Hype, Myths, Fundamental Limits and New Directions in Wireless Systems

Reinaldo A. Valenzuela,
Director, Wireless Communications Research Dept.,
Bell Laboratories
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Need to greatly increase rates for new apps and services....
...Not possible to break the laws of physics...

- Cellular revolution from extensive coverage and mobility
- Universal reuse maximizes spectral efficiency
- Classic deployments dominated by interference (Not the case for Hot Spot, Indoor)
- Link performance is approximating fundamental limits
- Gains from smaller cells, increased spectrum and Interference cancellation

Increasing BW or reducing range is expensive or ineffective

![Diagram showing achievable rate vs. required SNR and data rate vs. bandwidth for SISO and MIMO systems](image)
1-D FDM ORTHOGONAL RELAYS WITHOUT REUSE

K relays between source and destination at unit distance
N = K + 1 orthogonal channels, each gets 1/N of full system bandwidth
Reuse options also explored
All nodes transmit all the time
Reference SNR (K = 0): $\rho$

Propagation loss reduction: $N^\gamma$

**Capacity (total power constant):** $\frac{1}{N} \log_2 (1 + \rho N^\gamma)$

$\frac{1}{N}$ the power per node
Similar to TDM with peak power limit

**Capacity (power per node constant):** $\frac{1}{N} \log_2 (1 + \rho N^{\gamma+1})$

N times total power
Similar to TDM with average power limit

ORTHOGRONAL RELAYS - Power per node constant

Relays: 0 1 2 3 4 5

$\gamma = 4$

Rate (Bits/Symbol)

Reference SNR

-15 -10 -5 0 5 10 15 20

0 1 2 3 4 5

$\Gamma$
ORTHOGONAL RELAYS - Total power constant

No. of Relays = 0

γ = 4

Reference SNR (dB)

Rate (Bits/Symbol)

-15 -10 -5 0 5 10 15 20

0 1 2 3 4 5
Reuse improves performance below 3.18 b/symbol / 4 dB
ORTHOGONAL RELAYS WITH REUSE - Total power constant

Rate (Bits/Symbol) vs. Reference SNR (dB)

G = 4

Reuse 2 curves for 2, 3, 4, and 5 relays

No reuse

Reuse improves performance below 3.18 b/symbol / 7 dB

.5log2(82) = 3.18
Reducing out of cell interference with pico cells

- Increasing base station density for the same users
- Increases capacity per unit area
- At some point most neighboring cells will be idle
- Hardware Versus Software? (NetMIMO) approach

**Methodology**

Baseline network:
- Same number of users and bases
Denser base deployment
- Number of users and geographical coverage fixed
- Increase base density by N along each dimension

Single base detection
- Idle bases create a de facto guard band reducing ICI
- Infrastructure upgrade, hardware approach

Gerard Foschini, Dmitry Chizhik, Reinaldo Valenzuela - Bell Labs
Yifan Liang, Andrea Goldsmith - Stanford University
Reducing Out of Cell Interference with Net MIMO

Net MIMO methodology
- Realistic channel models
  - Planar array, downlink
  - Empirical propagation models

Criterion
- Portion $q$ of users allowed outage
- Deliver equal rate to remaining users

Tradeoff between rate region and complexity
- Dirty Paper Coding (DPC) optimal, complexity high
- Suboptimal schemes include Zero Forcing (ZF), ZF-DPC

Characterization at system level
- Maintain Infrastructure
- Advance signal processing
System Topology

Two dimensional planar array

One user per cell (TD/FD)

User location within each cell
i.i.d. uniform distributed
Propagation Model

Short-range (SR) model
- Mobile user in the neighborhood of the base
- Free-space path loss + Rayleigh

\[ P_r = \left( \frac{\lambda}{4\pi d} \right)^2 \cdot G \cdot g \cdot P_t \]

Long-range macro-cell model (Hata)
- Path-loss + shadowing + fading

\[ 10 \log_{10} \left( \frac{P_r}{P_t} \right) = -L_{dB} + G_{dB} + \psi_{dB} + 10 \log_{10} (g) \]

Propagation characteristics change at
- Transition distance \( d_t \), i.i.d. 30–70m
- Cutoff distance \( d_c \), \( 2\sqrt{3}R \)
Infrastructure Upgrade

$N = 1$

$N = 2$

$N = 3$
Operating Regime Shift

![Graph showing signal to impairment power ratio vs. number of bases relative to baseline network (N). The graph includes lines for combined, interference only, and noise only scenarios.]
CDF of SINR

![Graph showing the CDF of SINR with different values of N (1, 2, 3, 4, 5)]
Net MIMO: Zero-Forcing Beamforming

Declare portion $q$ of users in outage

- Users with smallest channel gain norms

Notations

- Input $X_{m_r \times 1}$
- Precoding $W_{m_t \times m_r}$
- Channel $H_{m_r \times m_t}$
- Output $Y_{m_r \times 1}$
- Noise $Z_{m_r \times 1}$

$$
Y_{m_r \times 1} = H_{m_r \times m_t} \cdot W_{m_t \times m_r} X_{m_r \times 1} + Z_{m_r \times 1}
$$

$$
H_{m_r \times m_t} \cdot W_{m_t \times m_r} = I
$$

ZF: NO ICI
Power Optimization for ZF

Criterion: max min received SNR

\[ \rho_i = \frac{P_i}{N_0} \]

Subject to per-antenna power constraint

\[ \sum_{i=1}^{m_r} |W_{ji}|^2 P_i \leq P_{\text{max}}, \quad \text{for} \quad 1 \leq j \leq m_t \]

Solution

\[ P_i = P_{ZF} = \frac{P_{\text{max}}}{\max_j \sum_{i=1}^{m_r} |W_{ji}|^2} \]
Zero-Forcing Dirty Paper Coding

Interference totally eliminated through

- Orthogonal constraint
- Dirty paper coding

Declare portion $q$ of users in outage

- Users with smallest channel gain norms

Specify encoding order

- Heuristic algorithm proposed in view of fairness
Optimization for ZF-DPC

Channel QR decomposition $H = LQ$

Precoding matrix $W = Q'$

Receive signal $y = HX + z = LQQ'x + z = Lx + z$

Criterion: max min received SNR

Subject to per-antenna power constraint

Solution

$$P_i = \frac{P_{ZF-DPC}}{\left|L_{ii}\right|^2} = \frac{P_{\text{max}}}{\max_j \sum_{i=1}^{m_r} \left|W_{ji} / L_{ii}\right|^2}$$
Comparison: Pico Cells Vs. Net MIMO

Target: max min SINR at outage level $q$

Under a realistic channel model

Denser deployment outperforms ZF when $N \geq 4$

Close-to-optimal ZF-DPC outperforms denser deployment
Network MIMO: Potential performance gains

Throughput (bps/Hz/base)

Uplink: Users to Bases

Downlink: Bases to Users

(1,1) (2,2) (4,4)

(1,1) (2,2) (4,4)

Conventional: SU MIMO, no coordination

Network MIMO

Up to a factor of 5 capacity gain using network MIMO under ideal conditions.

What gains could be achieved in practice?

[R. Valenzuela department]
## Summary: MIMO strategies

<table>
<thead>
<tr>
<th>Recommended strategy</th>
<th>Cellular network type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU MIMO techniques</td>
<td>Urban macrocell with reduced frequency reuse and peak rate is more important than throughput (6-sectors + SU-MIMO (SM))</td>
</tr>
<tr>
<td>SU MIMO techniques</td>
<td>Urban macrocell with universal frequency reuse (6-sectors + MU-MIMO (ZF-BF))</td>
</tr>
<tr>
<td>MU MIMO techniques</td>
<td>Suburban macrocell (adaptive BF for increasing throughput)</td>
</tr>
<tr>
<td>MU MIMO techniques</td>
<td>Rural macrocell (adaptive BF for increasing range)</td>
</tr>
<tr>
<td>Network MIMO</td>
<td>Cluster of cells with high-speed backhaul (indoor femtocell network or future macrocell network)</td>
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</tbody>
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Concluding remarks

Next generation systems must deliver a significant and cost effective performance improvement

- Increasing Bandwidth hits battery power limits
- Reducing cell size or increasing Tx power may be too expensive
- Relay help with coverage at low spectral efficiency

**Network MIMO** may deliver substantial performance gains:

- Initial uplink results are promising:
  - Median goodput more than doubled.
  - 5-fold increase in cell edge (90% availability) goodput.

Results show that network MIMO is viable within constraints of **WiMAX**.

- In particular, channel estimation not a problem indoors (but real test will be outdoors).