A Unified MAC Layer Framework for Ad-hoc Networks with Smart Antennas

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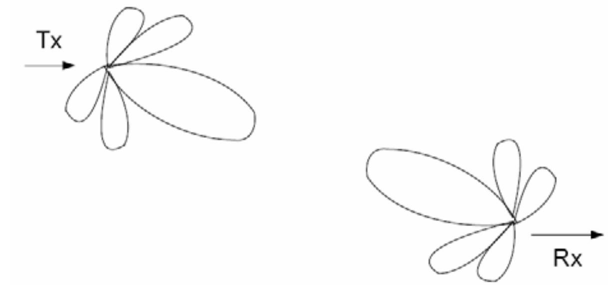
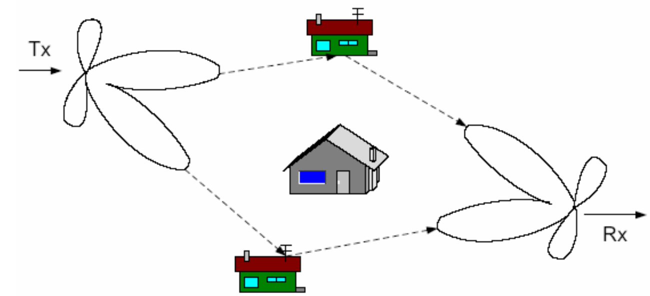
Introduction

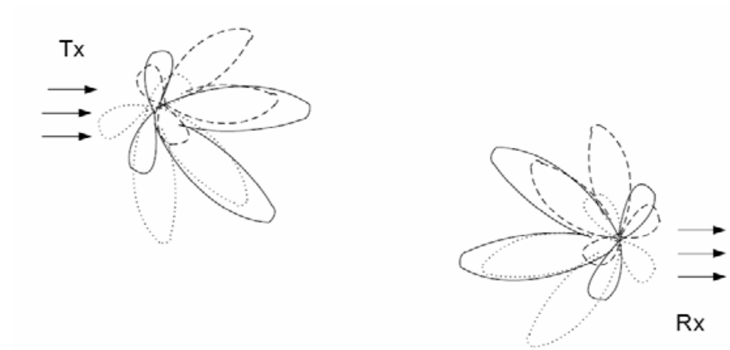
- Smart antennas provide fundamental performance improvement over omni-directional antennas
- Vary from switched beam to sophisticated digital adaptive arrays
- Research works have primarily focused on developing protocols at MAC and routing layers for the specific antenna technologies “in isolation” [Mobicom 2002, Mobihoc 2003]
- A unified approach to the problem of medium access control with smart antennas
  - Relative merits of the different technologies
  - Re-use solutions for related problems
  - Performance evaluation platform

Smart antennas: Overview

- Switched beam
  - Pre-determined beam pattern
  - Inefficient in multipath, require LOS
  - No flexible interference suppression
- Adaptive array
  - Adaptive beam pattern
  - Degrees of freedom (DOFs) handle interference suppression
  - Single DOF for transmission
- MIMO links
  - Multipath is exploited !
  - Flexible usage of DOFs
  - Spatial multiplexing and diversity







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Outline

- Smart antennas – overview and properties
- Mac layer considerations
- Problem formulation
- Unified centralized algorithm
- Performance insights
- Conclusions

MAC layer considerations

	Switched beam	Adaptive array	MIMO Links
Exploiting gains	Directional gain Range extension: $R_f = (MN)^{1/p}$ Capacity increase: $C=\log(1+(MN)^{1/p}\rho)$	Array, diversity gains $Rf = (\sqrt{M} + \sqrt{N})^{1/p}$ $C=\log(1+(\sqrt{M} + \sqrt{N})^{1/p}\rho)$	Array, diversity & spatial multiplexing gains $C = \min(M,N) \log(1+ \rho)$
Resource allocation & scheduling	Single resource Transmission on directional beam Accumulation of noise in side lobes	Multiple resources (DOFs = # elements) Transmission on strongest mode Passive receiver overloading	Multiple resources (DOFs = # elements) Transmission on all modes Stream control Passive receiver overloading

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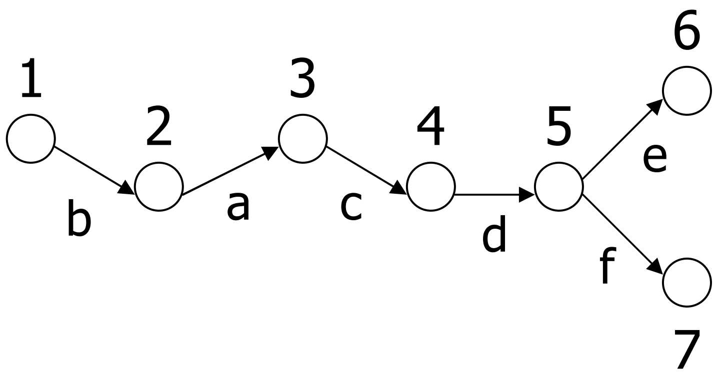
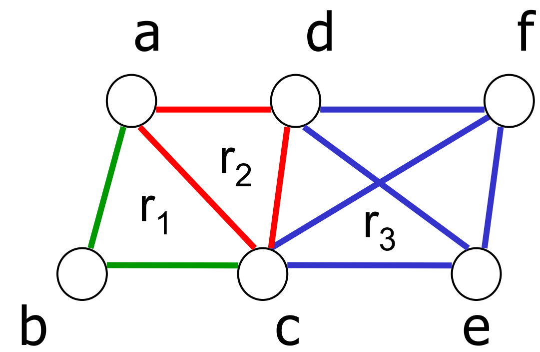
Problem Formulation

- Problem of channel access modeled as utility maximization problem
- Utility function determines fairness
  - Proportional fairness is considered
- Constraints to the optimization problem determined by the specific antenna technology
- Formulation in four steps:
  - Node graph generation
  - Flow contention graph generation
  - Resource constraint graph generation
  - Problem formulation

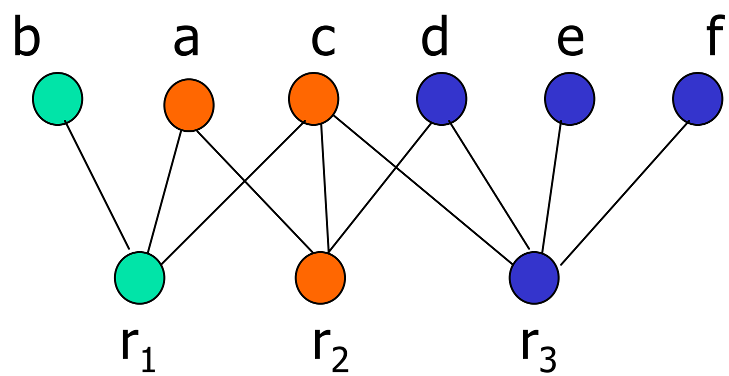
Example



Node graph



Flow contention graph



Resource constraint graph

Formulation: Switched beam

- Flow contention graph incorporates directionality and range extension
- Every contention region has only one resource, but effect of side lobes must be accommodated
- Constraints:

$$\forall j, \forall t \sum_i C_{i,j}(t) \leq 1,$$ → resource server constraint

$$where\ C_i(t) = 1,\ if\ \{C_{i,j}(t) = 1\},\ \forall j \in R$$ → link constraint

$$\&\& \sum_{m=0}^{K-1} \frac{N_i(m) \cdot w_{ij}}{f} \leq \frac{1}{SNR_{thresh}}$$ → side-lobe constraint

$$= 0,\ otherwise$$

$$N_i(m) = l,\ if\ \exists\ l\ transmissions\ along\ beam\ direction\ m$$

Formulation: Adaptive array

- Flow contention graph incorporates range extension if desired
- Every contention region has K (= # elements) resources
  - Transmission uses only one resource
  - Link weights used for flexible interference suppression
- Constraints:

$$\forall j,\ \forall t\ \sum_i C_{i,j}(t) \ \leq\ K, \quad \longrightarrow \text{resource server constraint}$$

$$\begin{aligned} where\ C_i(t) &= 1,\ if\{C_{i,j}(t) = 1\},\ \forall j \in R \\ &= 0,\ otherwise \end{aligned}$$

$$\forall t,\ \forall i\ \sum_l w_{li} C_l(t) \ \leq\ K,\ if\ C_i(t) \geq 0 \quad \longrightarrow \text{link constraint}$$

$$max(T_i(l)) \ \leq\ max(T_j(l)) \quad \longrightarrow \text{passive receiver overloading constraint}$$

$$where\ i \in RED,\ j \in WHITE$$

Formulation: MIMO link

- Every contention region has K resources
  - Resources used for both transmission and reception
  - Link weights used for flexible interference suppression
- Constraints:

$$\forall j,\ \forall t \sum_i C_{i,j}(t) \ \leq\ K,$$

→ resource server constraint

$$where\ C_i(t) = min\{C_{i,j}(t)\}$$

$$0 \ \leq\ C_{i,j}(t) \ \leq\ K \ \ if\ i \in WHITE,\ and$$

$$C_{i,j}(t) = \{0, K\}\ \ if\ i \in RED$$

→ stream control constraint

$$\forall t,\ \forall i \sum_l w_{li} C_l(t) \ \leq\ K,\ if\ C_i(t) \geq 0$$

→ link constraint

$$max(T_i(t)) \leq max(T_j(t))$$

$$where\ i \in RED,\ j \in WHITE$$

→ passive receiver overloading constraint

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Centralized algorithm

- Objective: Maximize aggregate network utilization subject to transmission constraints and conforming to proportional fairness model
- Proportional fairness exploits location based contention
  - necessitates distinction between bottleneck (“red”) and non-bottleneck (“white”) links – “coloring”
- Colored links are scheduled to maximize utilization subject to resource and transmission constraints
- 3 essential components: clique identification, coloring and schedule

Components

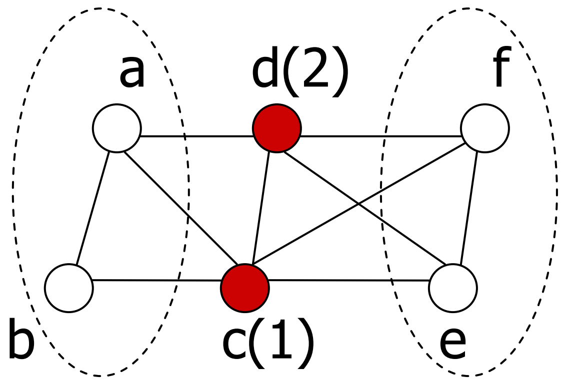
- Clique identification
  - First obtain PEO using LexBFS, then use the linear algorithm by Fulkerson and Gross
  - Works for chordal graphs
- Coloring
  - Recursive ranking based on (clique degree, max clique size) and coloring the highest ranked link red
- Schedule
  - Dual scheduling of red and white links eliminates passive receiver overloading problem
  - Transmission resources are governed by resource constraints and optimization considerations
  - Switching conditions between the schedule of colored links is done in accordance with proportional fairness

A MIMO example

- Clique identification, ranking and coloring
  - Maximal cliques in flow contention graph correspond to contention regions in the network
  - Ranking is done based on tuple (clique degree, max clique size)
  - Bottleneck links are colored red based on rank and non-bottleneck links are colored white

Example contd.

- Dual-level scheduling
  - Red links are scheduled first based on their rank
  - White links are scheduled next and perform stream control

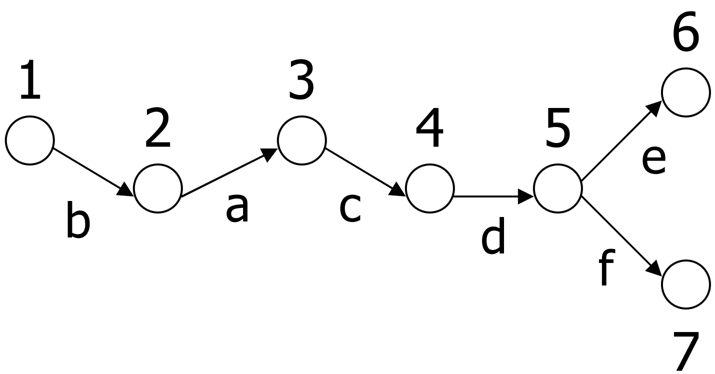


Flow contention graph

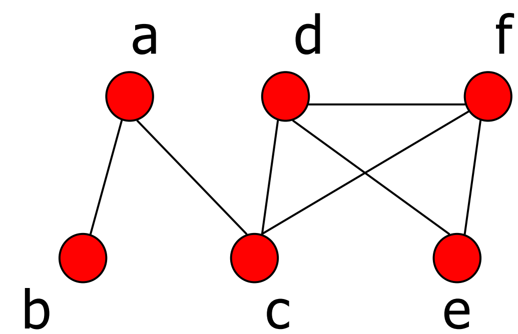
	a	b	c	d	e	f
Slot 1	0	0	4	0	0	0
Slot 2	0	4	0	4	0	0
Slot 3	2	2	0	0	2	2
Slot 4	2	2	0	0	2	2

Switched beam example

- No coloring required; all links red
- Single level scheduling



Node graph



Flow contention graph

	a	b	c	d	e	f
Slot 1	1	0	0	1	0	0
Slot 2	0	1	0	0	0	1
Slot 3	0	1	1	0	1	0

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Performance insights

- Adaptive beamforming is the best strategy in line of sight environments
- Switched beam gains degrade with increasing scattering
- Average number of neighboring links impacts performance in switched beam and adaptive
- Performance bounded by the number of available resources in contention regions when load is increased
- Rate increase provides better gains than range extension

Conclusions

- Outlined a unified representation of the relevant PHY properties of different antenna technologies
- Proposed a unified problem formulation framework and derived unified algorithms for relative performance evaluation
- Unified distributed algorithms have also been developed
- ☞ Exploiting of diversity gain has some interesting benefits; consideration of power; complexity-performance tradeoff
- http://www.ece.gatech.edu/research/GNAN