Non-cooperative Wireless Networks

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MIMO Wireless Systems

• With receive antenna cooperation: \( C = M \log(\text{SNR}) \)

• Without receive antenna cooperation: \( C = \log(\text{SNR}) \), (Interference channel, Carleial, 1975)

Can we realize a pre-log of \( M \) without receive antenna cooperation?
An Interference Relay Network
Review of Previous Work

- Ground-breaking work by Gupta & Kumar, 2000 shows that capacity in large ad-hoc networks scales at least as $\Theta(\sqrt{n})$.

- Capacity in large relay networks scales as $\Theta(\log n)$ (Gastpar & Vetterli, 2002).

- Capacity in large ad-hoc networks with node mobility scales as $\Theta(n)$ (Grossglauser & Tse, 2002).

- Capacity in large ad-hoc networks with network coding scales as $\Theta(n)$ (Gupta & Kumar, 2003).

- Power efficiency in large fading relay networks scales at least as $\Theta(\sqrt{n})$ (Dana & Hassibi, 2003).
Assumptions

- All terminals are equipped with single-antenna transceivers.

- A number of designated source-destination (S-D) pairs wants to establish communication assisted by a set of relays.

- No cooperation between source terminals and between destination terminals.

- No direct links between source and destination terminals.

- As the network grows large the number of S-D pairs remains constant, the number of relay terminals goes to infinity.

- Encompasses traditional relay networks as special case.
MIMO Gains in Coherent Point-to-Point Links

- In an $M \times M$ coherent MIMO system, capacity satisfies (receive antenna cooperation necessary)

\[ C \approx M \log(\text{SNR}) \]

with the **multiplexing gain** given by the pre-log $M$.

- **Array gain** is the SNR improvement resulting from coherent combining. In a $1 \times M$ system with perfect receive CSI

\[ C \approx \log(M \text{ SNR}) \]

with **array gain** $M$. 

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Interference Relay Network

M source nodes

First hop

Second hop

M destination nodes

Independent data streams

K single-antenna relay terminals
Interference Relay Network Cont’d

- **Source nodes** transmit independent data streams.

- **Two-hop communication** using a “listen and transmit” protocol with $K$ relays and **perfect synchronization**.

- **Channels** $H_k$ and $G_k$ are ergodic i.i.d. Gaussian block-fading.

- Random variables $E_k$ and $P_k$ capture **large-scale fading** and **path loss**.

- **Nodes** are placed in a **domain of fixed area** with a **dead-zone around source and destination nodes** ⇒ $E_k$ and $P_k$ are positive and bounded.
An Upper Bound on Network Capacity

- **Destination terminals** are assumed to be able to **cooperate** and have **perfect knowledge** of the composite MIMO channel.

- **Relay terminals** have **perfect knowledge** of all their **backward and forward channels**.

- **Upper bound** through "max-flow min-cut theorem"

\[
\sum_{i \in S, j \in S^c} R^{(i,j)} \leq I(X^{(S)}; Y^{(S^c)} | X^{(S^c)}).
\]
Cut set bound achieved if all the relay and destination terminals cooperate.
Lower Bound: Relay Partitioning
Lower bound through relay partitioning, MF, and independent decoding (i.e. no cooperation) at destination terminals.
Distributed multi-stream separation through smart scatterers performing matched-filtering.
Capacity Scaling: Main Result

• For $K \to \infty$, lower bound approaches upper bound and the network capacity converges (w.p.1) to

$$C = \frac{M}{2} \log(K) + O(1).$$

• Asymptotically in $K$ cooperation between destination terminals is not needed to achieve network capacity.

• Independent decoding at the destination terminals achieves network capacity ⇒ significant reduction in computational complexity compared to vector decoding.
Capacity Scaling: Implications

- **Multiplexing gain of** $M/2$ **without cooperation** between destination terminals.

- **Loss in spectral efficiency** (factor 1/2) due to “listen and transmit” protocol.

- **Distributed array gain of** $K$. 
Distributed Interference Cancelation
Practical Ramifications

- **Multi-stream separation** realized in a completely decentralized fashion ⇒ Distributed interference cancelation.

- **Network coding not needed** to achieve capacity in large interference relay networks ⇒ *Matched filtering is good enough.*
No Channel Knowledge at the Relays

• We relax the assumption of channel knowledge at the relays. $k$-th relay terminal needs to know $E_k +$ noise variance.

• Relays simply perform amplify-and-forward (AF).

• Receiver knows composite MIMO channel.
AF Interference Relay Networks

- M source nodes
- First hop
- Second hop
- M destination nodes

- Amplify-and-forward

- Independent data streams
- K single-antenna relay terminals

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Capacity Scaling in the AF Case

• In the large relay limit $K \to \infty$, AF interference relay network approaches point-to-point MIMO system with perfect receive CSI.

• Asymptotic capacity is half the capacity of a point-to-point coherent MIMO channel given by (receive terminal cooperation necessary)

$$C_{AF}^{\infty} = \frac{M}{2} \log(\text{SNR}) + O(1).$$

• SNR depends critically on $E_k$. 
Capacity Scaling in the AF Case Cont’d

- **Multiplexing gain** of $\frac{M}{2}$ realized.

- Number of relay terminals does not enter scaling law! $\Rightarrow$ No distributed array gain.

- **Relays** can help to **restore the rank of poor-scattering channels** (active (but dumb) scatterers).

- **Cooperation** between **destination terminals** is crucial.
Convergence of Capacity in the AF Case

Capacity vs. number of relays for the AF interference relay network
Conclusion

• We showed that **MIMO gains** can be realized in **large interference relay networks** in a **completely distributed fashion**.

• **Smart scatterers** realize **multi-stream separation** without cooperation between any of the terminals.

• **Dumb scatterers** rebuild multiplexing gain in poor-scattering environments.

• **Open Issues:** Synchronization, scaling number of source-destination terminals as well.