MICS
Mobile Information and
Communication Systems

ÉCOLE POLYTECHNIQUE
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Cross – Layer Design of Wireless MAC Protocol for Ad-Hoc Networks

With Application to Low Power UWB

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joint work with
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Introduction

- Goal: design MAC and routing protocol for given network technology.

  Q1: Which performance objective to use ?

  Q2: Which building blocks for MAC layer ?

Rate Performance Objectives

- Performance objectives in multi-hop wireless networks:
  - Rate based objectives (802.11, UWB, CDMA)
  - Energy based objectives (sensor networks)
  - Combined
- We focus on rate-based objectives

Commonly Used
Rate-based Performance Objectives

- **Total capacity**: maximize sum of rates of all flows.
  Commonly used everywhere

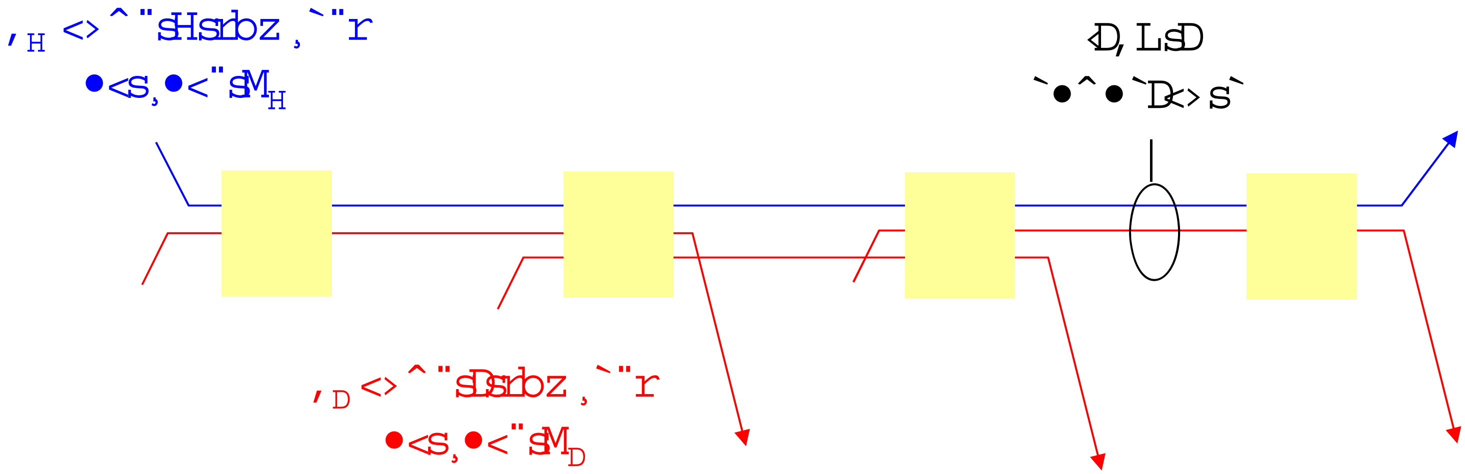
- **Max-min fairness**: a rate of a flow cannot be increased at the expense of a flow with an already smaller rate.
  Commonly used in networking community

- **Proportional fairness**: maximize sum of logs of rates of all flows.
  Based on human perception (Fechner's law)
  Close to TCP fairness

- **Transport rate** of a flow = rate * distance
  All above metrics applicable to transport capacities
  Gupta and Kumar

Efficiency versus Fairness

- It is known from networking textbooks that maximizing capacity may be grossly unfair

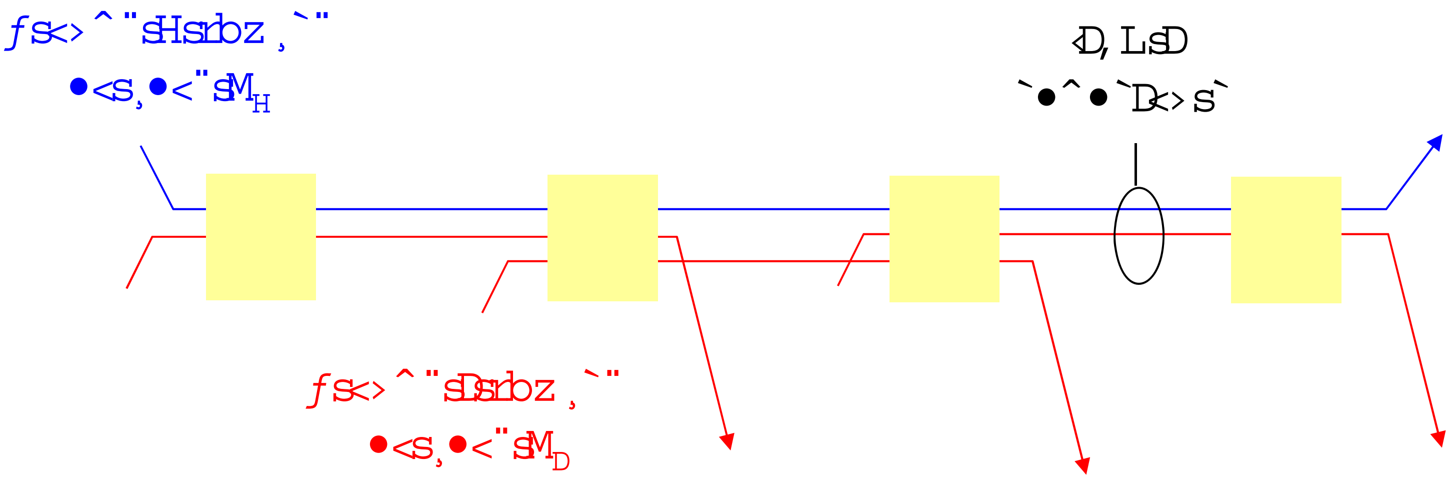


  - max capacity is for $x_0 = 0$
- In contrast, max-min fair allocation is considered « fairest »
  - max-min fair allocation

$$x_0 = \min\{\frac{c}{n_0 + n_i}\} \qquad x_i = \frac{c - n_0 x_0}{n_i}$$

Proportional Fairness

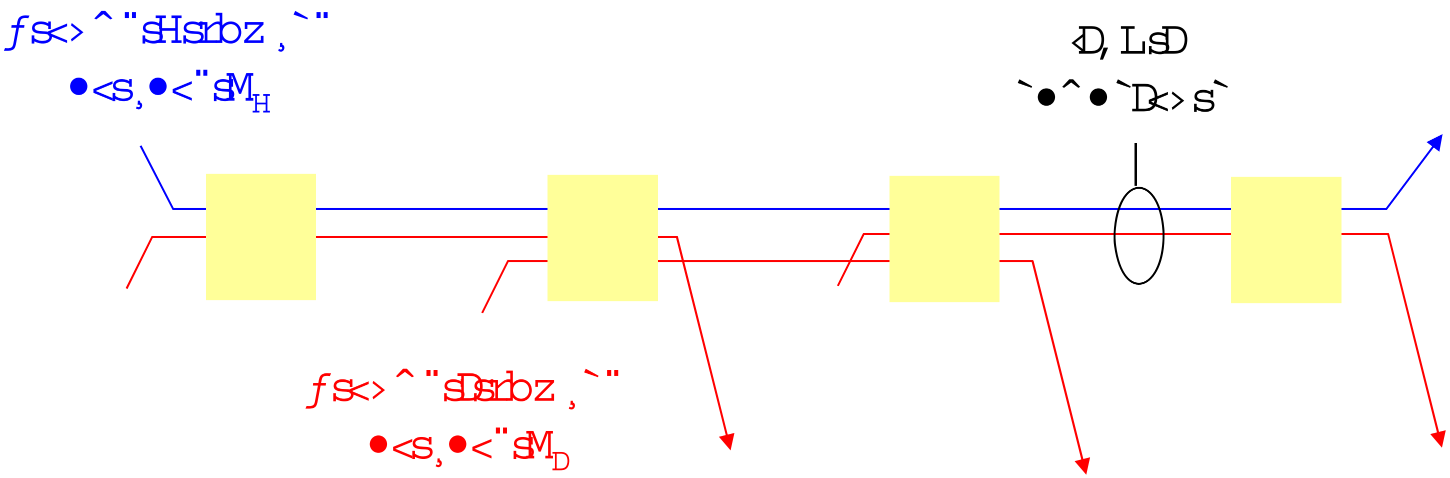
- A middle ground that gives less to the rich and the dispendious
  - maximize sum of logs of rates



Type	*Capacity*	*Max-Min Fairness*	*Prop. Fairness*
0	0	c / 2	c / 3
i	c	c / 2	2 c / 3

Transport Rates

- Use of transport rates instead of rates accounts for expense



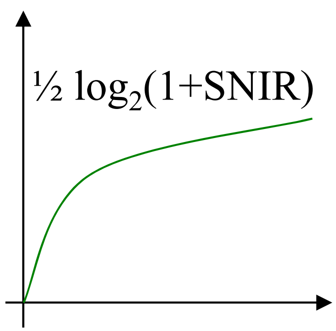
Type	*Capacity*	*Transport Capacity*	*Max-Min*	*Transport Max-Min*	*Prop. Fairness*
0	0	c - x	c / 2	c / 4	c / 3
i	c	x	c / 2	3 c / 4	2 c / 3

Revisiting Fairness / Capacity for Ad-Hoc Wireless

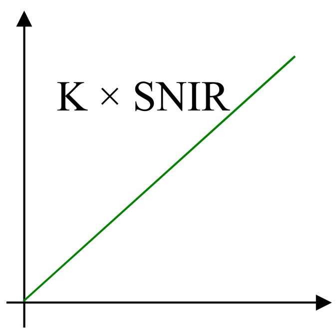
- We compute the allocations for a wireless ad-hoc network
- The model is more complicated than for wired networks

Modelling the Physical Layer

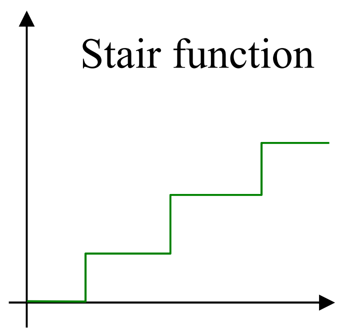
- Assume a static but random placement of nodes
- Point-to-point links: no broadcast, relay channels or multi-user detection
- Channel state s is random, according to some stationary process, constant during packet transmission
- Positive attenuation h_{ij}(s) between any two points *i,j*
- Interference allowed, no collisions.
- Signal-to-noise and interference ratio at the receiver of a link : ratio of received power over white noise plus interference of other transmitters.
- Rate r(SNIR) is strictly increasing function.



Gaussian channel



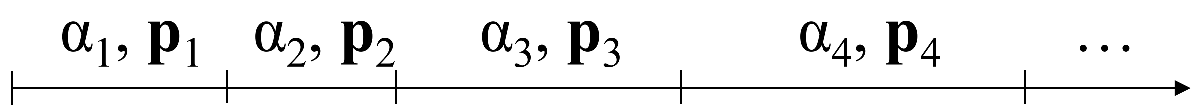
Ultra-wide band,
Win-Scholtz model



Variable rate 802.11
CDMA/HDR

Modelling the MAC Protocol

- **Schedule** consists of several **slots**, each of length α_n.
  In each slot, nodes have different **power allocations** $\mathbf{p}_n$.



- In each slot, a link achieves rate $\mathbf{x}_n$
  as a function of SNIR and corresponding coding.

- **Long term average rate** is average rate over all slots

$$\bar{x} = \sum_n \alpha_n x_n$$

- We assume ideal control plane – no protocol overhead

Routing Protocol and Traffic Flows

- Traffic demand is described by end-to-end flows.
- Each flow is unicast or multicast.
- Each flow is mapped to one path (single-path routing) or more paths (multi-path routing)
- Constraints on average rates:

$$\mathbf{f} = \mathbf{F}\mathbf{y}, \ \mathbf{x} \geq \mathbf{R}\mathbf{y}$$

x = vector of rates on links

y = vector of rates on paths

f = vector of flows

$F_{f,p}$ = 1 if path *p* belongs to flow *f*, else 0
$R_{p,l}$ = 1 if path *p* uses link *l*, else 0

Power Constraint

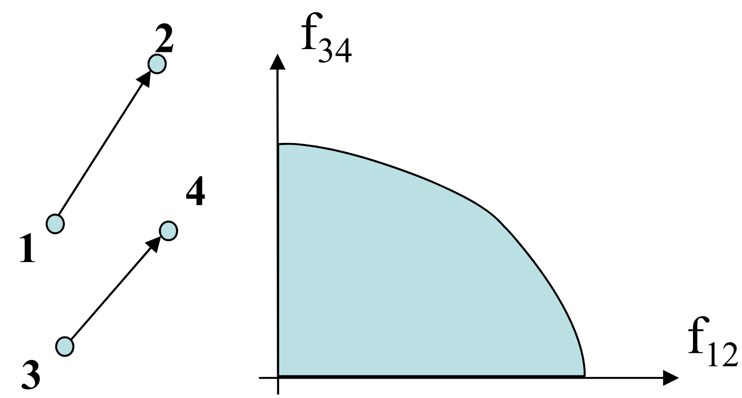
- **Peak power constraint**: maximum power of a symbol in a codebook. Integrated in model trough rate function.
- **Transmission power constraint** P^{MAX}: average power of transmission in given slot. Corresponds to average power of codebook used.
- **Long term average transmission power constraint** P^{MAX}_{avg}: average power dissipated over the schedule.
  It corresponds to battery lifetime:

$$T_{lifetime} \geq E_{battery} / (P^{MAX}_{avg} \times u)$$

u - fraction of time node has data to send

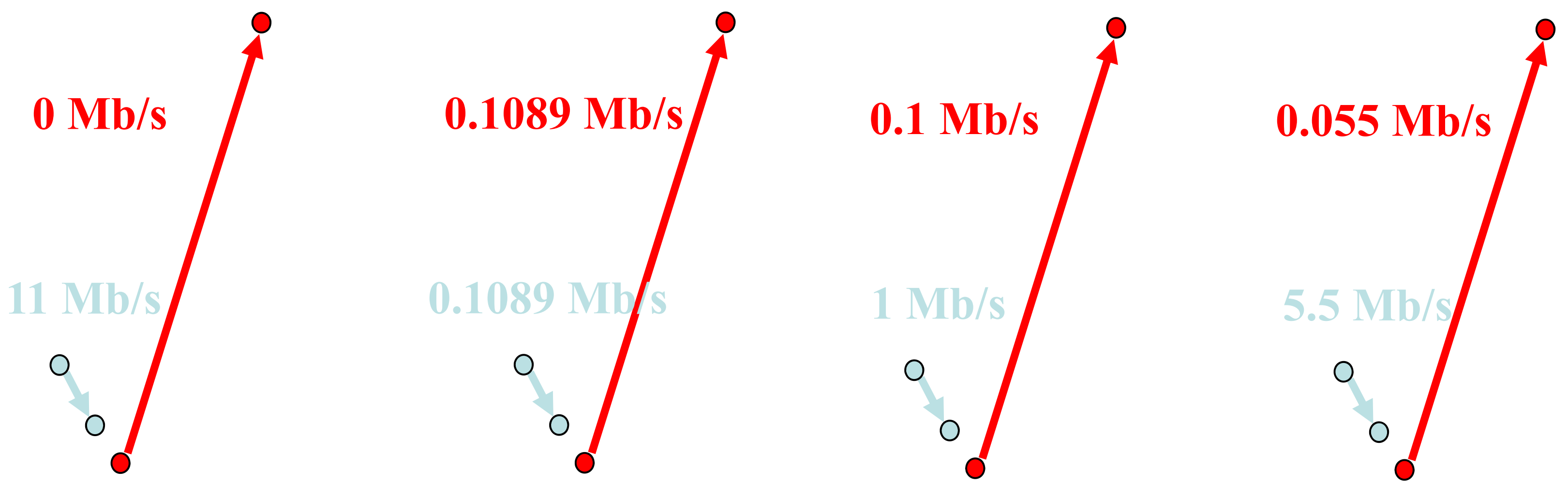
Allocation is solved as an optimization problem

- **Constraints:** flow, power
- **Given network topology and traffic matrix, we have set of feasible rates and set of feasible transport rates.**
  - **Set of feasible rates is convex but only implicitly defined**
  - **problem with all variables is non convex**
- **Maximization problem**
  - **∑ f (capacity),**
    ∑ f § length of link (transport capacity)
  - **iterative maximization (water filling): max-min fairness**
  - **∑ ln f (prop fairness)**



What we find

- Numerical solution on random networks :



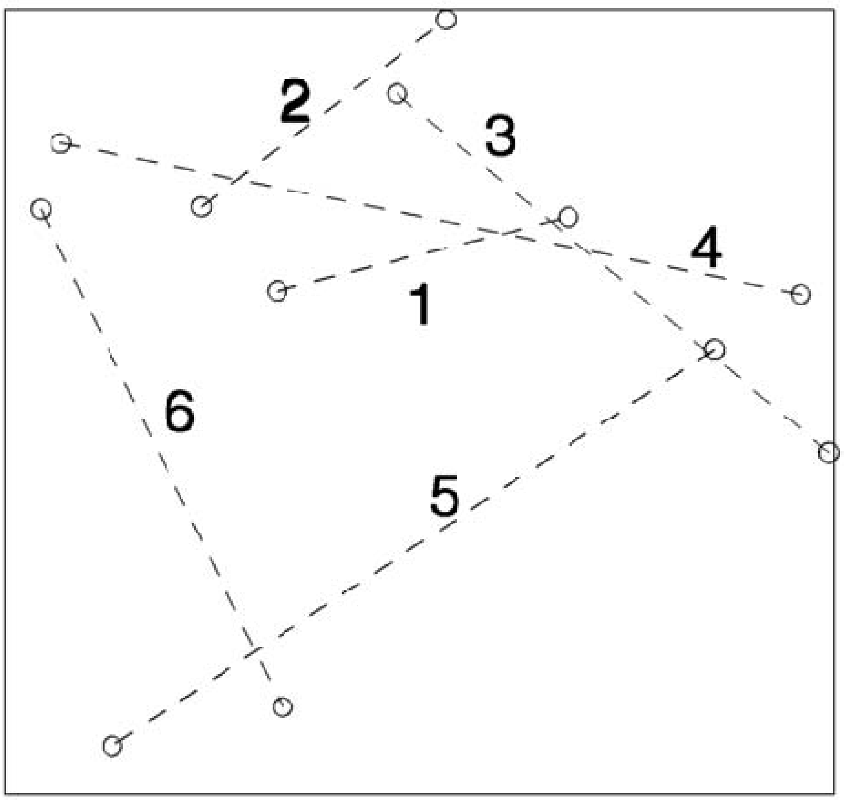
Maximize total capacity or transport capacity

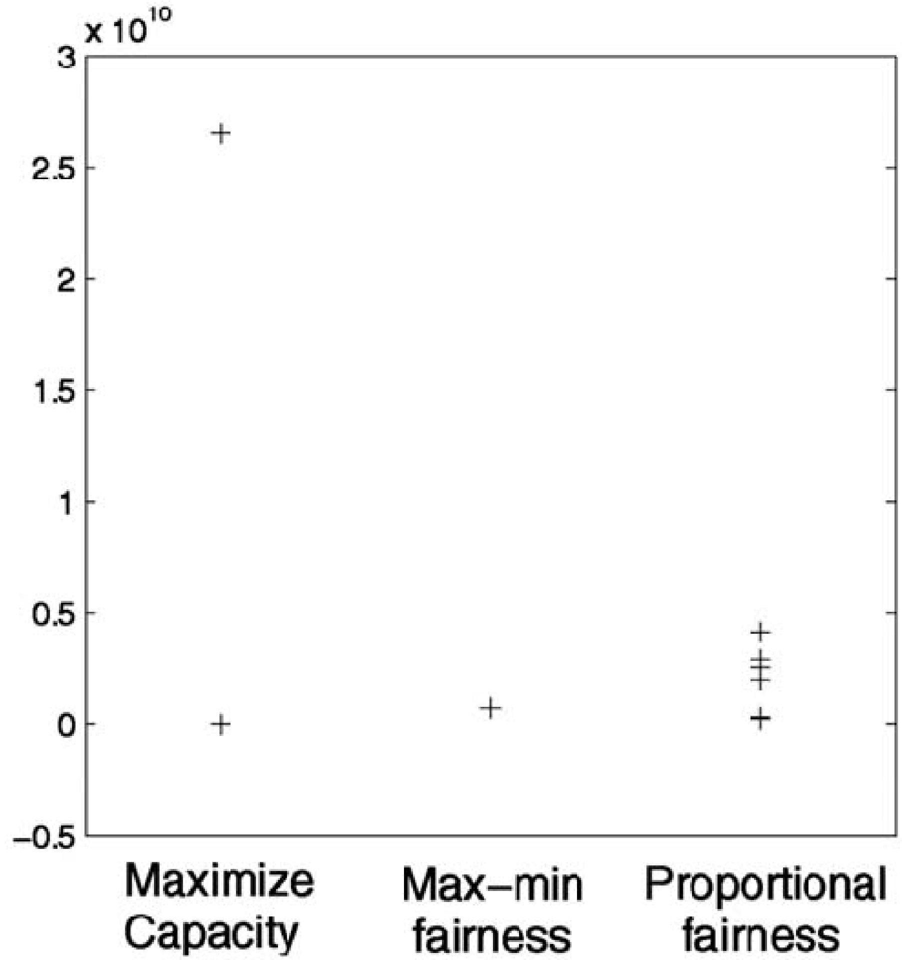
Max-min fairness

Transport Max-min fairness

Proportional fairness

The pattern is quite general



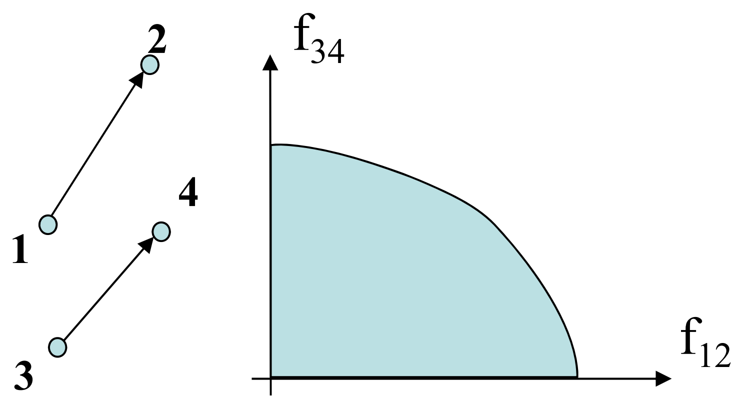


Max-min Fairness is always inefficient

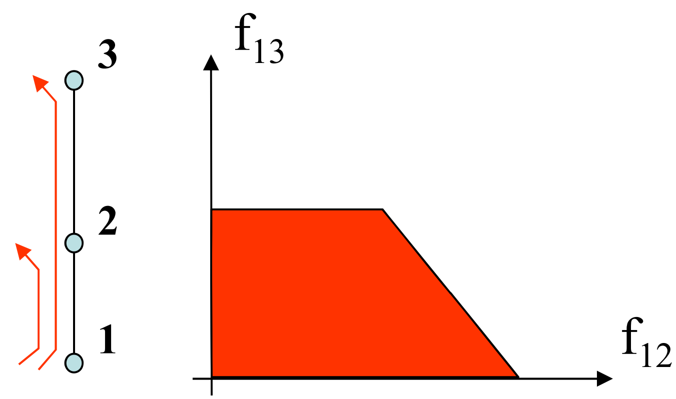
- **Theorem** [RL-TMC 2004]: Max-min fair rate allocation on arbitrary network, without battery lifetime constraint, has all rates equal
- Same for max-min fair transport rates

Equality of Max-Min fair rates is due to Solidarity Property

- A set has solidarity property if one can always trade value of one coordinate for some other coordinate.
- solidarity property of set , max-min rates are all equal
- Not all convex sets have solidarity property.
  - feasible set of rates for wireless network has
  - same for feasible set of transport rates

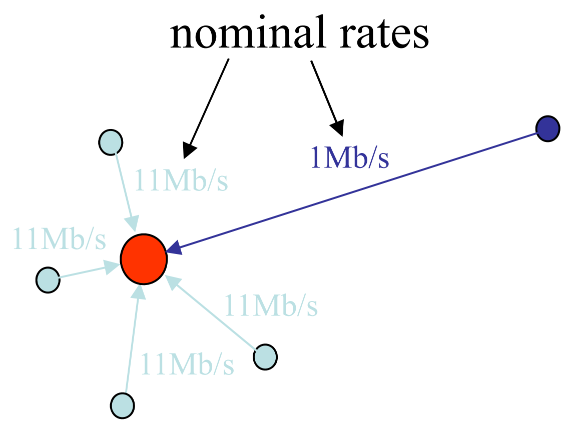


Example **with** solidarity property:
Feasible set of wireless network



Example **without** solidarity property:
Feasible set of wired network

Application to 802.11 Network



Actual rates of all flows in the example: 1 Mb/s!

- All nodes have equal probability to gain access to channel
- All nodes have packets of equal sizes: slower nodes take more time to send packet.
- System is essentially max-min fair
- Conclusion: All nodes will have the same average rate, regardless of coding used
- First reported by Duda et al [Infocom 03]

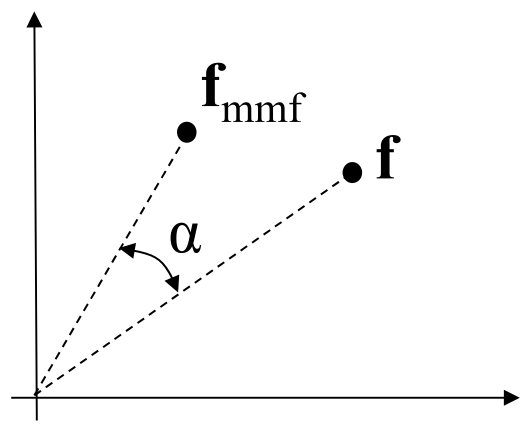
Phenomenon is not due to physical layer choice,
but due to choice of design objective.

Maximizing Total (Transport) Capacity is Grossly Inefficient

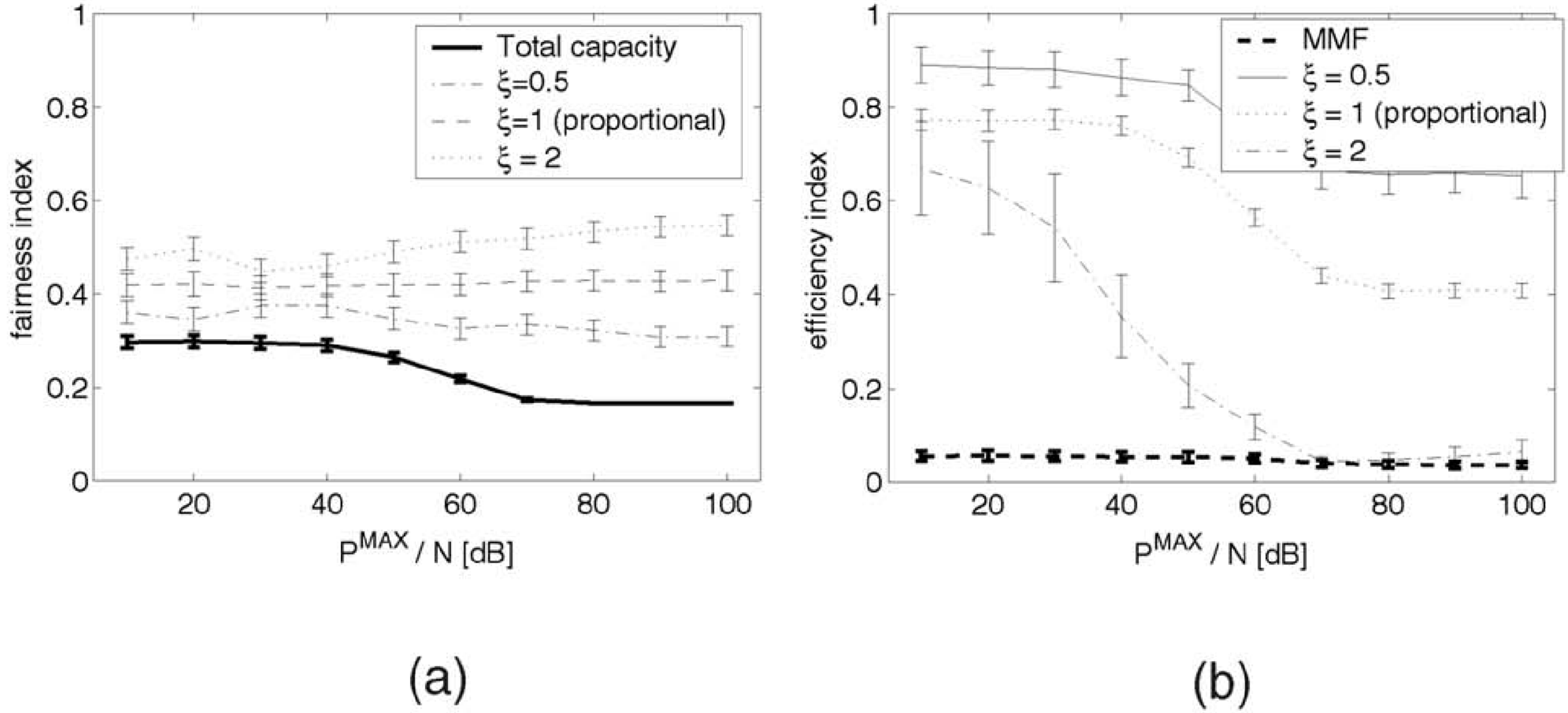
- **Theorem** [RL-TMC 2004] : Asymptotic results on maximizing (transport) capacity, no fading
  - when power constraint P^{MAX} goes to infinity, only the most efficient flows will have positive rate;
    the rates of other flows will be zero.
  - The same hold for maximizing transport rates – transport rates and rates of inefficient flows will be zero.

Evaluating Design Criteria

- **Q: How to quantify efficiency and fairness?**
- ***Efficiency index of rate allocation* f: $\sum f_i / \sum f^*_i$**
  where f^* is rate allocation that maximizes total capacity.
- ***Fairness index of rate allocation* f: $\cos^2(\alpha)$**
  where α is angle between f and max-min fair allocation f_{mmf}
  when MMF rates are equal, this coincides with Jain fairness index.



Proportional Fairness is a Good Compromise



Q1: Which performance objective to use ?

Q2: Which building blocks for MAC layer ?

- Optimal Design of MAC for new physical layers
- Apply to Very Low Power Ultra-Wide Band Communication in ad-hoc mode

State of the Art

- PHY and MAC are separated
  - PHY provides a « channel »
  - The goal of MAC is then « Mutual Exclusion »
    - TDMA (GSM), CSMA(WiFi) or combinations (Bluetooth, IEEE 802.15.3)
- Notable Exception
  - CDMA
  - allows interference
    - requires power control
- We want to exploit the following degrees of freedom
  - *coding*, thus channel rate can be variable packet per packet, or even block by block
  - *interference may* be allowed
- No joint coding /decoding (simple senders/receivers)

Our Method

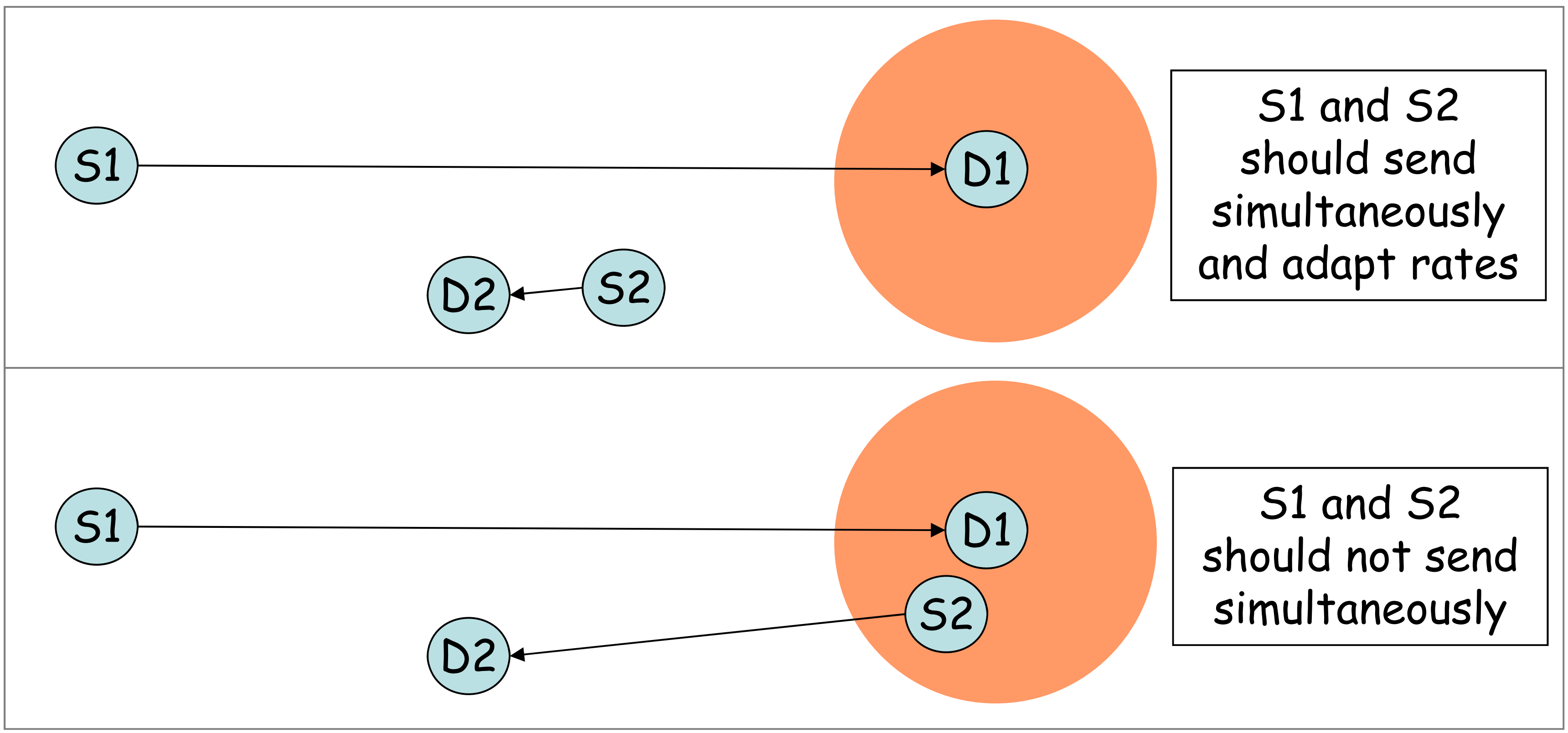
1. **Search for optimal design, ignoring protocol overhead**
   Look for patterns in optimal design
2. **Apply patterns to practical protocol implementations**
   Measure the results

Optimal Design

- Model a general wireless ad-hoc network with
  - variable coding rate
  - arbitrary power allocations with peak (voltage) and average (battery) constraints
  - random channel states (fading, mobility)
  - arbitrary schedule (i.e. mutual exclusion in the time domain)
  - arbitrary, possibly multipath, routing
  - arbitrary orthogonality factors (CDMA)
  - protocol overhead of exclusion not accounted for
- Numerically solve for proportional fairness

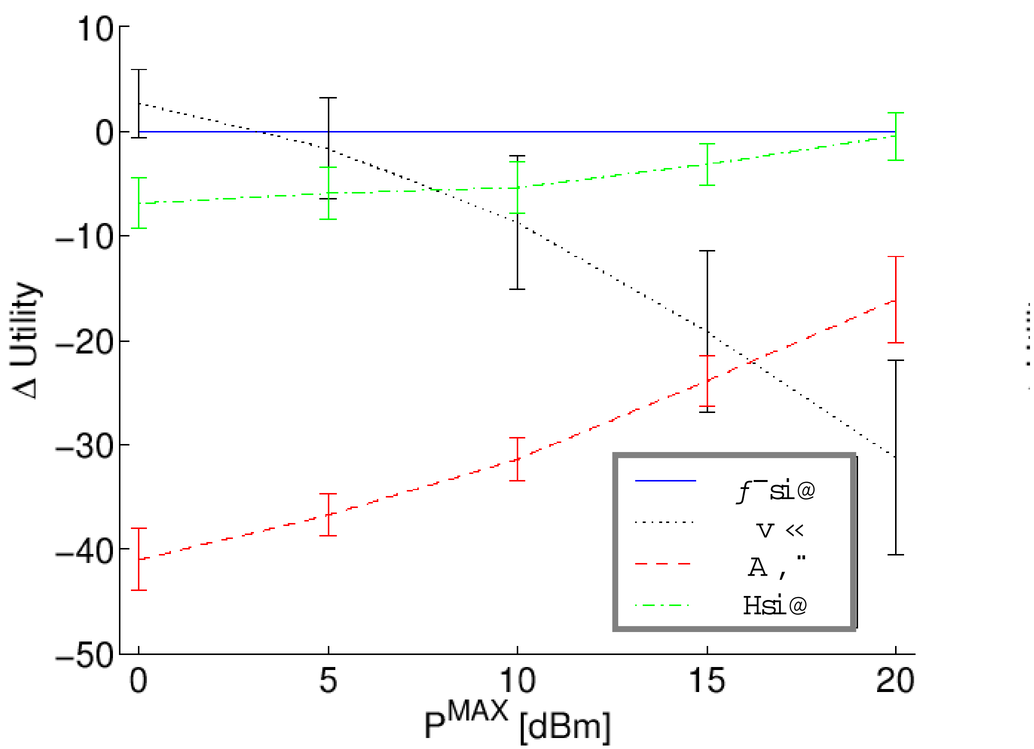
Finding 1: When Mutual Exclusion is not Optimal

- Interference should be allowed except when source is inside an « exclusion region » around a destination D1
  - size of exclusion region can be computed numerically based on characteristics of link S1-D1 and average power of interfering sources



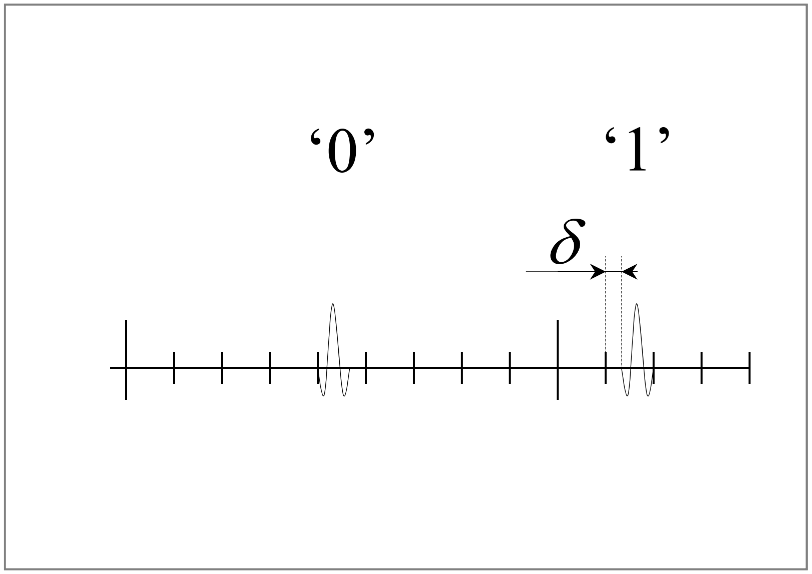
Application to IEEE 802.11

- IEEE 802.11 implements exclusion region by RTS/CTS
  - RTS/CTS decoded when received with SNR ¿ 0 dB
- we find numerically that it is optimal to *reduce* the range of RTS/CTS
  - RTS/CTS decoded when received with SNR ¿ 17 dB
- i.e. more interferece could be allowed
  - increase total rate by 50%



Application to Impulse Radio
Ultra Wide Band Communication

- Radio Transmission Technology, very low energy in all frequency bands
- Unlicensed
- Impulse radio = short pulses
  - in discussion at IEEE 802.15.4a very low power
  - other, non impulsive UWB : IEEE 802.15.3 frequency hopping (higher power)
- Example: [WinScholtz2000] pulse position modulation



Very Low Power UWB

- UWB has the potential to use very low power
- Our focus: reduced *emitted* power
  - environmental concern
  - pervasive computing

- Our threshold : order of microwatt emitted power

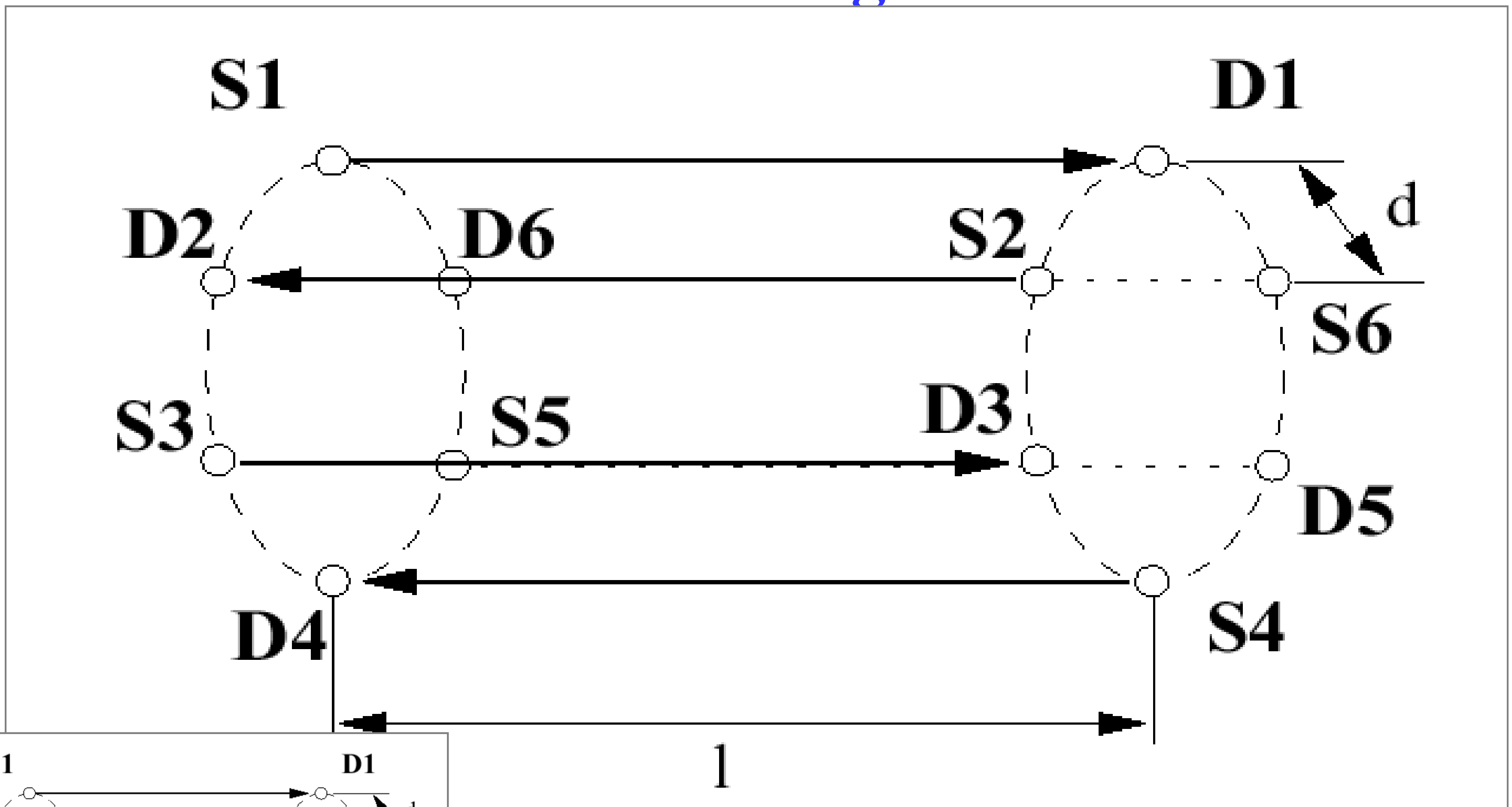
  - Maximum : 18 Mb/s for one user with line of sight
  - depends on noise and attenuation
    - 30 meters, maximum is 6 Mb/s for one user
    - in practice much less due to noise and interference

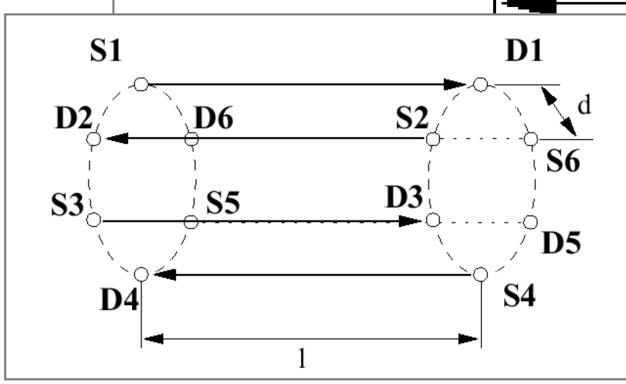
Finding 2 : On-Off Power

- **Optimal power control is On-Off**
  - **formally true in the linear regime rate = K × SNIR**

    Theorem 2 in [RadunovicL:05]
  - **numerically true, with confidence intervals, in other cases**
- **Any other policy is not optimal**
- **Contrast with CDMA design**

Finding 3 : Mutual Exclusion is not Optimal in Low Power Regime





What this tells us

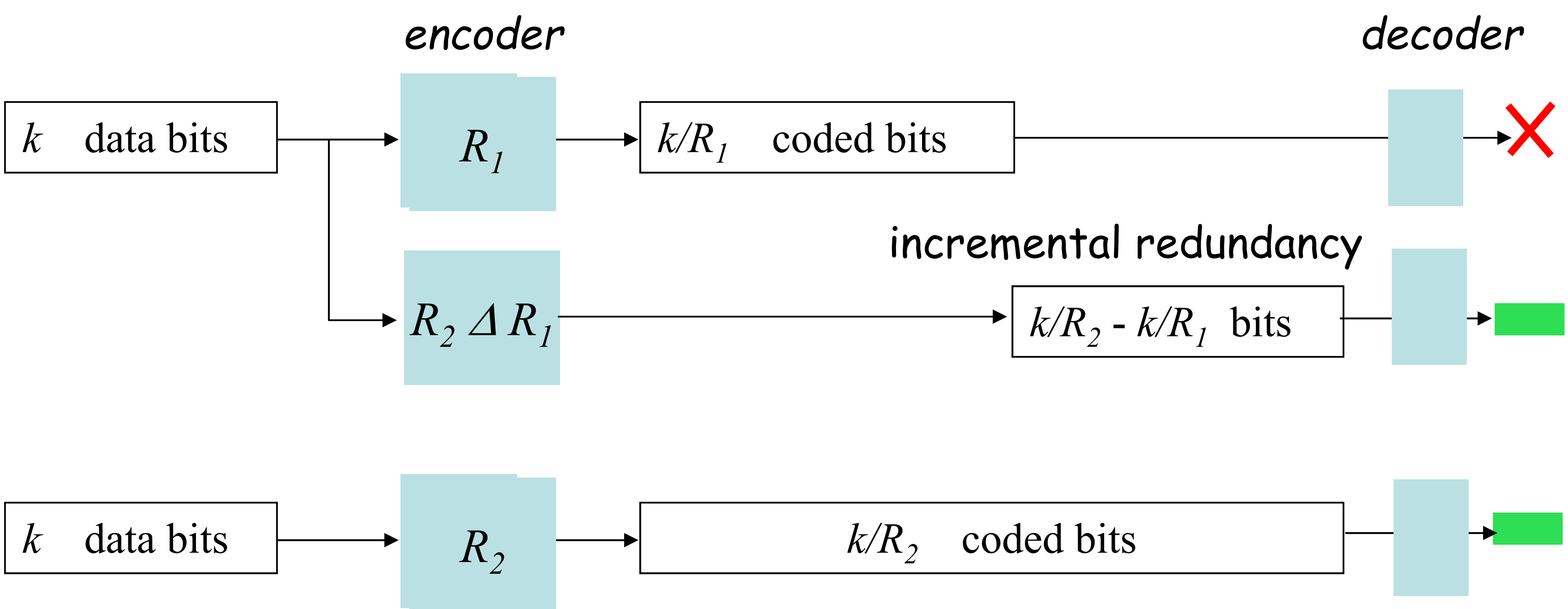
- Suggested MAC design for very low power with interference mitigation
  - 1. allow interference,
  - 2. no power control
  - 3. adapt the code rate to the level of interference

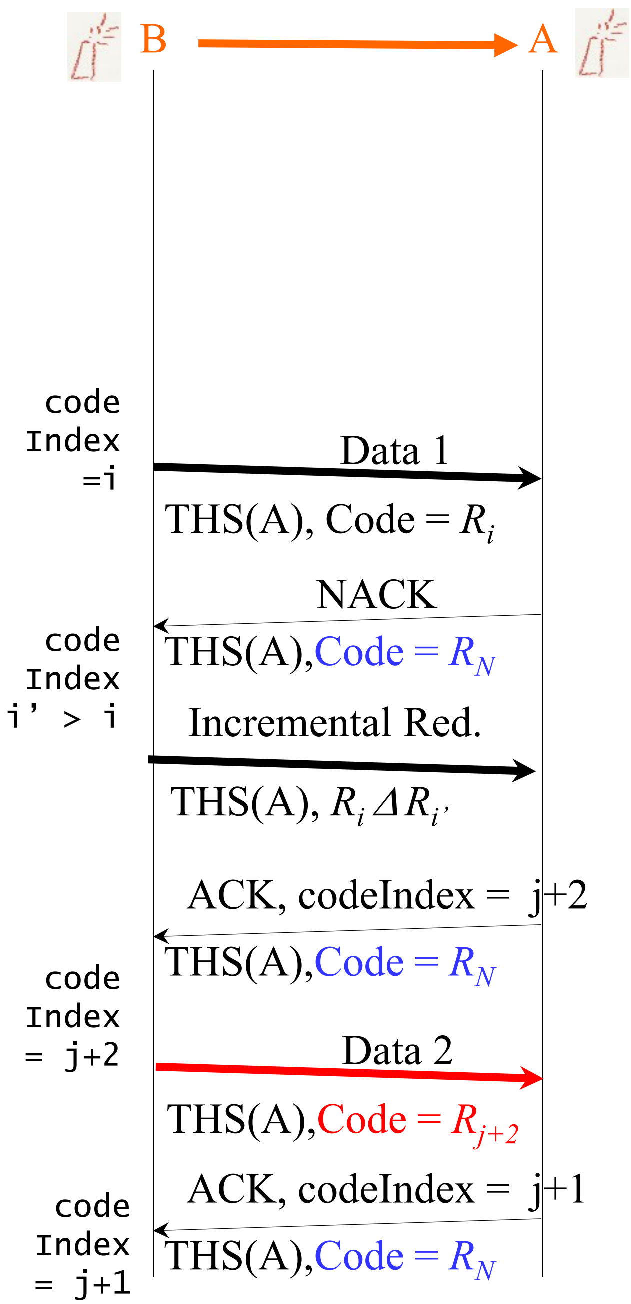
Our Concrete Protocol
Dynamic Channel Coding MAC Protocol

- Based on our theretical results
  - allow interference
  - adapt code
- It remains to solve
  - the « Private MAC Problem »:
    several sources send to same destination
  - carrier sensing not possible

We Use Incremental Redundancy Codes

- A family of codes that cover rates from 1 to 1/32
- No penalty for sending incremental bits later





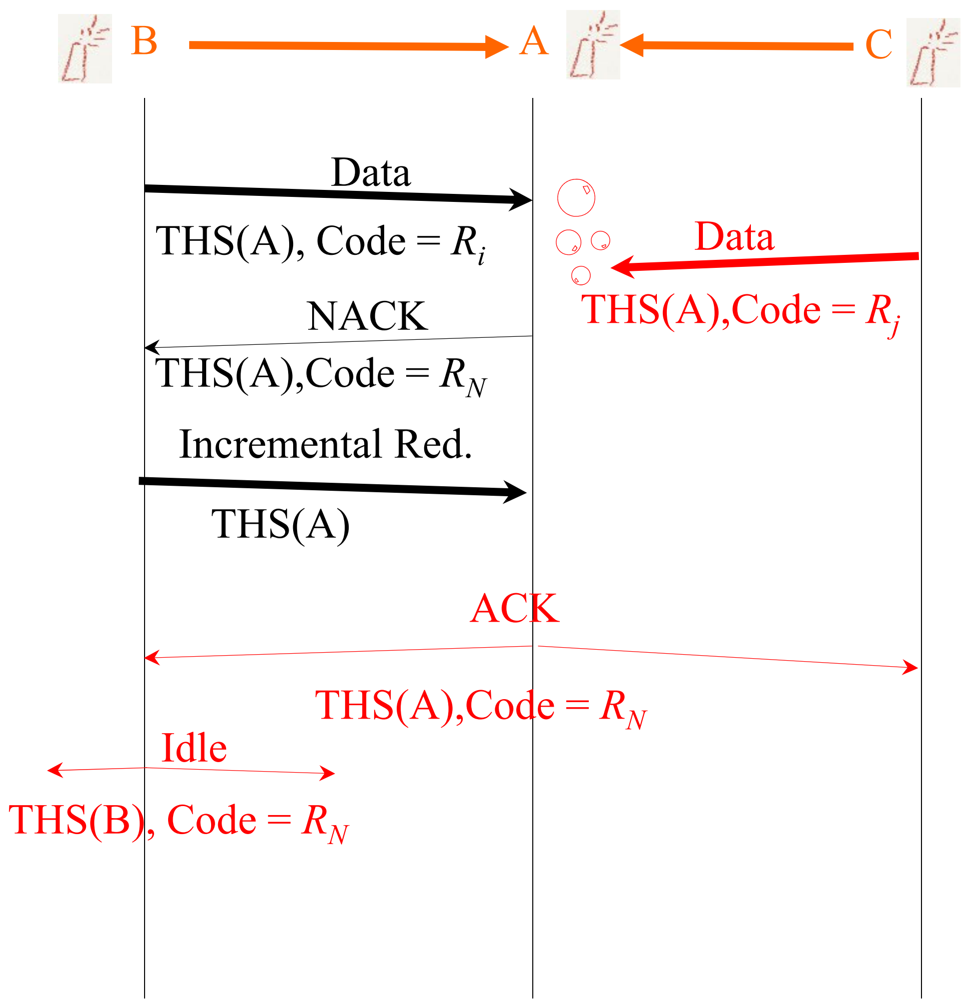
Dynamic Channel Coding

- Goal: use the most economical code
  - set for every packet
  - avoid hard failure
- Source keeps estimate of code to use with a safety margin
- Rate is adapted by an adaptation protocol at the MAC layer
  - no channel estimation

Concurrent Access is managed by « Private MAC »

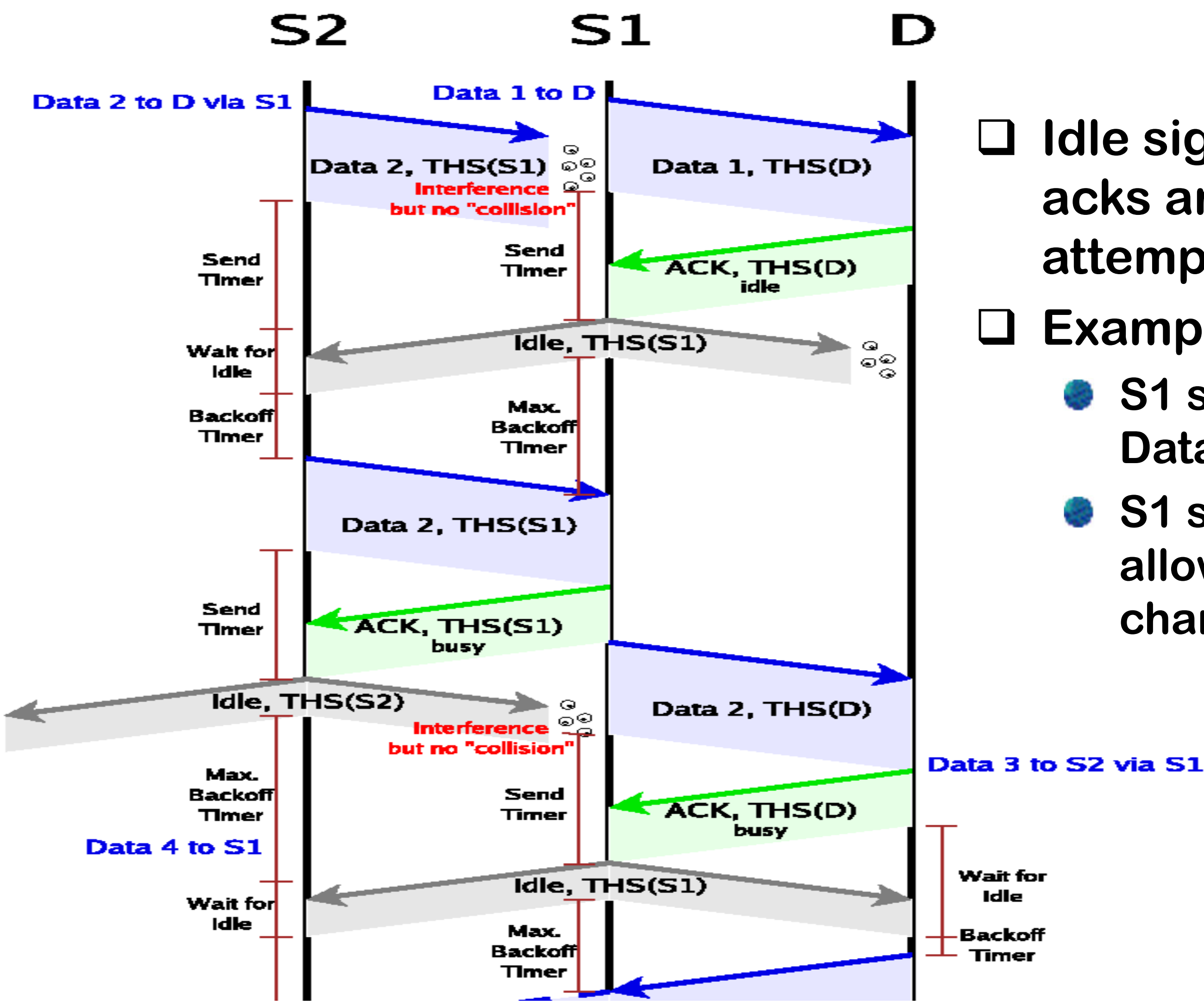
- Concurrent access to different destinations occurs without direct coordination
  - dynamic channel coding adapts automatically
- Access to same destination requires a mutual exclusion protocol
  - between competing sources
  - to arbitrate between sending and receiving
- Our "private MAC" protocol is a combination of invitation and receiver based

Concurrent Sources Do Not Collide



- ***C* attempts to transmit to *A***
  - **A is busy**
- **no collision, interference**
- **C waits for either**
  - **Ack**
  - **or Idle**

In ad-hoc network, interplay between sending / receiving requires careful tuning



- Idle signal + Idle/Busy in acks are used to avoid failed attempts
- Examples
  - S1 sends Idle after sending Data 1 – frees S2
  - S1 sends busy in ack allows S1 to keep the channel for sending

Simulation Results: No Collapse for Many Users

- We implemented the Dynamic Channel Coding MAC in ns2, based on tables computed in Matlab
  - we redesigned ns2 PHY to support interference /collision during a transmission
- We compared the performance to
  - mutual exclusion (TDMA, Random Access); power control

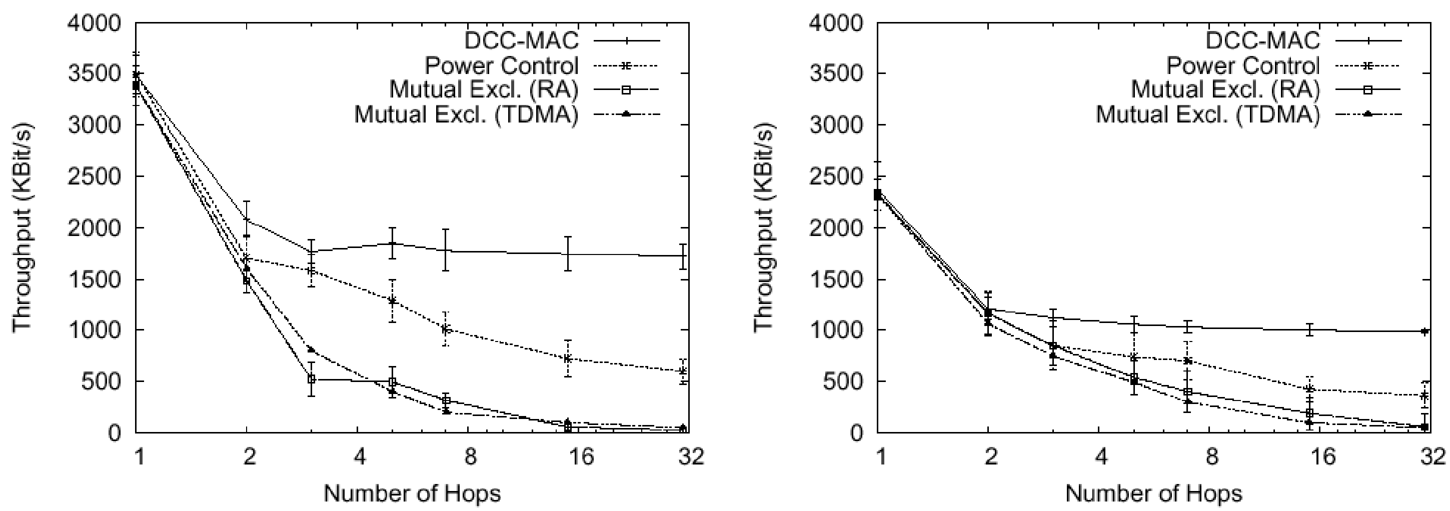


Fig. 7. Throughput on the multi-hop network for UDP (left graph) and TCP (right graph). We show throughput vs. number of hops. There is almost no drop in throughput for the DCC-MAC as the number of hops increases.

Conclusion

- A fundamental reflection, based on modelling, on how to organize the MAC leads to different approaches
  - the optimization criterion is important
  - interference is not collision
  - power control not always a good idea

More Information

1. [RL-TMC 2004] B. Radunovic, J. Y. Le Boudec
   "Rate Performance Objectives of Multihop Wireless Networks"
   In *IEEE Transactions on Mobile Computing*, October 2004, Vol. 3 No. 4, 334-349
2. R. Merz, J. Widmer, J. Y. Le Boudec, B. Radunovic
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   Proceedings of IEEE WoWMoM, Taormina, Italy, June 2005