Non-cooperative Wireless Networks

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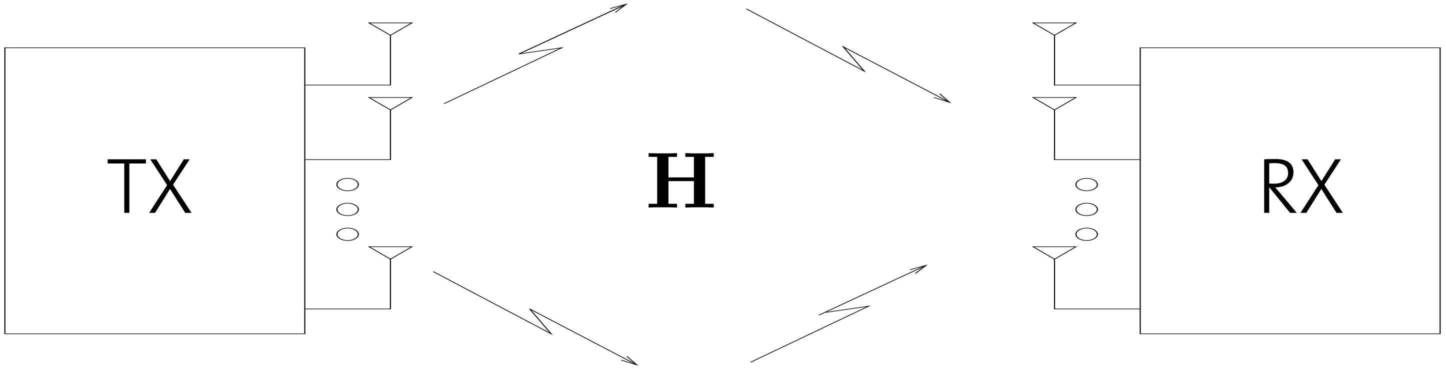
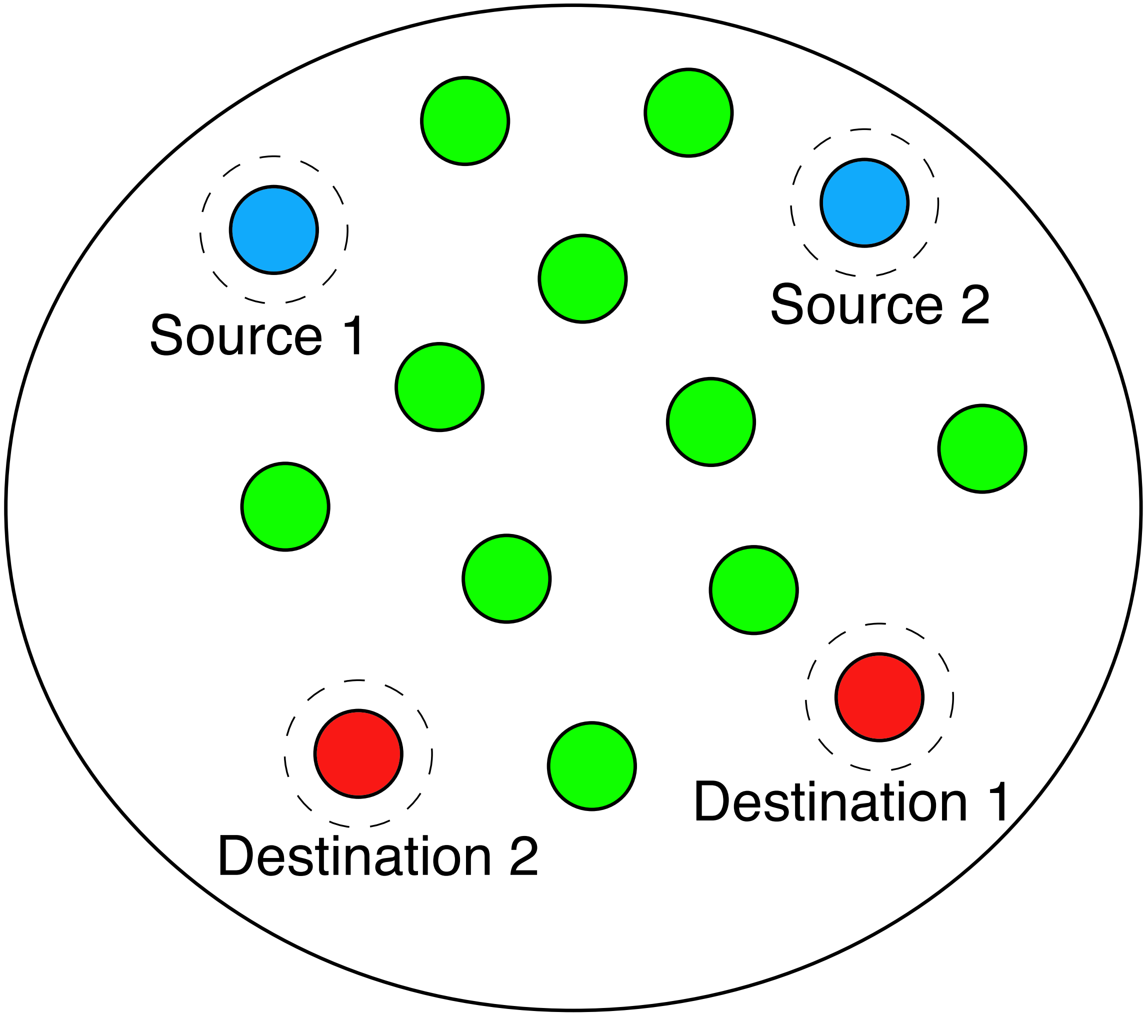
MIMO Wireless Systems



- 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)

  $$C \approx M \log(\mathsf{SNR})$$

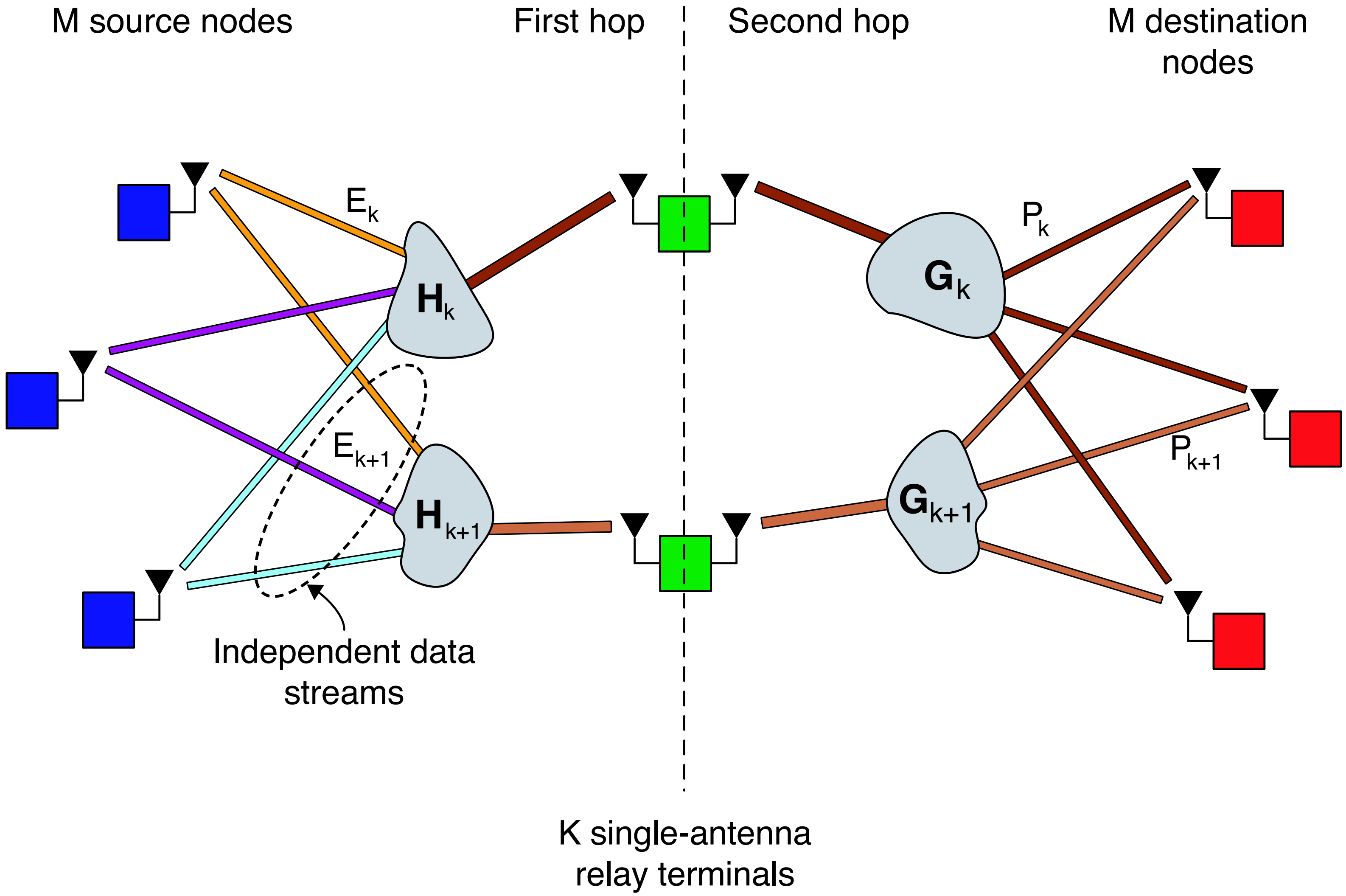
  with the **multiplexing gain** given by the pre-log M.

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

  $$C \approx \log(M\,\mathsf{SNR})$$

  with **array gain** M.

Interference Relay Network



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 $\mathbf{H}_k$** and $\mathbf{G}_k$ 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** $\Rightarrow E_k$ and P_k are positive and bounded.

An Upper Bound on Network Capacity

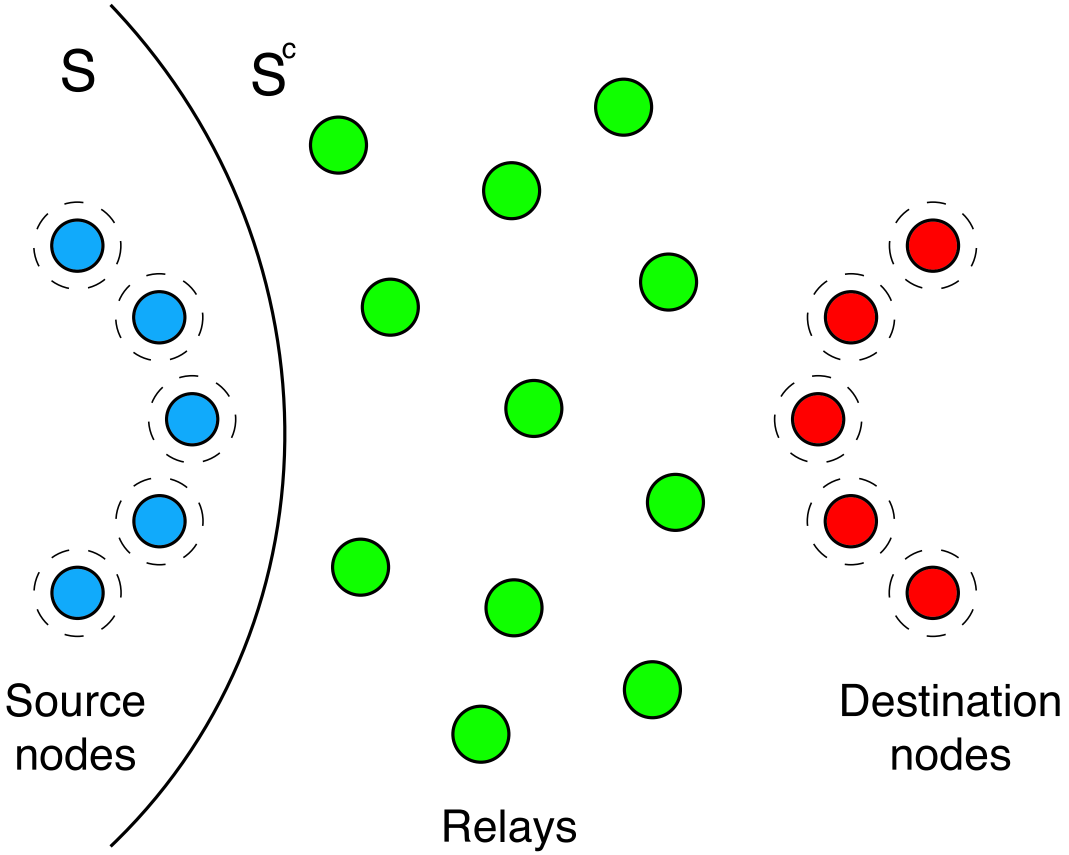
- **Destination terminals** are assumed to be able to **cooperate** and have **perfect knowledge** of the **composite MIMO channel**.

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

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

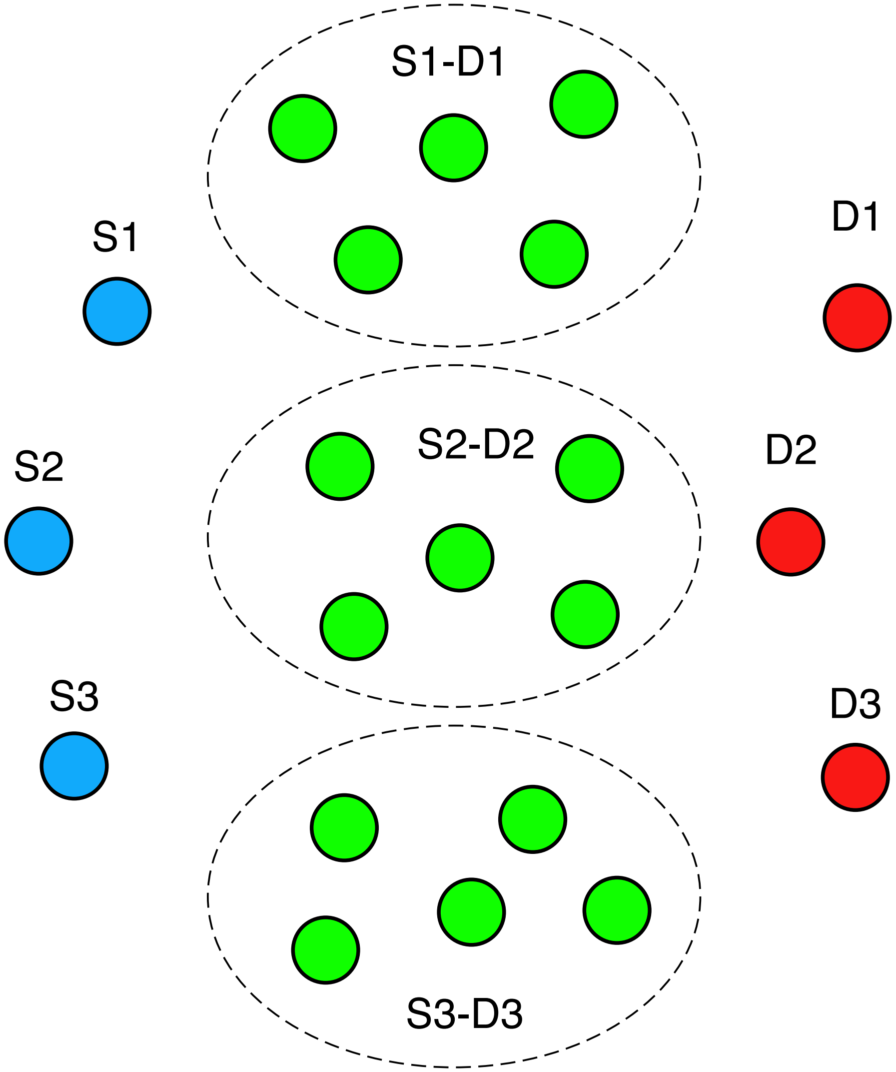
$$\sum_{i \in \mathcal{S}, j \in \mathcal{S}^c} R^{(i,j)} \leq I(\mathbf{X}^{(S)}; \mathbf{Y}^{(S^c)} | \mathbf{X}^{(S^c)}).$$

The Broadcast Cut

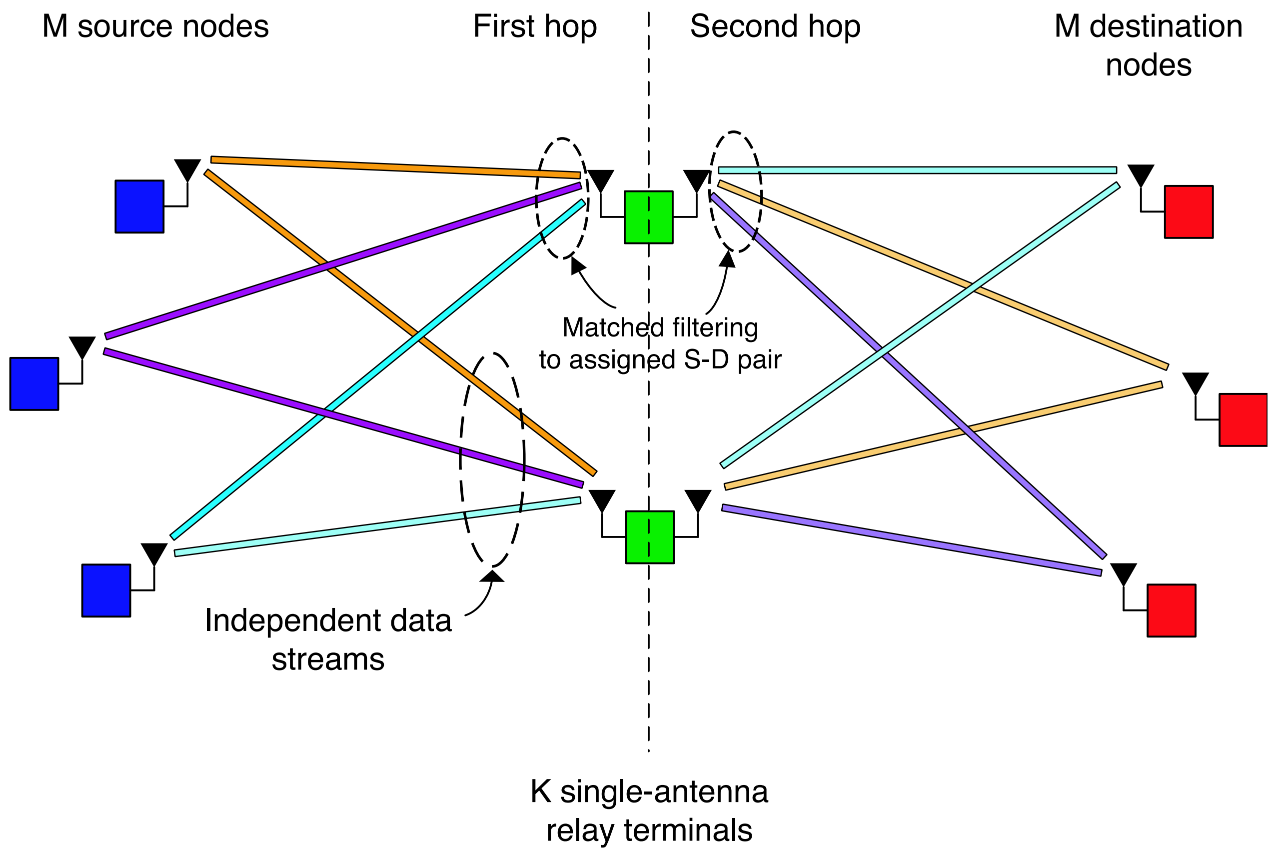


Cut set bound achieved if all the relay and destination terminals cooperate.

Lower Bound: Relay Partitioning

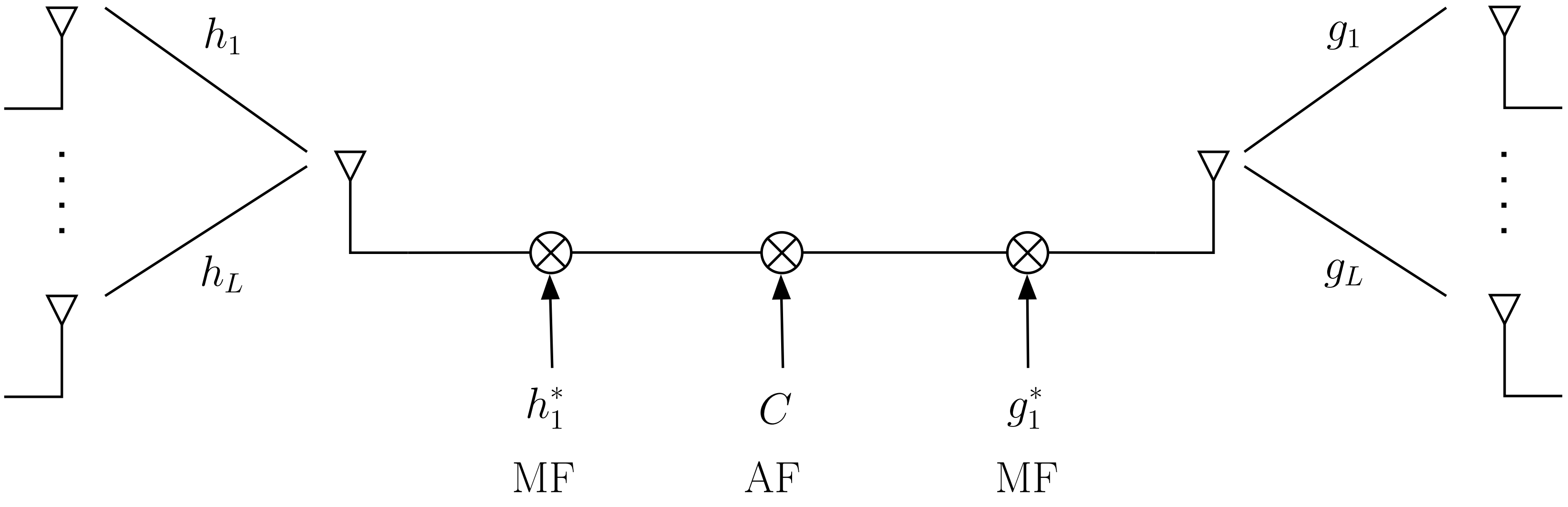


Lower Bound: Matched Filtering



Lower bound through relay partitioning, MF, and independent decoding (i.e. no cooperation) at destination terminals.

Smart Scattering



Distributed multi-stream separation through **smart scatterers** performing **matched-filtering**.

Capacity Scaling: Main Result

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

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

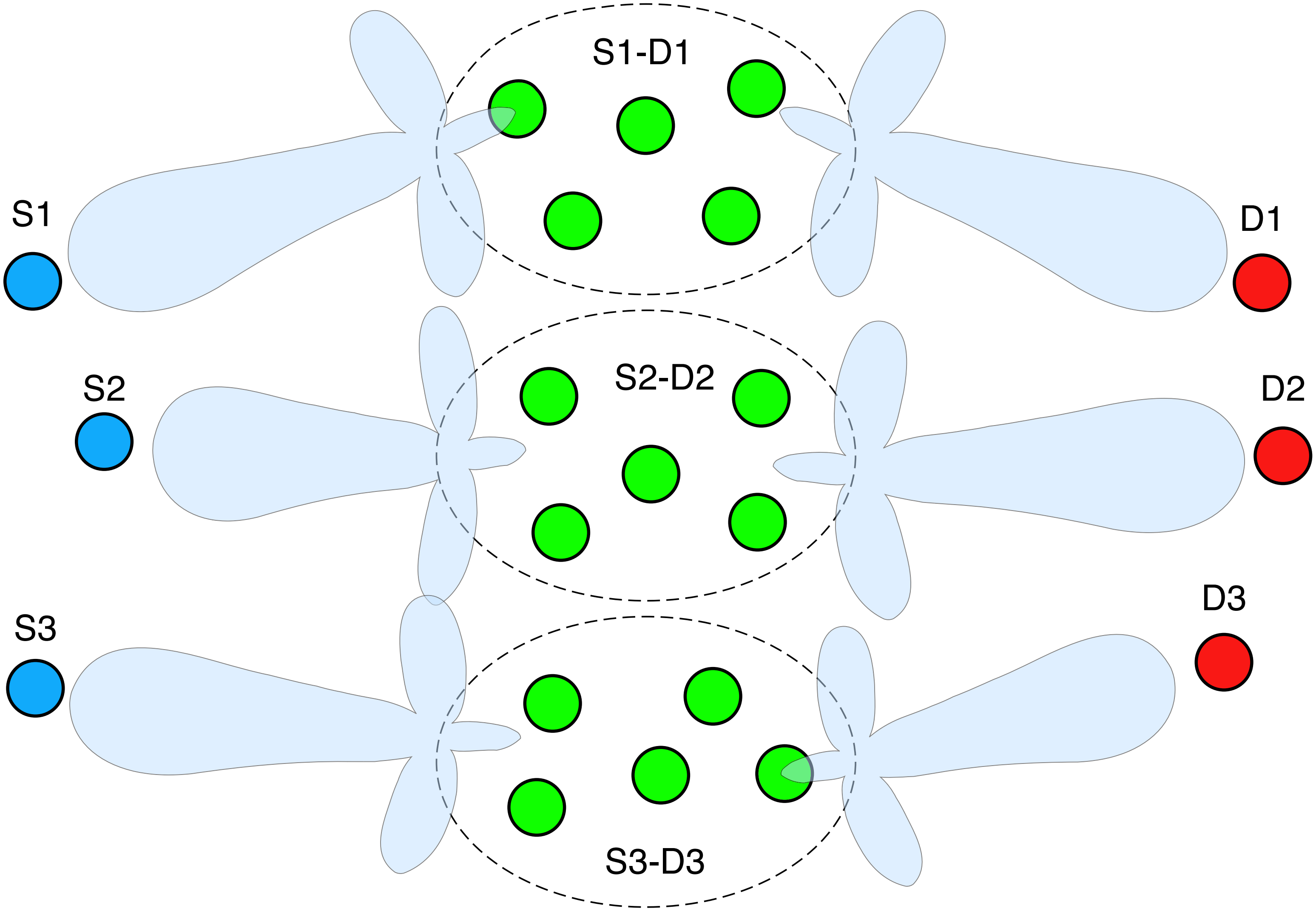
- **Asymptotically** in K **cooperation between destination terminals** is **not needed to achieve network capacity**.

- **Independent decoding** at the destination terminals **achieves network capacity** $\Rightarrow$ significant **reduction in computational complexity** compared to **vector decoding**.

Capacity Scaling: Implications

- **Multiplexing gain** of $\boldsymbol{M/2}$ **without cooperation** between destination terminals.
- **Loss in spectral efficiency** (factor $1/2$) due to "*listen and transmit*" protocol.
- **Distributed array gain** of $\boldsymbol{K}$.

Distributed Interference Cancelation



Practical Ramifications

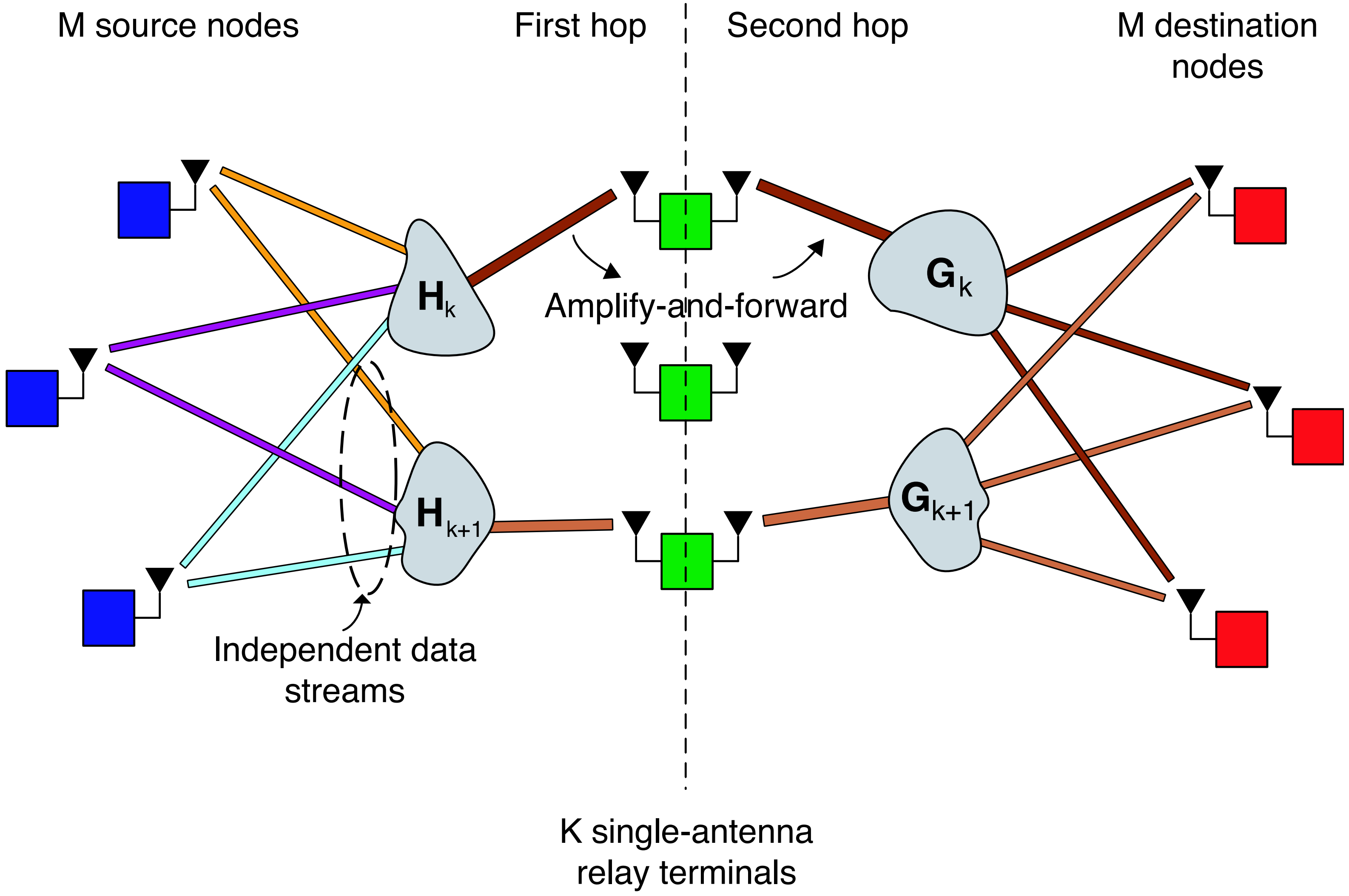
- **Multi-stream separation** realized in a completely **decentralized fashion** ⇒ **Distributed interference cancelation**.

- **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

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)

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

- SNR depends critically on E_k.

Capacity Scaling in the AF Case Cont'd

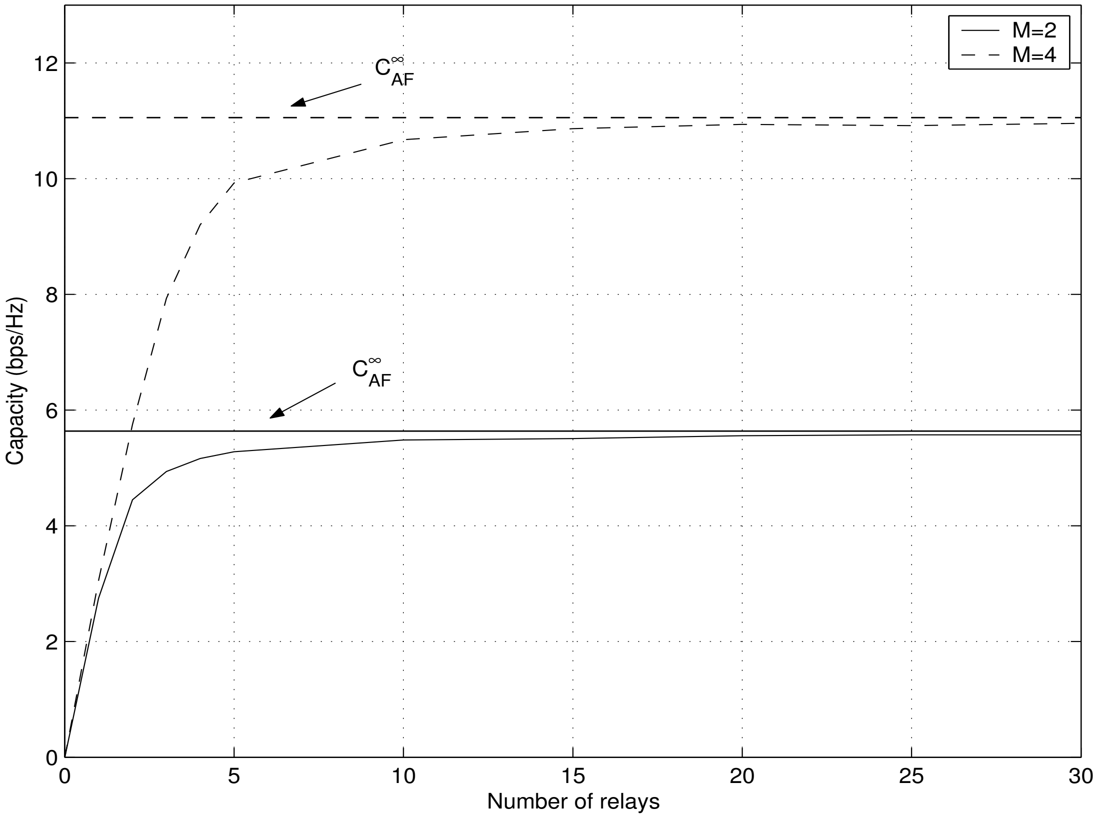
- **Multiplexing gain** of $M/2$ realized.

- **Number of relay terminals does not enter scaling law!** ⇒ **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.