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Balancing Transport and Physical Layers in Wireless Ad Hoc Networks: Jointly Optimal Congestion Control and Power Control

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A Motivation from Wired Networks

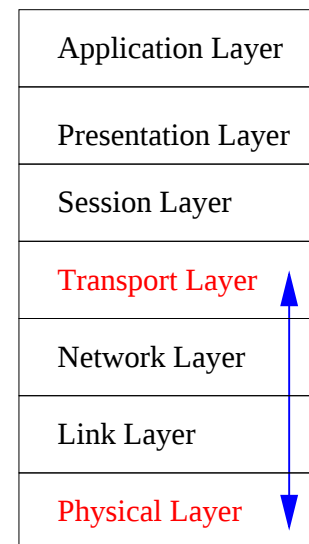
A major U.S. telecom service provider serving 80 million users

Engineering focus has been on **either** physical layer improvement (better coding, modulation ...) **or** upper layer network protocol (MPLS ...)

But end users only care about the net **end-to-end** performance

Layered network architecture

- Resource allocation (e.g., power control) in layer 1
- Congestion control (e.g., Transport Control Protocol TCP) in layer 4
- **To Layer or Not To Layer?**

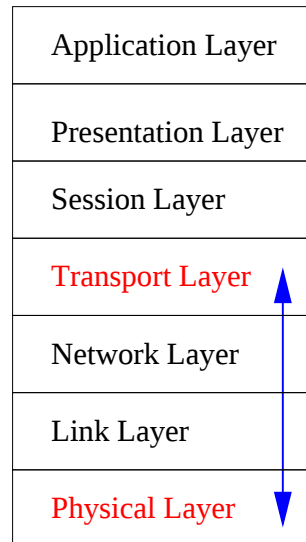


Outline

- Background and Formulation
- Algorithm, Performance, Example
- Other Properties and Open Issues

Thanks: S. Boyd, S. Low, D. O'Neill, L. Xiao

Why Cross Layer

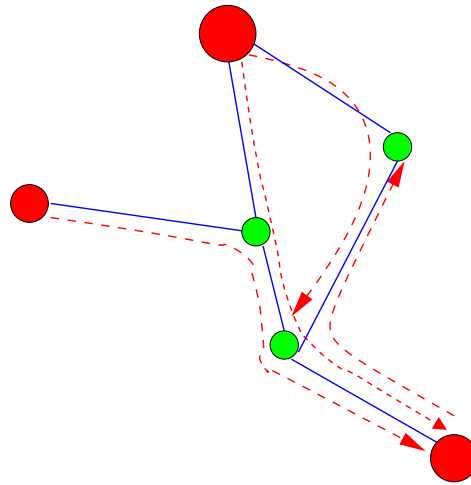


Beyond performance enhancement:

- Architectural **modularity**
- **Convergence, robustness, stability**
 - **Complexity**

Review: Internet Congestion Control

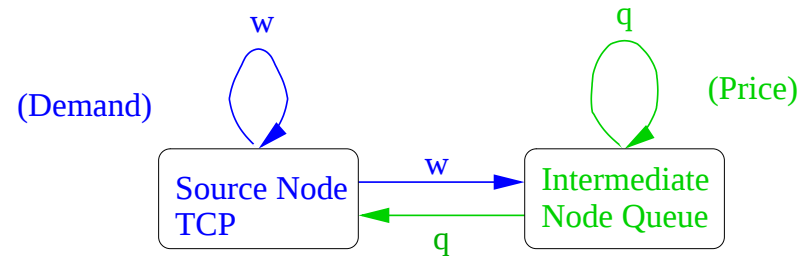
TCP end-to-end congestion control since 1980s



Sliding window $w_i(t)$ at sources. Probe network congestion

Large file transfers mainly in Congestion Avoidance phase

Review: TCP Vegas



- Each source node updates **allowed rate** (end-to-end throughput):

$$e.g., w_i(t+1) = \begin{cases} w_i(t) + \text{factor} & \text{if Expect-Rate} - \text{Actual-Rate} < \alpha_i \\ w_i(t) - \text{factor} & \text{if Expect-Rate} - \text{Actual-Rate} > \alpha_i \\ w_i(t) & \text{else} \end{cases}$$

- Each intermediate router updates congestion signal (link price):

e.g., TCP Vegas: **queuing delay** $\lambda_l(t)$ ($\Rightarrow$ Actual-Rate)

- **Distributed primal-dual** algorithm solving a **global** optimization (Low, Peterson, Wang 2002)

Review: Understanding Congestion Control

Congestion control distributively solves **network utility maximization**

TCP variants recently analyzed as implicitly solving this optimization

(Low, Doyle, Paganini 2002, Low 2003)

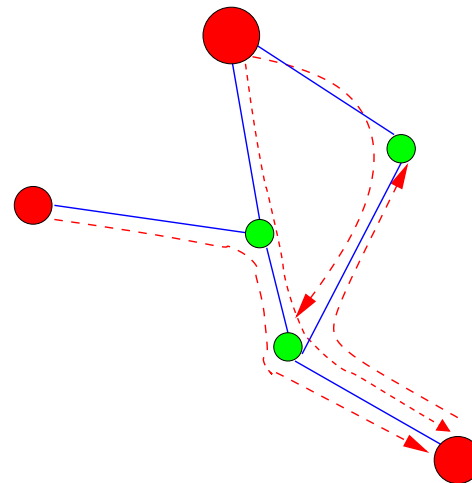
$$\begin{aligned} &\text{maximize} && \sum_i U_i(R_i) \\ &\text{subject to} && \sum_{i:l \in L(i)} R_i \leq c_l, \forall l, \\ &&& \mathbf{R} \succeq 0 \end{aligned}$$

R_i : rate from source i

c_l : capacity on link l

variables: $\mathbf{R}$

constants: $\mathbf{c}$



Utility Optimization in Wireless Networks

Link 'capacities' c **not** constants, but depend on **time-varying channel conditions** and **adaptive resource allocation**:

- Linear or nonlinear dependency (possibly non-convex)
- Local or global dependency
- Interference effects within resource allocation

We focus on **power control** as the primary adaptive resource allocation

- Power control determines data rate **supply** $c(\mathbf{P})$
- Rate allocation regulates user rate **demand** $\mathbf{R}$

Challenge and opportunity:

Maximize network utility **jointly** over rate allocation and power control

Channel Model

- No base stations, access points, or cluster heads
- Multihop transmission. Fixed single-path routing
- For each logical link l , **Signal to Interference Ratio**:

$$\text{SIR}_l(\mathbf{P}) = \frac{P_l G_{ll}}{\sum_{j \neq l}^N P_j G_{lj} + n_l}$$

G_{lj} : path loss from transmitter on link j to receiver on link l (including propagation loss and normalization factors)

G_{ll} : path gain for intended transmission on link l (including propagation loss, spreading gain, and beamforming effect)

- **Link 'capacity'** c_l in terms of attainable throughput:

$$c_l(\mathbf{P}) = \frac{1}{T} \log(1 + K \text{SIR}_l(\mathbf{P})) \approx \frac{1}{T} \log(K \text{SIR}_l(\mathbf{P}))$$

T : symbol time. K : constant depending on modulation and BER

Problem

i : index for sources

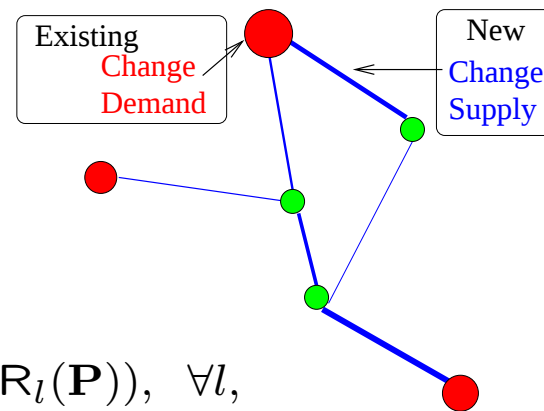
l : index for links

$L(i)$: set of links used by i

R_i : rate from source i

maximize $\sum_i U_i(R_i)$

subject to $\sum_{i:l \in L(i)} R_i \leq c_l(\mathbf{P}) = \log(\text{SIR}_l(\mathbf{P})), \forall l,$
 $\mathbf{R}, \mathbf{P} \succeq 0$



New Challenges:

- Global nonlinear (and nonconvex) dependency between rates and powers, and among powers
- Need distributive algorithm

New Opportunity for Congestion Control

Intuition:

Distributively put the right amount of power at each transmitter to alleviate global bandwidth bottleneck and dissolve congestion

Questions:

- Where're the bottlenecks?
- Are we creating new bottlenecks?
- Can we recycle the congestion prices?

Algorithm

1. At each intermediate node, **queuing delay** λ is implicitly updated:

$$\lambda_l(t+1) = \left[\lambda_l(t) + \frac{\gamma}{c_l(t)} \left(\sum_{i:l \in L(i)} R_i(t) - c_l(t) \right) \right]^+$$

2. At each source, **window size** updated (and $R_i(t+1) = \frac{w_i(t+1)}{D_i(t)}$):

$$w_i(t+1) = \begin{cases} w_i(t) + \frac{1}{D_i(t)} & \text{if } \frac{w_i(t)}{d_i} - \frac{w_i(t)}{D_i(t)} < \alpha_i \\ w_i(t) - \frac{1}{D_i(t)} & \text{if } \frac{w_i(t)}{d_i} - \frac{w_i(t)}{D_i(t)} > \alpha_i \\ w_i(t) & \text{else.} \end{cases}$$

3. Each transmitter j passes **message** m_j to all other transmitters:

$$m_j(t) = \frac{\lambda_j(t) \text{SIR}_j(t)}{P_j(t) G_{jj}}$$

4. Each transmitter updates its **power**:

$$P_l(t+1) = P_l(t) + \frac{\kappa \lambda_l(t)}{P_l(t)} - \kappa \sum_{j \neq l} G_{lj} m_j(t)$$

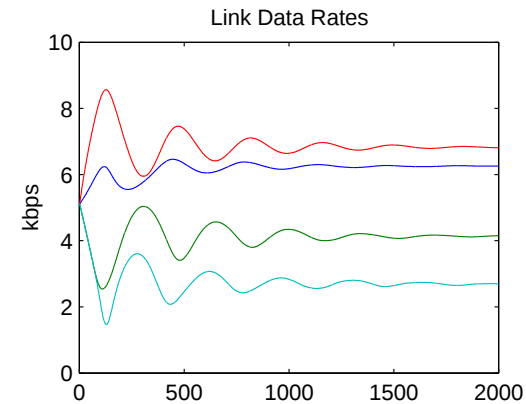
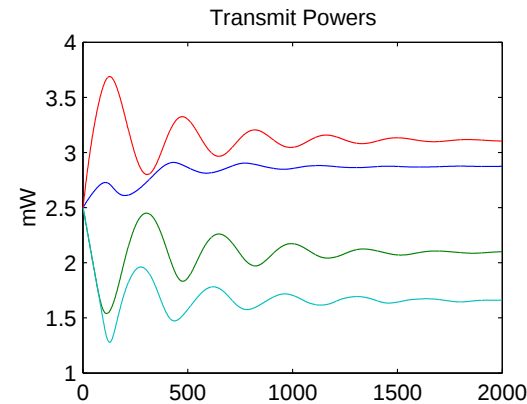
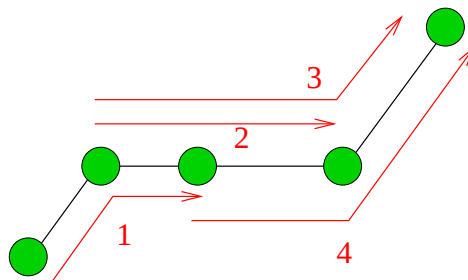
Performance Guarantee

Theorem:

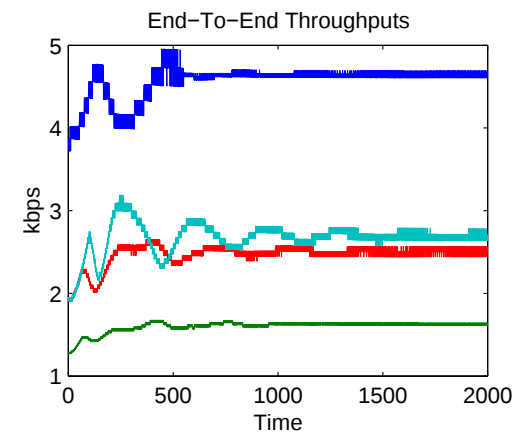
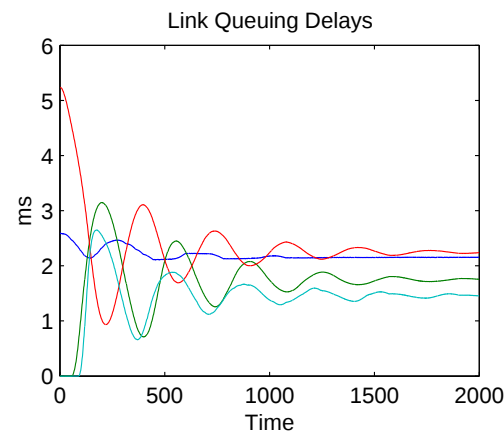
Assume finite powers and buffer sizes and strictly positive powers, for small enough positive constants γ and κ , Algorithm converges to the globally and jointly optimal powers and rates

Numerical Example

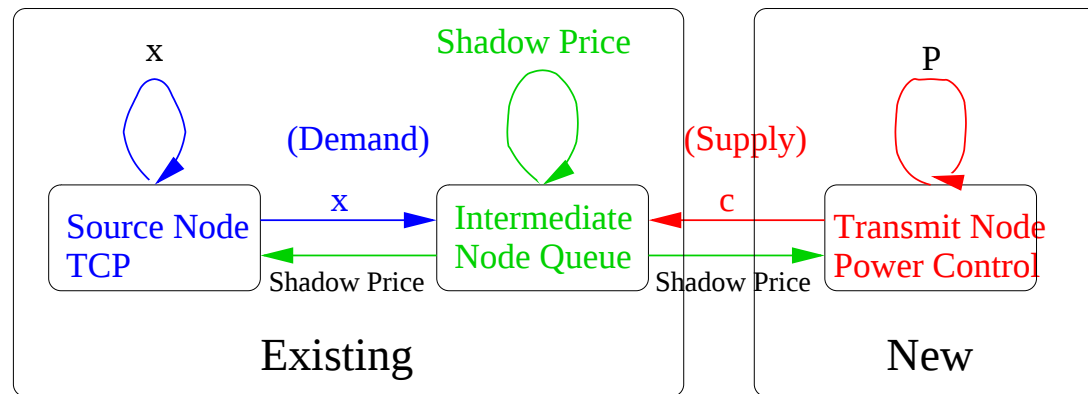
A small example:



- 82% increase in end-to-end throughput per watt of power transmitted
- Most benefits from limited message passing



Pricing Intuition



- Nonlinearly coupled system **converges** to joint, global optimality
- Advantage: **No need** to change the existing TCP congestion control and queue management algorithms. Just utilize the values of queue length in designing power control algorithm in physical layer
- Congestion price is also **layering price**

Further Results on Other Properties

- **Robustness** against channel estimation errors and fading
- Convergence of **asynchronized** message passing
- Convergence of **partial** message passing
- **Convergence rate** bounds
- Speedup methods
- Choices of constant parameters
- Energy efficiency and fairness **tradeoff**
- **General models** of link resource adaptation and source rate allocation

Open Issues

Open Issue 1: What about other physical layer models, such as Low SIR regime or the frame success probability model? (Level of difficulty: ★)

Open Issue 2: What about scheduling or contention-based wireless medium access control mechanisms? (Level of difficulty: ★, ★)

Open Issue 3: What's the transient behavior? If routing and topology change dynamically, will the overall system be unstable? (Level of difficulty: ★, ★, ★)

Layering as Decomposition of Global Optimization

Integrate various protocol layers into a single coherent theory

- Vertical decomposition
- Horizontal decomposition

Protocols as asynchronous distributed primal-dual algorithms over the network **implicitly** solving a **global optimization problem**

- TCP/AQM
- TCP/PHY
- TCP/IP
- TCP/MAC
- TCP/MAC/PHY