Greening the Internet

Tutorial at IEEE ICC 2013

Jaafar Elmirghani, University of Leeds, UK
j.m.h.elmirghani@leeds.ac.uk
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
• Embodied energy and topology optimisation, energy efficiency
• Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
• Peer-to-peer energy efficient networks
• Future Directions
• References
Outline

- Introduction and the need for energy efficiency
  - Tutorial on network optimisation and MILP
  - Energy efficient IP over WDM networks and renewable energy
  - Network design with data centres, energy-efficiency
  - Network topology optimisation
  - Embodied energy and topology optimisation, energy efficiency
  - Elastic optical networks using OFDM, energy efficiency
  - Data compression for energy efficiency
  - Caching and IPTV / VoD networks
  - Peer-to-peer energy efficient networks
  - Future Directions
  - References
Energy Supply and Consumption: Most Energy is Lost

Supply

Consumption

Estimated U.S. Energy Use in 2009: ~94.6 Quads

Most Energy is Lost!

Source: EIA, 2010. The data is based on EIA's Annual Energy Review, August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy. This chart was compiled by EIA. The data is based on the 2009 Annual Energy Review (AER) report. The data is based on the 2009 Annual Energy Review (AER) report. The data is based on the 2009 Annual Energy Review (AER) report.

Quads (10^15 BTUs)

- The case for better use of energy
World wide ICT Carbon footprint

- 2007 Worldwide ICT carbon footprint: 2% = 830 m tons CO₂
- Comparable to the global aviation industry
- Expected to grow to 4% by 2020
Internet Traffic Growth Rate

- Courtesy Thierry Klein, Alcatel-Lucent Bell Labs, Sources: RHK, 2004; McKinsey, JPMorgan, AT&T, 2001; MINTS, 2009; Arbor, 2009
Exponential traffic growth

Doubling every 2 years
- 40% per year
- 30x in 10 years
- 1000x in 20 years

Mix of services is important from energy perspective:
- Mobile less efficient than fiber optics

Data from: RHK, McKinsey-JPMorgan, AT&T, MINTS, Arbor, ALU, and Bell Labs Analysis: Linear regression on log(traffic growth rate) versus log(time) with Bayesian learning to compute uncertainty
Outline

• Introduction and the need for energy efficiency
  ➔ Tutorial on network optimisation and MILP
  • Energy efficient IP over WDM networks and renewable energy
  • Network design with data centres, energy-efficiency
  • Network topology optimisation
  • Embodied energy and topology optimisation, energy efficiency
  • Elastic optical networks using OFDM, energy efficiency
  • Data compression for energy efficiency
  • Caching and IPTV / VoD networks
  • Peer-to-peer energy efficient networks
  • Future Directions
  • References
Network Flow Example in Link-Path Formulation

- node: generic name for routing and switching devices
- link: communication channel between nodes, directed/undirected
- path: sequence of links
- demand: source-destination pair
- demand path-flow variables: amount of traffic flow on each path
Network Flow Example in Link-Path Formulation

\[ X_{11} + X_{12} = h_1 \]
\[ X_{21} + X_{22} = h_2 \]
\[ X_{31} + X_{32} = h_3 \]
\[ X_{11} + X_{22} + X_{32} \leq c_1 \]
\[ X_{12} + X_{21} + X_{32} \leq c_2 \]
\[ X_{12} + X_{22} + X_{31} \leq c_3 \]

- **Cost of Routing**: a longer path costs more (eg. delay, £…)
- **Therefore Minimise**
  \[ F = X_{11} + 2X_{12} + X_{21} + 2X_{22} + X_{31} + 2X_{32} \]

\( h_i \) is a demand and \( x_{ij} \) is a flow, both in Gbit/s
Network Flows

minimise

\[ F = x_{11} + 2x_{12} + x_{21} + 2x_{22} + x_{31} + 2x_{32} \]

Subject to (constraints)

\[
\begin{align*}
  x_{11} + x_{12} & = h_1 \\
  x_{21} + x_{22} & = h_2 \\
  x_{31} + x_{32} & = h_3 \\
  x_{11} + x_{22} + x_{32} & \leq c_1 \\
  x_{12} + x_{21} + x_{32} & \leq c_2 \\
  x_{12} + x_{22} + x_{31} & \leq c_3 \\
\end{align*}
\]

\[ x_{11}, x_{12}, x_{21}, x_{22}, x_{31}, x_{32} \geq 0. \]

- Linear programming problem
- Optimal solution/optimal cost, uniqueness?
  \[ x_{11} = 5, \quad x_{21} = 7, \quad x_{31} = 8, \quad F^* = 20 \]
- Multi-commodity network flow problem

Example
\[ h_1 = 5 \]
\[ h_2 = 7 \]
\[ h_3 = 8 \]
\[ c_1 = 10 \]
\[ c_2 = 10 \]
\[ c_3 = 15 \]
General Network Design Formulation

minimise

objective / cost function \[ F = \sum_{e} \xi_e y_e \]

Subject to (constraints)

demand constraints \[ \sum_{p} x_{dp} = h_d, \quad d = 1, 2, \ldots, D. \]

capacity constraints \[ \sum_{d} \sum_{p} \delta_{edp} x_{dp} \leq y_e, \quad e = 1, 2, \ldots, E. \]

constraints on variables: \[ x \geq 0, \quad y \geq 0. \]
Constraints on Demand Path-Flow Variables

- Legitimate flow variables
- Demand Constraints (equalities)
- Link Capacity Constraints (inequalities)
- Set of feasible solutions
Objective Function

• Objective function: design goal expressed through a function of design variables

• Routing cost, congestion, delay, delay on the most congested link

• Routing cost of unit flow on each link
Linear Programming - a problem and its solution

- maximize $z = x_1 + 3x_2$
- subject to
  - $-x_1 + x_2 \leq 1$
  - $x_1 + x_2 \leq 2$
  - $x_1 \geq 0, x_2 \geq 0$

Extreme point (vertex) $(1/2, 3/2)$
Basic facts of Linear Programming

• **feasible solution** – satisfies the constraints

• **Theorem 1.**
The objective function, $z$, assumes its maximum at an extreme point of the constraint set.

• **Theorem 2.**
A vector $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ is an extreme point of the constraint set if and only if $\mathbf{x}$ is a basic feasible solution.
Solution Methods for Linear Programs

• Simplex Method
  • Optimum must be at the intersection of constraints
  • Intersections are easy to find, change inequalities to equalities
  • Jump from one vertex to another
  • Efficient solution for most problems, exponential time worst case.
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
  ➔ Energy efficient IP over WDM networks and renewable energy
  • Network design with data centres, energy-efficiency
  • Network topology optimisation
  • Embodied energy and topology optimisation, energy efficiency
  • Elastic optical networks using OFDM, energy efficiency
  • Data compression for energy efficiency
  • Caching and IPTV / VoD networks
  • Peer-to-peer energy efficient networks
• Future Directions
• References
We focus on reducing the CO2 emissions of backbone IP over WDM networks.

A LP optimization model is developed for “hybrid-power” IP over WDM networks where the power supply is mixed, composed of non-renewable energy and renewable energy.

A new heuristic is set up to minimize the non-renewable energy consumption (REO-hop).

Issues addressed include
- how to use renewable energy more effectively,
- how to reduce the non-renewable energy consumption,
- how to select the location of nodes that use renewable energy,
- load dependent energy consumption of hardware.
“Hybrid-power” IP over WDM network architecture
The total non-renewable energy consumption of the network is composed of:

1. Non-renewable energy consumption of ports without access to renewable energy:
   \[ \sum_{i \in N} PR \cdot \left( Q_i^e + \sum_{p \in P} \delta_{ip} \cdot W_p \right) \]

2. The non-renewable energy consumption of EDFAs:
   \[ \sum_{e \in E} PE \cdot E_e \cdot f_e \]

3. The non-renewable energy consumption of router ports that have access to renewable energy:
   \[ \sum_{i \in N} PRS \cdot \left( Q_i^s + \sum_{p \in P} \delta_{ip} \cdot W_{sp} \right) \]

4. The non-renewable energy consumption of transponders that have access to renewable energy and that of the transponders without access to renewable energy:
   \[ \sum_{e \in E} \left( PT \cdot \omega_e + PTS \cdot \omega_{se} \right) \]
LP Model for Renewable Energy IP over WDM Network

Objective: minimize

\[
\sum_{i \in N} PR \cdot \left( Q_i^e + \sum_{p \in P} \delta_{ip} \cdot W_p \right) + \sum_{e \in E} PE \cdot E_e \cdot f_e
\]

\[
+ \sum_{i \in N} PRS \cdot \left( Q_i^s + \sum_{p \in P} \delta_{ip} \cdot Ws_p \right)
\]

\[
+ \sum_{e \in E} \left( PT \cdot \omega_e + PTS \cdot \omega_s_e \right)
\]

Subject to:

\[
\sum_{p \in P} x_p^d = h_d \quad \forall \ d \in D,
\]

(2)

\[
\sum_{d \in D} x_p^d \leq \left( W_p + Ws_p \right) \cdot B \quad \forall \ p \in P,
\]

(3)

\[
\sum_{p \in P} \left( \delta_{ip} \cdot W_p + \delta_{ip} \cdot Ws_p \right) \cdot Q_i \leq V^i \quad \forall \ i \in N,
\]

(4)

\[
\sum_{e \in E} \delta_{ep} \cdot \omega_e = W_p + Ws_p \quad \forall \ p \in P,
\]

(5)
LP Model for Renewable Energy IP over WDM Network

\[ PR^s \cdot \left( Q_i^s + \sum_{p \in P} \delta_{ip} \cdot Ws_p \right) + \sum_{e \in E} PT^s \cdot \omega_{se} \cdot \delta_{ie} \leq S_i \]  \quad (6)

\[ \forall i \in N, \]

\[ \sum_{p \in P} \omega_e^p \leq W \cdot f_e \quad \forall e \in E, \]  \quad (7)

\[ Q^e_i + Q^s_i = Q_i \quad \forall i \in N, \]  \quad (8)

\[ \sum_{p \in P} \omega_e^p = \omega_e + \omega_{se} \quad \forall e \in E \]  \quad (9)
Heuristic Approach

- Multi-hop bypass heuristic [1] based on shortest-path routing will only minimize the total energy consumption not taking into account whether this energy comes from renewable or non-renewable sources.

- To minimize the utilization of non-renewable energy, we propose a new heuristic where the traffic flows are allowed to traverse as many nodes as possible that use renewable energy.

- To maintain QoS, only the two shortest-path routes are considered.

- Due to the changing traffic pattern and the fact that the output power of renewable energy sources varies during different times of the day, the routing paths are dynamic.

- The new heuristic is known as Renewable Energy Optimization hop (REO-hop).

The performance of the REO-hop heuristic is evaluated through simulations on the NSFNET network.

Solar energy is used as the renewable energy source.

As the NSFNET network covers the US, nodes will experience different levels of solar energy and traffic demands at any given point in time.

- There are four time zones, Eastern Standard Time (EST), Central Standard Time (CST), Mountain Standard Time (MST) and Pacific Standard Time (PST). We use EST as the reference time.
• The average traffic demand between each node pair ranges from 20 Gb/s to 120 Gb/s; random with a uniform distribution and no lower than 10 Gb/s.

• Note that time zones dictate habits and therefore network utilization and traffic demands.
Solar energy available at different nodes

- The geographical location of nodes dictates the sunset and sunrise time, and therefore the solar energy generated in each node.
## Network parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between two neighboring EDFAs</td>
<td>80 (km)</td>
</tr>
<tr>
<td>Number of wavelength in a fiber ((W))</td>
<td>16</td>
</tr>
<tr>
<td>Capacity of each wavelength ((B))</td>
<td>40 (Gb/s)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a router port ((PR))</td>
<td>1000 (W)</td>
</tr>
<tr>
<td>Renewable energy consumption of a router port ((P_{Rs}))</td>
<td>1000 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of an optical switch in node (i) ((PO_i)).</td>
<td>85 (W)</td>
</tr>
<tr>
<td>Renewable energy consumption of an optical switch in node (i) ((PO_{is})).</td>
<td>85 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of an optical switch that has access to renewable energy in node (i) ((POS_i))</td>
<td>0 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a router port that has access to renewable energy ((PRS))</td>
<td>0 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a multiplexer or a demultiplexer ((PMD)).</td>
<td>16 (W)</td>
</tr>
<tr>
<td>Renewable energy consumption of a multiplexer or a demultiplexer ((PMD_{is})).</td>
<td>16 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a multiplexer or a demultiplexer that has access to renewable energy ((PMDS)).</td>
<td>0 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a transponder ((PT))</td>
<td>73 (W)</td>
</tr>
<tr>
<td>Renewable energy consumption of a transponder ((PT_{is}))</td>
<td>73 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of a transponder that has access to renewable energy ((PTS))</td>
<td>0 (W)</td>
</tr>
<tr>
<td>Non-renewable energy consumption of an EDFA ((PE))</td>
<td>8 (W)</td>
</tr>
</tbody>
</table>
Non-renewable Energy Consumption of the Network
Node Non-renewable Energy Consumption per node (centre nodes consume more)
Hardware energy consumption profiles vs traffic
• The energy profiles are only applied to partially loaded wavelengths while an ‘on-off’ profile is applied to fully loaded wavelengths. cubic 9% lower
With only 20 kW renewable in 5 nodes the energy saving compared to the non-bypass case without solar energy is approximately 85% (maximum) and 65% (average).

Note that the 85% and 65% savings are almost real energy savings since the renewable energy is low here and has limited effect.

When all nodes use 80 kW renewable energy, the energy saving is approximately 97% (maximum) and 78% (average).
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
  ➔ Network design with data centres, energy-efficiency
  • Network topology optimisation
  • Embodied energy and topology optimisation, energy efficiency
  • Elastic optical networks using OFDM, energy efficiency
  • Data compression for energy efficiency
  • Caching and IPTV / VoD networks
  • Peer-to-peer energy efficient networks
  • Future Directions
  • References
Objectives

• Three problems are investigated:
  • Firstly, the optimization of the data centres locations to minimize the Power consumption.
    • We develop a Linear Programming (LP) model with this objective.
    • Investigate the IP over WDM routing approach (bypass and non-bypass), the regularity of the network topology and the number of data centres in the network.
  • Secondly, we investigate the energy savings introduced by implementing a data replication scheme in the IP over WDM network with data centres, where frequently accessed data objects are replicated over multiple data centres according to their popularity.
  • We propose a novel algorithm, Energy-Delay Optimal Routing (EDOR), to minimize the power consumption under the replication scheme while maintaining QoS.
Objectives

- Thirdly, we investigate introducing renewable energy sources (wind and solar energy) to the IP over WDM network with data centres.

- We evaluate the merits of transporting bits to where renewable energy is (wind farms), instead of transporting renewable energy to where data centres are.

- We consider the impact of the electrical power transmission losses, network topology, routing, traffic.

- A LP model is set up to optimize the location of data centres by minimizing the network non-renewable energy consumption taking into account the utilization of the renewable energy resources and the losses.
Data Centres in an IP over WDM Network
LP model for Data Centres location optimisation

- Each node writes and retrieves data from all data centres equally.
- Different data centres have different content.
- We consider regular traffic demand and data centre traffic demand.
- The traffic demand between data centres and nodes at time $t$ is assumed to be a certain ratio of the regular traffic demand $\lambda^{sd}$ between nodes.
- The uplink traffic demand ratio from nodes to data centres, $R_u$, is smaller than the downlink traffic from data centres to nodes ratio, $R_d$. 
LP model for Data Centres location optimisation

- **Objective: Minimise**

\[
\sum_{t \in T} \left( \sum_{m \in M} \sum_{n \in N_{pm}} PR \cdot \omega_{mnt} + \sum_{i \in N} PR \cdot Q_{it} \right. \\
+ \sum_{m \in M} \sum_{n \in N_{pm}} PT \cdot \omega_{mnt} \\
+ \sum_{m \in M} \sum_{n \in N_{pm}} PE \cdot EA_{mn} \cdot f_{mn} + \sum_{i \in N} PO_i \\
+ \left. \sum_{i \in N} PMD \cdot DM_i \right)
\]

- **Subject to**

\[
\sum_{j \in N: i \neq j} \lambda_{d_{ij}}^{sd} - \sum_{j \in N: i \neq j} \lambda_{d_{ji}}^{sd} = \begin{cases} \\
\lambda_{sdt} \cdot Rd \cdot \delta_s & \text{if } i = s \\
-\lambda_{sdt} \cdot Rd \cdot \delta_s & \text{if } i = d \\
0 & \text{otherwise} \\
\end{cases} \\
\forall t \in T, \forall s, d, i \in N: s \neq d
\]

\[
\sum_{j \in N: i \neq j} \lambda_{u_{ij}}^{sd} - \sum_{j \in N: i \neq j} \lambda_{u_{ji}}^{sd} = \begin{cases} \\
\lambda_{sdt} \cdot Ru \cdot \delta_d & \text{if } i = s \\
-\lambda_{sdt} \cdot Ru \cdot \delta_d & \text{if } i = d \\
0 & \text{otherwise} \\
\end{cases} \\
\forall t \in T, \forall s, d, i \in N: s \neq d
\]
LP model for Data Centres location optimisation

\[ \sum_{j \in N : i \neq j} \lambda_{r_{ij}}^{sd} - \sum_{j \in N : i \neq j} \lambda_{r_{ji}}^{sd} = \begin{cases} \lambda_{sdt} & \text{if } i = s \\ -\lambda_{sdt} & \text{if } i = d \\ 0 & \text{otherwise} \end{cases} \quad \forall \ t \in T, \forall s, d, i \in N : s \neq d \]

\[ \sum_{s \in N} \sum_{d \in N : s \neq d} \left( \lambda_{d_{ij}}^{sd} + \lambda_{u_{ij}}^{sd} + \lambda_{r_{ij}}^{sd} \right) \leq C_{ij} \cdot B \quad \forall \ t \in T, \forall i, j \in N : i \neq j \]

\[ \sum_{n \in N_{pm}} W_{mnt}^{ij} - \sum_{n \in N_{pm}} W_{nt}^{ij} = \begin{cases} C_{ij} & m = i \\ -C_{ij} & m = j \\ 0 & \text{otherwise} \end{cases} \quad \forall \ t \in T, \forall i, j, m \in N : i \neq j \]

\[ \sum_{i \in N} \sum_{j \in N : i \neq j} W_{mnt}^{ij} \leq W \cdot f_{mn} \quad \forall \ t \in T, \forall m \in N, n \in N_{pm} \]

\[ \sum_{i \in N} \delta_i = Ndc \]

\[ \sum_{i \in N} \sum_{j \in N : i \neq j} W_{mnt}^{ij} = \omega_{mnt} \quad \forall \ t \in T, \forall m \in N, n \in N_{pm} \]

\[ Q_{it} = \left( \sum_{d \in N : d \neq i} \lambda_{idt} + \sum_{s \in N : s \neq i} \lambda_{sit} \cdot R_d \cdot \delta_s + \sum_{d \in N : d \neq i} \lambda_{idt} \cdot R_u \cdot \delta_d \right) / B \quad \forall \ t \in T, \forall \ i \in N \]
Data Centres in an IP over WDM network

Irregular network topology

- We investigate the optimal location for the non-bypass and the multi-hop bypass heuristics under two traffic scenarios:
  - In the first traffic scenario we only consider the traffic to and from data centres.
  - In the second scenario, we consider the traffic between regular nodes in addition to the data centre traffic.

Irregular network topology with link distances in km

Average traffic demand between regular nodes
## Power consumption parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between two neighbouring EDFAs</td>
<td>80 (km)</td>
</tr>
<tr>
<td>Number of wavelength in a fibre ($W$)</td>
<td>16</td>
</tr>
<tr>
<td>Capacity of each wavelength ($B$)</td>
<td>40 (Gb/s)</td>
</tr>
<tr>
<td>Power consumption of a router port ($PR$)</td>
<td>1000 (W)</td>
</tr>
<tr>
<td>Power consumption of a transponder ($PT$)</td>
<td>73 (W)</td>
</tr>
<tr>
<td>Power consumption of an EDFA ($PE$)</td>
<td>8 (W)</td>
</tr>
<tr>
<td>Power consumption of an optical switch ($PO$)</td>
<td>85 (W)</td>
</tr>
<tr>
<td>Power consumption of a multiplexer or a demultiplexer ($PMD$)</td>
<td>16 (W)</td>
</tr>
</tbody>
</table>
Irregular topology

DC traffic only

Non-bypass:
LP optimal node = 5
Power saving=37.5%

Bypass:
LP optimal node = 7
Power saving=11.2%
Simulations opposite confirm

DC & regular traffic

Non-bypass:
LP optimal node = 5
Power saving=17.2%

Bypass:
LP optimal node = 4
Power saving=6.3%
Simulations opposite confirm
• The optimal (node 5) has not increased the propagation delay compared to other node choices.

• Nodes at the centre of the network are less affected by a change in the data centre location compared to nodes at the edge as nodes in the centre have a lower average hop count to other nodes in the network.
Data Centres in NSFNET (IP over WDM network)

5 data centres, Ndc=5
NSFNET with one Data Centre (regular net, less saving)

DC traffic only
Non-bypass:
LP optimal node = 5
Power saving=26.6%

Bypass:
LP optimal node = 5
Power saving=12.7%
Simulations opposite confirm

DC & regular traffic
Non-bypass:
LP optimal node = 5
Power saving=8.6%

Bypass:
LP optimal node = 5
Power saving=4.6%
Simulations opposite confirm
The optimal data centre locations are distributed throughout the network to provide optimal number of hops and distance to all nodes.
NSFNET with FIVE Data Centres (regular net, less saving)

DC traffic only
Non-bypass:
LP optimal nodes = (5,6,8,10,13)
Power saving=11.4%

DC & regular traffic
Non-bypass:
LP optimal nodes = (5,6,8,10,13)
Power saving=4.4%
## Summary of power savings as a result of data centre location optimisation

<table>
<thead>
<tr>
<th>Topology</th>
<th>Data centre traffic only</th>
<th>Data centre traffic and regular traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irregular topology under the non-bypass heuristic</td>
<td>37%</td>
<td>11%</td>
</tr>
<tr>
<td>Irregular topology under the multi-hop bypass heuristic</td>
<td>17%</td>
<td>6.3%</td>
</tr>
<tr>
<td>NSFNET topology with a single data centre under the non-bypass heuristic</td>
<td>26.6%</td>
<td>12.7%</td>
</tr>
<tr>
<td>NSFNET topology with a single data centre under the multi-hop bypass</td>
<td>8.6%</td>
<td>4.6%</td>
</tr>
<tr>
<td>NSFNET topology with 5 data centres under the non-bypass heuristic</td>
<td>11.4%</td>
<td>4.4%</td>
</tr>
<tr>
<td>NSFNET topology with 5 data centres under the multi-hop bypass heuristic</td>
<td>6.5%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>
Data replication in IP over WDM Networks with Data Centres

- Previously we assumed each data centre has different content.
- Large operators (e.g. BBC, YouTube, Amazon...) have multiple data centres.
- Content (that has different popularity) can be replicated to reduce delay and power consumption.
- Replicating data objects to multiple data centres allows a node to access a data object from a closer data centre.
- We investigate the energy savings introduced by implementing a replication scheme in the IP over WDM network with data centres.
- A LP model is developed to optimize the selection of data centres to replicate data objects under the lightpath bypass approach.
Data replication in IP over WDM Networks with Data Centres

- The optimal data centre locations are obtained using the previous LP model.
- Data objects in the network are classified into five different popularity groups.
- A Zipf distribution is assumed for content popularity.
- With 5 data objects, the popularities are: 43.7%, 21.8%, 14.5%, 10.9% and 9%.
- A traffic demand between a node and a data centre is distributed among different data object groups according to their popularity.
- In addition to the LP solution, an Energy-Delay Optimal Routing (EDOR) Algorithm was developed.
Energy-Delay Optimal Routing (EDOR) Algorithm

1. Reorder traffic demands between nodes and data centers from the highest to the lowest and create an empty virtual topology.

2. Retrieve a demand from the ordered list and check the popularity of the requested data objects and find out all the available paths between the node and the required data centers.

3. If no sufficient free capacity available on the paths, return to the previous step.

4. If sufficient free capacity available on the paths, route the demand based on the shortest path.

5. Build a new virtual link based on minimum number of hops.

6. Update the virtual topology.

7. Compute total energy consumption.
NSFNET with FIVE Data Centres, 5 objects & replication

DC & regular traffic
Non-bypass:

LP optimal DC nodes = (5,6,8,10,13)

LP determines where each object is replicated

Power saving = 28%

DC & regular traffic
Bypass and shortest path routing:

LP optimal nodes = (5,6,8,10,13)

EDOR vs Bypass+SP routing
Renewable Energy in IP over WDM Networks with Data Centres

- We compare moving bits to where renewable energy is (wind farms) to transporting renewable energy to data centres.
- We study the impact of the power losses associated with transporting electrical power to data centres on the optimal data centres locations.
- We also study the impact of the other networking factors including network topology, routing, and traffic.
- We assume that solar energy is employed to partly power regular nodes (20kW).
- We assume that data centres are powered by energy generated from wind farms.
- The first LP model is extended to support the objective of minimizing the non-renewable energy consumption of data centres by optimizing the locations of data centres in the IP over WDM network assuming the lightpath bypass approach but taking into account renewable energy sources and the transmission losses.
Wind farms in NSFNET and transmission power losses

- The NSFNET network is considered to identify the optimal location of data centres using the LP model.
- We have selected only 3 wind farms based on their location and maximum output power to power the data centres in the network: 1) WF1: Cedar Creek Wind Farm, 2) WF2: Capricorn Ridge Wind Farm, 3) WF3: Twin Groves Wind Farm in blue. The maximum output power of the three wind farms is 300MW, 700 MW and 400 MW, respectively.
- We assume the transmission power loss is 15% per 1000km [25] and the percentage of the power of wind farms allocated to data centres is assumed to be 0.3%.
Data centre, computing, cooling and lighting power usage

- The cooling & lighting power consumption of a typical data centre is 150-200W/ft². Assuming a 3500ft² data centre, the total power consumed in a typical data centre for cooling is 700kW and the computing power consumption in a data centre is assumed to be 300kW which is typical for this data centre size.

- The power allocated by a wind farm to a data centre is known and is assumed here to be 1.4MW. This corresponds to a power usage efficiency (PUE) of 2 which is typical for a data centre.

- The renewable energy available to a data centre is a function of the transmission losses and these are location dependent. Furthermore the network topology, traffic, components’ power consumption also play an important role in determining the optimum data centre location.

- Therefore the LP model here takes into account the previous trade-offs as well as the trade-offs introduced by the losses associated with the transmission of renewable energy to the data centre locations.
Renewable Energy in the IP over WDM Network with Data Centres

**LP, Simulation and Results**

- We run the LP model with five data centres ($Ndc=5$) under the previous assumptions.

- The optimal locations of data centres obtained from the LP model are as follows (4, 5, 6, 7, 8) where data centres 4 and 5 are powered by WF1, data centre 6 and 7 are powered by WF2, and data centre 8 is powered by WF3.

- The LP model results are such that all the data centres are located in the centre of the network.

- It can be observed that the optimum data centres locations are next to or near wind farms.
The non-renewable energy consumption obtained from the LP model under the optimal locations represents a lower bound.

Compared with the random locations (1, 2, 4, 6 and 13), the optimal locations have reduced on average the non-renewable energy consumption by 26.2% for the LP model.
Wind farms power data centres, solar at other nodes

- Compared to non-bypass heuristic
  - Multi-hop bypass + SP routing without renewable energy 46%.
  - Non-bypass with renewable energy 58%.
  - Multi-hop bypass + renewable energy 77% obtained from the LP network design and 71% obtained from the Multi-hop bypass + SP.
  - Introducing the replication scheme increases the average saving to 73% (Multi-hop bypass + SP).
Summary

• Data centre location optimisation is particularly important if the network topology is irregular, there are few data centres and non-bypass is used.

• Power savings up to 37.5% were obtained in the networks considered.

• Saving comes at no extra cost in terms of bandwidth or storage capacity, increase in delay limited.

• Implementing the replication scheme under the non-bypass heuristic with shortest distance routing has resulted in an average energy savings of 28%. This significant reduction is due to the reduction in the number of hops and distance between data centres and nodes.

• The results show that moving the data centres closer to renewable energy sources maximizes the utilization of renewable energy sources and consequently reduces CO2 emissions.

• By combining the multi-hop bypass heuristic with renewable energy and the replication scheme power consumption savings up to 73% have been achieved.
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
  ➔ Network topology optimisation
    • Embodied energy and topology optimisation, energy efficiency
    • Elastic optical networks using OFDM, energy efficiency
    • Data compression for energy efficiency
    • Caching and IPTV / VoD networks
    • Peer-to-peer energy efficient networks
• Future Directions
• References
Outline

• Energy Efficient Physical Topology Design for IP over WDM Networks
  • LP Model for Energy Efficient Physical Topology Design
  • Physical Topology Optimization under Symmetric, Asymmetric Traffic
  • Physical Topology Optimization Considering Renewable Energy
Energy Efficient Physical Topology Design for IP over WDM Networks

- LP power optimization of the physical topology of IP over WDM networks.
- Node locations are given (for example city locations) and
- The objective is to optimize the deployment of the physical links connecting these nodes so that the total network power consumption is minimized.
LP Model for Energy Efficient Physical Topology Design

- The total power consumption of the network is composed of:
  1. The power consumption of IP ports at time $t$
     \[
     \sum_{i \in N} \sum_{j \in N: i \neq j} PR \cdot C_{ijt}
     \]
  2. The power consumption of transponders at time $t$
     \[
     \sum_{m \in N} \sum_{n \in N: m \neq n} PT \cdot \omega_{mnt}
     \]
  3. The power consumption of EDFAs at time $t$
     \[
     \sum_{m \in N} \sum_{n \in N: m \neq n} PE \cdot EA_{mn} \cdot f_{mn}
     \]
  4. The power consumption of optical switches at time $t$
     \[
     \sum_{i \in N} PO_i
     \]
  5. The power consumption of de/multiplexers at time $t$
     \[
     \sum_{i \in N} PMD \cdot DM_i
     \]
LP Model for Energy Efficient Physical Topology Design

- The total power consumption of the network is composed of:
  1. The power consumption of IP ports at time $t$

\[
\sum_{i \in N} \sum_{j \in N: j \neq i} PR \cdot C_{ijt}
\]

  2. The power consumption of transponders at time $t$

\[
\sum_{m \in N} \sum_{n \in N: m \neq n} PT \cdot \omega_{mnt}
\]

  3. The power consumption of EDFAs at time $t$

\[
\sum_{m \in N} \sum_{n \in N: m \neq n} PE \cdot EA_{mn} \cdot f_{mn}
\]

  4. The power consumption of optical switches at time $t$

\[
\sum_{i \in N} PO_i
\]

  5. The power consumption of de/multiplexers at time $t$

\[
\sum_{i \in N} PMD \cdot DM_i
\]
LP Model for Energy Efficient Physical Topology Design

- **Objective**: minimize

\[
\sum_{t \in T} \left( \sum_{i \in N} \sum_{j \in N, j \neq i} PR \cdot C_{ijt} + \sum_{m \in N} \sum_{n \in N, m \neq n} PT \cdot \omega_{mnt} + \sum_{m \in N} \sum_{n \in N, m \neq n} (PE \cdot EA_{mn} \cdot f_{mn}) + \sum_{i \in N} PO_i + \sum_{i \in N} PMD \cdot DM_i \right)
\]

- **Subject to**:

\[
\sum_{j \in N, j \neq i} \lambda_{ijt} - \sum_{j \in N, i \neq j} \lambda_{jnt} = \begin{cases} 
\lambda_{sd}^{sdt} & \text{if } i = s \\
-\lambda_{sd}^{sdt} & \text{if } i = d \\
0 & \text{otherwise}
\end{cases} \quad \forall t \in T, \forall s, d, i \in N : s \neq d
\]

\[
\sum_{s \in N} \sum_{d \in N: s \neq d} \lambda_{ijt}^{sd} \leq C_{ijt} \cdot B \quad \forall t \in T, \forall i, j \in N : i \neq j
\]

\[
\sum_{m \in N, m \neq n} W_{mnt} - \sum_{m \in N, m \neq n} W_{mnt}^{ij} = \begin{cases} 
C_{ijt} & \text{if } m = i \\
-C_{ijt} & \text{if } m = j \\
0 & \text{otherwise}
\end{cases} \quad \forall t \in T, \forall i, j \in N : i \neq j
\]

**Flow conservation**: Virtual paths

**Link capacity**: Virtual paths

**Flow conservation**: Physical links
LP Model for Energy Efficient Physical Topology Design

\[ \sum_{i \in N \atop j \in N: i \neq j} W_{mnt}^{ij} \leq W \cdot f_{mn} \quad \forall t \in T, \forall m \in N, n \in N \]

\[ \sum_{i \in N \atop j \in N: i \neq j} W_{mnt}^{ij} \leq W \cdot NF \cdot link_{mn} \quad \forall t \in T, \forall m \in N, n \in N : m \neq n \]

\[ \sum_{i \in N \atop j \in N: i \neq j} W_{mnt}^{ij} = \omega_{mnt} \quad \forall t \in T, \forall m \in N, n \in N : m \neq n \]

\[ \sum_{n \in N : m \neq n} link_{mn} \geq Ndgr \quad \forall m \in N \]

\[ \sum_{m \in N \atop n \in N : m \neq n} link_{mn} = 2 \cdot N\text{link} \]

Link capacity: Physical links

Minimum Nodal Degree (chosen)

Number of links in the network (chosen)
Physical Topology Optimization under Symmetric Traffic Demand

- We use the model to redesign the NSFNET physical topology

Distance between two neighbouring EDFAs: 80 (km)
Capacity of each wavelength ($B$): 40 (Gb/s)
Power consumption of a router port ($PR$): 1000 (W)
Power consumption of a transponder ($PT$): 73 (W)
Power consumption of an EDFA ($PE$): 8 (W)
Power consumption of an optical switch ($PO$): 85 (W)
Power consumption of a multiplexer/demultiplexer ($PMD$): 16 (W)
Physical Topology Optimization under Symmetric Traffic Demand

More direct, longer links

Ndgr=1 results in isolated nodes

Mesh: Optimum topology from LP with no constraint on number of links, or node degree

Star: Nodes separation comparable to mesh, Less links, less resilience
Physical Topology Optimization under Symmetric Traffic Demand

- Optimizing the physical topology without a limit on the number of links resulted in a full mesh topology.
- The full mesh topology eliminates the need for IP routers, the most energy consuming devices in the network.

- Full mesh: power saving 95%.
- STAR topology, no IP routers: 92% power saving.
- Savings of 6% and 5% with $Ndgr=1$ and $Ndgr=2$, $Nlink=21$
Physical Topology Optimization under Asymmetric Traffic Demand

- The presence of data centres in the network creates a hot node scenario.

- The optimized physical topology with a single data center at node 7 has saved an average of 22% and 20% with Ndgr=1 and Ndgr=2 respectively under the non-bypass approach.

- Using a star topology centred at the data centre node has reduced the energy consumption by 97%.
Physical Topology Optimization under Asymmetric Traffic Demand

- The presence of data centres in the network creates a hot node scenario.

- The optimized physical topology has resulted in power saving of an average of 20% and 18% of the network total power consumption with $Ndgr=1$ and $Ndgr=2$, respectively under the non-bypass approach.

- Power Savings are limited to 1% under the Multi-hop bypass heuristic.
Physical Topology Optimization under Asymmetric Traffic Demand

- The presence of data centres in the network creates a hot node scenario.

- The optimized physical topology with 5 data centres has resulted in 10% and 8% power savings with $Ndgr=1$ and $Ndgr=2$, respectively under the non-bypass approach.

- A key conclusion of this section is that topology optimization becomes more important with fewer data centres and as the traffic asymmetry increases.
Physical Topology Optimization Considering Renewable Energy

- The optimized topology has saved an average of 16% and 10% of the non-renewable energy consumption with $Ndgr=1$ and $Ndgr=2$, respectively under the non-bypass approach.

- The average non-renewable power savings under the bypass approach is limited to 7% and 1% with $Ndgr=1$ and $Ndgr=2$, respectively.

Renewable energy in nodes 2, 5, 8, 11 and 13

$Ndgr=1$

$Ndgr=2$
**Relationship between hop count and energy savings**

- $HC'$ is defined as the percentage reduction in the hop count compared to the original NSFNET topology (NSFNET average hop count is 2.5).
- The energy savings introduced by deploying a topology increases as $HC'$ increases.
- The maximum reduction is achieved by the full mesh topology with a hop count equal to 1.
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
- Embodied energy and topology optimisation, energy efficiency
• Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
• Peer-to-peer energy efficient networks
• Future Directions
• References
Outline

• Introduction

• Objective

• Network Devices Embodied Energy
  • IP Router
  • Transponder, EDFA, Regenerator and Multi/Demultiplexer
  • Optical Switches
  • Optical Fibre Cable

• MILP Model for Energy Efficient Physical Topology Design

• Results and Analysis
  • Network Scenario
  • Optimized Physical Topologies Considering Operational and Embodied Energies
  • Optimized Physical Topologies without Considering the Embodied Energy of the Optical Cables

• Summary
Introduction

• Introducing additional devices to minimize the operational energy might be associated with embodied energy higher than the operational energy savings and consequently the total Carbon footprint of the network will increase.

• The embodied energy ($E_{EMB}$) of a device is defined as the energy associated with the different processes of its production and maintenance.

• The average commercial lifetime ($LT$) of network devices is estimated as 10 years and the maintenance embodied energy ($E_{EMB-m}$) is considered to consume 10% of the device production embodied energy ($E_{EMB-p}$) annually.
Introduction

- Network operators are particularly interested in the minimization of the operational energy as it is directly reflected in the OPEX.
- On the other hand the embodied energy is not necessary reflected on the CAPEX as CAPEX is controlled by the economic and pricing policies.
- Embodied energy is already considered in the energy efficiency studies of other fields such as buildings, cars, solar cells, computers, mobile phones, and network switches.
- The need to rethink the previous approaches of evaluating the energy efficiency of ICT networks emerge from the sophisticated and energy-intensive process involved in the production of network devices.
To the best of our knowledge, the existing research literature has not investigated the impact of embodied energy on the energy efficiency of wired network.

We rethink the energy efficiency of the physical topology of IP over WDM networks taking into account the embodied energy of the network devices in addition to the operational energy.

We disassemble the considered network devices to their basic components and materials, and based on the data available about the embodied energy of these components and materials, we estimate the total embodied energy of the devices.
Network Devices Embodied Energy

• The embodied energy of most network devices is mainly composed of three parts:
  • Printed Circuit Board (PCB),
  • semiconductor devices (silicon wafers, integrated circuitry),
  • bulk materials (plastic, glass and rubber) and metal (aluminum, copper, steel, lead and zinc).
Network Devices Embodied Energy

The Embodied Energy and the Density of the Different Materials of Network Devices

<table>
<thead>
<tr>
<th>Materials/Processing</th>
<th>Embodied Energy MJ/kg</th>
<th>Density g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor device</td>
<td>120000</td>
<td>400 (on PCBs)</td>
</tr>
<tr>
<td>Metals</td>
<td>100-400</td>
<td>Various</td>
</tr>
<tr>
<td>Bulk materials</td>
<td>20-400</td>
<td>Various</td>
</tr>
<tr>
<td>PCB</td>
<td>300-500</td>
<td>2000-4500</td>
</tr>
</tbody>
</table>
Embodied Energy of IP Router

• We consider the Cisco CRS-1 16 Slots Chassis Routing System (795 kg).

• Each IP port is composed of two module cards: physical layer interface module card (PLIM) and module service card (MSC).

• In addition to the IP ports, the router has different modules including: power module, fan controller (FC), switch module (SM) and router processor (RP).

• Given the size of the module cards, we can calculate the weight of PCB and semiconductor devices in each module card.

• The chassis weight is calculated as the difference between the router total weight and modules weight. We assume that only 10% of the chassis weight is bulk materials and the remaining is metal.
Embodied Energy of IP Router
### Embodied Energy of IP Router

The Embodied Energy of CRS-1 16 Slots Chassis Routing System

<table>
<thead>
<tr>
<th>Module</th>
<th>Dimension (cm)</th>
<th>Weight (kg)</th>
<th>Embodied energy (MJ)</th>
<th>PCB</th>
<th>Semiconduct or</th>
<th>Bulk Materials</th>
<th>Metals</th>
<th>Units</th>
<th>Total (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP Port</td>
<td>PLIM H52.3, D47.2, W4.6</td>
<td>3.8</td>
<td>555</td>
<td>9480</td>
<td>144</td>
<td>900</td>
<td>16</td>
<td>177.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MSC H52.3, D47.2, W4.6</td>
<td>6.68</td>
<td>555</td>
<td>8280</td>
<td>200</td>
<td>2000</td>
<td>16</td>
<td>176.6</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>H50,D46,W90 (estimate)</td>
<td>35</td>
<td>980</td>
<td>1440</td>
<td>1300</td>
<td>11900</td>
<td>1</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>H52.3, D28.4, W7.1</td>
<td>5.8</td>
<td>335</td>
<td>7080</td>
<td>228</td>
<td>1800</td>
<td>2</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>H52.2, D28.5, W7.1</td>
<td>5.6</td>
<td>223</td>
<td>4920</td>
<td>224</td>
<td>1820</td>
<td>2</td>
<td>14.4</td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td>H52.3, D28.5, W3.6</td>
<td>5.4</td>
<td>335</td>
<td>6960</td>
<td>182</td>
<td>1690</td>
<td>8</td>
<td>73.3</td>
<td></td>
</tr>
<tr>
<td>Fan Tray</td>
<td>N/A</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8000</td>
<td>2</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>System Chassis</td>
<td>N/A</td>
<td>486</td>
<td>0</td>
<td>0</td>
<td>19440</td>
<td>17496</td>
<td>1</td>
<td>194.4</td>
<td></td>
</tr>
</tbody>
</table>

Total embodied energy of a full load CRS-1 16 Slots Chassis Routing System: **686.5 GJ**
Embodied Energy of Transponder, EDFA, Regenerator and Multi/Demultiplexer

- Similar to the IP router, we estimate the embodied energy of:
  - Cisco ONS 15454 10-Gbps multi-rate transponder card
  - Cisco ONS 15501 EDFA
  - Cisco ONS 15104 OC-48/STM-16 bidirectional regenerator
  - Cisco ONS 15454 100-GHz 4-CH Multi/Demultiplexer

- Note that all the estimations above are subject to uncertainties in terms of the data of the embodied energy of materials and the amount of material in devices. Variations in data are considered to be ±30% for bulk materials and semiconductor, ±21% for PCB.
## The Embodied Energy of Network Active Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Dimension (cm)</th>
<th>Weight (kg)</th>
<th>Embodied energy (MJ)</th>
<th>Total (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PCB</td>
<td></td>
</tr>
<tr>
<td>Transponder</td>
<td>H32.1, D22.8, W2.3</td>
<td>1.4</td>
<td>164</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3480</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>EDFA</td>
<td>H4.5, D25.9, W48.3</td>
<td>3.08</td>
<td>135</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3393</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>224</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>899</td>
<td></td>
</tr>
<tr>
<td>Regenerator</td>
<td>H4.4, D30, W43.9</td>
<td>4.4</td>
<td>197</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4425</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>320</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>Multi/Demultiplexer</td>
<td>H32.1, D22.8, W2.3</td>
<td>1.5 Estimated</td>
<td>164</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2446</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>225</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>414</td>
<td></td>
</tr>
</tbody>
</table>
Embodied Energy of Optical Switches

- We consider the Glimmerglass Intelligent Optical System 500-192 × 192 optical switch, (17.2 kg, 35.6 × 43.7 × 41.0 cm³).
- A single MEMS mirror is made of single-crystal silicon (SCS) with a gold plated layer (3 μm thickness).
- The main contributor to the embodied energy of the MEMS mirror is the SCS processing.
- The total weight of gold used in the switch is negligible.
- Given the density of silicon (2.3 g/cm³) and the single MEMS mirror chip size (1.55 × 1.7 × 0.5 mm³), we calculate the embodied energies of SCS processing, semiconductor device and metals.
# Embodied Energy of Optical Switches

## The Embodied Energy of the 192x192 Glimmerglass Optical Switch

<table>
<thead>
<tr>
<th>Materials/Processing</th>
<th>Embodied Energy (MJ)</th>
<th>Weight (g)</th>
<th>Total Embodied Energy (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCS processing</td>
<td>30.3</td>
<td>0.253</td>
<td></td>
</tr>
<tr>
<td>Semiconductor device</td>
<td>4116</td>
<td>34.3</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>5440</td>
<td>13600</td>
<td>11</td>
</tr>
<tr>
<td>Bulk materials</td>
<td>1200 (Estimated)</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>PCB</td>
<td>220.5 (Estimated)</td>
<td>490</td>
<td></td>
</tr>
</tbody>
</table>
Embodied Energy of Optical Fibre Cable

- We consider the GYTY53 optical cable for the analysis of the embodied energy of optical fibre cables.

- The strength member in the centre of the cable to be made of steel,
- The loose tubes to be made of Polybutylene Terephthalate (PBT).
- The filling compound to be made of a mixture of different polymers.
## Embodied Energy of Optical Fibre Cable

The Embodied Energy per km of the GYTY53 Optical Cable

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Thickness or Diameter (estimation)</th>
<th>Weight kg/km</th>
<th>Embodied Energy MJ/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE outer sheath</td>
<td>PE</td>
<td>3mm</td>
<td>122.46 (analysis)</td>
<td>9907</td>
</tr>
<tr>
<td>Steel tape</td>
<td>steel</td>
<td>0.5 mm</td>
<td>37.5 (analysis)</td>
<td>1200 MJ/km</td>
</tr>
<tr>
<td>PE inner sheath</td>
<td>PE</td>
<td>1 mm</td>
<td>25.12 (analysis)</td>
<td>2302 MJ/km</td>
</tr>
<tr>
<td>Strength member</td>
<td>steel</td>
<td>2 mm</td>
<td>24.8 (analysis)</td>
<td>793 MJ/km</td>
</tr>
<tr>
<td>Fibers</td>
<td>glass</td>
<td>125 μm</td>
<td>1.73 (analysis)</td>
<td>123 MJ/km</td>
</tr>
<tr>
<td>Loose tube (6 items)</td>
<td>PBT</td>
<td>1 mm</td>
<td>25.2 (estimated)</td>
<td>2245 MJ/km</td>
</tr>
<tr>
<td>Filling compound</td>
<td>Polymers</td>
<td>--</td>
<td>14.9 (estimated)</td>
<td>1490 MJ/km</td>
</tr>
<tr>
<td><strong>Total embodied energy</strong></td>
<td></td>
<td></td>
<td><strong>18.059 GJ/km</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Given the cable weight and diameter as 250kg/km and 15.7mm, respectively and the diameter of the fibre as 125 μm.
### MILP Model for Energy Efficient Physical Topology Design

The model defines the following parameters:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$ and $j$</td>
<td>Denote end points of a virtual link in the IP layer</td>
</tr>
<tr>
<td>$s$ and $d$</td>
<td>Denote source and destination points of a traffic demand between a node pair</td>
</tr>
<tr>
<td>$m$ and $n$</td>
<td>Denote end points of a physical fibre link in the optical layer</td>
</tr>
<tr>
<td>$L_{mn}$</td>
<td>The length of the link between nodes $m$ and $n$ in the optical layer</td>
</tr>
<tr>
<td>$T$</td>
<td>The set of time points</td>
</tr>
<tr>
<td>$S$</td>
<td>Distance between neighbouring EDFAs</td>
</tr>
<tr>
<td>$N$</td>
<td>The set of nodes</td>
</tr>
<tr>
<td>$W$</td>
<td>The number of wavelengths in a fibre</td>
</tr>
<tr>
<td>$B$</td>
<td>The capacity of each wavelength</td>
</tr>
<tr>
<td>$\lambda^{sdt}$</td>
<td>Traffic demand between source $s$ and destination $d$</td>
</tr>
<tr>
<td>$EA_{mn}$</td>
<td>The number of EDFAs on physical link $(m, n)$. Typically $EA_{mn} = \lfloor L_{mn}/S - 1 \rfloor + 2$, where $S$ is the distance between two neighbouring EDFAs</td>
</tr>
<tr>
<td>$EG_{mn}$</td>
<td>The number of regenerators on physical link $(m, n)$. Typically $EG_{mn} = \lfloor L_{mn}/5S - 1 \rfloor$</td>
</tr>
</tbody>
</table>
## MILP Model for Energy Efficient Physical Topology Design

The model defines the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ndgr$</td>
<td>Minimum nodal degree</td>
</tr>
<tr>
<td>$Nlink$</td>
<td>Total number of links</td>
</tr>
<tr>
<td>$NF$</td>
<td>Maximum number of fibres on one physical link</td>
</tr>
<tr>
<td>$PR$</td>
<td>Power consumption of a router port</td>
</tr>
<tr>
<td>$PT$</td>
<td>Power consumption of a transponder</td>
</tr>
<tr>
<td>$PE$</td>
<td>Power consumption of an EDFA</td>
</tr>
<tr>
<td>$PG$</td>
<td>Power consumption of a regenerator.</td>
</tr>
<tr>
<td>$PO_i$</td>
<td>Power consumption of the optical switch at node $i$</td>
</tr>
<tr>
<td>$PMD$</td>
<td>Power consumption of a multi/demultiplexer</td>
</tr>
<tr>
<td>$EBR$</td>
<td>Embodied energy of IP router</td>
</tr>
<tr>
<td>$EBT$</td>
<td>Embodied energy of transponder</td>
</tr>
<tr>
<td>$EBE$</td>
<td>Embodied energy of EDFA</td>
</tr>
<tr>
<td>$EBG$</td>
<td>Embodied energy of regenerator</td>
</tr>
<tr>
<td>$EBO$</td>
<td>Embodied energy of optical switches</td>
</tr>
<tr>
<td>$EBM$</td>
<td>Embodied energy of a multi/demultiplexer</td>
</tr>
<tr>
<td>$EBF$</td>
<td>Embodied energy of per kilometre optical fiber cable</td>
</tr>
</tbody>
</table>
The model defines the following variables:

- $C_{ijt}$: The number of wavelength channels in the virtual link $(i, j)$ at time $t$
- $\omega_{mnt}$: The number of wavelength channels in the physical link $(m, n)$ at time $t$
- $W_{mnt}^{ij}$: The number of wavelength channels in the virtual link $(i, j)$ that traverse physical link $(m, n)$ at time $t$
- $DM_i$: The number of multi/demultiplexers in node $i$
- $\lambda_{sdt}^{sd}$: The traffic flow from node $s$ to node $d$ that traverses the virtual link $(i, j)$ at time $t$
- $link_{mn}$: If there is a link between nodes $m$ and $n$, $link_{mn} = 1$, otherwise $link_{mn} = 0$
- $f_{mn}$: The number of fibres on physical link $(m,n)$
MILP Model for Energy Efficient Physical Topology Design

- The total operational power consumption of the network under the bypass approach \((\text{Power\_bypass})\) is composed of:
  1. The power consumption of IP ports at time \(t\)
     \[
     \sum_{i \in N} \sum_{j \in N: i \neq j} PR \cdot C_{ijt}
     \]
  2. The power consumption of transponders at time \(t\)
     \[
     \sum_{m \in N} \sum_{n \in N: m \neq n} PT \cdot \omega_{mnt}
     \]
  3. The power consumption of EDFAs and regenerators at time \(t\)
     \[
     \sum_{m \in N} \sum_{n \in N: m \neq n} (PE \cdot EA_{mn} \cdot f_{mn} + PG \cdot EG_{mn} \cdot f_{mn})
     \]
  4. The power consumption of optical switches at time \(t\)
     \[
     \sum_{i \in N} PO_i
     \]
  5. The power consumption of de/multiplexers at time \(t\)
     \[
     \sum_{i \in N} PMD \cdot DM_i
     \]
MILP Model for Energy Efficient Physical Topology Design

- The total production embodied energy, $E_{EMB-P}$, of the network under the bypass approach is given as follows:

$$
\sum_{m \in N} \sum_{n \in N: m \neq n} EBF \cdot L_{mn} \cdot link_{mn} \\
+ \sum_{i \in N} \sum_{j \in N: i \neq j} EBR \cdot C_{ij} + \sum_{m \in N} \sum_{n \in N: m \neq n} EBT \cdot \omega_{mnt} \\
+ \sum_{m \in N} \sum_{n \in N: m \neq n} \left( EBE \cdot EA_{mn} \cdot f_{mn} + EBG \cdot EG_{mn} \cdot f_{mn} \right) \\
+ \sum_{i \in N} EBO \cdot PO_{i} + \sum_{i \in N} EBM \cdot DM_{i}
$$

where $t = T_{max}$. The number of devices in the network is based on the maximum traffic demand, therefore $T_{max}$ is the time of a day where the traffic demand is maximum.
MILP Model for Energy Efficient Physical Topology Design

- **Objective:** minimize

\[
\text{Power}_\text{bypass} \times LT + E_{\text{EMB}-P} + 0.1 \times E_{\text{EMB}-P} \times LT
\]

- **Subject to:**

\[
\sum_{j \in N:i \neq j} \lambda_{ijt}^{sd} - \sum_{j \in N:i \neq j} \lambda_{jit}^{sd} = \begin{cases} 
\lambda_{sdt}^{sd} & \text{if } i = s \\
-\lambda_{sdt}^{sd} & \text{if } i = d \\
0 & \text{otherwise}
\end{cases} \quad \forall t \in T, \forall s, d, i \in N : s \neq d
\]

\[
\sum_{s \in N} \sum_{d \in N:s \neq d} \lambda_{ijt}^{sd} \leq C_{ijt} \cdot B \quad \forall t \in T, \forall i, j \in N : i \neq j
\]

\[
\sum_{n \in N:m \neq n} W_{mnt}^{ij} - \sum_{n \in N:m \neq n} W_{mnt}^{ij} = \begin{cases} 
C_{ijt} & \text{if } m = i \\
-C_{ijt} & \text{if } m = j \\
0 & \text{otherwise}
\end{cases} \quad \forall t \in T, \forall i, j \in N : i \neq j
\]

- **Flow conservation**
- **Virtual paths**
- **Link capacity:**
- **Virtual paths**
- **Flow conservation:**
- **Physical links**
MILP Model for Energy Efficient Physical Topology Design

\[ \sum_{i \in N} \sum_{j \in N : i \neq j} W_{mnt}^{ij} \leq W \cdot f_{mn} \quad \forall t \in T, \forall m \in N, n \in N \]

\[ \sum_{i \in N} \sum_{j \in N : i \neq j} W_{mnt}^{ij} \leq W \cdot N_{F \cdot link}_{mn} \quad \forall t \in T, \forall m \in N, n \in N : m \neq n \]

\[ \sum_{i \in N} \sum_{j \in N : i \neq j} W_{mnt}^{ij} = \omega_{mnt} \quad \forall t \in T, \forall m \in N, n \in N : m \neq n \]

\[ \sum_{n \in N : m \neq n} link_{mn} \geq Ndgr \quad \forall m \in N \]

\[ \sum_{m \in N} \sum_{n \in N : m \neq n} link_{mn} = 2 \cdot \text{Nlink} \]

Link capacity: Physical links

Link capacity: Physical links

Link capacity: Physical links

Minimum Nodal Degree (chosen)

Number of links in the network (chosen)
The model can be extended to represent the non-bypass approach by redefining the power consumption of ports at time $t$ as follows:

$$\sum_{m \in N} \sum_{n \in N: m \neq n} PR \cdot \omega_{mnt}$$

and redefining the embodied energy of ports at time $t$ as follows:

$$\sum_{m \in N} \sum_{n \in N: m \neq n} EBR \cdot \omega_{mnt}$$
Results and Analysis

- We considered the NSFNET network to evaluate the physical topology optimization model in a real world network.

- There are four time zones. There is an hour time difference between each time zone and the next, we use EST as the reference time.
Network Scenario

- The average traffic demand between each node pair ranges from 20 Gb/s to 120 Gb/s and the peak occurs at 22:00.
### Network parameters

#### Input Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between two neighbouring EDFAs</td>
<td>80 (km)</td>
</tr>
<tr>
<td>Capacity of each wavelength ($B$)</td>
<td>40 (Gb/s)</td>
</tr>
<tr>
<td>Power consumption of a router port ($PR$)</td>
<td>1000 (W)</td>
</tr>
<tr>
<td>Power consumption of a transponder ($PT$)</td>
<td>73 (W)</td>
</tr>
<tr>
<td>Power consumption of an EDFA ($PE$)</td>
<td>8 (W)</td>
</tr>
<tr>
<td>Power consumption of an optical switch ($PO$)</td>
<td>85 (W)</td>
</tr>
<tr>
<td>Power consumption of a multiplexer/demultiplexer ($PMD$)</td>
<td>16 (W)</td>
</tr>
</tbody>
</table>
Network lifetime results: Operational and Embodied energies

Lifetime (10 year) energy, original NSFNET
Optimized Physical Topologies under Symmetric Traffic

Compared to the operational-power-minimized topologies, considering both energies has resulted in topologies with shorter links.

Operational-power-minimized, Symmetric traffic, non-bypass

Symmetric traffic, bypass
Symmetric traffic, non-bypass

Optimized physical topologies considering operational and embodied energies
Optimized Physical Topologies under Asymmetric Traffic

Operational-power-minimized, Asymmetric traffic, non-bypass

Asymmetric traffic, bypass
(Date centre at node 7)

Asymmetric traffic, non-bypass
(Date centre at node 7)

Optimized physical topologies considering operational and embodied energies
The Operational and Embodied Energy Consumption

- The embodied energy is the major contributor to the total network energy consumption

- Significant embodied energy savings of 20% and 59% are achieved compared to the original NSFNET topology and the operational-power-optimized topology, respectively resulting in a total energy saving of 47% and 13%.
Deploying the full mesh has resulted in an increase in the embodied energy more than 500% compared to the original NSFNET topology.

In addition to the operational energy savings (92%), the star topology has saved 31% of the embodied energy resulting in a total saving of 44%.
Optimized physical topologies without considering the embodied energy of the optical cables

- With technological advances the embodied energy of optical cables is anticipated to be reduced. We investigate energy-efficient topology design without considering the embodied energy of the optical cable.

- Similar trends to the operational-power-optimized topologies where a number of long links exist between nodes in two ends of the network.

Symmetric traffic, bypass

Asymmetric traffic, bypass

Symmetric traffic, non-bypass

Asymmetric traffic, non-bypass
The Operational and Embodied Energy Consumption without considering the embodied energy of the optical cables

- Compared with the original NSFNET, the total energy consumption have saved 12% (here 28% of the total energy is contributed by embodied energy).

- Resulting a very limited energy saving (less than 1%), compared to optimizing with respect to operational energy only.
Summary

• we reconsider the physical topology design optimization taking into account the embodied energy of the different network devices.

• The analysis of the embodied energy of network devices shows that the embodied energy accounts for up to 80% of the total energy consumption of the IP over WDM network over the network commercial lifetime.

• Considering both the operational and embodied energies in the physical topology optimization has resulted in topologies with shorter links as the embodied energy of the optical fibre cable is the main contributor to the network total energy.

• The operational energy of these topologies has increased by up to 20% compared to the operational-power-optimized topologies, however significant embodied energy savings of up to 59% are achieved, resulting in a total energy saving of 47%.
Summary

• With technological advances the embodied energy of optical cable is anticipated to be reduced, making the embodied energy contribution of other network devices more significant, therefore, we have also optimized the physical topologies without considering the embodied energy of the optical fibre cables.

• The results show that considering the embodied energy of the other devices has a limited effect on the physical topology optimization.
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
• Embodied energy and topology optimisation, energy efficiency

⇒ Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
• Peer-to-peer energy efficient networks
• Future Directions
• References
Energy Efficient Elastic Optical Networks

Power Consumption of WDM Router Ports and Transponders

<table>
<thead>
<tr>
<th>Power consumption</th>
<th>Value (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption of a WDM router port (40Gb/s)</td>
<td>1000</td>
</tr>
<tr>
<td>Power consumption of a WDM transponder (10Gb/s)</td>
<td>45</td>
</tr>
<tr>
<td>Power consumption of a WDM transponder (40Gb/s)</td>
<td>73</td>
</tr>
<tr>
<td>Power consumption of a WDM transponder (100Gb/s)</td>
<td>135</td>
</tr>
</tbody>
</table>

- Optical Orthogonal Frequency Division Multiplexing (OFDM) has been proposed as an enabling technique for elastic optical networks.
- In addition to the spectral efficiency, optical OFDM supports distance-adaptive spectrum allocation by adapting the modulation format according to the end-to-end physical conditions of the optical path.
• We estimate the power consumption of OFDM transponders working at lower rates assuming linear ALR profile.

• We assume BPSK is the modulation format associated with the maximum transmission distance in the NSFNET.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Modulation format</th>
<th>Data Rate</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>DSP</td>
</tr>
<tr>
<td>500 km</td>
<td>8QAM</td>
<td>120 Gb/s</td>
<td>160 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 km</td>
<td>QPSK</td>
<td>80 Gb/s</td>
<td>106 W</td>
</tr>
<tr>
<td>2000 km</td>
<td>BPSK</td>
<td>40 Gb/s</td>
<td>53 W</td>
</tr>
</tbody>
</table>
The optical OFDM-based network saves 55%, 29% and 48% of the optical layer power consumption compared to WDM networks deploying wavelength capacities of 10Gb/s, 40Gb/s and 100Gb/s, respectively.
• Optical OFDM-based networks saves 10%, 14%, 31% and 8% of the total power consumption compared to WDM networks deploying wavelength capacities of 10Gb/s, 40Gb/s, 100Gb/s and MLR, respectively.
The power consumption of the 120Gb/s OFDM transponder should not exceed 425W to outperform MLR.
Spectral Efficiency of Optical OFDM-based Networks under Symmetric traffic

- The spectrum-minimized OFDM MILP model uses 34% less subcarries compared to the power-minimized under symmetric traffic, but less than 1% extra power.
Outline

- Introduction and the need for energy efficiency
- Tutorial on network optimisation and MILP
- Energy efficient IP over WDM networks and renewable energy
- Network design with data centres, energy-efficiency
- Network topology optimisation
- Embodied energy and topology optimisation, energy efficiency
- Elastic optical networks using OFDM, energy efficiency
  ➔ Data compression for energy efficiency
- Caching and IPTV / VoD networks
- Peer-to-peer energy efficient networks
- Future Directions
- References
Energy-Efficient Data Compression for Optical Networks

- Trade-off between the power consumption of computational resources and memory required to compress and decompress data and the network power savings.
- In [1], the authors considered semantic compression to reduce the video storage space.
  - YouTube videos can be compressed by a ratio of 20:1 compared to ordinary histogram representations.
- In [2], the data compression energy per bit is given as:
  \[ E_c = A(\eta - 1)^\beta \]
  \[ \eta = \frac{1}{1 - R_c}, \quad A, \beta > 0 \]
- Parameter \( \beta \) represents the efficiency of the data compression algorithm.

2. Dan Kilper et. al "Insights on coding and transmission energy in optical networks", *E-energy 2011*. 
Results and Analysis

- The power consumption of decompression is equal to the power consumption of compression.
- We considering a mixture of traffic (video, images, text) to reflect the global Internet traffic where 91% of the global Internet is video.
- Average power savings of 29% and 39% are achieved by the MILP model under the bypass approach for $\beta=1$ and $\beta=2$, respectively.
- Comparable power savings are achieved by the energy-efficient data compression and routing heuristic.
- High power savings of 45% and 55% for $\beta=1$ and $\beta=2$, respectively are achieved under the non-bypass approach.

### Algorithms and Compression Ratios for Different types of data

<table>
<thead>
<tr>
<th>Traffic type</th>
<th>Compression algorithm</th>
<th>Compression ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Text</td>
<td>bzip2, ppmd (lossless)</td>
<td>4:1</td>
</tr>
<tr>
<td>Image</td>
<td>JPEG, GIF, PNG (lossy)</td>
<td>10:1</td>
</tr>
<tr>
<td>Video</td>
<td>MPEG-4, H.264(lossy)</td>
<td>20:1</td>
</tr>
</tbody>
</table>

Power consumption under the bypass approach
Outline

- Introduction and the need for energy efficiency
- Tutorial on network optimisation and MILP
- Energy efficient IP over WDM networks and renewable energy
- Network design with data centres, energy-efficiency
- Network topology optimisation
- Embodied energy and topology optimisation, energy efficiency
- Elastic optical networks using OFDM, energy efficiency
- Data compression for energy efficiency
- Caching and IPTV / VoD networks
  - Peer-to-peer energy efficient networks
  - Future Directions
  - References
Outline

- Energy Efficient Caching for IPTV On-Demand Services
  - LP Model for Energy Efficient Caching
  - Energy-Minimized Cache Size Optimization
  - The Impact of Caching the Most Popular Objects
• By 2014 over 91% of the global IP traffic is projected to be a form of video (IPTV, VoD, P2P), with an annual growth in VoD traffic of 33%.

• In proxy-based architectures, proxies (or caches) are located closer to clients to cache some of the server’s content.

• Our goal is to minimize the power consumption of the network by storing the optimum number of the most popular content at the nodes’ caches.
Energy Efficient Caching for IPTV On-Demand Services

- We develop a LP model to optimize the cache size of each node in the network at different times of the day.

- We assume that each node in the network is allocated a cache with a limited capacity populated by $M$ objects out of the total video server’s objects $N$.

- The objects stored in the cache are the most popular objects available.

- The cache hit ratio $H$ is defined as the ratio of the number of requests served from the cache to the total number of requests.

- The traffic demand between a node and a video server represents $(1-H)$ of the total access network’s demand.

- The relationship between the hit ratio $H$ and the cache size $M$ is represented by a convex function.
LP Model for Energy Efficient Caching

1. The power consumption of router ports and optical switches at time $t$:

$$\sum_{i \in N} P_{p}\left(P_{agg_{it}} + \sum_{j \in N: i \neq j} C_{it}\right) \sum_{i \in N} P_{o_{i}}$$

2. The power consumption of transponders at time $t$:

$$\sum_{t} \sum_{m \in N \cap n \in Nm[i]} P_{t} \cdot \omega_{ijt}$$

3. The power consumption of amplifiers at time $t$:

$$\sum_{i \in N} \sum_{j \in Nm[i]} \left(P_{a} \cdot A_{mp_{ij}} \cdot f_{ij}\right)$$

4. The power consumption de/multiplexers at time $t$:

$$\sum_{i \in N} \sum_{j \in Nm[i]} P_{md} \cdot f_{ij}$$

5. The power consumption of caches at time $t$:

$$\sum_{i \in N} P_{c_{it}}$$
LP Model for Energy Efficient Caching

Objective: minimize

$$\sum_{i \in T} \left( \sum_{i \in N} P_{pp} \left( P_{agg_{i}} + \sum_{j \in N: j \neq i} C_{ij} \right) + \sum_{i \in N} P_{o} + \sum_{m \in N \cap N[m]} \sum_{k \in N[m]} \left( P_{t} \cdot \omega_{ijk} \right) + \sum_{i \in N} \sum_{j \in N[m]} \left( P_{md} \cdot f_{ij} \right) + \sum_{j \in N} P_{c_{it}} \right)$$

Subject to:

$$P_{agg_{it}} + \sum_{j \in N[m]: j \neq i} C_{ij} \leq P_{max_{i}} \quad \forall i \in N, \forall t \in T$$

$$P_{agg_{it}} + \sum_{j \in N[m]: j \neq i} C_{ij} \leq P_{max_{i}} \quad \forall i \in N, \forall t \in T$$

$$\sum_{x \in N} \sum_{y \in N: x \neq y} \omega_{xij} \leq W \cdot f_{ij} \quad \forall i \in N, \forall j \in N[m], \forall t \in T$$

$$\sum_{x \in N} \sum_{y \in N: x \neq y} \omega_{xij} \leq \omega_{ij} \quad \forall i \in N, \forall j \in N[m], \forall t \in T$$

Constraints on number of router ports available

Number of wavelength used not more than those in fibre
LP Model for Energy Efficient Caching

\[
\sum_{j \in \mathbb{N}[i]} \omega_{ij}^{yx} - \sum_{j \in \mathbb{N}[i]} \omega_{ij}^{xy} = \begin{cases} 
C_{xyt} & i = x \\
-C_{xyt} & i = y \\
0 & \text{otherwise}
\end{cases} \\
\forall i, x, y \in \mathbb{N}, \forall t \in T
\]

Flow conservation constraint in the optical layer

\[
\sum \lambda_{ij}^{yx} - \sum_{j \in \mathbb{N}:i \neq j} \lambda_{ij}^{xy} = \begin{cases} 
\lambda_{xt}^{yt} & i = x \\
-\lambda_{xt}^{yt} & i = y \\
0 & \text{otherwise}
\end{cases} \\
\forall i, x, y \in \mathbb{N}, \forall t \in T
\]

Flow conservation constraint for regular traffic in the IP layer

\[
\sum \lambda_{ij}^{xy} - \sum_{j \in \mathbb{N}:i \neq j} \lambda_{ij}^{xy} = \begin{cases} 
\lambda_{ij}^{xy} . R_j . \delta_y & i = x \\
-\lambda_{ij}^{xy} . R_j . \delta_y & i = y \\
0 & \text{otherwise}
\end{cases} \\
\forall i, x, y \in \mathbb{N}, \forall t \in T
\]

Flow conservation constraint for upload traffic (to server nodes) in the IP layer
LP Model for Energy Efficient Caching

\[
\sum_{i \in \mathcal{N}} \lambda_{i}^{xy} d_{ijt}^{xy} - \sum_{i \in \mathcal{N}} \lambda_{i}^{xy} d_{jit}^{xy} = \begin{cases} 
\lambda_{i}^{xy} R_d \delta_x (1 - H_{it}) & i = x \\
-\lambda_{i}^{xy} R_d \delta_x (1 - H_{it}) & i = y \\
0 & \text{otherwise}
\end{cases} \\
\forall i, x, y \in \mathcal{N}, \forall t \in T
\]

Flow conservation constraint for upload traffic (to server nodes) in the IP layer

\[
P_{agg_{it}} = \left( \sum_{y \in \mathcal{N}: y \neq i} \lambda_{ij}^{yt} + \sum_{y \in \mathcal{N}: y \neq i} \lambda_{ij}^{yt} \cdot R_u \cdot \delta_y + \sum_{x \in \mathcal{N}: x \neq i} \lambda_{ix}^{yt} \cdot R_d \cdot \delta_x (1 - H_{it}) \right) / B \\
\forall i \in \mathcal{N}, \forall t \in T
\]

Number of aggregation ports used

\[
\sum_{x \in \mathcal{N}} \sum_{y \in \mathcal{N}: x \neq y} (\lambda_{ij}^{xy} + \lambda_{ij}^{xy} \cdot u_{ij}^{xy} + \lambda_{ij}^{xy} \cdot d_{ijt}^{xy}) \leq C_{ijt} \cdot B \\
\forall i, j \in \mathcal{N}, \forall t \in T
\]

Traffic on a wavelength does not exceed its capacity

\[
Pc_{it} \geq \alpha (a_k \cdot H_{it} + b_k) \\
\forall i \in \mathcal{N}, \forall t \in T, \forall k \in K
\]

Piecewise linear approximation of convex hit ratio
Results

- We consider the NSFNET network with 7 nodes serving as video servers.
- The location of the video servers is optimized using the model (1, 3, 5, 8, 10, 12, and 14).
- The traffic demand between nodes and video servers is generated based on the regular traffic demand.
- We consider three different values of uplink ($R_u$) and downlink traffic ratios ($R_d$) to match the input and output rates of a typical video server and reflect the expected growth in VoD traffic:
  1) $R_d=1.5$ and $R_u=0.2$, 2) $R_d=4.5$ and $R_u=0.6$ and 3) $R_d=7.5$ and $R_u=1.0$
- A library of 2 million objects of the same size.
- Object popularities follow a Zipf-like distribution:

$$P_i = \frac{1}{i \cdot ln N}$$
The power consumption of the network falls with the increase in the cache size to a certain cache size after which increasing the cache size results in increasing the total energy consumption.

In this range, the energy consumed for storage exceeds the energy consumed if some of the requests are served remotely.
Fixed optimum cache is found considering all the nodes over the full day.

Fixed size caching reduces the network energy consumption by a maximum of 19% (average of 8%) and a maximum of 38% (average of 30%) for (Rd=1.5, Ru=0.2) and (Rd=7.5, Ru=1), respectively.

Variable size cache max network power saving 42%
Optimum cache size at different nodes during the day (need cache size adaptation (sleep))

(a) $Rd = 1.5$

(b) $Rd = 7.5$
The power consumption increases by removing the 10 most popular items.

Increase in the power consumption of the network by over 20% (average 18.4%) for \((Rd=7.5, Ru=1)\).
Increasing the cache size by storing more of the less popular objects does not compensate for the energy loss caused by displacing the most popular objects (due to their high popularity).

2 Million objects, Zipf distributed, 10 most popular removed
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
• Embodied energy and topology optimisation, energy efficiency
• Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
  ➔ Peer-to-peer energy efficient networks
• Future Directions
• References
• Energy Efficient BitTorrent over IP over WDM Networks
  • MILP Model for Energy-Efficient BitTorrent
  • Energy-Efficient BitTorrent Heuristic
  • Performance Evaluation
  • Summary
The two content distribution schemes, Client/Server (C/S) and Peer-to-Peer (P2P), account for a high percentage of the Internet traffic.

We investigate the energy consumption of BitTorrent in IP over WDM networks.

We show, by mathematical modelling (MILP) and simulation, that peers’ co-location awareness, known as locality, can help reduce BitTorrent’s cross traffic and consequently reduces the power consumption of BitTorrent on the network side.
Energy Efficient BitTorrent over IP over WDM Networks

• The file is divided into small pieces.
• A tracker monitors the group of users currently downloading.
• Downloader groups are referred to as swarms and their members as peers. Peers are divided into seeders and leechers.
• As a leecher finishes downloading a piece, it selects a fixed number (typically 4) of interested leechers to upload the piece to, i.e., unchoke. 
• Tit-for-Tat (TFT) ensures fairness by not allowing peers to download more than they upload.
• We consider 160,000 groups of downloaders distributed randomly over the NSFNET network nodes.
• Each group consists of 100 members.
• File size of 3GB.
• Homogeneous system where all the peers have the same upload capacity of 1Mbps.
Energy Efficient BitTorrent over IP over WDM Networks

- **Optimal Local Rarest First** pieces dissemination where Leechers select the least replicated piece in the network to download first.

- BitTorrent traffic is 50% of total traffic.

- **Flash crowd** where the majority of leechers arrive soon after a popular content is shared.

- We compare BitTorrent to a C/S model with 5 data centers optimally located at nodes 3, 5, 8, 10 and 12 in NSFNET.

- The upload capacity and download demands are the same for BitTorrent and C/S scenarios (16Tbps).
Under the bypass approach, the total network power consumption is composed of:

1) The power consumption of router ports
\[ \sum_{i \in N} Erp \cdot Q_i + Erp \cdot \sum_{i \in N} \sum_{j : i \neq j} C_{ij} \]

2) The power consumption of transponders
\[ \sum_{m \in N} \sum_{n \in N} Et \cdot W_{mn} \]

3) The power consumption of EDFAs
\[ \sum_{m \in N} \sum_{n \in N} Ee \cdot A_{mn} \cdot F_{mn} \]

4) The power consumption of optical switches
\[ \sum_{i \in N} PO_i \]

5) The power consumption of Multi/Demultiplexers
\[ \sum_{m \in N} \sum_{n \in N} Emd \cdot F_{mn} \]
MILP Model for Energy-Efficient BitTorrent

Objective: Maximize

\[ \alpha \cdot \left( \sum_{k \in Sw} \sum_{i \in p_k, k \in S_d} Avd_{r_k} \right) - \]

\[ \beta \cdot \left( \sum_{i \in EN} Erp \cdot Q_i + Erp \cdot \sum_{i \in EN} \sum_{j \neq i} C_{ij} + \right. \]

\[ \sum_{m \in N} \sum_{n \in N_{m_n}} Et \cdot W_{mn} - \sum_{m \in N} \sum_{n \in N_{m_n}} Ee \cdot A_{mn} \cdot F_{mn} - \]

\[ \sum_{i \in EN} PO_i + \sum_{m \in N} \sum_{n \in N_{m_n}} Emd \cdot F_{mn} \]

Subject to:

\[ \sum_{j \in N : i \neq j} L_{i j k}^{sd} - \sum_{j \in N : i \neq j} L_{j i k}^{sd} = \begin{cases} L_{k}^{sd} & \text{if } i = s \\ -L_{k}^{sd} & \text{if } i = d \\ 0 & \text{otherwise} \end{cases} \]

\[ \forall k \in Sw \quad \forall s, d, i \in N: \ s \neq d \]

Flow conservation constraints in the IP layer

Setting \( \beta = 0 \) gives the original BitTorrent
MILP Model for Energy-Efficient BitTorrent

Virtual link capacity constraint

\[ \sum_{{s \in N}} \sum_{{d \in N : s \neq d}} \left( L_{{ij}}^{sd} + \sum_{{k \in SW}} L_{{ijk}}^{sd} \right) \leq C_{{ij}} \cdot B \]
\[ \forall i, j \in N: \ i \neq j \]

Flow conservation constraint in the optical layer

\[ \sum_{{m \in Nm}} W_{{mn}}^{ij} - \sum_{{m \in Nm}} W_{{nm}}^{ij} = \begin{cases} C_{{ij}} & \text{if } m = i \\ -C_{{ij}} & \text{if } m = j \\ 0 & \text{otherwise} \end{cases} \]
\[ \forall i, j, m \in N: \ i \neq j \]

Physical link capacity constraints

\[ \sum_{{i \in N}} \sum_{{j \in N : i \neq j}} W_{{mn}}^{ij} \leq W \cdot F_{{mn}} \]
\[ \forall m \in N \quad \forall n \in Nm \]

Number of aggregation ports constraint

\[ Q_{{i}} = \frac{1}{B} \cdot \sum_{{d \in N : i \neq d}} \left( L_{{ir}}^{id} + \sum_{{k \in SW}} L_{{ik}}^{id} \right) \]
\[ \forall i \in N \]
MILP Model for Energy-Efficient BitTorrent

\[ \text{Avdr}_{ik} = \sum_{j \in P_k: i \neq j} SR \cdot U_{ijk} \]
\[ \forall k \in S_w \quad \forall i \in P_k: \quad i \not\in S_d_k \]

\[ \text{Avdr}_{ik} \leq D_p \]
\[ \forall k \in S_w \quad \forall i \in P_k: \quad i \not\in S_d_k \]

\[ \sum_{j \in P_k: j \not\in S_d_k, i \neq j} U_{ijk} \leq SLN \]
\[ \forall k \in S_w \quad \forall i \in P_k \]

\[ SR \cdot U_{ijk} = SR \cdot U_{jik} \]
\[ \forall k \in S_w \quad \forall i,j \in P_k: \quad i,j \not\in S_d_k \quad i \neq j \]

Peers download rate constraint

Peers upload rate constraints

Fairness constraint, Tit-For-TAT (TFT)
Energy-Efficient BitTorrent Heuristic

- Energy-Efficient BitTorrent model performs peer selection based on the co-location of peers within the same nodes to minimize energy consumption.
- The heuristic tries to mimic this behavior by:
  - Seeders span the neighboring nodes only.
  - Leechers are limited to their local nodes as long as there are sufficient number of peers (5 at least), otherwise they span to neighboring nodes.

Distribute Peers on IP/WDM Nodes randomly

Perform initial Optimistic unchoke based on locality

Perform one TFT Round based on locality

Calculate average download rates for leechers, average downloaded file size and transient demands between nodes per round

Use the multi-hop bypass/nonbypass heuristic to route the swarms transient traffic between IP/WDM nodes with the network regular traffic

Calculate the network power consumption per round of the swarms traffic and the regular traffic

Leechers finished downloading the files

- No
- Yes

Calculate peers average download rate, average Power consumption and average Energy Consumption for the whole scenario
## Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption of a router port $Er_p$</td>
<td>1000 W</td>
</tr>
<tr>
<td>Power consumption of transponder $Et$</td>
<td>73 W</td>
</tr>
<tr>
<td>Power consumption of EDFA $E_e$</td>
<td>8 W</td>
</tr>
<tr>
<td>Power consumption of an optical switch in node $i$ $EO_i$</td>
<td>85 W</td>
</tr>
<tr>
<td>Power consumption of a Mux/Demux $Em_d$</td>
<td>16 W</td>
</tr>
<tr>
<td>No. of Wavelengths in a fiber $W$</td>
<td>16</td>
</tr>
<tr>
<td>Bit rate of each Wavelength $B$</td>
<td>40 Gbps</td>
</tr>
<tr>
<td>Span distance between EDFAs $S$</td>
<td>80 km</td>
</tr>
<tr>
<td>Number of Swarms $SN$</td>
<td>160,000</td>
</tr>
<tr>
<td>Number of peers in single Swarm $PN$</td>
<td>100</td>
</tr>
<tr>
<td>Number of upload slots $SLN$</td>
<td>4</td>
</tr>
<tr>
<td>Total upload capacity for each peer $Up$</td>
<td>0.001 Gbps</td>
</tr>
<tr>
<td>Total download capacity for each peer $D_p$</td>
<td>0.01 Gbps</td>
</tr>
<tr>
<td>Total data centers upload capacity $Us$</td>
<td>16Tbps</td>
</tr>
<tr>
<td>Number of Data Centers DCN</td>
<td>5</td>
</tr>
<tr>
<td>Average download rate weight $\beta$</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Power weight $\beta$</td>
<td>0 or 1</td>
</tr>
</tbody>
</table>
Peer Selection
(100 Peer: 30 Seeders and 70 Leechers in Swarm 1)

Original BitTorrent (Random Selection)

Energy Efficient BitTorrent (Optimized Selection)
Average Download Rate

- All models reach optimal performance
- Energy-efficient heuristic reduce performance by 13%
Non-bypass:
Model Power Saving = 36%
Heuristic Power Saving = 36%

Bypass:
Model Power Saving = 30%
Heuristic Power Saving = 28%
Energy Consumption

Non-bypass:
MILP average Energy Saving = 36%
Heuristic average Energy Saving = 25%

Bypass:
MILP average Energy Saving = 30%
Heuristic average Energy Saving = 15%
Summary

• We have developed a MILP model to evaluate the energy consumption of BitTorrent, the most popular P2P application, over bypass and non-bypass IP/WDM networks and compared it to C/S systems.

• The energy-efficient BitTorrent model has reduced the energy consumption of BitTorrent in IP/WDM networks by 30% and 36% compared to the C/S model under the bypass and non-bypass approaches, respectively, while maintaining the optimal download rate.

• The model converges to locality where peers select each other based on their location rather than randomly.
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
• Embodied energy and topology optimisation, energy efficiency
• Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
• Peer-to-peer energy efficient networks

Future Directions

• References
Future Directions

• “The carbon free network”
• “The routing free network”
• Network architecture optimisation
  • Use of other renewable energy sources (eg. wind)
  • Data centres and renewables: optimisation framework, locations and architecture
  • Varying energy cost at producer and consumer
• Dynamic architectures to reduce / eliminate over provisioning (QoS and resilience op), eg. dynamic $\lambda$ allocation
• Optimum (power) wired-wireless access architectures
Future Directions

- Optimisation of wired wireless access architectures, metro rings - wireless mesh, PON, RoF.
- Architectures that support photonic switching instead of electronic routing.
- Optical band and flow switching.
- Auction based and self-organising dynamic architectures for energy minimisation.
Future Directions

• Extend the work to access networks and study end-to-end energy saving

• Study optimum caching location in an end-to-end network

• Evaluate energy savings in network topologies that maximise transmission at the expense of switching and routing, eg. through large star nodes

• Develop the optimisation and simulation tools so that address energy efficiency specifically
Outline

• Introduction and the need for energy efficiency
• Tutorial on network optimisation and MILP
• Energy efficient IP over WDM networks and renewable energy
• Network design with data centres, energy-efficiency
• Network topology optimisation
• Embodied energy and topology optimisation, energy efficiency
• Elastic optical networks using OFDM, energy efficiency
• Data compression for energy efficiency
• Caching and IPTV / VoD networks
• Peer-to-peer energy efficient networks
• Future Directions

⇒ References
General references


Related Publications


Related Publications


