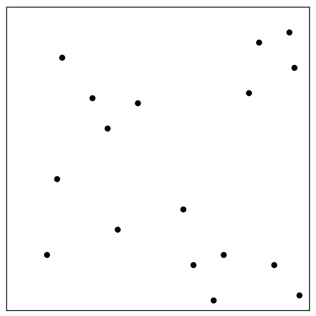
On Capacity Scaling in Arbitrary Wireless Networks

Urs Niesen — uniesen@mit.edu
Piyush Gupta — pgupta@research.bell-labs.com
Devavrat Shah — devavrat@mit.edu

Laboratory for Information and Decision Systems
Massachusetts Institute of Technology
Cambridge, MA 02139

Complex Systems Analysis and Optimization Department
Bell Labs, Alcatel-Lucent
Murray Hill, NJ 07974

Model



- Place n nodes on $[0,\sqrt{n}]^2$ with minimum-separation $c > 0$
- n source-destination pairs; each node is source and destination for exactly one of them
- $y_v[t] = \sum_{u \neq v} h_{u,v}[t] x_u[t] + z_v[t]$
- $h_{u,v}[t] = r_{u,v}^{-\alpha/2} \exp(\sqrt{-1}\theta_{u,v}[t])$
- $\{\theta_{u,v}[t]\}_{u,v}$ i.i.d. uniform over $[0, 2\pi)$; either i.i.d. in t (fast fading) or constant in t (slow fading)
- Full CSI

Main Results

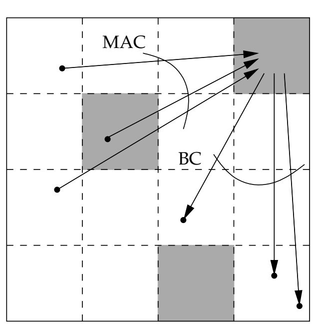
Hierarchical Relaying

- We present a hierarchical cooperative communication scheme, achieving a per node rate of $\rho^{\text{HR}}(n) \geq n^{1-\alpha/2-o(1)}$ for any $\alpha > 2$
- We show that for the best communication scheme $\rho^*(n) = O(n^{1-\alpha/2+\varepsilon})$ for $\varepsilon > 0$ arbitrarily small and for any $2 < \alpha \leq 3$
- Thus our scheme is order optimal for $2 < \alpha \leq 3$

Cooperative Multi-hop

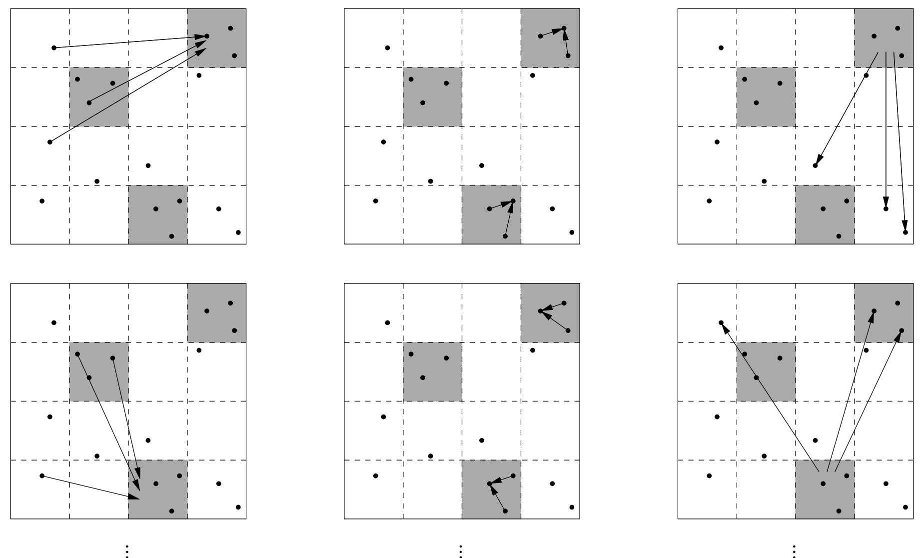
- For random and regular networks, multi-hop communication is optimal for $\alpha > 3$
- For arbitrary node placements this is no longer true
- Optimality of multi-hop depends on regularity of network
- We present a cooperative multi-hop scheme that "interpolates" between our hierarchical relaying scheme and multi-hop depending on the amount of regularity
- For $\alpha > 3$ we show that our scheme is order optimal under adversarial node placement with regularity constraint

Hierarchical Relaying Scheme

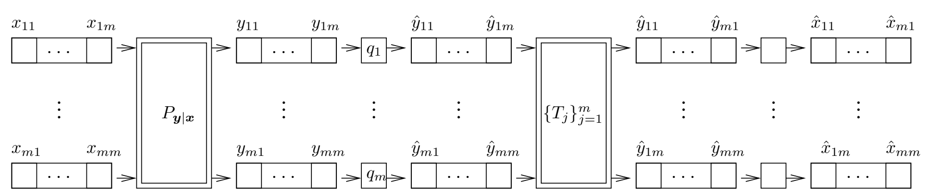


- Divide $[0,\sqrt{n}]^2$ into squarelets
- Constant fraction of squarelets are dense (contain many nodes)
- Source-destination pairs relay traffic over dense squarelets
- Induces virtual multiple antenna multiple access and broadcast channels

Hierarchical Relaying Scheme:Details



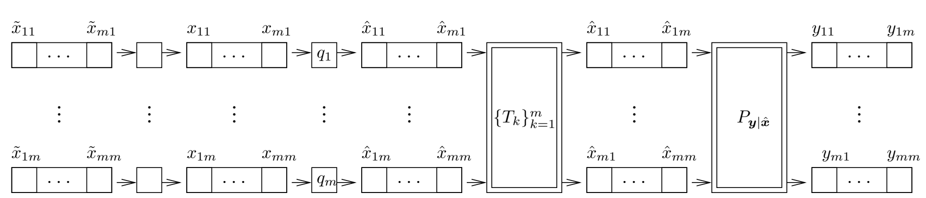
MAC Phase



MAC phase at level ℓ in the hierarchy.

- Block 1: Wireless channel between source and relay nodes
- Block 2: Quantizers $\{q_i\}_{i=1}^m$ used at the relay nodes
- Block 3: Use m times the scheme at level $\ell + 1$
- Block 4: matched filters at the relay nodes

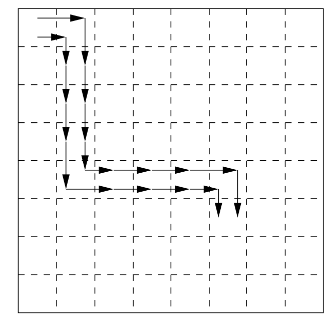
BC Phase



BC phase at level ℓ in the hierarchy.

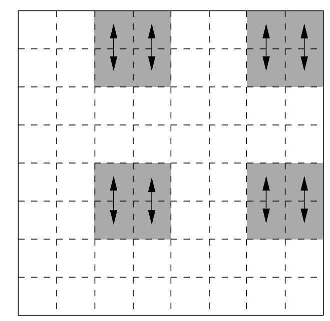
- Block 1: Transmit beamforming at each relay node
- Block 2: Quantizers $\{q_j\}_{j=1}^m$ used at the relay nodes
- Block 3: Use m times the scheme at level $\ell + 1$
- Block 4: Wireless channel between relay and destination nodes

Cooperative Multi-Hop Scheme

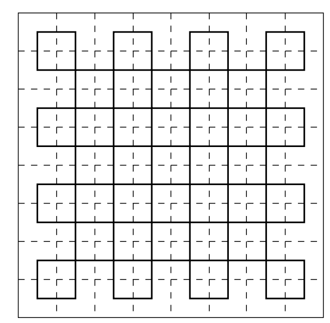


- A node placement is **regular at resolution $h(n)$** if every square of sidelength $h(n)$ contains $Kh(n)^2$ nodes
- Squares of sidelength $h(n)$ cooperatively communicate with their neighbors
- Multi-hop routing across squares

Cooperative Multi-Hop Scheme: Details

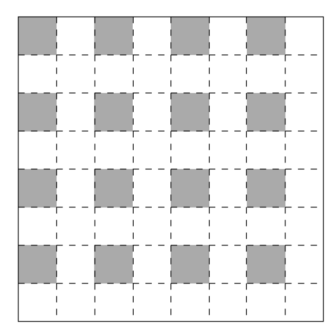


- Divide $[0,\sqrt{n}]^2$ into squares at level of regularity $h(n)$
- Use hierarchical relaying scheme between neighboring squares (shown for vertical communication)
- Neighbors far enough apart communicate simultaneously (spatial reuse)



- This procedure defines a regular communication graph
- Each edge can simultaneously support rate $h(n)^{2-\alpha-o(1)}$
- Use standard multi-hop communication scheme over this graph
- This achieves $\rho^{\text{CMH}}(n) \geq h(n)^{3-\alpha} n^{-1/2-o(1)}$

Optimality under Adversarial Node Placement



- Divide $[0,\sqrt{n}]^2$ into squares at level of regularity $h(n)$ as before
- Place equal number of nodes in every fourth square
- For this node placement can show that best scheme achieves $\rho^*(n) = O(h(n)^{3-\alpha} n^{-1/2+\varepsilon})$ for $\varepsilon > 0$ arbitrarily small, and $\alpha > 3$