Cooperating with Smartness: Using Heterogeneous Smart Antennas in Ad-hoc Networks

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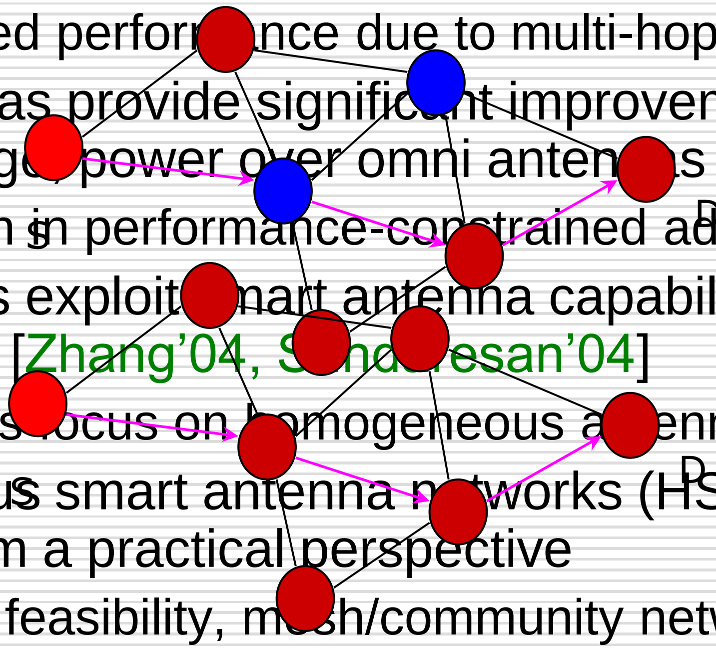
Introduction

- Ad-hoc networks are multi-hop wireless networks
  - Constrained performance due to multi-hop, mobility, interference
- Smart antennas provide significant improvements in capacity, reliability, range, power over omni antennas
  - Application in performance-constrained ad-hoc networks
- Several works exploit smart antenna capabilities at MAC and routing layers [Zhang'04, Sundaresan'04]
  - Most works focus on homogeneous antenna networks
- Heterogeneous smart antenna networks (HSANs) are more promising from a practical perspective
  - Economic feasibility, mesh/community networks, digital battlefields
- Focus: Efficient utilization of heterogeneous antenna capabilities available in HSANs
  - Achieved through a simple form of node cooperation



Outline

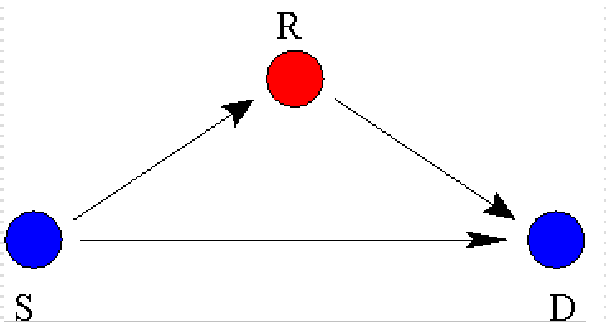
- Smart antennas overview
- Motivation for cooperation in HSANs
- Some properties of node cooperation
- Adaptive cooperation mechanism
- MAC protocol for cooperation
- Performance evaluation
- Conclusions

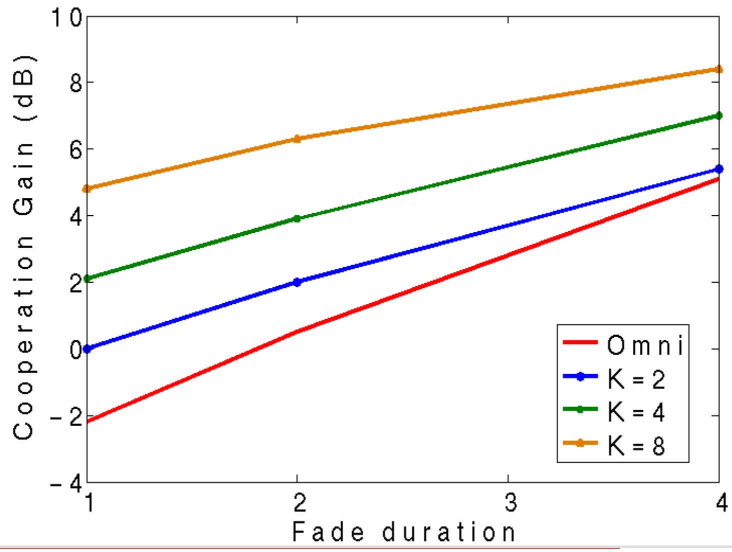
Smart antenna

- Switched-beam (directional) and adaptive arrays
- Beamform energy in specific patterns to provide higher SNR in desired directions
- Pre-determined patterns in switched beam effective only in LOS
- Adaptive patterns required for multipath environments
  - necessitate adaptive arrays
- SNR gain bounded by 'K^2', (K-# elements)
- Gain (G) exploited for increased reliability, rate, or range, or reduced power
  - Exploitation of SNR gain for reliability and rate: $C = \log(1+\rho G)$

Motivation

- Simple form of node cooperation: retransmit diversity
- Neighbors of ‘S’ exploit broadcast advantage to assist ‘D’ in successful reception of pkts during fading losses
- Diversity benefits in omni networks only if ‘R’ has better link gain to ‘D’ and in time-correlated fading
  - Not common characteristics!
- Large benefits in HSANs
  - ✓ Low gain omni nodes exploit high gain smart neighboring nodes for improved retransmit diversity gains
  - ✓ Efficient exploitation of smart antenna capabilities by replacing omni retransmissions with smart ones
  - ✓ Simple deployable mechanism: only one relay node exploited



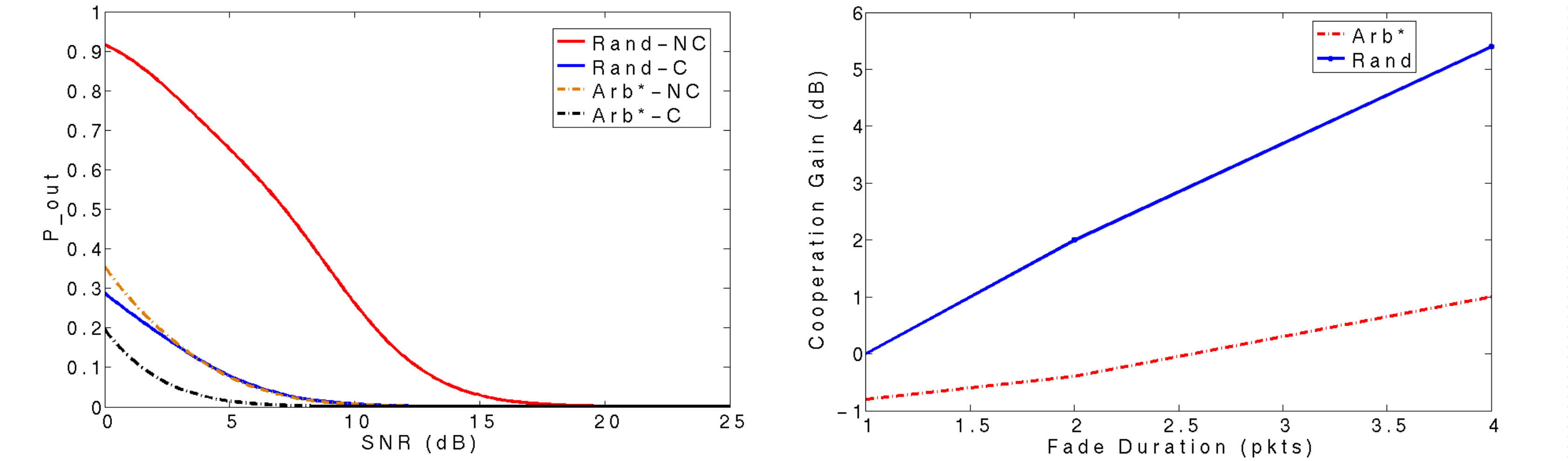


Environment

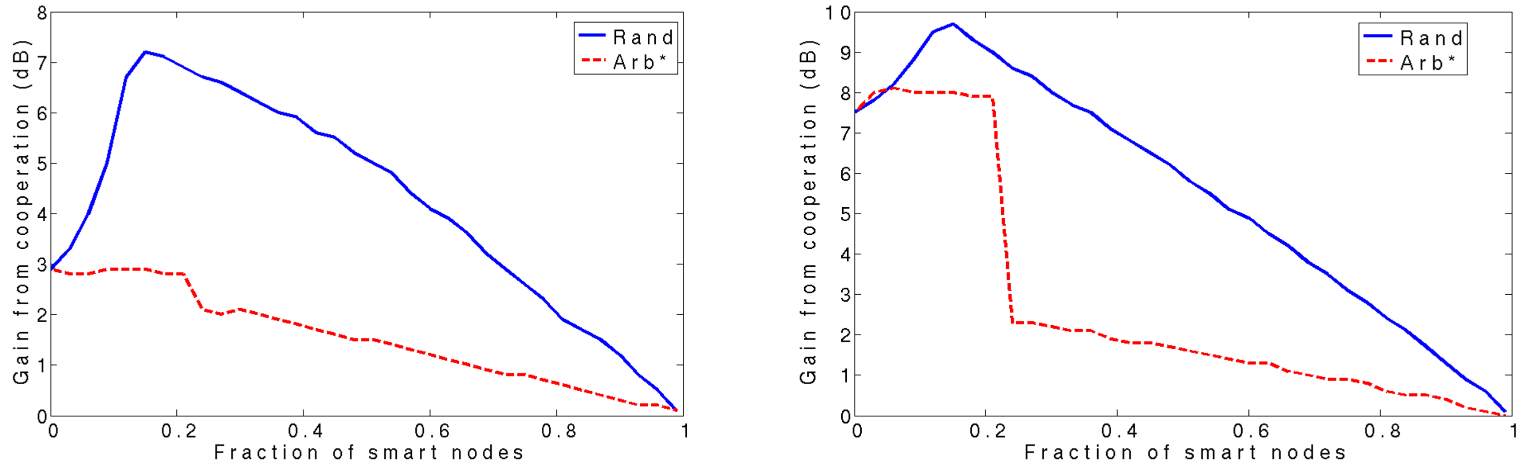
- Network model
  - Mixture of omni and smart nodes
  - Random: random node placement and traffic pattern
  - Arbitrary*: controlled node placement of some nodes, random traffic pattern
    - Controlled nodes form a routing backbone, consisting of mainly smart nodes; eg. Mesh networks with smart mesh routers
- Link model
  - Block (time-correlated) Rayleigh fading
  - Fixed # MAC layer retransmissions: ‘F’ retrials
- Basic communication model
  - No cooperation: available antenna gain used for reliability at smart node transmitters, relays do not participate
  - Cooperation: neighboring nodes within communication pattern of S and D participate in cooperation during fading losses
- Metric
  - Outage probability and cooperation gain (SNR gain in dB)

Properties of Cooperation Gain

- *Property 1: $G_{c\_R} > G_{c\_A}$*
  - Cooperation gains are more in random networks; although absolute performance is better for arbitrary*
  - More room for exploitation of smart antenna capabilities in random nets
  - Tool for bridging performance gap



Properties of Cooperation Gain



- *Property 2:* G_{c_R} has a concave nature in the fraction of smart nodes in network
  - Higher degree of heterogeneity results in higher degree of cooperation
  - Homogeneous omni better than homogeneous smart
    - Increasing # smart nodes increases spatially sensitive transmissions but reduces potential for cooperation

Tradeoff in Random Networks

- Increasing # smart nodes, antenna elements
  - More antenna gain – higher absolute performance (rate/reliability)
  - More spatial sensitive transmissions – lesser cooperation gain (diversity)
- Fundamental tradeoff in exploiting antenna gain and cooperation gain!
- Relative importance of gains depends on fading conditions and availability of smart nodes

Tradeoff in Random Networks

- C_{ant}: all antenna gain used for reliability on experiencing fading loss
- C_{coop}: switch to omni mode after loss to favor cooperation

- *Property 3*
  - $G_{ant} \geq G_{coop}$; $f \rightarrow 1$ and $p_x \rightarrow 1$; or $p_x \rightarrow 0$
  - $G_{coop} \geq G_{ant}$, $f \rightarrow F$ and $p_x \rightarrow 1$

- C_{ant}: best strategy under fast fading + smaller # smart nodes
- C_{coop}: best strategy under block fading + larger # smart nodes
- Difficult to estimate dynamic fading statistics
  - Need an adaptive mechanism transparent to fading statistics

Adaptive Mechanism

- C_{adap} strikes a balance between C_{ant} and C_{coop}
- On fading, employs an intermediate stage of transmission on reduced # elements (three)
  - Favors higher cooperation while retaining some antenna gain
- On further loss, returns to maximum antenna gain if smaller degree of smart neighbors
- Moves to omni if sufficient smart neighbors
- Probabilistic guarantee of locating a relay: atleast 1/3 that of an omni transmission
- Better than rate adaptation schemes
- Incorporation in a distributed MAC protocol

Distributed Channel Access

- Weighted proportional fairness model
  - Proportional fairness provides good tradeoff between fairness and efficiency
  - Weighted arises from heterogeneous link gains
  - Notion of fairness in channel access time
- Distributed persistence-based access adaptation:
  - w_i proportional to link gain
  - Link weight scaled by two constants: c_1, c_2
  - Cooperating links contend with higher priority than source links of similar type: $c_2 > c_1$

Protocol Operations

- RTS-CTS-DATA-ACK
- Omni RTS, CTS
  - Neighbors identify feasibility for cooperation
- Data/ACK transmitted using nature of source/destination
- Pre/post-ambles for fading loss detection
- NACK transmitted on omni
  - Indicates need for cooperation
- Source initiates adaptive cooperation mechanism

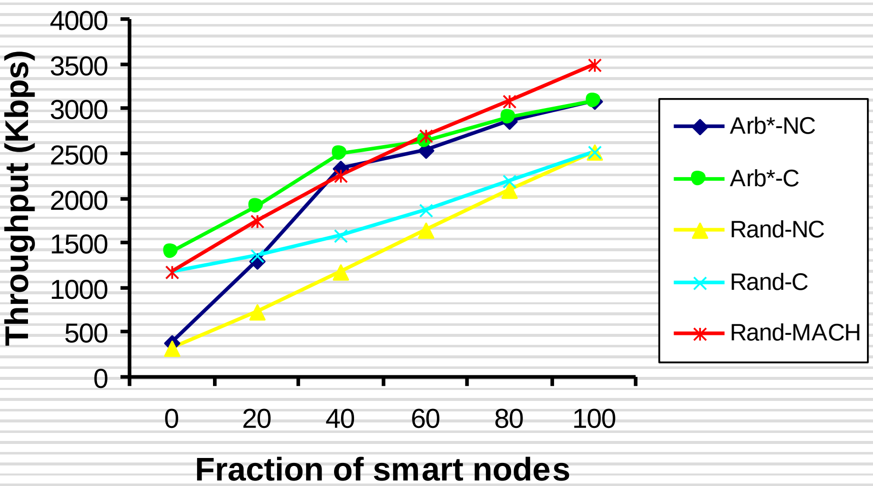
Protocol Operations

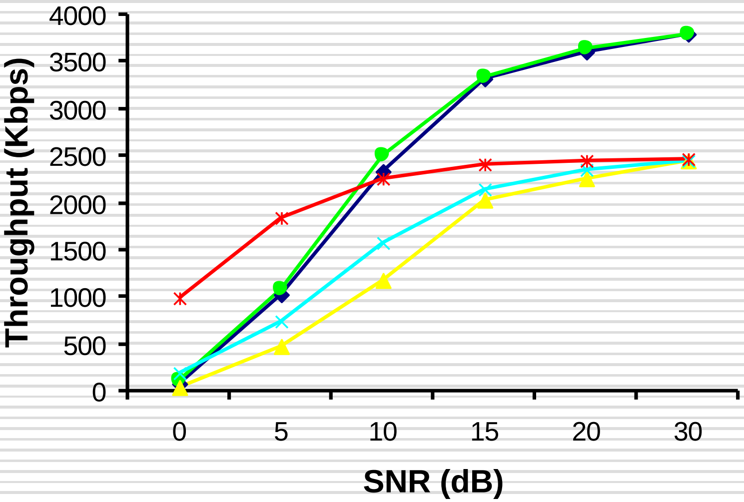
- Relays store DATA pkt if decoded
- Contention winner determines participating relay
  - Favors cooperating neighbor with high gain
- Winner sends omni RTS
- Omni CTS confirms pkt responsibility transfer to R
  - S, other contenders drop DATA
- DATA/ACK sent using R/D mode
- Lack of cooperation
  - S falls back to omni/ant gain based on smart neighbor degree

Performance Evaluation

- Set-up
  - ns2 simulator used for evaluations
  - 100 nodes in 1000m x 1000m
  - Random source-destination pairs
  - Backlogged sources with UDP
- Environment
  - LOS (omni+directional) and NLOS (omni+adaptive)
  - Random and arbitrary* networks
- Strategies and metrics
  - Non-cooperation (NC), basic cooperation (C), MACH
  - Aggregate throughput, cooperation gain, throughput standard deviation

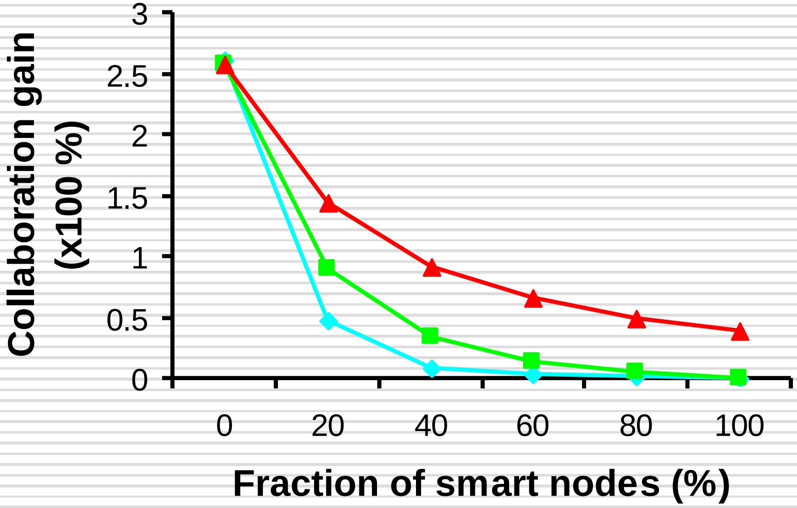
Throughput Results (1)

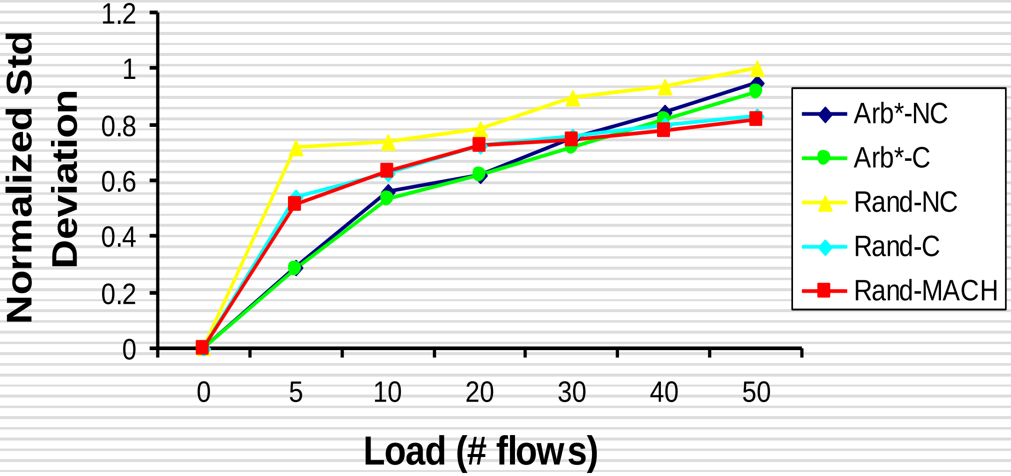




- C brings more gains in random networks
- MACH provides gains close to 100% over C
  - Higher gains at larger fraction of smart nodes
- Gains more at low SNR region, emphasizing cooperation
  - C improves over NC by 2 folds and MACH over C by 3 folds

Cooperation & Fairness Results (2)





- Increasing smart nodes reduces cooperation gain
  - MACH retains 40% gain even in all-smart network unlike C
- Fairness
  - MACH gains not from aggressive channel access by smart nodes – fairness measure better for MACH than for C

Conclusions

- Motivated the potential for a simple form of node cooperation in HSANs
  - Highlighted importance in random networks
- Analysis to capture some key properties of cooperation in HSANs
- Proposed an adaptive mechanism to address the tradeoff in antenna and cooperation gain
- Proposed a simple distributed MAC protocol (MACH) to incorporate the adaptive mechanism
  - Compatible with more sophisticated smart antenna MAC protcols

Thank You!