Power Aware and Computationally Efficient Optical Network Design

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Outline

- Power-Aware Traffic Grooming
  - Power Consumption in Networks: Trends and Challenges
  - Optical Networks to the Rescue: Power-Aware Traffic Grooming
  - Results and Discussion
- Computationally Scalable Optical Network Design
  - Routing and Wavelength Assignment (RWA)
  - New Computationally Efficient ILP Formulations for Ring and Mesh
  - Numerical Results
- Conclusions and Future Research Directions
The challenge of power consumption:

- High operating costs
- High capital costs → cooling equipment

Significant environmental impact:

- Industry responsible for \( \approx 2-3\% \) of man-made CO\(_2\)
- Growing at double-digit rates
Why Energy Efficiency For Networks

- Compute: 44%
- Cooling: 33%
- Network: 15%
- Other: 8%
So far, energy efficiency focus has been on servers and cooling

Networks are shared resources → always on

In the US: 6 TWatts of power on networks
Addressing the Challenge

Energy-efficient designs:

1. Low-power techniques in design of components
   - Support low-power states in processors, memory, disks
   - Disable clock signal to unused parts of processor
   - Replace complex uniprocessors with multiple simple cores

2. Power management techniques across systems
   - Intelligent policies to exploit low-power states
   - Workload management
Addressing the Challenge

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   - intelligent policies to exploit low-power states
   - workload management

Seek inexpensive energy sources

→ build data/compute centers wherever energy is cheap
The Networking Infrastructure

- **Forwarding table lookup** → routers operate at very high speeds
  - high energy consumption
  - low-power operation not feasible
The Networking Infrastructure

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  - low-power operation not feasible
- **New routing architecture?**
  - partition Internet address space
  - multiple parallel networks of “virtual” routers
  - each network handles small address space → energy-efficient routers
Internet traffic is already in the Exabytes (10^18 bytes) per-year, and is estimated to reach Zettabytes (10^21 bytes) by 2020. This growth has been doubling every 20 months forward in the past 20 years, unless some operators will increase router capacities as much as 256 times the power and cost 100 times as much.
Trends: Router Power Consumption

\[ P = C^{2/3} \]
where \( P \) is in Watts
where \( C \) is in Mb/s

- \( P \approx 10 \) at 1 Mb/s
- \( 10 \text{ nJ/bit} \) at 1 Gb/s
- \( 100 \text{ nJ/bit} \) at 1 Tb/s

Router Throughput

IEEE DLT, May 2011 – p.8
Trends: Energy Demand Will Exceed Supply

Average access rate [Mbit/s] vs. Power [MW/10^6 users]

- **Dominated by core routers**
- **Total**
- **Core**
- **WDM links**
- **Metro + Access**

% of electricity supply

IEEE DL T, May 2011 – p.9
If 33% of the world’s population were to obtain broadband access:

<table>
<thead>
<tr>
<th>Access rate</th>
<th>1 Mbps</th>
<th>10 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>100 GW</td>
<td>1 Tw</td>
</tr>
<tr>
<td>electricity supply</td>
<td>5%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Optical Networks to the Rescue

Optical networks:
- energy efficient
  - many passive components
  - active components (e.g., repeaters) can be solar/wind-powered
- low carbon footprint
Juniper Core Router T640

- 8 ports at 40 Gbps each
- Power consumption: 4500 W overall, 550 W/port
- Cost (10c/kWh): $4000/year, $500/port/year
- Add AC+UPS: ≈ double power consumption → $1000/port/year
- Power consumption increases with line rate
Motivation: Optical Switch Power Consumption

Calient DiamondWave PXC 128

- 128 × 128 switch
- Power Consumption:
  - < 750 W overall
  - < 6 W/port
  - independent of line rate
- PXC consumes ≈ 1% of power per port consumed by the Juniper router
Most (≈ 80%) network links: < 200 miles in length

Most traffic demands (≈ 80%): travel > 200 miles
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Most traffic demands (≈ 80%): travel > 200 miles
What is traffic grooming?

Efficiently set up lightpaths and groom (i.e., pack/unpack, switch, route, etc.) low-speed traffic onto high capacity wavelengths so as to minimize network resources.
Inputs to the problem:
- physical network topology (fiber layout)
- traffic matrix $T = [t_{sd}] \rightarrow$ int multiples of unit rate (e.g., OC-3)

Output:
- logical topology
- lightpath routing and wavelength assignment (RWA)
- traffic grooming on lightpaths
Traffic Grooming Subproblems

Diagram:

1 -- 2 -- 5
1 -- 3 -- 6
1 -- 4 -- 6
Traffic Grooming Subproblems

Logical topology design → determine the lightpaths to be established
Traffic Grooming Subproblems

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- **Lightpath routing** → route the lightpaths over the physical topology
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- **Logical topology design** → determine the lightpaths to be established
- **Lightpath routing** → route the lightpaths over the physical topology
- **Wavelength assignment** → assign wavelengths to lightpaths w/o clash
- **Traffic grooming** → route traffic on virtual topology
Grooming Objectives

- Minimize the number of lightpaths → \( \text{minL} \)
- Equivalent to minimizing the number of electronic ports
- Minimizes initial deployment cost
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- Minimize the amount of electronically switched traffic \( \rightarrow \text{minT} \)
  
  - minimizes average processing delay
  
  - minimizes electronic switching capacity
Grooming Objectives

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  - equivalent to minimizing the number of electronic ports
  - minimizes initial deployment cost

- Minimize the amount of electronically switched traffic → \( \min T \)
  - minimizes average processing delay
  - minimizes electronic switching capacity

- Minimize the amount of power consumption → \( \min P \)
  - maximizes power efficiency (in Watts/bit)
  - minimizes operational costs
  - most general objective
Power Consumption: Assumptions

- Optical power \ll \text{Electronic power} \\
  \rightarrow \text{energy consumed by optical ports is negligible}

- Inactive ports and transceivers may be shut down

- Power consumption of each component (electronic input/output port, O/E and E/O converters) increases \text{linearly} with amount of traffic handled
Power Consumption: Router Port Model

Equivalent to minimizing the number of lightpaths $\rightarrow \text{min} L$
Power Consumption: Router Port Model

Equivalent to minimizing amount of electronically switched traffic → \( \text{min} T \)
Power Consumption: Router Port Model

Most general model: minimize power consumption $\rightarrow \min P$

$P = P_0 + pt$

$P = 0$

$P_{\text{max}}$

power, $P$

traffic rate, $t$

$P_0 = 0$

$P_0$

$C$

IEEE DLT, May 2011 – p.19
ILP Formulation

Objective:

1. \textbf{minL}: min # of lightpaths
2. \textbf{minT}: min amount of electronically switched traffic
3. \textbf{minP}: min power consumption \(
\rightarrow\) most general model

subject to:

- lightpath routing constraints
- wavelength assignment constraints
- traffic routing constraints
Performance Evaluation

- \( W = 3 \) wavelengths
- \( C = 48 \) wavelength capacity
- Source-destination traffic \( t_{sd} \leftarrow \text{uniform}[0, t_{\text{max}}] \)
- \( P_0 = 0.25 \)
- \( P_{\text{max}} = 1 \)
- Each data point: average of 40 problem instances
Results: Number of Lightpaths

The graph shows the number of lightpaths as a function of $t_{\text{max}}$, with three curves representing different metrics:

- $\text{minT}$ (blue triangles)
- $\text{minL}$ (red circles)
- $\text{minP}$ (green squares)

As $t_{\text{max}}$ increases, the number of lightpaths for each metric increases as well, indicating a positive correlation between the two variables.
Results: Amount of Electronically Switched Traffic
Results: Relative Power Consumption

![Graph showing relative power consumption](image)

- **minT**
- **minL**

- **excess power consumption w.r.t. minP (%)**
- **t_{max}**
Power-aware design may lead to significant energy savings even for small networks.

The benefits are expected to increase with the network size.

Challenges:
- existing ILPs do not scale to realistic networks
- performance of heuristics difficult to characterize
Routing and Wavelength Assignment (RWA)

- Fundamental control problem in optical networks

- Objective: for each connection request determine a lightpath, i.e.,
  - a path through the network, and
  - a wavelength

- Two variants:
  1. online RWA: connection requests arrive/depot dynamically
  2. static RWA: a set of traffic demands to be established simultaneously
Static RWA

Input:
- network topology graph $G = (V, E)$
- traffic demand matrix $T = [t_{sd}]$

Objective:
- minRWA: establish all demands with the minimum # of $\lambda$s
- maxRWA: maximize established demands for a given # of $\lambda$s

Constraints:
- wavelength continuity: each lightpath uses the same $\lambda$ along path
- distinct wavelength: lightpaths using the same link assigned distinct $\lambda$s

NP-hard problem (both variants)
RWA Example
RWA: Symmetry

Diagram of a network with nodes 1, 2, 3, 4, 5, and 6 connected by edges that represent symmetry.
Nodes/links are entities of interest

Focus on traffic demand to and from nodes, on links

Bridging variable: demand between nodes on links
Nodes/paths are entities of interest

Demand is still between nodes

For each given demand node pair, list all paths
  → typically, a subset of all paths

assign variable to path traffic flow → implicitly identifies demand

for each link, sum up path flow variables
  → constrain with capacities
RWA As Graph Coloring
Independent set: a set of vertices in a graph no two of which are adjacent

Maximal independent set: not a subset of any other independent set
Precompute \( k \) paths for each source-destination pair

Create the path graph \( G_p \):
- each node in \( G_p \) corresponds to a path in the original network
- two nodes connected in \( G_p \) if corresponding paths share a link

Enumerate the MISs of \( G_p \)

Set up ILP to assign wavelengths to each MIS
Comparison

- **Link ILP formulation**
  - $O(N^4 W)$ variables
  - $O(N^3 W)$ constraints
  - symmetry with respect to $\lambda$ permutations

- **Path ILP formulation**
  - $O(N^2 W)$ variables
  - $O(N^2 W)$ constraints
  - symmetry with respect to $\lambda$ permutations

- **MIS ILP formulation**
  - $O(3^{N^2/3})$ variables
  - $O(N^2)$ constraints
  - no symmetry
  - size independent of $W \rightarrow$ future-proof
Vast parts of network infrastructure based on SONET/SDH rings

AT&T operates ≈ 6,700 rings in North America

→ optimal solutions for rings important for foreseeable future

Max size of SONET ring: 16 nodes

Operators have started transition to mesh networks → next ...
Running Time Results, $W = 120$
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Running Time Results, $W = 120$
Clockwise paths do not intersect with counter-clockwise paths:

\[ G_p = G_{cw}^p \cup G_{ccw}^p \]

- \( M, M_{cw}, M_{ccw} \): # of MISs of \( G_p, G_{cw}^p, G_{ccw}^p \):

\[ M_{cw} = M_{ccw} = \sqrt{M} \]

→ orders of magnitude decrease in # of variables/size of formulation

- Slight modifications to formulation
Consider clockwise direction only

→ similar steps for counter-clockwise

Partition ring in two parts such that:

\[ G_{cw}^p = G_{cw,0}^p \cup G_{cw,1}^p \cup G_{cw,core}^p \]
Express each MIS $m$ of $G^{cw}_p$ as:

$$m = m^0 \cup m^1 \cup q$$

Modify the formulation appropriately

- # MIS variables ↓
- # constraints ↑

Recursively partition the two ring parts to effect higher-order decompositions (MISD-8, MISD-16, . . .)
Results: # of MIS Variables

![Graph showing the number of MIS variables vs. N. The graph includes four lines representing different MIS types: MIS, MISD-2, MISD-4, and MISD-8. The y-axis is labeled # of MISs with logarithmic scale values from 10^1 to 10^10. The x-axis is labeled N with values from 6 to 32.]
Running Time Results, $W = 120$
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RWA in Mesh Networks

- MIS decomposition does not work
- Devised new exact decompositions for path formulation
- May solve efficiently 40-node networks
Running Time Results: Torus

![Graph showing running time results for Torus]

- **tLim**: 72,000
- **Num of Nodes**: 9, 16, 25, 36
- **Solution Time (s)**: 0.01, 0.1, 1, 10, 100, 1,000, 10,000, 100,000, 720,000

IEEE DL T, May 2011 – p.44
Running Time Results: Torus

- **tLim**: 72000
- **Num of Nodes**:
  - 9
  - 16
  - 25
  - 36
- **Solution Time (s)**:
  - 0.01
  - 0.1
  - 1
  - 10
  - 100
  - 1000
  - 10000
  - 72000

**Graph Details**:
- **Original Path** (blue line)
- **Improved Path** (red line)

IEEE DL T, May 2011 – p.44
Running Time Results: Asymmetric Topologies

<table>
<thead>
<tr>
<th>Networks (Number of Nodes)</th>
<th>Solution Time (s)</th>
</tr>
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<tbody>
<tr>
<td>NSF(14)</td>
<td>10</td>
</tr>
<tr>
<td>Havana(17)</td>
<td>100</td>
</tr>
<tr>
<td>EON(20)</td>
<td>1000</td>
</tr>
<tr>
<td>US 32−node</td>
<td>72000</td>
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Graph showing the relationship between solution time (in seconds) and network size (number of nodes). The networks are ordered from NSF(14) to US 32−node, with solution times increasing as the network size increases.
### Running Time Results: Asymmetric Topologies

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IEEE DL T, May 2011 – p.45
Conclusion & Ongoing Research

Traffic grooming is ideal candidate for encompassing energy concerns

Power-aware network design may lead to significant energy savings

RWA subproblem can be solved efficiently

Current research focuses on:

- more accurate power consumption models for traffic grooming
- computationally efficient formulations for optical network design problems
- traffic grooming
- impairment-aware RWA
- multicast RWA and grooming