Distributed Antennas:
The Concept of Virtual Antenna Arrays

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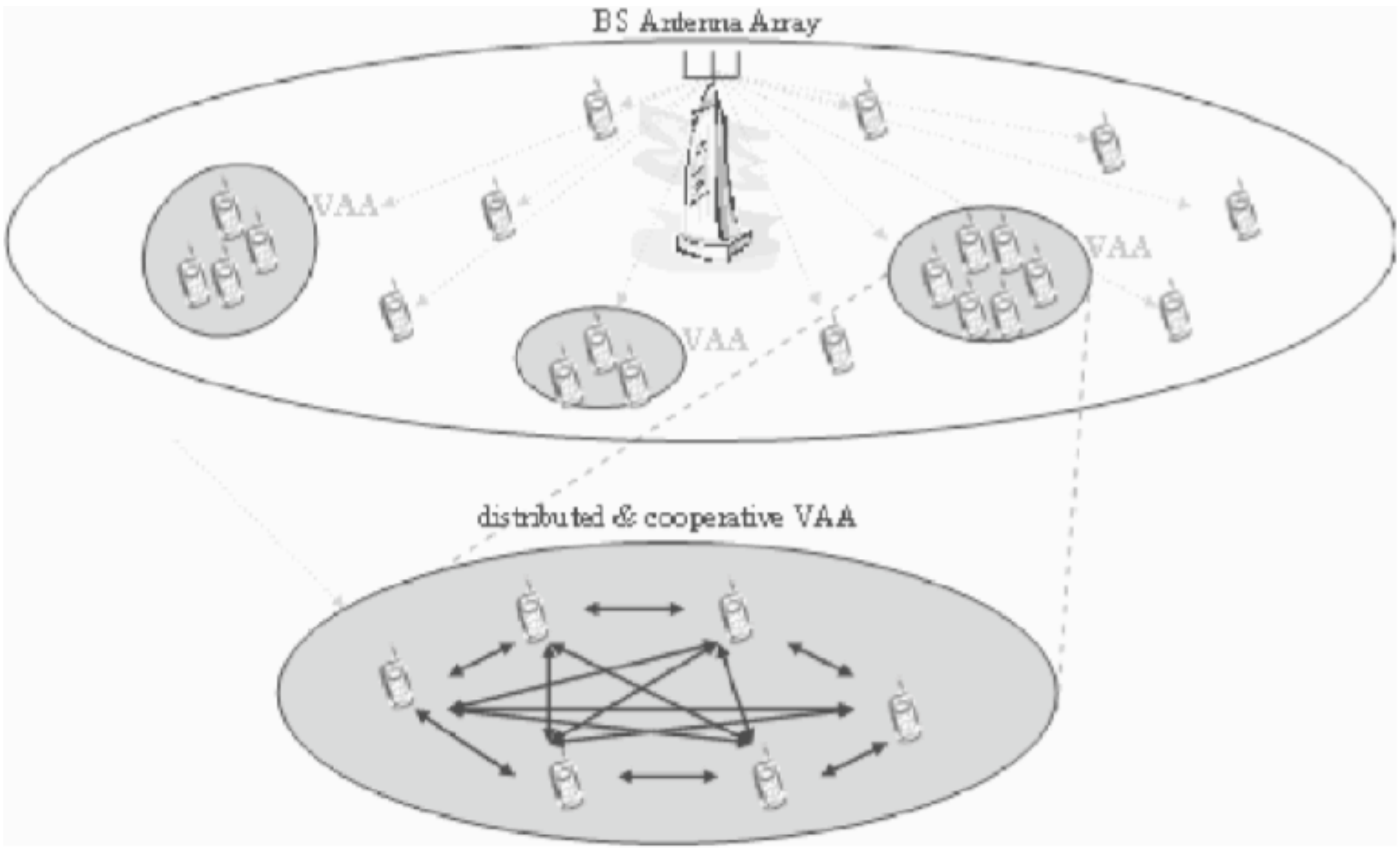
Outline

- Basic Idea: Cooperation
- Combining Great Ideas: Relays and MIMO
- Network Topologies and Application to Existing Architectures
- MIMO Capacity
  - Ergodic Capacity
  - Orthogonal MIMO Channel Capacity
- Resource Allocation

Basic Idea

- Idea: Allow cooperation between spatial adjacent mobile terminals (MTs)
  - Space-time coding across MTs and MT antennas



Motivation: Relay Channels

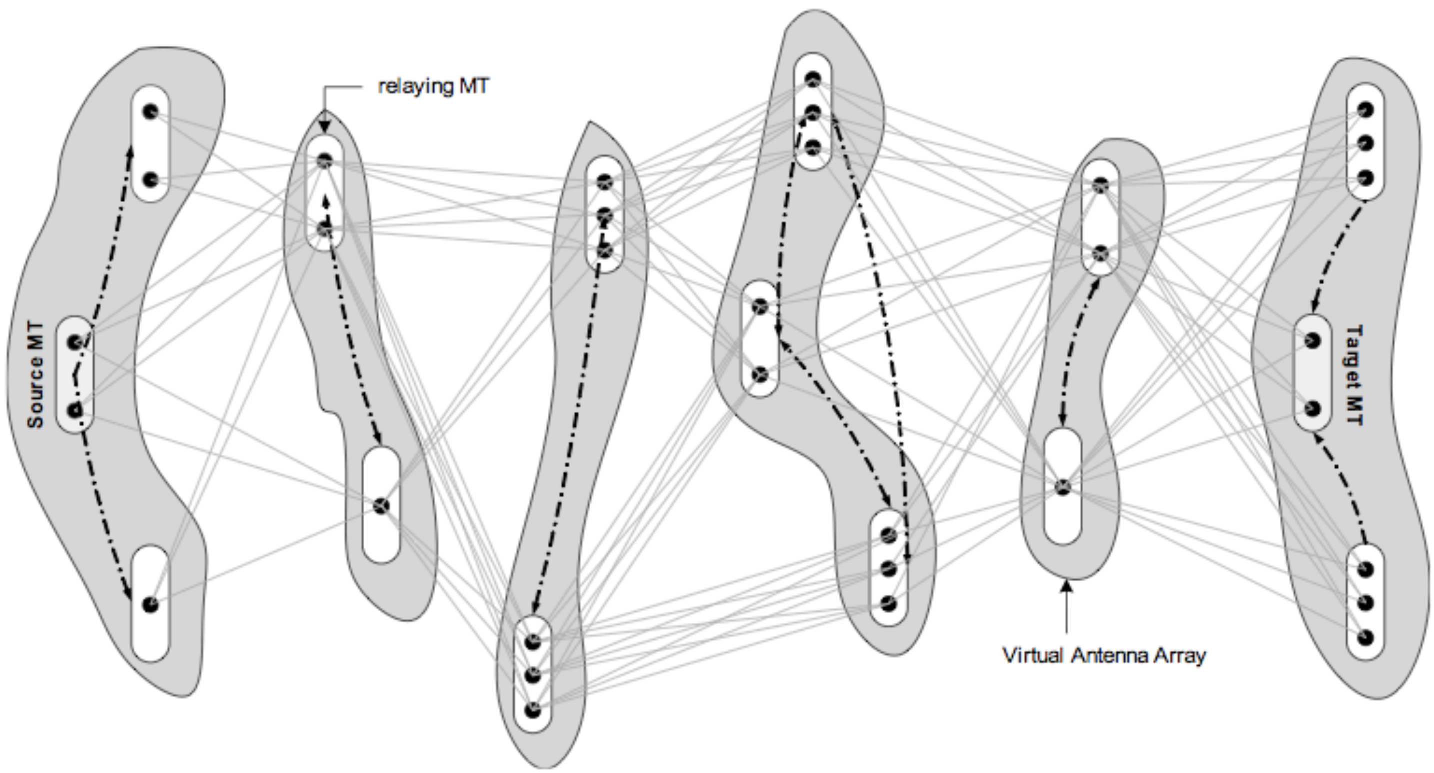
- Practical Importance: MT relay to other MTs on service boundary
- Theoretical Motivation: information theoretic formulation by Cover and El Gamal
- Simple Proposed Protocols:
  - Senonaris: MTs broadcast to BS, adjacent MTs retransmit to BS
  - Wornell: Similar but with decode-and-forward and amplify-and-forward
- Laneman: cooperation yields full spatial diversity Scaling Laws:
  - Gupta & Kumar: per MT capacity decreases with number of users in fixed (although could be random) topology
  - Grossglauser & Tse: Mobility counter-acts decrease in per MT capacity
    - hand off information to MTs that are passing by

Motivation: MIMO Systems

- Telatar: Capacity gains with additional antennas
- Alamouti: Space-time codes to achieve full transmit diversity
- Tarokh: Generalized theory of space-time codes
- MIMO Relaying results of Gupta & Kumar:
  - Considered general topology allowing MTs to communicate to whomever is needed to maximize the system capacity
  - Characterized achievable rate region of the network
    - Requires sophisticated multi-user coding schemes to achieve
    - How achieve in real systems?

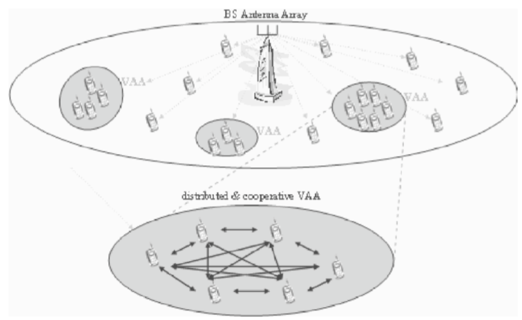
Virtual Antenna Array Relaying Topology

- Specific case of Gupta & Kumar
  - Group MTs into relay tiers and allow cooperations within tiers
  - Trade-off between absolute optimality and complexity



Virtual Antenna Arrays in Cellular Networks

- MIMO base station transmit space-time encoded data stream to MTs.
- MTs may form VAAs. Each MT extracts the information it can from the data stream and then relays the information to the other MTs in its VAA.
- After all MTs in a VAA share data, can decode the entire data stream.



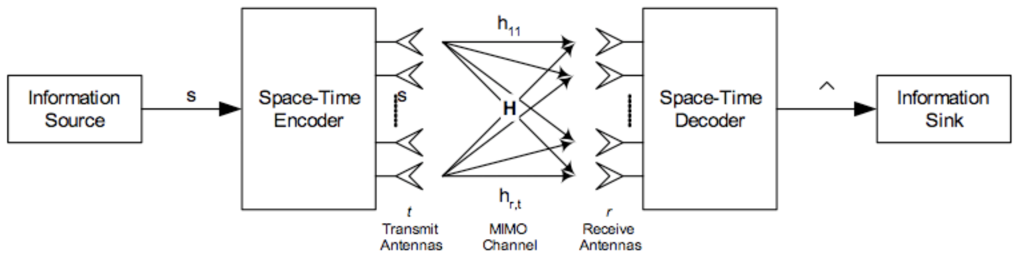
- Example: Use W-CDMA for BS-MT link, bluetooth between MTs
- Difficulties: Full duplex, frequency division, transparent vs. regenerative relay.

Virtual Antenna Arrays in other Networks

- WLAN
  - Issues at coverage edges and possible interference between access points.
  - Rarely power issues.
  - WLAN protocol to access point; blue tooth or UWB between devices.
  - HiperLAN2: direct communication between terminals
- Ad Hoc Networks
  - No QoS. Trade-off capacity for latency, jitter, and overhead
  - Robustness
- Sensor Networks
  - Severely power limited
  - VAAs may save on transmit power, but more reception/processing power is required.

System Model

- Information source communicates with t transmit antennas and the information sink receives with r antennas



- Transmit codeword $\mathbf{x} \in \mathbb{C}^{t\times 1}$. Receive codeword $\mathbf{y} \in \mathbb{C}^{r\times x}$.

- Input-output relation $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$

  - rank$(\mathbf{H}) = \min\{t, r\}$
  - $\mathbf{n} \sim \mathcal{N}_c\left(\mathbf{0}_r, N \cdot \mathbf{I}_r\right)$

- Transmit avg power constrain: trace $\left(E\left\{\mathbf{x}\mathbf{x}^h\right\}\right)$

Ergodic MIMO Capacity

- Telatar's result for uncorrelated Rayleigh fading
  - Apply to VAA $\Rightarrow$ distances between MTs in cluster small compared to distances between clusters

$$C = \int_0^{\infty} m \log_2 \left(1 + \frac{\lambda}{t} \frac{S}{N} \right) \cdot$$

$$\frac{1}{m} \sum_{k=0}^{m-1} \frac{k!}{(k+n-m)!} \left[L_k^{n-m}(\lambda) \right]^2 \lambda^{n-m} e^{-\lambda} \cdot d\lambda$$

$\lambda =$ unordered eigenvalues of the associated Wishart matrix, $m \triangleq \min\{r, t\}$, $n \triangleq \max\{r, t\}$, and $L_k^{n-m}(\lambda)$ is the Laguerre polynomal of order k.

- Asymptotic Capacity $(d \triangleq n - m)$

$$C \rightarrow m \log_2 \left(\frac{1}{t} \frac{S}{N} \right) + \frac{1}{\log(2)} \left[\sum_{\mu=1}^{m-1} \frac{m-\mu}{d+\mu} + m \left(\sum_{\mu=1}^{d} \frac{1}{\mu} \right) - \mathcal{C} \right]$$

Orthogonal MIMO Channels

- Orthogonal space-time block codes orthogonalize the MIMO channel into parallel SISO channels.
  - Can optimize over simplified structure

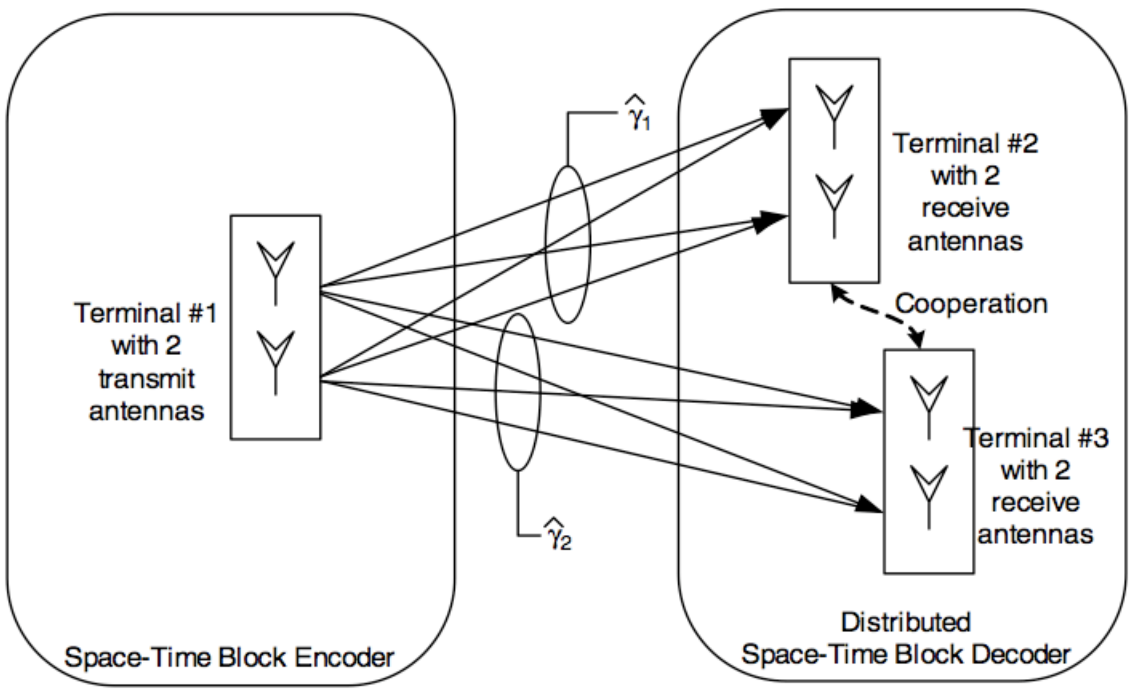
- Space-time block code structure
  - Encoder receivers symbols $x_1, x_x, \ldots, x_s$ which are part of a longer codeword $\mathbf{x}$.
  - Space-time encoder uses a matrix $\mathcal{G} \in \mathbb{C}^{d \times t}$ where d is the number of symbol durations required to transmit the space-time codeword and t is the number of (distributed) transmit elements.
  - Transmission rate $R \triangleq \frac{s}{d}$

- <u>Note:</u> space-time codes improve diversity, but do not provide coding gains.

Orthogonal MIMO Capacity

- For a fixed channel realization $\mathbf{H}$

$$C = R\log_2\left(1 + \frac{1}{R}\frac{\|\mathbf{H}\|^2}{t}\frac{S}{N}\right)$$

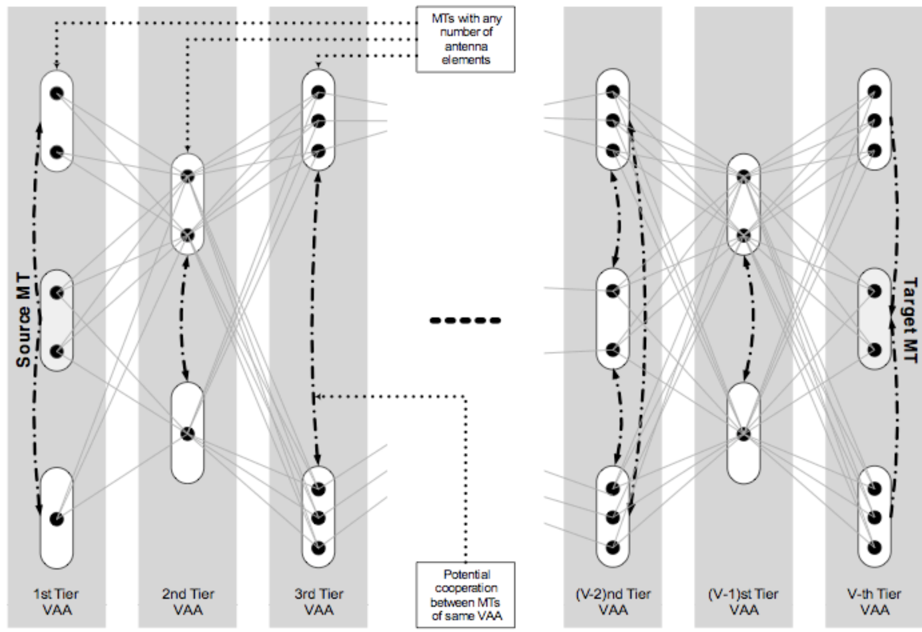


System Model

- Source MT (s-MT) wants to transmit to target MT (t-MT)
- Spatially adjacent relaying MT (r-MT) are grouped into VAAs.
  - Optimization of topology not considered
  - MTs can have arbitrary number of antennas
- Cost of architecture: complexity. Ignoring relaying power and bandwidth.
- Intra-VAA communication assumed error free.
- Orthogonal Relaying: resources partitioned such that no interference between relaying stages
- Non-Orthogonal Relaying: resource reuse, but interference between stages
- Average channel conditions of all links assumed to be known at all nodes

Resource Allocation Protocols

- General relay architecture

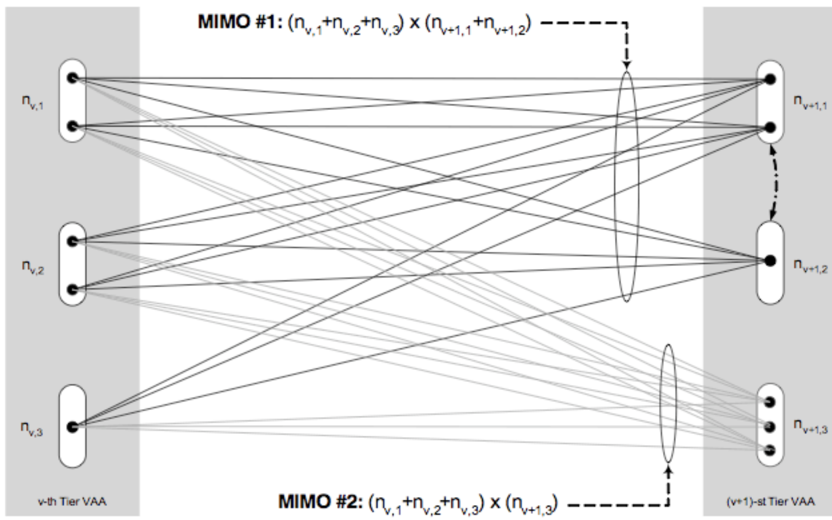


- *Fractional Resource Allocation Strategies* over total power S, bandwidth W, and frame duration T

- Regenerative vs. Transparent relaying

End-to-End Throughput

- In relaying architecture, capacity limited by the weakest link.
  - Strength of MIMO channel measured by # of receive antenna
  - Generally desirable to have cooperation so all virtual MIMO clusters have the same # of receive antenna



$$C = \sup_{\alpha,\beta} \left\{ \min \left\{ C_1(\alpha_1, \beta_1, \lambda_1, \gamma_1), \ldots, C_K(\alpha_K, \beta_K, \lambda_K, \gamma_K) \right\} \right\}$$

$$C_v = \alpha_v \cdot E_{\lambda_v} \left\{ m_v \log_2 \left(1 + \lambda_v \frac{\gamma_v}{t_v} \frac{\beta_v}{\alpha_v} \frac{S}{N} \right) \right\}$$

Optimal Resource Allocation

- Minimum is maximized if all capacities are equated and then maximized.

$$\alpha_v = \frac{\prod_{w \neq v} E_{\lambda_w}\left\{m_v \log_2(1+\lambda_w \frac{\gamma_w}{t_w}\frac{\beta_w}{\alpha_w}\frac{S}{N})\right\}}{\sum_{k=1}^{K}\prod_{w \neq k} E_{\lambda_w}\left\{m_v \log_2(1+\lambda_w \frac{\gamma_w}{t_w}\frac{\beta_w}{\alpha_w}\frac{S}{N})\right\}}$$

$$C = \left[\sum_{k=1}^{K} \frac{1}{E_{\lambda_k}\left\{m_v \log_2(1+\lambda_k \frac{\gamma_k}{t_k}\frac{\beta_k}{\alpha_k}\frac{S}{N}\right\}}\right]^{-1}$$

- Lagrange Multipliers

$$\mathcal{L} = \left[\sum_{k=1}^{K} \frac{1}{E_{\lambda_k}\left\{m_v \log_2(1+\lambda_k \frac{\gamma_k}{t_k}\frac{\beta_k}{\alpha_k}\frac{S}{N}\right\}}\right]^{-1} + \iota\left[1-\sum_{k=1}^{K}\alpha_k\right] + \kappa\left[1-\sum_{k=1}^{K}\beta_k\right]$$

Resource Allocation Strategies

- Near-optimal fractional bandwidth and fractional power allocation

$$\sum_{k=1}^{K} \frac{\beta_k}{\alpha_k} \approx K$$

- Equal fractional bandwidth but optimized fractional power allocation

$$\alpha_v = \frac{1}{K}$$

- Equal fractional bandwidth and power allocation
  - Select minimum of C_v

$$C_v = \frac{1}{K} E_{\lambda_v} \left\{ m_v \log_2(1 + \lambda_v \frac{\gamma_v}{t_v} \frac{S}{N} \right\}$$

Conclusions

- MIMO + Relay = Virtual Antenna Arrays
- Applications to existing domains
- Review of MIMO capacity
- Resource allocation in a relay network

Thank You for Listening