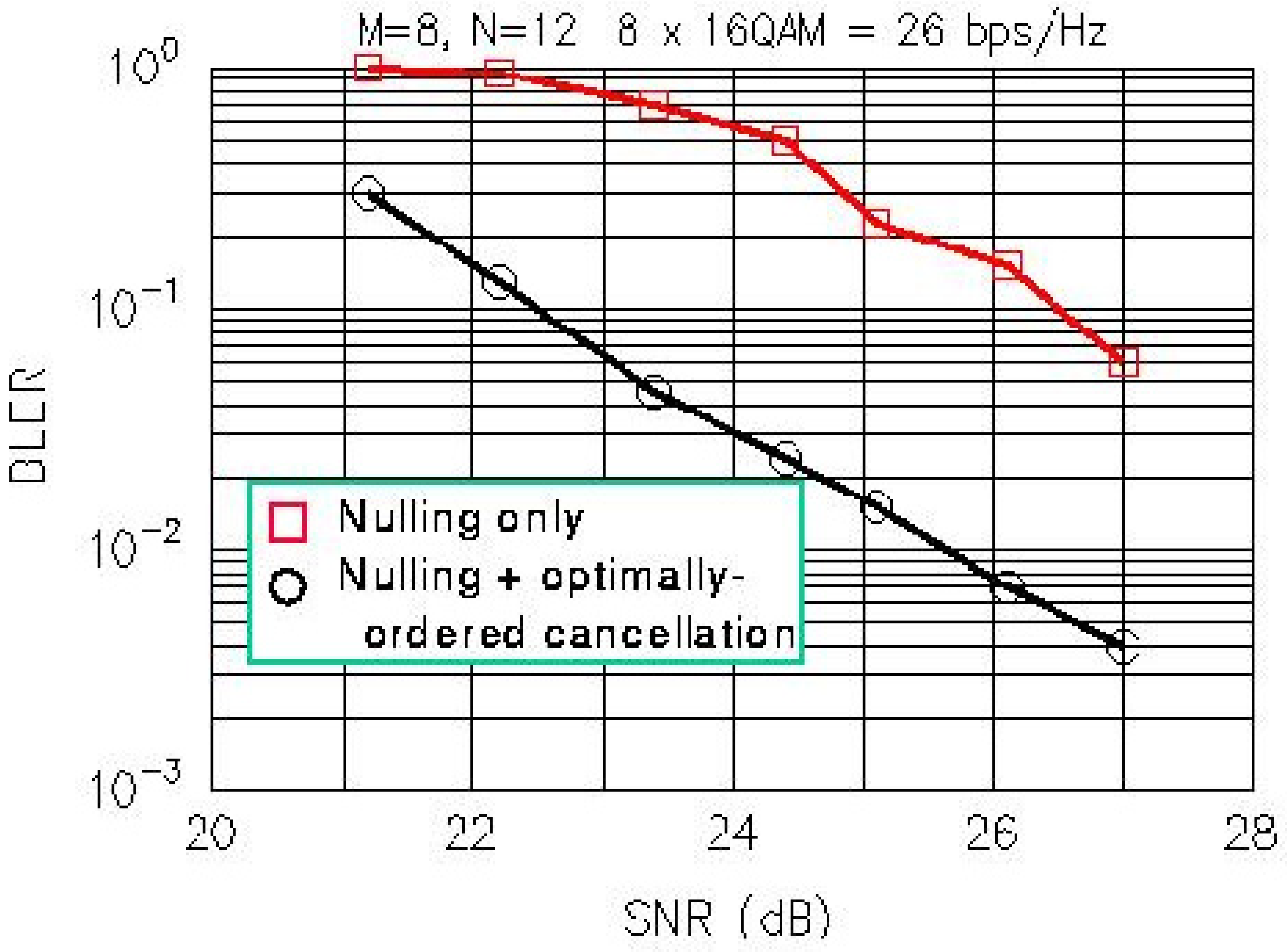
Laboratory system

- ω_c = 1.9 GHz
- $1/T$ = 24.3 ksymbols/sec
- BW = 30 kHz

  $1 \leq M \leq 8$

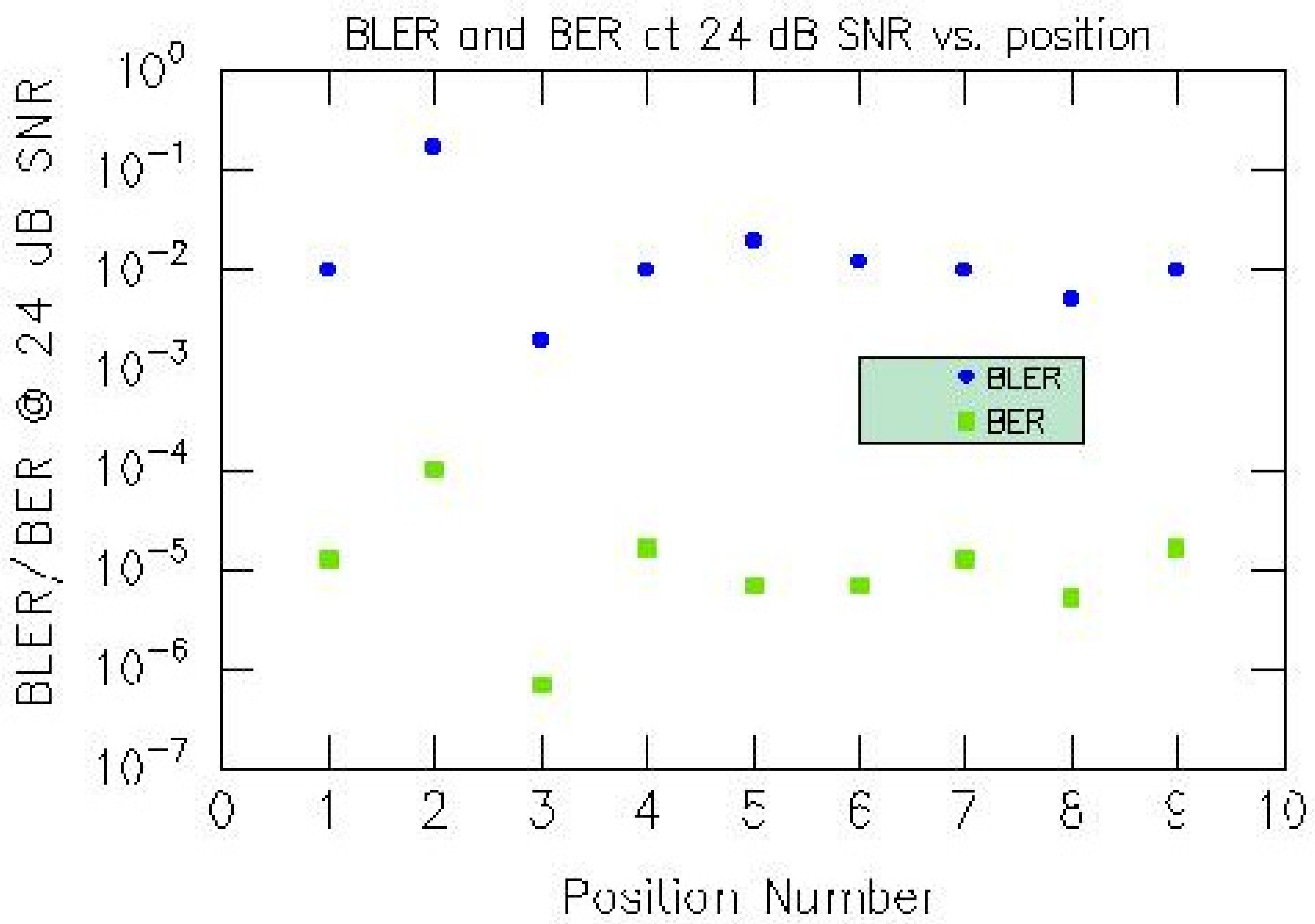
  $M \leq N \leq 12$
- Environment: Flat-fading, indoor, quasi-stationary.
- Channel is *unknown at transmitter*.
- *No coding!*

Over-the-air: Single-position results



- Burst length: **100 *T***
- Training: **20 *T***
- System BW: **30 kHz**
- α: **0.23**
- Raw data rate: **780 kbps**
- Payload rate: **624 kbps**
- BLER is burst error rate: 1 burst = **3200 bits**

Over-the-air: Multi-position results



- Burst length: **100 *T***
- Training: **20 *T***
- System BW: **30 kHz**
- α: **0.23**
- Raw rate: **780 kbps**
- Payload rate: **624 kbps**
- BLER is burst error rate: 1 burst = **3200 bits**

References

[1] G. J. Foschini, "*Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multiple Antennas*", Bell Laboratories Technical Journal, Vol. 1, No. 2, Autumn, 1996, pp. 41-59.

[2] G. G. Raleigh and J. M. Cioffi, "*Spatio-Temporal Coding for Wireless Communications*", Proc. 1996 IEEE Globecom, Nov. 1996, pp. 1809-1814.

[3] G. J. Foschini and M. J. Gans, "*On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas*", Wireless Personal Communications, Vol. 6, No. 3, 1998, pp. 311-335.

[4] G. G. Raleigh and J. M. Cioffi, "*Spatio-Temporal Coding for Wireless Communications*", IEEE Trans. Communictions, Vol. 46, No. 3, 3/98.

[5] G. J. Foschini, "*Wireless Communications System having a Layered Space-Time Architecture...*", patent application filed 7/96.

[6] G. J. Foschini and G. D. Golden, "*Wireless Communications System having a Space-Time Architecture...*", patent application filed 4/98.

[7] P. W. Wolniansky, et. al., "V-BLAST: An Architecture for Realizing Very High Data Rates Over the Rich-Scattering Wireless Channel", Proc. ISSSE-98, Pisa, Italy, Sept. 29, 1998.