Managing Massive Interference

Helmut Bőlcskei

ETH Zurich

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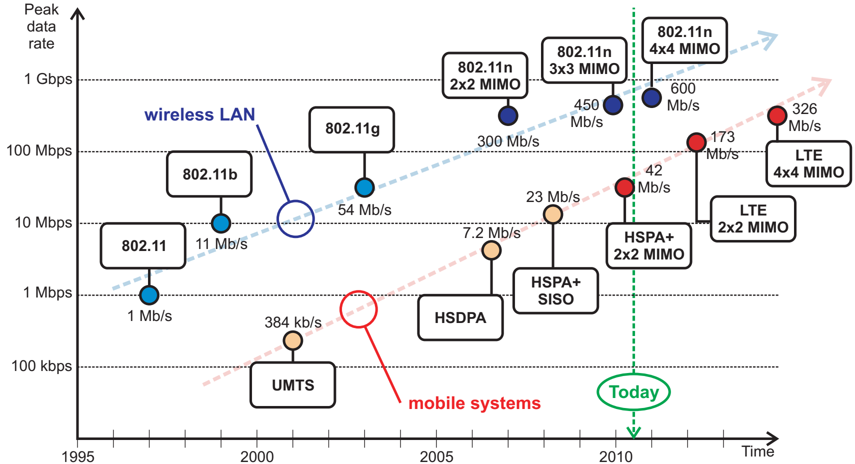
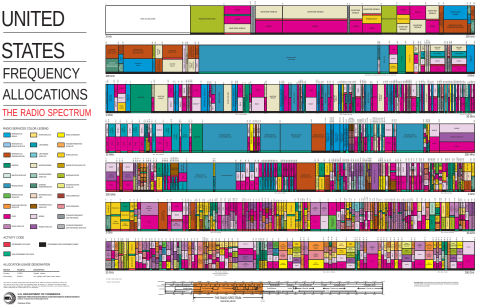
joint work with C. Studer, M. Wenk, and A. Burg

Data rates in wireless double every 18 months



Wireless spectrum is crowded



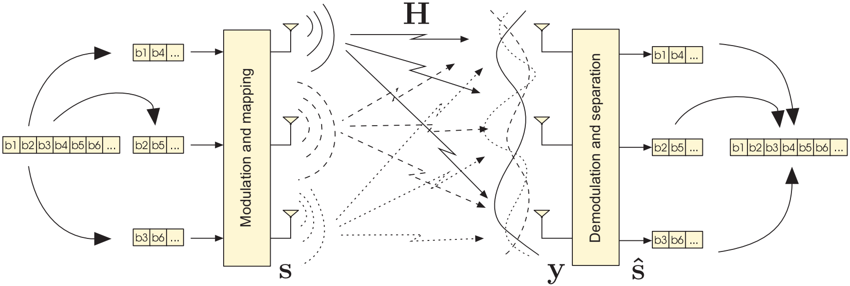
Licensed spectrum is expensive:

- In 2000 and 2010, German operators paid 50 billion and 5 billion EUR for 3G and 4G licenses, respectively

Massive interference in unlicensed spectrum:

- ISM radio located at 2.4 GHz and 5.8 GHz
- Spectrum shared among cordless phones, WiFi, car alarms, microwave ovens, bluetooth devices, etc.

MIMO: Nature offers "spatial bandwidth"

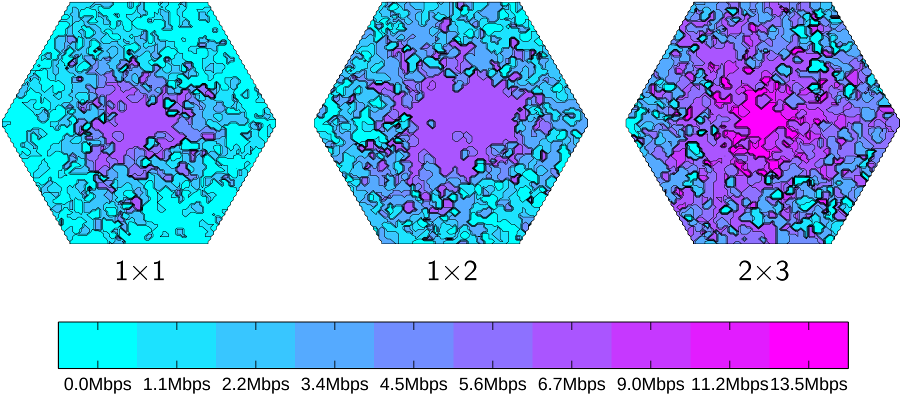


$$C_{\mathrm{MIMO}} \propto N C_{\mathrm{SISO}}$$

- Requires **rich scattering**, i.e., that $\mathbf{H}$ is full-rank

Price to be paid: Separation of signal mixtures at receiver incurs **significant computational burden**

MIMO gains carry through to system level

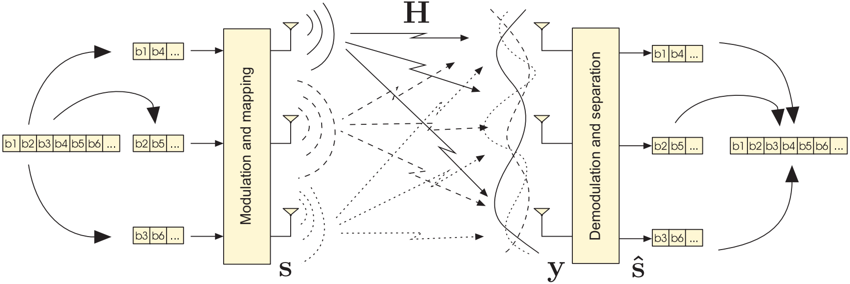


- MIMO networks offer increased coverage and capacity
- MIMO is part of IEEE 802.11n, IEEE 802.16e, and 3GPP LTE

A brief historic perspective of MIMO

- Pioneered by Paulraj and Kailath (Stanford University, 1994), Foschini (Bell Labs, 1996)
- First successful technology demonstration under laboratory conditions: Wireless Research Department, Bell Labs, Sept. 1998
- First successful outdoor prototype demonstration: Iospan (then Gigabit) Wireless Inc. and Stanford University, June 1999
- First commercial product: Iospan Wireless Inc., Sept. 2002
- First 600 Mbps 4-stream solution for IEEE 802.11n: Celestrius AG and ETH Zurich, Sept. 2008

Optimum signal separation: Maximum likelihood detection



$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

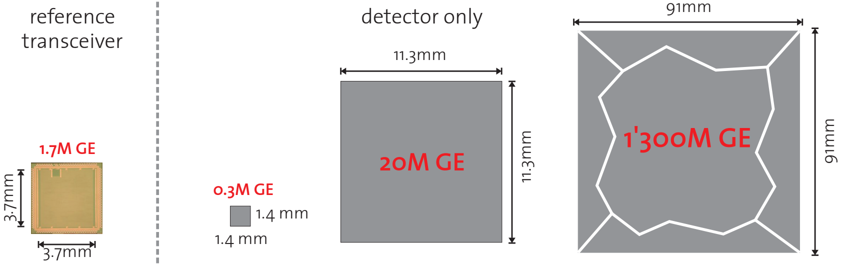
Maximum likelihood (ML) MIMO detection

$$\hat{\mathbf{s}} = \arg \min_{\mathbf{s} \in \mathcal{O}^{M_T}} ||\mathbf{y} - \mathbf{H}\mathbf{s}||^2$$

ML detection through exhaustive search

Exhaustive search: Enumerate all possible candidate vectors

- Complexity grows exponentially in number of transmit antennas
- IEEE 802.11n devices, e.g., require *evaluation* of up to **0.5 quadrillion** $(0.5 \cdot 10^{15})$ candidate vectors per second



4x4 IEEE 802.11n baseband ASIC [ETH Zurich, 2008]

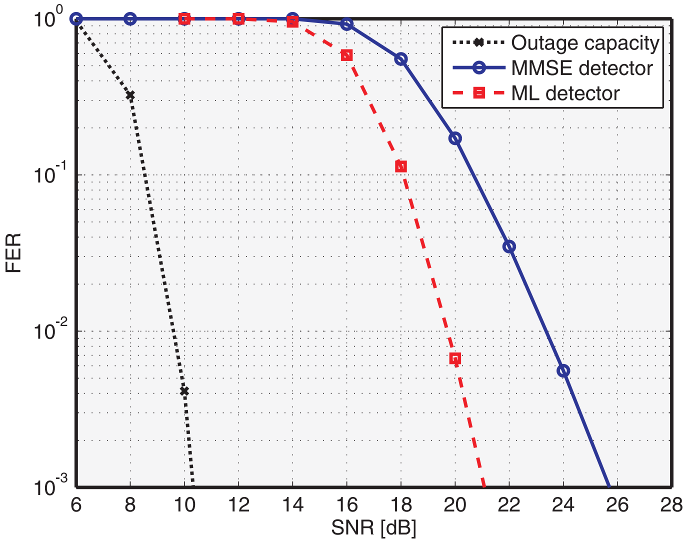
2x2 exhaustive search detector 64-QAM

3x3 exhaustive search detector 64-QAM

4x4 exhaustive search detector 64-QAM

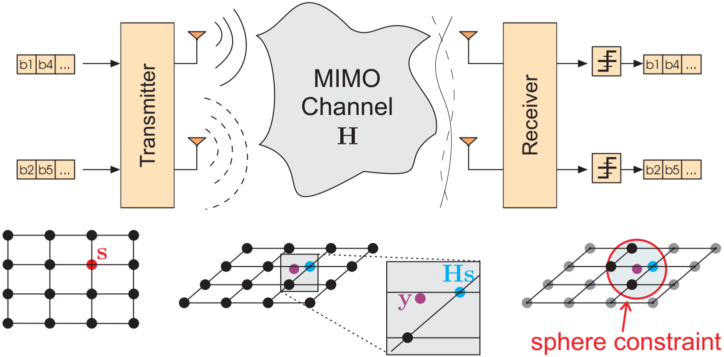
Results are for 130nm CMOS technology

Performance gain through ML detection



4×4 MIMO system using 16-QAM

Sphere decoding: Exploiting the structure of the MIMO-ML detection problem

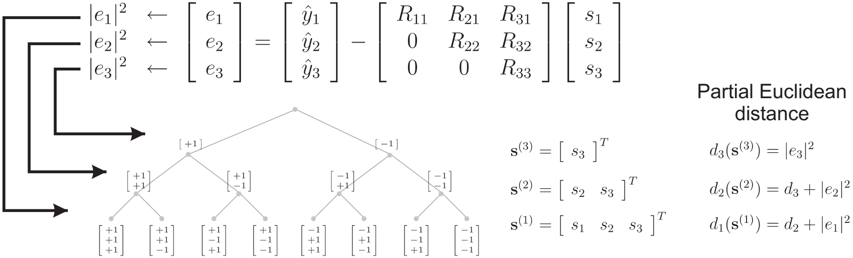


$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}\in\mathcal{O}^{M_T}} ||\mathbf{y}-\mathbf{H}\mathbf{s}||^2 \quad \text{s.t.} \quad ||\mathbf{y}-\mathbf{H}\mathbf{s}||^2 \leq r^2$$

The MIMO ML-detection problem corresponds to finding the closest point in a finite lattice

Sphere decoding reduces to a tree-search problem

1. Translate the problem into a tree search (triangularization)
2. Nodes associated with partial Euclidean distances (PEDs) $d(\mathbf{s})$
3. Update rule: $d_i(\mathbf{s}^{(i)}) = d_{i+1}(\mathbf{s}^{(i)}) + |e_i|^2$, $i = M_T, \ldots, 1$ (tree level)
4. ML detection corresponds to finding the leaf with smallest PED



$$\begin{array}{l} |e_1|^2 \leftarrow \\ |e_2|^2 \leftarrow \\ |e_3|^2 \leftarrow \end{array} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \hat{y}_1 \\ \hat{y}_2 \\ \hat{y}_3 \end{bmatrix} - \begin{bmatrix} R_{11} & R_{21} & R_{31} \\ 0 & R_{22} & R_{32} \\ 0 & 0 & R_{33} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}$$

Partial Euclidean distance

$$\mathbf{s}^{(3)} = \begin{bmatrix} s_3 \end{bmatrix}^T \qquad d_3(\mathbf{s}^{(3)}) = |e_3|^2$$

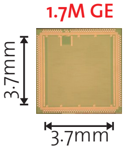
$$\mathbf{s}^{(2)} = \begin{bmatrix} s_2 & s_3 \end{bmatrix}^T \qquad d_2(\mathbf{s}^{(2)}) = d_3 + |e_2|^2$$

$$\mathbf{s}^{(1)} = \begin{bmatrix} s_1 & s_2 & s_3 \end{bmatrix}^T \qquad d_1(\mathbf{s}^{(1)}) = d_2 + |e_1|^2$$

A **branch-and-bound** strategy realized through the sphere constraint leads to efficient pruning of the tree

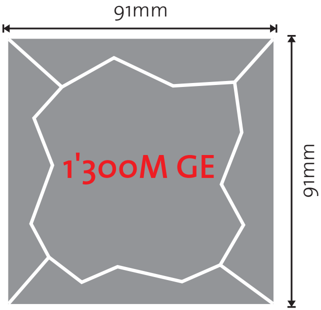
Sphere decoding substantially reduces complexity

reference
transceiver



4x4 IEEE 802.11n
baseband ASIC
[ETH Zurich, 2008]

detector
only



4x4 exhaustive
search detector
64-QAM

4x4 sphere
decoder
64-QAM

Sphere decoding leads to 6500-fold area
reduction compared to exhaustive search

Soft-output MIMO detection through sphere decoding

Detector computes reliability information for each bit $x_{i,b}$ in the form of log-likelihood ratios (LLRs):

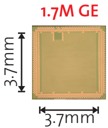
$$L(x_{i,b}) = \underbrace{\min_{\mathbf{s}\in\mathcal{X}_{i,b}^{(0)}} ||\mathbf{y}-\mathbf{H}\mathbf{s}||^2}_{\lambda^{\mathrm{ML}}} - \underbrace{\min_{\mathbf{s}\in\mathcal{X}_{i,b}^{(1)}} ||\mathbf{y}-\mathbf{H}\mathbf{s}||^2}_{\lambda_{i,b}^{\overline{\mathrm{ML}}}}$$

Repeated Tree Search (RTS) [Wang and Giannakis, 2004]

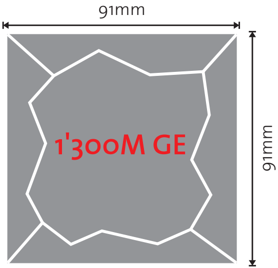
1. Use the sphere decoding algorithm to find λ^{ML}
2. Restart the search to identify the QM_T remaining minima by operating sphere decoder on pre-pruned trees

Soft-output detection with RTS entails high complexity

reference
transceiver



4x4 IEEE 802.11n
baseband ASIC
[ETH Zurich, 2008]

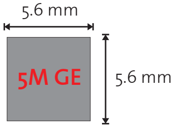


4x4 exhaustive
search detector
64-QAM

hard-output
detector only

4x4 sphere
decoder
64-QAM

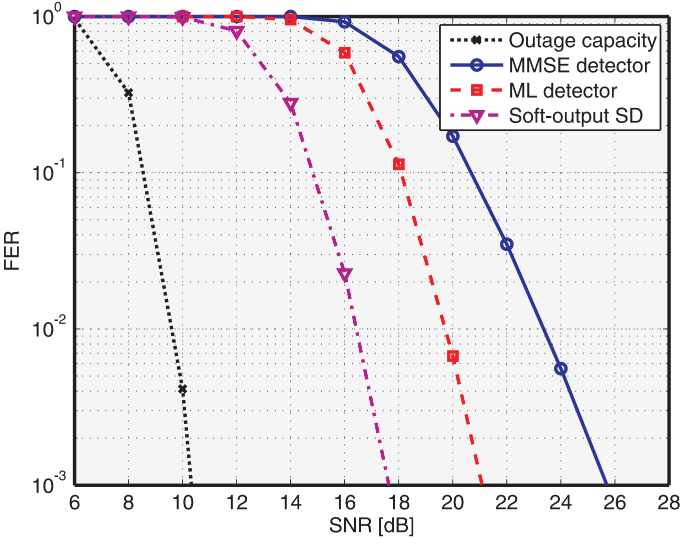
soft-output
detector only



4x4 RTS
detector
64-QAM

RTS for 4 streams with 64-QAM essentially requires solving
25 ML-detection problems per received vector

Performance gain through soft-output SD



4×4 MIMO system using 16-QAM

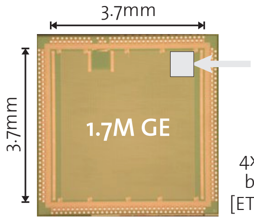
Ensure that each node is visited at most once: The single tree-search (STS) SD algorithm [Studer et al., 2008]

- Concurrent search for ML solution and all counter-hypotheses
- Search a subtree only if the result can lead to an update of either λ^{ML} or of at least one of the metrics $\lambda_{i,b}^{\overline{\mathrm{ML}}}$

STS-SD complexity is **one order of magnitude lower** than RTS complexity

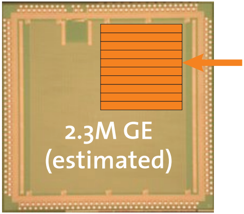
Application of STS-SD to IEEE 802.11n

- 4-stream MIMO in 40 MHz bandwidth
- 600 Mbps operation with real-world RF chains



4x4 MMSE detector 0.05M GE

4x4 IEEE 802.11n baseband ASIC [ETH Zurich, 2008]



4x4 STS detector 0.6M GE

- Commercially available 300 Mbps, 2-stream solutions using sub-optimal MIMO detectors require roughly 2M GEs
- Recall: 1’300M GEs for exhaustive-search 4-stream ML detector

A brief history of the sphere decoding algorithm

- 1981: Pohst describes an algorithm to efficiently identify the closest point in an infinite lattice

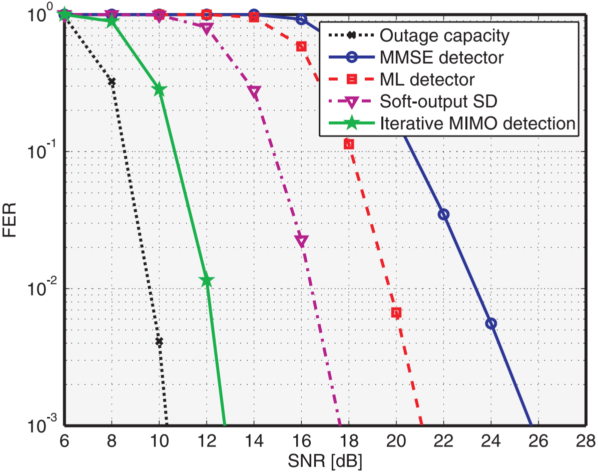
- 1993: Viterbo and Biglieri apply the Pohst strategy to lattice-codes in wireless communication

- 2003: Hochwald and ten Brink propose the first soft-output sphere decoding algorithm

- 2005: Burg et al. provide first VLSI implementation of hard-output sphere decoding

- 2008: Studer et al. develop soft-output STS-SD algorithm and provide a corresponding VLSI implementation

Major challenges ahead



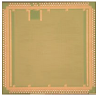
Implementation of iterative MIMO detection: Offers additional 5 dB SNR gain (3 dB away from outage capacity) at 10-fold area increase

Major challenges ahead (cont'd)

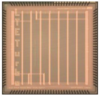
Industry is starting to offer products that employ three spatial streams

- Integration of multiple antennas in small devices
- Detection algorithms that are efficient for more than 6 streams
- Sensitivity to RF impairments

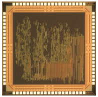
Thank you!



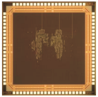
4x4 IEEE 802.11n
baseband ASIC



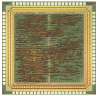
326 Mbps turbo
decoder for LTE



BCJR algorithm
for IEEE 802.11n

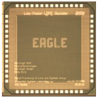


SVD for 802.11n
beamforming

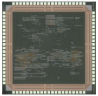


1st sphere
decoder ASIC

1st iterative MIMO
detector ASIC

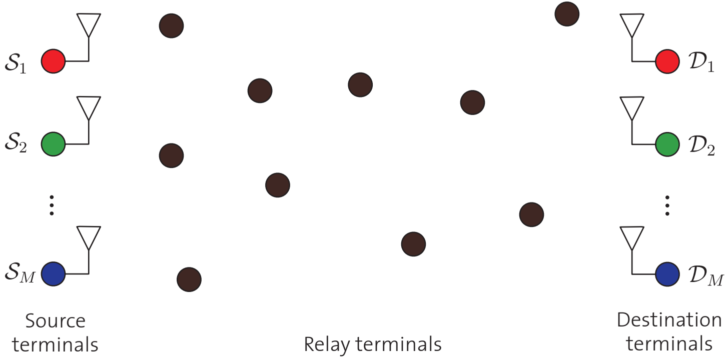


LDPC decoder
for IEEE 802.11n



QR-decomposition
for STS-SD

Relays induce scattering or "clean up" interference [Morgenshtern and HB, 2007]



- "Dumb relays" improve scattering conditions
- Streams can be **separated** at relay level through "smart scatterers"