Previous work on the scaling behavior of capacity of ad hoc networks studied two regimes: the dense regime, where an increasing number of nodes is placed in a fixed area; and the extended regime, where area and the number of nodes scale identically.

We aim to study a regime where the scaling of area is treated as a free parameter.

This is joint work with A. Ozgur and O. Leveque (EPFL) and D. Tse (Berkeley).

**STATUS QUO**

**NEW INSIGHTS**

We characterize the capacity of a random ad hoc network model when area scales independently of the number of nodes. The scaling regime we consider reveals optimal communication strategies as we vary the area scaling and the path loss.

**END-OF-PHASE GOAL**

Develop scaling regimes to obtain insights into better schemes.

Determine robustness of scaling results to channel model definition.

**COMMUNITY CHALLENGE**

Physical area is a fundamentally distinct parameter from network size, and should be allowed to scale independently.
Motivating philosophy

We are interested in developing a parsimonious characterization of the various operating regimes for wireless networks, and how these operating regimes depend on engineering parameters such as:

- Number of nodes
- Power
- Area
- Path loss characteristics

*Joint work with A. Ozgur, O. Leveque, D. Tse.*
Prior results on scaling

Two main network models:

- **Dense networks:**
  Area held constant, and number of nodes $\rightarrow 1$

- **Extended networks:**
  Area increases proportional to number of nodes

Starting with Gupta and Kumar (2000), where the dense network model was studied under a multihop transmission strategy, various works studied performance in these regimes.

Most recently Ozgur et al. (2007) characterized scaling laws for capacity in both dense and extended networks.
Intermediate density model formulation

Our approach here: area should be a distinct parameter!

- We consider a random network model where \( n \) nodes are located uniformly at random in an area \( A \).

As we only consider scaling behavior of capacity, we assume \( A = n^{\beta} \), where \( \beta > 0 \).

- Nodes are grouped into random source-destination pairs, with uniform traffic matrix.

- We assume that each node has a transmit power constraint \( P \) that does not scale with \( n \), and that the path loss exponent is \( \alpha \).
We employ a cutset bound.

For presentation simplicity, consider 1-D.

Start by considering $n^\gamma$ sources transmitting to $n^\gamma$ destinations, separated by $n^\gamma$ nodes:

Using an analog of the argument in Ozgur et al., we can show that the capacity of this system is exactly the cutset bound for the full 1-D network.
By showing that independent transmissions give the upper bound, then adding together received power from all transmit nodes, we obtain:

\[ C(S, D) \cdot n^\gamma \in O(\min\{ n^{(1-\beta)\alpha + \gamma(1 - \alpha)}, 1\}). \]

Thus the best exponent is:

\[ \max_{0 \leq \gamma \leq 1} \min \{(2 - \alpha)\gamma + (1 - \beta)\alpha, \gamma\} \]

We refer to the optimizing value \( \gamma^* \) as the optimal cluster size.
Achievability

- When $\beta > 1$: The network is “overextended”, but capacity achieving schemes are identical to extended network (cf. Ozgur et al.): hierarchical cooperation with MIMO if $\alpha < 2$, multihop if $\alpha > 2$.

- When $\beta < 1$:
  - If $\alpha < 1/\beta$ or $\alpha < 2$, then hierarchical cooperation is optimal.
  - If $\alpha > 1/\beta$ and $\alpha > 2$: *Neither hierarchical cooperation nor multihop is optimal!*
Achievability

We consider a scheme that uses multihop transmission at the level of clusters; each hop is realized using hierarchical cooperation via MIMO.

Suppose we use the optimal cluster size, and consider two adjacent clusters of size $n^\gamma$.

These two clusters can be equivalently viewed as a dense network with $O(n^\gamma)$ nodes and per node power constraint $P \psi (A n^\gamma /n)^{-\alpha}$.

Our key insight is that this per node power constraint is equal to $P /n^\gamma$, which is exactly the power threshold needed to execute the hierarchical cooperation scheme of Ozgur et al. in dense networks.

Thus between adjacent clusters, hierarchical cooperation suffices to achieve throughput $O(n^\gamma)$. 
Treating area as a free parameter leads to a new, “intermediate density” operating regime with a new transmission scheme: Multihop transmission between clusters, with hierarchical cooperation via MIMO to achieve cluster-to-cluster hops.

The diagram on the first slide is the generalization to 2-D, and demonstrates how the optimal scheme depends on the area scaling and the path loss exponent.

However, this is still not a complete story: we are still investigating whether there is a unifying perspective that resolves the different schemes present in that diagram.