The Network Design Cycle

Optimal Rate Control for Wireless Networks

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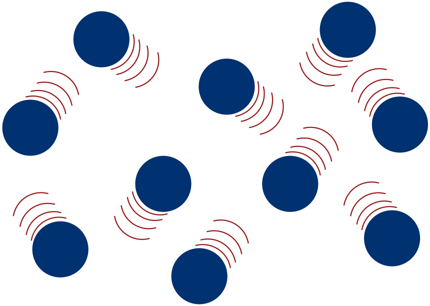
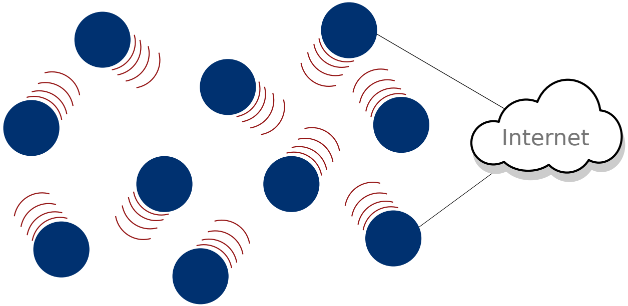
Wireless Networks



- entirely wireless networks
  - mesh network – stable backbone, mobile clients
  - mobile ad hoc network – every node mobile
- economical
  - $\sim \$50K - \$1M$ per mile for fiber optic cable (rural vs urban)
  - developing countries want cheap infrastructure

Wireless Networks



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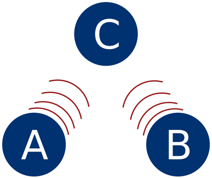
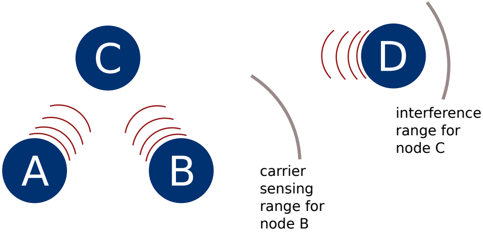
Wireless Challenges to Fairness



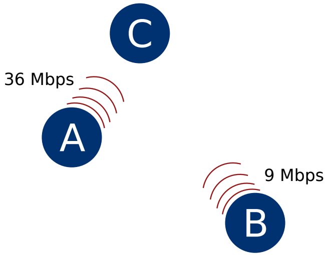
- contention
  - A and B must share wireless channel
  - fairness subject to MAC protocol
  - 802.11 is known to be unfair

Wireless Challenges to Fairness



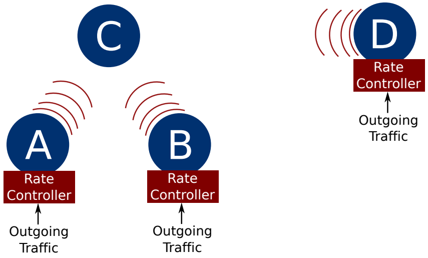
- interference
  - remote node D can cause collisions
  - RTS/CTS doesn't help if D is outside C's carrier sensing range
  - may severely impact fairness

Wireless Challenges to Fairness



- channel quality
  - A may have much high bitrate than B
  - max-min fairness (bandwidth equality) leads to poor network utilization
  - proportional fairness (airtime equality) makes better use of shared resource

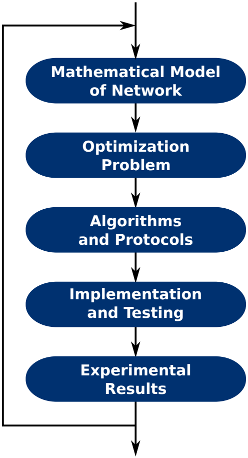
Rate Control



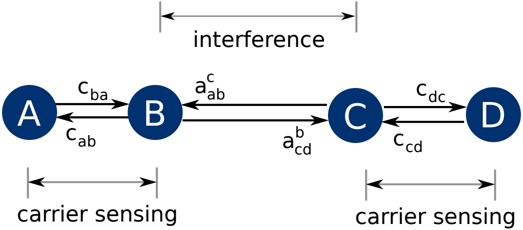
- use rate control on top of 802.11 MAC
- transparent to applications and transport protocol
- what rate should each flow get?

Network Design Cycle

- unify theoretical and experimental results



Network Model

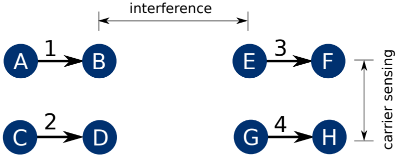


- c_{ij}: amount node i can carrier sense node j [0..1]
- a^k_{ij}: amount rate from i to j is impacted by interferer k [0..1]

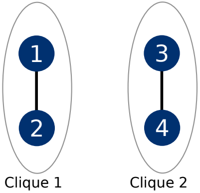
Niculescu, *Interference map for 802.11 networks*, ACM Internet Measurement Conference, 2007

Binary Contention Model

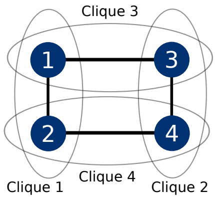
topology:



contention graph:



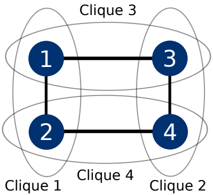
ignore interference



interference as contention

- model contention as binary and symmetric
- form maximal cliques among contending links

Binary Contention Model: Link-Based Optimization



$$\mathbf{Q} : \max f(s) = \sum_{l \in L} U(s_l)$$

(maximize utility of sending rates of all links)

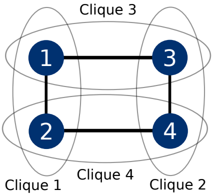
$$\sum_{l \in L(j)} s_l \leq \epsilon_j, \ \forall j \in C$$

(link rates can't exceed clique capacity)

$$s_l \geq 0, \ \forall l \in L$$

(link rates must be non-negative)

Binary Contention Model: Flow-Based Optimization



$$\mathbf{P} : \max f(s) = \sum_{t \in T} U(s_t)$$ *(maximize utility of sending rates of all flows)*

$$FRs \leq \epsilon$$ *(link rates can't exceed clique capacity)*

$$s \geq 0$$ *(link rates must be non-negative)*

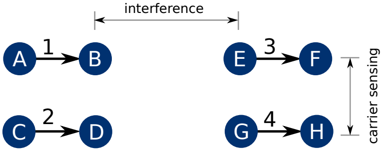
- F maps links to cliques, R maps flows to links
- s is a vector of *flow* sending rates
- c is a vector of clique capacities

Binary Contention Model

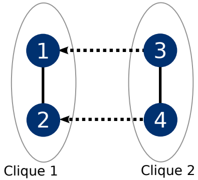
- advantages
  - classic model – well understood and used in many papers
  - both the link-based and the flow-based problem formulations are convex
  - standard techniques can be used to derive distributed solutions
- disadvantages
  - finding the set of maximal cliques for a graph is NP hard
    - approximation: all links within two hops are in the same clique
    - may overly restrict rates
  - doesn't accurately model interference
  - doesn't model partial carrier sensing
- how good is this model?

Partial Interference Model

topology:

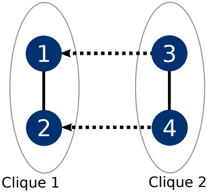


contention graph:



- model contention as binary and symmetric
- model interference as partial and asymmetric

Partial Interference Model: Link-Based Optimization



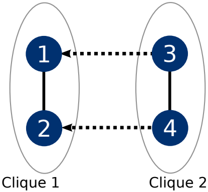
$$\mathbf{P}: \max_{s} f(r) = \sum_{l \in L} U(r_l)$$ *(maximize utility of receiving rates of all links)*

$$\sum_{l \in L(j)} s_l \leq \epsilon_j, \ \forall j \in C$$ *(link rates can't exceed clique capacity)*

$$s_l \geq 0, \ \forall l \in L$$ *(link rates must be non-negative)*

$$r_l = d_l s_l \prod_{i \in I(l)} (1 - a_{il} s_i), \ \forall l \in L$$ *(receiving rate impacted by interference)*

Partial Interference Model: Flow-Based Optimization



$$\mathbf{Q} : \max_{s} f(r) = \sum_{t \in T} U(r^t_{end})$$

(maximize utility of receiving rates of all flows)

$$\sum_{l \in L(j)} \sum_{t \in T(l)} s^t_{k(t,l)} \leq \epsilon_j, \ \forall j \in C,$$

(link rates can't exceed clique capacity)

$$s^t_k \geq 0, \ \forall t \in T, \ k = 1, \dots, h(t),$$

(link rates must be non-negative)

$$s^t_k = r^t_{k-1}, \ \forall t \in T, \ k = 2, \dots, h(t),$$

(sending rate at a hop = receiving rate at previous hop)

$$r_l = d_l s_l \prod_{i \in I(l)} (1 - a_{il} s_i), \ \forall l \in L$$

(receiving rate impacted by interference)

$h(t)$: length of flow t in hops

Partial Interference Model: Distributed Solution

- construct the dual problem, use Lagrangian relaxation
- gradient projection method

1. advertise/exchange link rates within each clique
2. given link rates, compute a price for each clique:

$$\lambda_j(k+1) = \max\left(0, \lambda_j(k) - \gamma(\epsilon_j - \sum_{l \in L(j)} \bar{s}_l(\lambda(k)))\right)$$

3. given clique prices, compute a new rate for each link

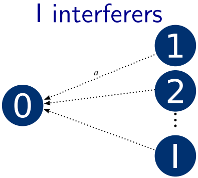
$$\bar{s}_l(\lambda) = \arg\max_{s_l} g(s_l, \lambda)$$

$$g(s_l, \lambda) = \ln s_l + \sum_{i \in F(l)} \ln(1 - a_{li} s_l) - s_l \sum_{j \in C(l)} \lambda_j$$

Partial Interference Model

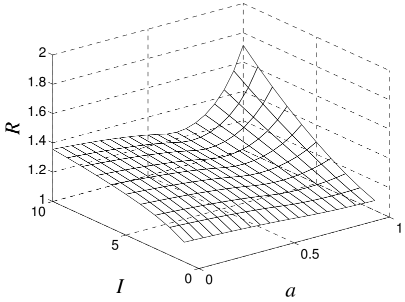
- advantages
  - nice extension to classic model
  - models interference well, assuming interferers don't carrier sense each other
  - link-based formulation is convex, has a distributed solution
- disadvantages
  - flow-based formulation is non-convex, no re-formulation known yet
  - finding the set of maximal cliques for a graph is NP hard
  - doesn't model partial carrier sensing
- how good is *this* model?

Numerical Results: Interference as Contention



R: *ratio of normalized performance*

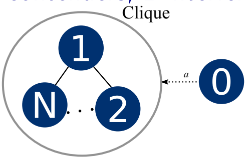
Partial Interference vs.
Binary Contention
(interference as contention)



- it often makes sense for some nodes to cause interference rather than making them take turns – treating contention as interference is too conservative

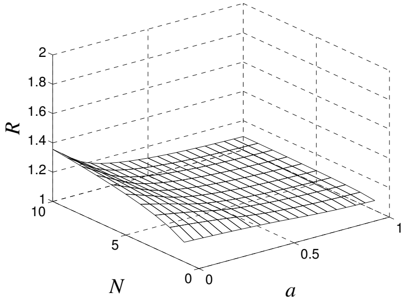
Numerical Results: Interference as Contention

N contenders, 1 Interferer



R: *ratio of normalized performance*

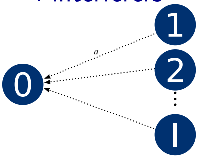
Partial Interference vs. Binary Contention (interference as contention)



- it often makes sense for some nodes to cause interference rather than making them take turns – treating contention as interference is too conservative

Numerical Results: Interference Ignored

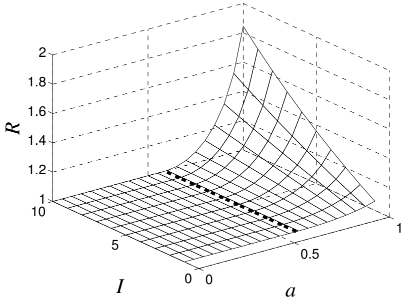
I interferers



R: ratio of normalized performance

Partial Interference vs. Binary Contention

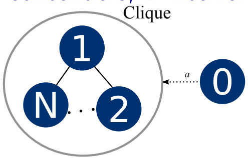
(interference ignored)



- ignoring interference is OK when it is low, but costly when high – ignoring interferers allows them to send at too high a rate, causing high packet loss

Numerical Results: Interference Ignored

N contenders, 1 Interferer



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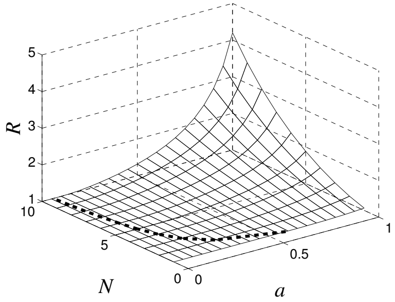
Partial Interference vs. Binary Contention (interference ignored)



- ignoring interference is OK when it is low, but costly when high – ignoring interferers allows them to send at too high a rate, causing high packet loss

Numerical Results: Conclusions

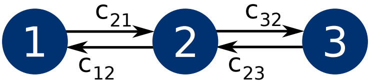
- Partial Interference model
  - performance is significantly improved compared to Binary Contention
  - problem is still convex, with a decentralized algorithm
  - no extra computational cost

but ...

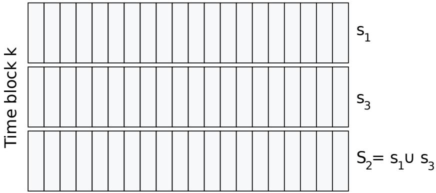
- what about partial carrier sensing?

Random Set Model

contention graph of 3 links:



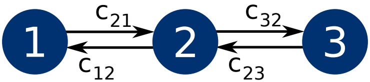
divide time into discrete slots:



- each sender has a rate s indicating which percentage of the total slots it will choose to send
- S_2 = combined rate of links 1 and 3 as seen by link 2

Random Set Model

contention graph of 3 links:



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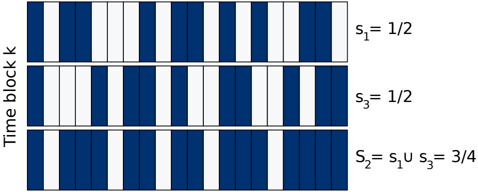


- example: $s_1 = 1/2, s_2 = 0, s_3 = 1/2$
  - perfect overlap: $S_2 = 1/2$ (Binary Contention model)
  - no overlap: $S_2 = s_1 + s_3 = 1$
  - random set theory: $S_2 = 3/4$

Random Set Model

$$\mathbf{P} : \max_{s} \sum_{i \in L} U(r_i)$$

$$s_i + S_i \leq 1, \quad \forall i \in L$$ *(sending constraint)*

$$r_i = d_i(1 - R_i)s_i, \quad \forall i \in L$$ *(receiving constraint)*

Random Set Model

$$\mathbf{P} : \max_{s} \sum_{i \in L} U(r_i)$$

$$s_i + S_i \leq 1, \quad \forall i \in L$$ *(sending constraint)*

$$S_i = \sum_{p \in \mathcal{P}(L_i)} (-1)^{|p|-1} f_i(p) g_i(p) h(p)$$ *(amount link i senses medium is busy)*

$$f_i(p) = \prod_{j \in p} c_{ij} s_j$$ *(amount link i sees links in subset p send simultaneously)*

$$g_i(p) = \frac{\phi_i(p)}{\prod_{j \in p} \phi_i(j)}$$ *(normalizes by the size of free space p has to choose from)*

$$\phi_i(p) = 1 - s_i \sum_{p' \in \mathcal{P}(p)} (-1)^{|p'|-1} \prod_{j \in p'} c_{ji}$$ *(how much p does not sense i)*

$$h(p) = \prod_{\{i,j\} \in \mathcal{P}_2(p)} (1 - c_{ij} - c_{ji} + c_{ij} c_{ji})$$ *(independence of set p: how little they carrier sense each other)*

Random Set Model

$$\mathbf{P} : \max_{s} \sum_{i \in L} U(r_i)$$

$$r_i = d_i(1 - R_i)s_i, \quad \forall i \in L$$

(receiving constraint)

$$R_i = \sum_{p \in \mathcal{P}(L_i)} (-1)^{|p|-1} f_i'(p) h(p)$$

(amount link i interfered by all other links)

$$f_i'(p) = \prod_{j \in p} a_{ij} s_j.$$

(how much links in subset p interfere simultaneously with i)

Random Set Model

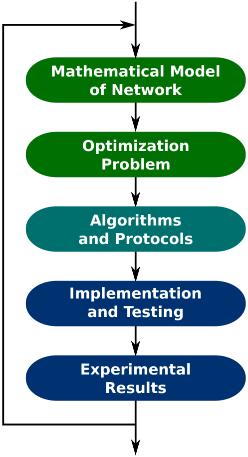
- reduces to Binary Contention when limited to
  - binary, symmetric carrier sensing
- reduces to Partial Interference when limited to
  - binary, symmetric carrier sensing
  - partial interference, with no contention among interferers
- both link and flow optimization

but ...

- non-convex, so no distributed solution

Current Work

- how good are these models on wireless mesh testbeds?
- developing a branch-and-bound solution for Random Set model so it can be used as a benchmark
- simulating and implementing all three models
- experimenting on BYU's mesh network
- evaluating non-invasive methods for discovering the interference map of a network – wireless network measurement and mapping



More Info

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