FAST Copper For Broadband Access

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joint work with R. Cendrillon, M. Chiang, M. Moonen, C.-W. Tan

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What's FAST Copper?

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- Princeton, Stanford, Fraser Research Lab
- Main industry collaborator: AT&T

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- Through fiber/DSL deployment, engineering innovations, and fundamental research

- Four key dimensions: Frequency, Amplitude, Space, Time (FAST)

Why Fiber/Copper?

- Alternatives of broadband access:
  - Wireless: reliability, coverage, and backhaul issues
  - Cable modem: not ubiquitous, bandwidth sharing issues
  - Fiber to the closet: per-customer labor cost prohibitive
  - Existing DSL: 160 million users, but not fast enough

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  - Existing DSL: 160 million users, but not fast enough
- Fiber/Copper: best of ubiquity, broadband, reliability, and migration
- Broadband over phone wires
- Example: AT&T's Lightspeed Project

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- Realistic estimates on improvements coming from research:
  - Frequency: 2X (even more through signal processing)
  - Amplitude: $>$2X
  - Space: enabler of rate, reach, reliability
  - Time: 2X

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- Realistic estimates on improvements coming from research:
  - Frequency: 2X (even more through signal processing)
  - Amplitude: >2X
  - Space: enabler of rate, reach, reliability
  - Time: 2X
- Not even bringing in wider bandwidth, multiple telephone lines, and systems debugging yet

Key Ideas

- It's not a dedicated line, it's a (multi-carrier) interference channel
  - From "low frequency" mentality to "high frequency" mentality
  - Turn competition to cooperation in frequency and time
- It's not a voice line, it's a bursty data and video line
  - From "deterministic" mentality to "statistical" mentality
  - Squeeze in more than you have bandwidth for
- A lot of research (and deployment) challenges

Challenges and Connections

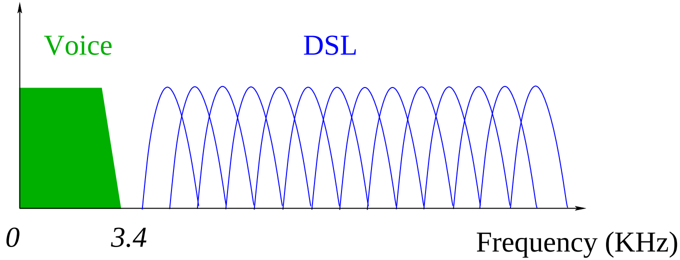
- Information theory: multi-carrier interference channel
- Signal processing: multi-user transmissions
- Stochastic theory: statistical multiplexing
- Graph theory: survivable tree design
- Optimization theory: nonconvex and globally coupled optimization
- Networking: resource allocation and "Layering As Optimization Decomposition"

Our focus today will be Frequency and Time.

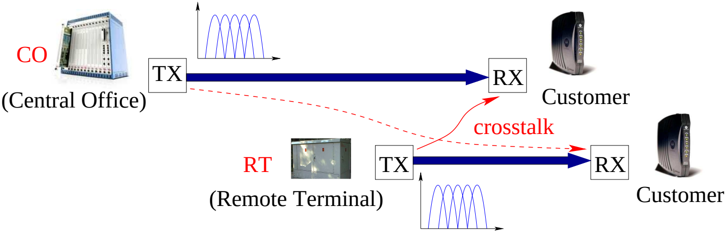
Frequency

Transmission Model

- Copper line can support signal transmissions over a large bandwidth
- Voice transmission: up to 3.4 KHz
- DSL transmissions: up to 30 MHz
  - Multi-carrier transmissions: Discrete Multitone Modulation



Network and Channel Model



Mathematical model: multi-user multi-carrier interference channel

- Each telephone line is a user (transmitter-receiver pair)
- Generate mutual crosstalks over multiple frequency tones

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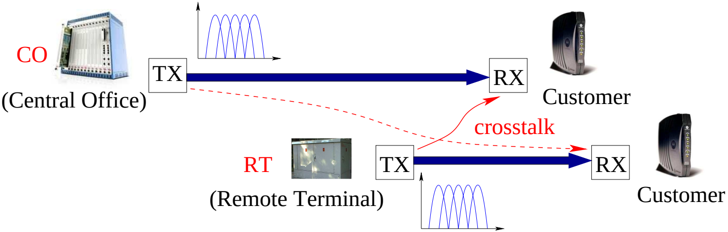
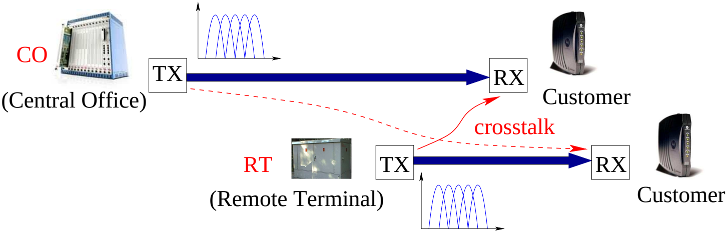


Physical model: mixed CO/RT case

- Channel attenuates with distance
- Central Office (CO) connect customers who are reasonably close
- Remote Terminal (RT) connect customers who are farther away

Network and Channel Model



Frequency-Dependent Channel

- Direct channel gain decreases with frequency
- Crosstalk channel gain increases with frequency

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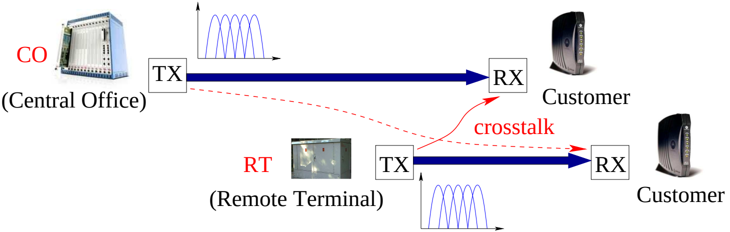
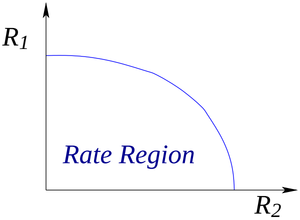


Frequency-Dependent Channel

- Direct channel gain decreases with frequency
- Crosstalk channel gain increases with frequency
- Lead to near-far problem
  - RT generates strong crosstalk to CO line, especially in high tones
  - CO generates little crosstalk to RT in all tones

Network Objective: Maximize Rate Region

Rate Region: set of all achievable rate vectors



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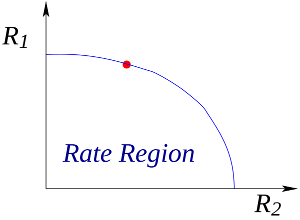

Problem A: (Find One Point On the Rate Region Boundary)

$$\underset{\{\mathbf{p}_n \in \mathcal{P}_n\}_n}{\text{maximize}} \sum_n w_n R_n$$

- User n's achievable rate $R_n = \sum_k \log\left(1 + \mathtt{SINR}_n^k\right)$.
  - No multi-user joint decoding
- User n chooses a power vector $\mathbf{p}_n \in \mathcal{P}_n = \left\{\sum_k p_n^k \leq P_n^{\max}, p_n^k \geq 0\right\}$.

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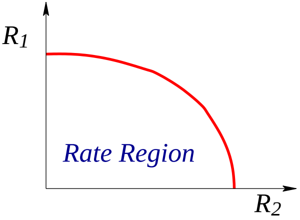

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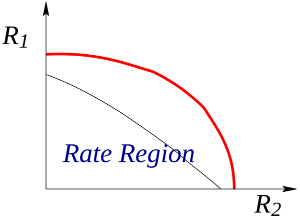

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- Changing different weights trace the entire rate region boundary
- A suboptimal algorithm leads to a reduced rate region

Properties of Problem A

- **Technical difficulties**
  - Non-convexity: total weighted rate not concave in power.
  - Physically distributed: local channel information
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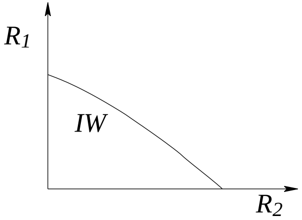
- **Our Solution**: ASB algorithm

Dynamic Spectrum Management (DSM)

- State-of-art DSM algorithms:
  - IW: Iterative Water-filling [Yu, Ginis, Cioffi'02]



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IW	Autonomous	$O(KN)$	Suboptimal

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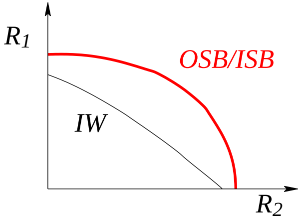

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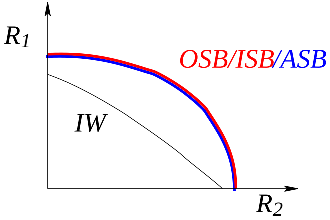
  - ASB: Autonomous Spectrum Balancing [Huang et al.'06]



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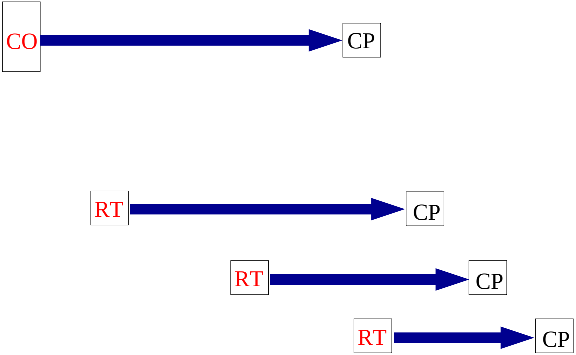
ASB	Autonomous	$O(KN)$	Near Optimal

Key Idea: Reference Line

- **Reference line**: static pricing for static channel
  - A virtual line representative of the typical victim in the network
  - Good choice: the longest CO line
  - Parameters (power, noise, crosstalk) are publicly known
- Each user will choose its transmit power to protect the reference line

Reference Line



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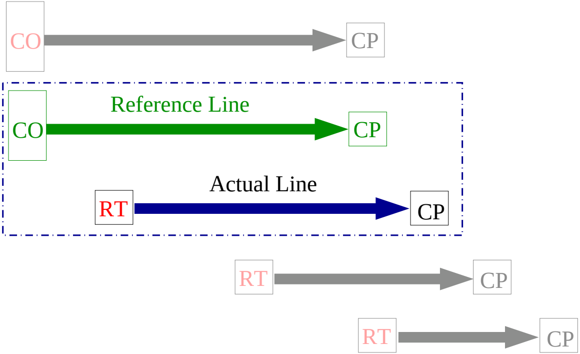
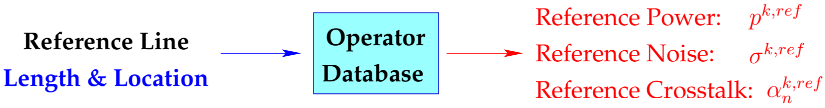


Reference Line's Rate

- User n's obtains the reference line parameters locally



Reference Line's Rate

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Reference Line **Length & Location** → **Operator Database** →

Reference Power: $p^{k,ref}$
Reference Noise: $\sigma^{k,ref}$
Reference Crosstalk: $\alpha_n^{k,ref}$

- The reference line rate

$$R_n^{\text{ref}} = \sum_k \log \left(1 + \frac{p^{k,\text{ref}}}{\alpha_n^{k,\text{ref}} p_n^k + \sigma^{k,\text{ref}}} \right)$$

  - Interference only depends on user n's transmit power p_n^k
  - Locally computable without explicit message passing

Noncooperative Game

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- User n wants to maximize his **payoff**:

$$S_n\left(\mathbf{p}_n;\mathbf{p}_{-n}\right) \triangleq R_n^{\text{ref}}\left(\mathbf{p}_n\right) + w_n R_n\left(\mathbf{p}_n;\mathbf{p}_{-n}\right)$$

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- **Best response**: power vector that maximizes his payoff:

$$\mathcal{B}\left(\mathbf{p}_{-n}\right) \triangleq \arg\max_{\mathbf{p}_n\in\mathcal{P}_n} S_n\left(\mathbf{p}_n;\mathbf{p}_{-n}\right)$$

  - Requires solving a nonconvex optimization problem
  - Duality gap is zero (under large number of tones)
  - Satisfied in real DSL networks (ADSL: 256 tones, VDSL: 4096 tones)
  - Can be solved using dual decomposition

Solution of the Game: Nash Equilibrium

- **Nash Equilibrium (N.E.)**: $\mathbf{p}^* = \{\mathbf{p}_n^*, \forall n\}$
- Everyone is happy with the result
- Fixed point solution of all users' best responses

$$\mathbf{p}_n^* = \boldsymbol{\mathcal{B}}\left(\mathbf{p}_{-n}^*\right), \forall n$$

- Stable outcome of the game

Frequency Selective Water-filling

- Under high SNR approximation of the reference line

$$\mathcal{B}_n^k\left(\mathbf{p}_{-n}\right) = \left(\frac{w_n}{\lambda_n + \alpha_n^{k,\text{ref}}/\sigma^{k,\text{ref}} \cdot \mathbf{1}_{\{p^{k,\text{ref}}>0\}}} - \sum_{m\neq n} h_{n,m}^k / h_{n,n}^k p_m^k - \sigma_n^k \right)^+$$

  - Reference line is not active in high frequency tones
- Special case: traditional water-filling (ignore $\alpha_n^{k,\text{ref}}/\sigma^{k,\text{ref}}$)

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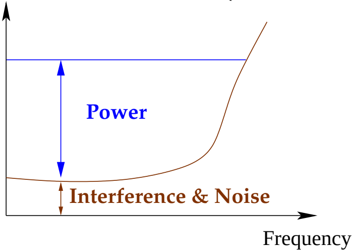

Traditional Water–Filling

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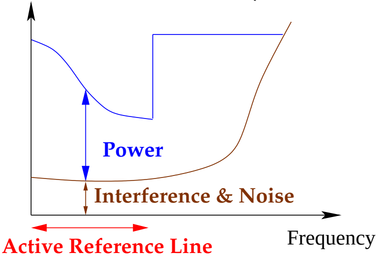


Frequency–Selective Water–Filling

Convergence of ASB Algorithm

- **ASB** Algorithm: users update their individual power allocation according to best responses either sequentially or in parallel

Theorem

ASB algorithm globally and geometrically converges to the unique N.E. if the crosstalk channel is small, i.e.,

$$\max_{n,m,k} \frac{h_{n,m}^k}{h_{n,n}^k} < \frac{1}{N-1}.$$

- Independent of the reference line parameters.
- Recover the convergence of iterative water-filling as a special case.

Proof: contraction mapping

Proof Outline

1. **Key Lemma**: min-max of an increasing function and an decreasing function is achieved at the intersection.
2. Construct two such functions based on the ASB algorithm.
3. Show the maximum difference between the PSD during adjacent iterations is decreasing.

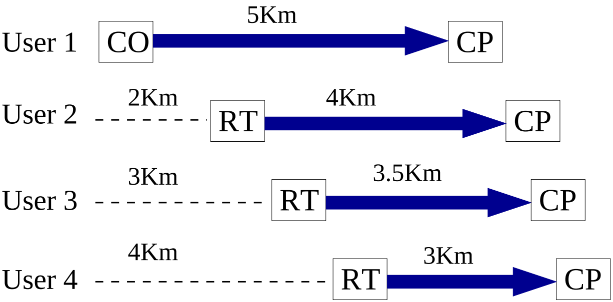
$$\max_n \max \left\{ \sum_k \left[p_n^{k,t+1} - p_n^{t,t} \right]^+ , \sum_k \left[p_n^{k,t+1} - p_n^{k,t} \right]^- \right\}$$

$$\leq \max_n \max \left\{ \sum_k \left[p_n^{k,t} - p_n^{k,t-1} \right]^+ , \sum_k \left[p_n^{k,t} - p_n^{k,t-1} \right]^- \right\}$$

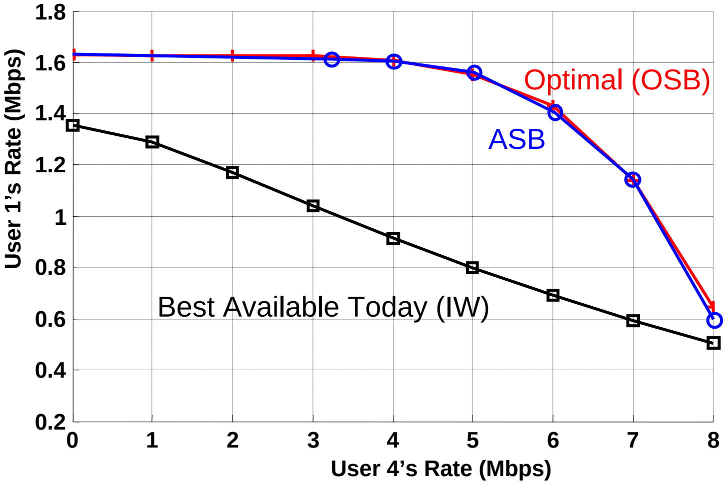
- Sequential updates: bound the maximum eigenvalue of the mapping matrix.
- Parallel updates: more realistic with cleaner proof.

ASB Performance

- Realistic industry simulator
- Mixed CO/RT deployment
- Practical channel and background noise models



Achievable Rate Regions of Different Algorithms



Quick Summary

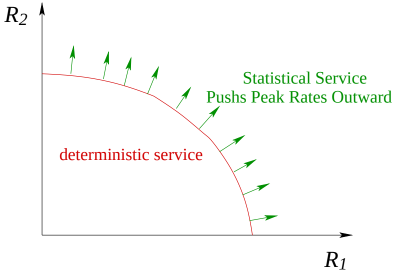
- **Topic**: spectrum management in DSL multiuser interference channels
- **Key idea**: static pricing using reference line
- **Algorithm**: ASB: autonomous, low complexity, and robust
- **Performance**: close to optimal, provable convergence
- **Extension**: asynchronous transmissions with inter-carrier-intererences

Amplitude

Service Provision of Stochastic Traffic

- Deterministic service: guarantee lossless transmissions.
  - Peak rate allocation.
- Statistical service: meet probabilistic QoS requirements.
  - Example: $\Pr\{\text{Packet Loss}\} < \epsilon$.
  - More efficient sharing of the same fixed communication channel.
  - Performance metric: **statistical multiplexing** gain.

Rate Region



- Deterministic service: stay inside the region.
- Statistical service: push outside the region.

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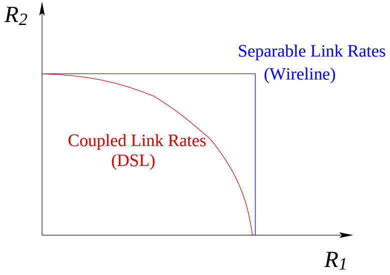

- Deterministic service: stay inside the region.
- Statistical service: push outside the region.
- Separable link rates (most wireline): $R_1 \leq C_1, R_2 \leq C_2$
- Coupled link rates (e.g., DSL): $(R_1, R_2) \in \mathcal{C}$

Cross-layer Statistical Multiplexing

- Previous results on statistical multiplexing in wireline network
  - Only considers link layer resource allocation.
  - Assume underlining link rates are fixed.

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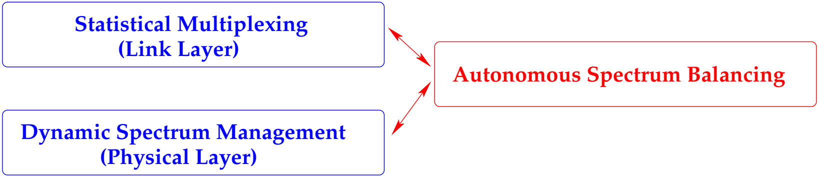
  - Only considers link layer resource allocation.
  - Assume underlining link rates are fixed.
- Here we also optimize physical layer resource.
  - Provide optimal rate allocation for upper layers.
  - Additional degree of freedom leads to better performance.

What We Solve Today

- Network performance optimization under stochastic traffic arrivals.



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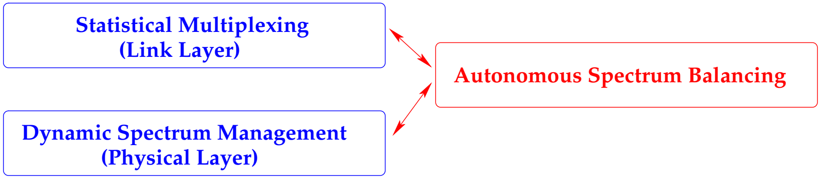

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  - QoS requirements: packet loss, delay, ...

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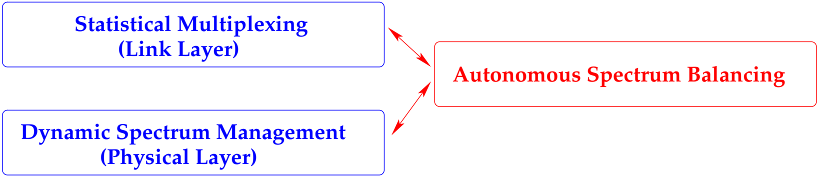
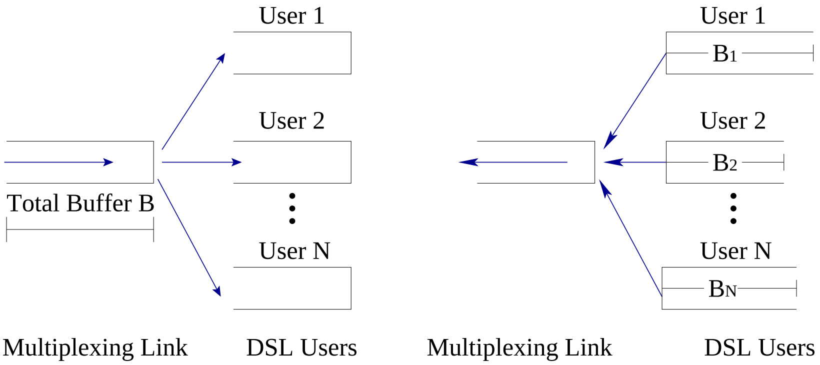


- What we know:
  - Traffic arrival statistics: mean, peak, variance ...
  - QoS requirements: packet loss, delay, ...
- What we want to solve:
  - Optimal rate allocation (physical layer)
  - Optimal buffer allocation (link layer)
  - Determine the admission region

Network Model



(a) Downstream Transmissions (b) Upstream Transmissions

Effective Bandwidth

- Simplify the analysis in the asymptotic regime
  - Large buffer, a lot of users, ...
- Estimate the bandwidth consumption of a stochastic traffic by a constant rate traffic.
- Depends on
  - Traffic arrival statistics.
  - QoS requirements.
  - Available network resource (e.g., buffer space).
- Many results available:
  - Large buffer asymptotic (in this talk).
  - Many source asymptotic (on-going work).

Effective Bandwidth

- Mathematical expression: $g(\delta)$
  - Function g depends on traffic characteristics
  - Parameter δ depends on QoS and network resource
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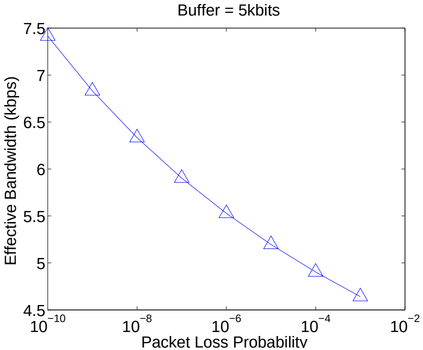
- Example: Compound Poisson arrival
  - Arrival rate λ, with exponential file size with mean $1/\mu$
  - QoS: packet loss prob less than ϵ
  - Resource: allocated buffer space B
  - Effective bandwidth:

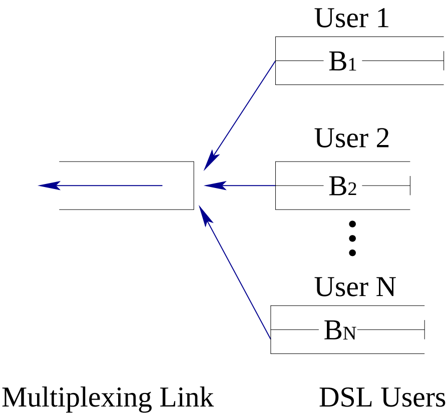
$$g(\delta) = \frac{\lambda}{\mu - \delta} = \frac{\lambda}{\mu - \frac{|\log(\epsilon)|}{B}}$$

Numerical Examples



Average rate 4kbps

Upsteam Transmissions



Rate Allocation in Upstream

- Each user has fixed flow traffic characteristics, QoS requirements and buffer space $\Rightarrow$ fixed Effective Bandwidth
- Rate allocation problem:

$$
\begin{aligned}
\text{maximize} \quad & \sum_i w_i a_i n_i && \text{(total weighted throughput)} \\
\text{subject to} \quad & \mathbf{c} \in \mathcal{C} && \text{(rate region constraint)} \\
& n_i g_i \leq c_i, \forall i && \text{(EB less than allocated rate)} \\
\text{variables} \quad & \mathbf{n}, \mathbf{c} \geq \mathbf{0} && \text{(\# of flows, rate)}
\end{aligned}
$$

Rate Allocation in Upstream

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- Rate allocation problem:

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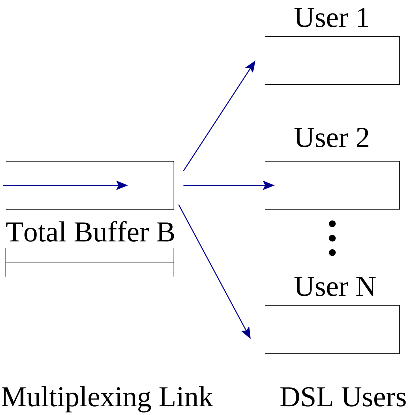
- Determine accordingly $n_i = c_i / g_i$
  - Different weights $\{w_i\}$ trace the admission region boundary
- **Implication**: opportunistic spectrum management responding to heterogeneous traffic characteristics and buffer allocations.

Downstream Transmissions



Joint Buffer and Rate Allocation in Downstream

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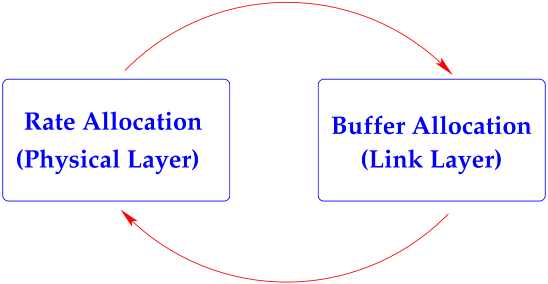
- Solution: **Alternate Maximization** algorithm
  - Provable convergence



Buffer Allocation

- Buffer allocation:

$$
\begin{aligned}
\text{maximize} \quad & \sum_i \overline{w}_i n_i && \text{(total weighted throughput)} \\
\text{subject to} \quad & \sum_i B_i \leq B && \text{(total buffer constraint)} \\
& n_i g_i \left(-\frac{\log(\epsilon)}{B_i} \right) \leq c_i && \text{(EB less than allocated rate)} \\
\text{variables} \quad & \mathbf{n}, \mathbf{B} \geq \mathbf{0} && \text{(\# of flows, buffer)}
\end{aligned}
$$

- Can be translated into a quasi-concave optimization, generally requires a centralized search.
  - Closed-form solution possible for special cases.

Algorithm and Convergence

Alternate Maximization Algorithm

Repeat

1. Solve number of admitted flows ($\mathbf{n}$) and rate allocation ($\mathbf{c}$), under fixed buffer allocation $\mathbf{B}$, using ASB algorithm.
2. Solve number of admitted flows ($\mathbf{n}$) and buffer allocation $\mathbf{B}$, under fixed rate allocation ($\mathbf{c}$), using bi-section search (or in closed form in some special cases).

Until Convergence

Algorithm and Convergence

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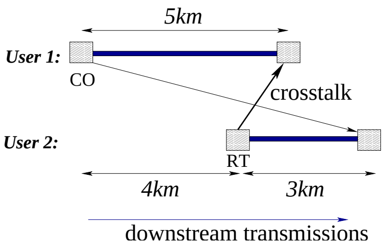
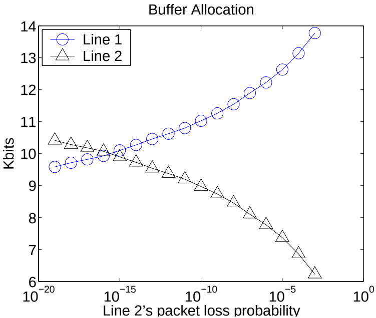
Until Convergence

Theorem (Convergence of AM Algorithm)

The AM Algorithm converges to a feasible (and typically local optimal) solution of the joint buffer and rate allocation problem.

Buffer Allocation

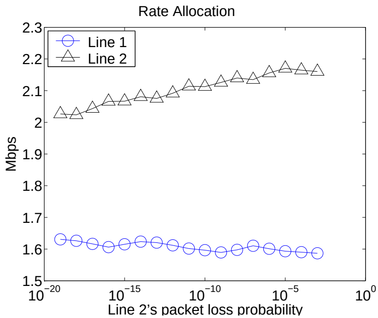


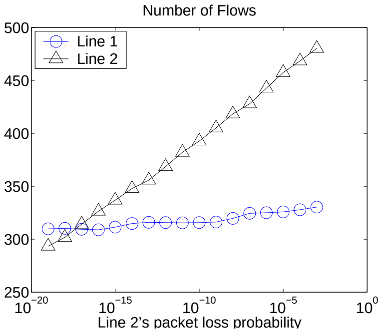


Assumption: Compound Poisson arrivals (both lines), line 1 has fixed QoS requirement

Implication: Relaxed QoS reduces the need for buffer space (line 2).

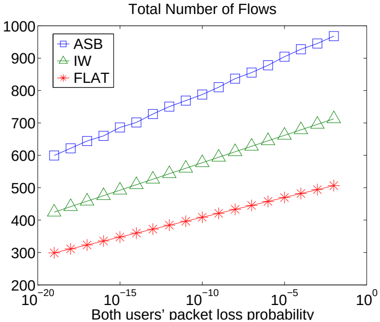
Rate Allocation and Number of Flows





Implication: Relaxed QoS increases rate allocation and admitted flows.

Different Power Control Algorithms

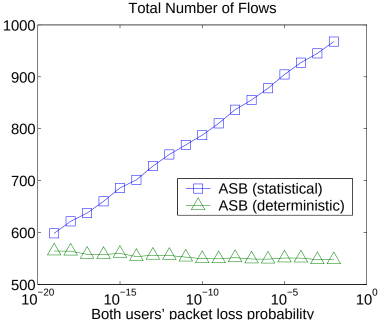


Notations:

- ASB: Autonomous Spectrum Sharing (what we proposed)
- IW: Iterative Water-filling (best distributed algorithm available today)
- FLAT: Flat power allocation (currently used in DSL operations)

Implication: ASB provides the optimal rate region.

Statistical Multiplexing Gain



Implication: large statistical multiplexing gain.

Quick Summary

- **Framework**: cross-layer statistical multiplexing in interference limited DSL networks.
- **Algorithm**: dynamically adjust to traffic characteristics, QoS requirements, network topology, and interference structure.
- **Performance**: substantial performance gain over deterministic service and static spectrum management.
- **Extension**: delay sensitive multimedia traffic.

Summary

Conclusion and Promise

- Presents intellectually challenging research issues in broadband access networking
- Motivates many new problems in optimization theory, information theory, signal processing, networking, stochastic systems
- Offers an opportunity to make visible, tangible impacts to practical deployment

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- The promise of FAST Copper:
  - Rate: Fast
  - Reach: Ubiquitous
  - Reliability: Survivable
  - Quality: QoS for triple play

Contacts

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