Design and Dimensioning of a Novel Composite-Star WDM Network with TDM Channel Partitioning

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Outline

1. The Petaweb
   - The architecture
   - Network model
   - Classes of service

2. Petaweb network design
   - Design problem
   - Results
   - Quasi-regular topology

3. Open issues
   - Reliability problem
   - Upgrade problem
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An innovative composite-star architecture

Network elements
1. optical core nodes
2. optical links
3. electronic edge nodes
An innovative composite-star architecture

Network elements

1. optical core nodes
2. optical links
3. electronic edge nodes
The Petaweb

Network design

Open issues

Summary

The architecture

An innovative composite-star architecture

Network elements

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The Petaweb

Network design

Open issues

Summary

The architecture

An innovative composite-star architecture

Network elements

1. optical core nodes
2. optical links
3. electronic edge nodes

Core node (CN)

Different types.
Structure capable to switch wavelengths and time-slots in the optical domain (Huang, 2000).
An innovative composite-star architecture

- **Network elements**
  1. optical core nodes
  2. optical links
  3. electronic edge nodes

- **Optical link**
  Connects an EN to a CN.
  Group of unidirectional fibers.
  \( W = 16 \) wavelength per fiber
  \( C_{ch} = 10\text{Gb/s} \) of channel capacity
The Petaweb

Network design

Open issues

Summary

The architecture

An innovative composite-star architecture

Network elements

1. optical core nodes
2. optical links
3. electronic edge nodes

Edge node (EN)

Electronic equipment defining a set of static connection requests
Network model

Traffic and Costs

Traffic model
Two types of static traffic:
A. From industrial data
B. Given by a gravitational model

Cost model
Three costs:
1. Core node cost
   \[ f_r + 2 |M| W s_r^{(s_r-1)} P \]

   Fix cost
   Variable cost

2. Fiber cost
   \[ \phi(W) F \ [Km]^{-1} \]

3. Propagation delay cost
   \[ \beta \ [Km Gb/s]^{-1} \]
### Traffic and Costs

#### Traffic model

Two types of static traffic:

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   \[ \beta [Km Gb/s]^{-1} \]

Matrixes with many zero values
Network model

Traffic and Costs

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3. Propagation delay cost
   \[ \beta [Km Gb/s]^{-1} \]

Dense matrixes

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<th>BTN</th>
<th>CHRL</th>
<th>CLEV</th>
<th>MIAM</th>
<th>NYCM</th>
<th>PHILA</th>
<th>TAMP</th>
<th>TLHS</th>
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**Traffic and Costs**

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Classes of service

**TLP-1**

\[ Z_1 = \frac{1}{2^n} C_{ch}, \quad n \in \mathbb{N} \]

**TLP-2**

\[ Z_2 = C_{ch} \]

**TLP-3**

\[ Z_3 = WC_{ch} \]
Classes of service

**TLP-1**
\[ Z_1 = 0.625 \text{ Gb/s} \]

**TLP-2**
\[ Z_2 = 10 \text{ Gb/s} \]

**TLP-3**
\[ Z_3 = 160 \text{ Gb/s} \]
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The Petaweb design problem

**Given**
- the network architecture and model
- the virtual topology: set of TLPs
The Petaweb design problem

**Given**
- the network architecture and model
- the virtual topology: set of TLPs

**Find optimally**
- the core nodes location and size → the resources Allocation
- the assignment of ts-lightpaths to core nodes → their 1-hop Route
- the Assignment of Fibers, Wavelengths and Time-slots to the ts-lightpaths
The Petaweb design problem

Given
- the network architecture and model
- the virtual topology: set of TLPs

Design problem

Divided in the two sub-problems:
- RFA: Route and Fiber Allocation
  resources allocation: core nodes location and TLPs 1-hop routes
- WTA: Wavelength and Time-slot Assignment
  resources assignment: wavelength and time-slot assignment
The Petaweb design problem

Given
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Divided in the two sub-problems:

- **RFA**: Route and Fiber Allocation
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Divided in the two sub-problems:
- **RFA: Route and Fiber Allocation**
  - resources allocation: core nodes location and TLPs 1-hop routes
- **WTA: Wavelength and Time-slot Assignment**
  - resources assignment: wavelength and time-slot assignment
Design problem

RFA: dimensioning problem

Similarities with CFLP

Capacitated Facility Location Problem (CFLP): given set of clients with specific demands for a product; the goal is to optimally locate plants that send the product to clients.

- core nodes $\approx$ plants, edge nodes $\approx$ clients
- fiber cost $\approx$ transport cost
- core node cost $\approx$ plant cost
- capacity constraints on links

Differences

- the product is not sent from plant, but uses plant as transit
- the plant cost is variable; the delay cost is not present
- capacity constraints even on edge nodes
Design problem

RFA resolution via Integer Linear Programming

\[
\min G(y_{ire}, x_{phl}^{ire}) = \sum_{(i,r,e)} \left( 2 |M| W s_r \gamma^{(s_r-1)} P + f_r \right) y_{ire} \\
+ \sum_{(i,r,e)} 2 \phi(W) F s_r \left( \sum_{j \in M} \Delta_{ij} \right) y_{ire} \\
+ \sum_{(i,r,e)} \sum_{(p,h,l)} \beta d_{ip} Z_h x_{phl}^{ire}
\]  
(1)
RFA resolution via Integer Linear Programming

\[
\begin{align*}
\min \quad G(y_{ire}, x_{phl}^{ire}) &= \sum_{(i,r,e)} \left( 2 |M| W s_r \gamma^{(s_r-1)} P + f_r \right) y_{ire} \\
&\quad + \sum_{(i,r,e)} 2 \phi(W) F s_r \left( \sum_{j \in M} \Delta_{ij} \right) y_{ire} \\
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\end{align*}
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\]
RFA resolution: constraints

\[ \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_1 l_1}^{ire} = \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_2 l_2}^{ire} \quad (2) \]

\[ \sum_{(p \in O_j, h, l)} Z_h x_{ph l}^{ire} \leq C_{ch} W s_r y_{ire} \quad (5) \]

\[ \forall i \in M, \forall p \in T, \forall h_1 \in H, \forall h_2 \in H, \forall l_1 |1 \leq l_1 \leq L_{h_1}, \forall l_2 |1 \leq l_2 \leq L_{h_2}, (h_1, l_1) \neq (h_2, l_2) \]

\[ \sum_{(i, r, e)} x_{ph l}^{ire} = 1 \quad \forall (p, h, l) \quad (3) \]

\[ \sum_{(p \in D_k, h, l)} Z_h x_{ph l}^{ire} \leq C_{ch} W s_r y_{ire} \quad (6) \]

\[ \forall k \in M, \forall (i, r, e) \]

\[ y_{ire} \in \{1, 0\}, \forall (i, r, e) \quad (7) \]

\[ \sum_{(i, r, e)} C_{ch} W s_r y_{ire} \leq C_j \quad \forall j \in M \quad (4) \]

\[ x_{ph l}^{ire} \in \{1, 0\}, \forall (i, r, e) \forall (p, h, l) \quad (8) \]
Design problem

RFA resolution: **Capacity Constraints**

\[
\sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_1l_1} = \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_2l_2} \quad (2)
\]

\[
\forall i \in M, \forall p \in T, \forall h_1 \in H, \forall h_2 \in H, \forall l_1 \leq l_1 \leq L_{h_1}, \forall l_2 | 1 \leq l_2 \leq L_{h_2}, (h_1, l_1) \neq (h_2, l_2)
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The Petaweb
Network design
Open issues
Summary

Design problem

RFA resolution: Routing Constraints

\[ \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_1 l_1}^{ire} = \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_2 l_2}^{ire} \quad (2) \]

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\[ \sum_{(i,r,e)} x_{phl}^{ire} = 1 \forall (p, h, l) \quad (3) \]

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\[ x_{phl}^{ire} \in \{1, 0\}, \forall (i, r, e) \forall (p, h, l) \quad (8) \]
RFA resolution: **Variables** Constraints

\[
\sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_1 l_1}^{ire} = \sum_{r \in V} \sum_{e=1}^{E_r} x_{ph_2 l_2}^{ire} \quad (2)
\]

\[
\forall i \in M, \forall p \in T, \forall h_1 \in H, \forall h_2 \in H, \forall l_1 | 1 \leq l_1 \leq L_{h_1},
\forall l_2 | 1 \leq l_2 \leq L_{h_2}, (h_1, l_1) \neq (h_2, l_2)
\]

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\sum_{(i, r, e)} x_{p h l}^{ire} = 1 \forall (p, h, l) \quad (3)
\]

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\sum_{(p \in O_j, h, l)} Z_h x_{ph l}^{ire} \leq C_{ch} W s_r y_{ire} \quad (5)
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x_{ph l}^{ire} \in \{1, 0\}, \forall (i, r, e) \forall(p, h, l) \quad (8)
\]
WTA resolution algorithm

- One optical link at a time
  - TLP-3s assigned to whole fibers
  - TLP-2s and TLP-1s grouped on the base of their CR
    - TLP-2s assigned to contiguous wavelengths
    - TLP-1s assigned to contiguous time-slots
WTA resolution algorithm

One optical link at a time

- TLP-3s assigned to whole fibers
- TLP-2s and TLP-1s grouped on the base of their CR
  - TLP-2s assigned to contiguous wavelengths
  - TLP-1s assigned to contiguous time-slots

Design problem

TLP-2 to assign?  ASSIGN LAMBDA
YES
NO
Lambda available?
Catch next CR
YES
ASSIGN SLOT
TLP-3 to assign?
YES
ASSIGN FIBER
NO
Catch next opt. link
Catch next fiber
TLP-3 to assign?
YES
ASSIGN FIBER
NO
Catch next CR
Lambda available?
TLP-2 to assign?  ASSIGN LAMBDA
YES
NO
Slots available?
TLP-1 to assign?  ASSIGN SLOT
YES
NO
More CRs?
NO
START
More CNs?
YES
Catch next CN
NO
More CN−EN connections?
YES
Catch next opt. link
Catch next fiber
TLP-3 to assign?
YES
ASSIGN FIBER
NO
Catch next CR
Lambda available?
TLP-2 to assign?  ASSIGN LAMBDA
YES
NO
Slots available?
TLP-1 to assign?  ASSIGN SLOT
YES
NO
More CRs?
NO
END
### WTA resolution algorithm

**One optical link at a time**
- TLP-3s assigned to whole fibers
- TLP-2s and TLP-1s grouped on the base of their CR
  - TLP-2s assigned to contiguous wavelengths
  - TLP-1s assigned to contiguous time-slots

**Diagram:**
```
START

More CNs?
    NO
    END
    YES
    Catch next CN

More CN-EN connections?
    NO
    Catch next opt. link
    YES
    Catch next fiber

TLP-3 to assign?
    NO
    ASSIGN FIBER
    YES

Catch next CR

Lambda available?
    NO
    TLP_Cr^2 to assign?
    NO
    TLP_Cr^1 to assign?
    NO
    ASSIGN SLOT
    YES
    Slots available?
    NO
    ASSIGN LAMBDA
    YES

More CRs?
```
WTA resolution algorithm

One optical link at a time
- TLP-3s assigned to whole fibers
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## RFA results

<table>
<thead>
<tr>
<th>Model</th>
<th>10A</th>
<th>10B</th>
<th>34A</th>
<th>34B</th>
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<td>Objective</td>
<td>2281804</td>
<td>2155353</td>
<td>31995440</td>
<td>42596082</td>
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<tr>
<td>Execution time</td>
<td>169s</td>
<td>100s</td>
<td>12.07h</td>
<td>1685s</td>
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<tr>
<td>Fibers cost</td>
<td>77.8%</td>
<td>83.27%</td>
<td>82.46%</td>
<td>81.27%</td>
</tr>
<tr>
<td>CNs cost</td>
<td>11.22%</td>
<td>11.88%</td>
<td>5.44%</td>
<td>5.26%</td>
</tr>
<tr>
<td>Delays cost</td>
<td>10.98%</td>
<td>4.86%</td>
<td>12.1%</td>
<td>13.47%</td>
</tr>
<tr>
<td>$\mu_R$</td>
<td>17.91%</td>
<td>15.15%</td>
<td>16.83%</td>
<td>12.39%</td>
</tr>
</tbody>
</table>

### Diagrams

**10A**
- Cleveland
- Miami
- Charlotte
- Albany
- New York
- Philadelphia
- Washington
- Tampa

**10B**
- Cleveland
- Miami
- Charlotte
- Albany
- New York
- Philadelphia
- Washington
- Tampa

---

**Model 10A**
- Objective: 2281804
- Execution time: 169s
- Fibers cost: 77.8%
- CNs cost: 11.22%
- Delays cost: 10.98%
- $\mu_R$: 17.91%

**Model 10B**
- Objective: 2155353
- Execution time: 100s
- Fibers cost: 83.27%
- CNs cost: 11.88%
- Delays cost: 4.86%
- $\mu_R$: 15.15%

**Model 34A**
- Objective: 31995440
- Execution time: 12.07h
- Fibers cost: 82.46%
- CNs cost: 5.44%
- Delays cost: 12.1%
- $\mu_R$: 16.83%

**Model 34B**
- Objective: 42596082
- Execution time: 1685s
- Fibers cost: 81.27%
- CNs cost: 5.26%
- Delays cost: 13.47%
- $\mu_R$: 12.39%
## RFA results

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Low utilization!
Results

RFA results

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High fiber cost!
Low utilization!

10A

10B

Low utilization!
A competitive quasi-regular topology

We need to:
1. reduce the network cost
2. improve the network utilization

Observation
- the traffic matrix contains few peaks and a lot of low connection requests
- the regular architecture implies few high used optical links and lots of under-used ones

Quasi-regular topology
- deactivation of the unused fibers in optical links
- regularity preserved and reachable through further upgrades
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The Petaweb
Network design
Open issues
Summary

Quasi-regular topology

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**Benefits**

- Utilization triplicated
- Fiber cost weight decreased of 10p%
- Network cost halved

A Petaweb quasi-regular topology can now compete with mesh topology
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High exec. time! ↓ Repeated Matching

Heuristic
Quasi-regular topology

RFA results with a quasi-regular topology

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New York
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Charlotte
Cleveland
Miami
Boston
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Tampa
Washington

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Outline

1. The Petaweb
   - The architecture
   - Network model
   - Classes of service

2. Petaweb network design
   - Design problem
   - Results
   - Quasi-regular topology

3. Open issues
   - Reliability problem
   - Upgrade problem
Absence of reliability

Optimised 10A quasi-regular

Trunk-line failure

Two possible cases deserve attention in case of one trunk-line failure:

- isolated edge nodes connected through only one trunk (possible for quasi-regular topologies)
- all the edge nodes connected through only one trunk (possible for little topologies)

Only 1 switching site
Absence of reliability

Optimised 10A quasi-regular

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Upgrade problem

Upgrade of an optimised Petaweb

Problem
- the requested traffic volume doubles every 6 to 12 months
- an optimised architecture has the 50% of idle capacity

Question
How to upgrade an existing optimised Petaweb architecture?
Upgrade problem

Upgrade of an optimised Petaweb

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We furnished, for the first time, a tool for the design optimization of a Petaweb architecture. The results are realistic and showed.

Ease in network operation and management
- The 1-hop connection guarantees full access to the available capacity.
- The core node-based architecture offers simple routing, network configuration and operations.

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- The inexpensive quasi-regular topology offers a network around 50% cheaper than a regular one.
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Summary: further works

Open Problems

- straighth optimization of a quasi-regular Petaweb architecture
- comparison mesh - Petaweb quasi-regular topologies
- partial adaptation to an existing infrastructure

Other papers

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Appendix

The Petaweb Architecture
Heuristic
Explanation of core nodes structure

**Figure:** Core node with one switching plane

**Figure:** Core node with two switching planes
Time-Division at switching equipments

**Figure:** Time-division Space Router (Huang, 2000), replacing a switching plane
A repeated matching heuristic

At every iteration:
- calculation of matching costs matrix
- resolution of the matching problem
- solution exploitation $\Rightarrow L_1', L_2', L_3'$
- exit if not decreasing Packing cost

Jonker + Forbes algorithms

Jonker:
$$\min_{V_s} \sum_{i=1}^{n_1+n_2+n_3} c_{i,V_s[i]} \Rightarrow V_s[i]$$

Forbes:
$$V'_s \mid V'_s[i] = j, \land V'_s[j] = i$$
A repeated matching heuristic

Network status: Packing

- $L_1$: disabled core nodes
- $L_2$: unassigned TLPs
- $L_3$: Kits

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Jonker + Forbes algorithms

Jonker: $\min \sum_{i=1}^{n_1+n_2+n_3} c_{i,V[i]} \Rightarrow V_s[i]$  

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Jonker + Forbes algorithms

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## RFA results through an heuristic

### Adapted repeated matching heuristic (Rönnqvist, 1999)

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</tr>
</tbody>
</table>
## RFA results through an heuristic

### Adapted repeated matching heuristic (Rönnqvist, 1999)

<table>
<thead>
<tr>
<th>Model</th>
<th>10A</th>
<th>10B</th>
<th>34A</th>
<th>34B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>2281803</td>
<td>2155353</td>
<td>31990695</td>
<td>42677557</td>
</tr>
<tr>
<td>ILP-optimum gap</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Execution time</td>
<td>1.8s</td>
<td>2.1s</td>
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<td>186s</td>
</tr>
<tr>
<td>Fibers cost</td>
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</tr>
<tr>
<td>CNs cost</td>
<td>11.22%</td>
<td>11.88%</td>
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<td>5.43%</td>
</tr>
<tr>
<td>Delays cost</td>
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<td>12.71%</td>
<td>13.45%</td>
</tr>
<tr>
<td>$\mu_R$</td>
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## RFA results for large networks

**Adapted repeated matching heuristic (Rönnqvist, 1999)**

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<table>
<thead>
<tr>
<th>Model</th>
<th>40B</th>
<th>50B</th>
<th>60B</th>
<th>70B</th>
<th>80B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective</strong></td>
<td>37963706</td>
<td>43210103</td>
<td>55099935</td>
<td>50886627</td>
<td>66910660</td>
</tr>
<tr>
<td><strong>Exec. time</strong></td>
<td>418s</td>
<td>1547s</td>
<td>1945s</td>
<td>4022s</td>
<td>6681s</td>
</tr>
<tr>
<td>$\mu_R$</td>
<td>11.79%</td>
<td>9.9%</td>
<td>8.09%</td>
<td>9.03%</td>
<td>7.22%</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>20.858 Tb/s</td>
<td>21.725 Tb/s</td>
<td>22.908 Tb/s</td>
<td>23.935 Tb/s</td>
<td>25.54 Tb/s</td>
</tr>
</tbody>
</table>

**Quasi-regular**

<table>
<thead>
<tr>
<th>Cost</th>
<th>14559611(-61%)</th>
<th>16150759(-62%)</th>
<th>2190680(-60%)</th>
<th>21718007(-57%)</th>
<th>23367917(-65%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_R$</td>
<td>35.48%</td>
<td>30.65%</td>
<td>22.69%</td>
<td>22.94%</td>
<td>23.44%</td>
</tr>
</tbody>
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# RFA results for large networks

Adapted repeated matching heuristic (Rönnqvist, 1999)

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<thead>
<tr>
<th>Model</th>
<th>90B</th>
<th>100B</th>
<th>110B</th>
<th>120B</th>
<th>130B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>57212363</td>
<td>71277709</td>
<td>67253170</td>
<td>86432202</td>
<td>88164068</td>
</tr>
<tr>
<td>Exec. time</td>
<td>7663s</td>
<td>11347s</td>
<td>5.31h</td>
<td>6.45h</td>
<td>8.01h</td>
</tr>
<tr>
<td>$\mu_R$</td>
<td>8.66%</td>
<td>7.61%</td>
<td>8.74%</td>
<td>7.15%</td>
<td>7.61%</td>
</tr>
<tr>
<td>Capacity</td>
<td>27.13 Tb/s</td>
<td>28.927 Tb/s</td>
<td>30.484 Tb/s</td>
<td>32.683 Tb/s</td>
<td>34.565 Tb/s</td>
</tr>
</tbody>
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Quasi-regular

<table>
<thead>
<tr>
<th>Cost</th>
<th>23955221(-58%)</th>
<th>22309225(-69%)</th>
<th>31493248(-53%)</th>
<th>33031715(-62%)</th>
<th>34770969(-61%)</th>
</tr>
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<tbody>
<tr>
<td>$\mu_R$</td>
<td>23.23%</td>
<td>28.34%</td>
<td>19.93%</td>
<td>20.89%</td>
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