Managing Massive Interference

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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”

\[ C_{\text{MIMO}} \propto NC_{\text{SISO}} \]

- Requires rich scattering, i.e., that \( H \) 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 600 Mbps 4-stream solution for IEEE 802.11n: Celestrius AG and ETH Zurich, Sept. 2008
Optimum signal separation: Maximum likelihood detection

### Maximum likelihood (ML) MIMO detection

\[
\hat{s} = \arg \min_{s \in \mathcal{O}^{MT}} \| y - Hs \|^2
\]
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

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

\[ \hat{s} = \arg \min_{s \in \mathcal{O}^{MT}} \| y - Hs \|^2 \quad \text{s.t.} \quad \| y - Hs \|^2 \leq r^2 \]

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) \(d(s)\)
3. Update rule: \(d_i(s^{(i)}) = d_{i+1}(s^{(i)}) + |e_i|^2, \ i = M_T, \ldots, 1\) (tree level)
4. ML detection corresponds to finding the leaf with smallest PED

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

Partial Euclidean distance

- \(d_3(s^{(3)}) = |e_3|^2\)
- \(d_2(s^{(2)}) = d_3 + |e_2|^2\)
- \(d_1(s^{(1)}) = d_2 + |e_1|^2\)
Sphere decoding substantially reduces complexity

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):

$$L(x_{i,b}) = \min_{s \in \mathcal{X}^{(0)}_{i,b}} ||y - HS||^2 - \min_{s \in \mathcal{X}^{(1)}_{i,b}} ||y - HS||^2$$

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

1. Use the sphere decoding algorithm to find $\lambda_{\text{ML}}$
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.

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 $\lambda^{ML}$ or of at least one of the metrics $\lambda^{ML}_{i,b}$

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

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
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
- SVD for 802.11n beamforming
- 326 Mbps turbo decoder for LTE
- BCJR algorithm for IEEE 802.11n
- QR-decomposition for STS-SD
- 1st iterative MIMO detector ASIC
- LDPC decoder for IEEE 802.11n
- 1st sphere decoder ASIC
- SVD for 802.11n beamforming
- 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”