Towards a Power-Efficient Network
--Emphasizing Multi-layer Network Design

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    - ✓ An ILP Formulation
  - IP-WDM Network Design
    - ✓ Principles
    - ✓ An ILP Formulation & a Heuristic
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  - IP-TDM-WDM Network Design
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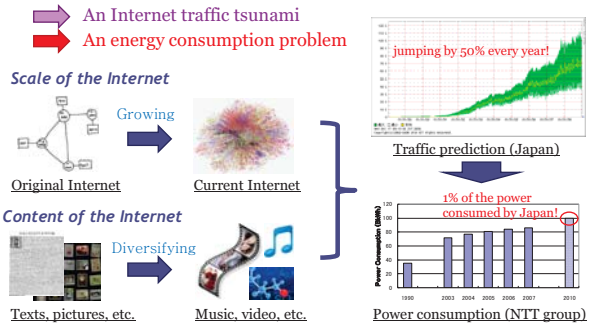
- Conclusion

Power Consumption of the Internet

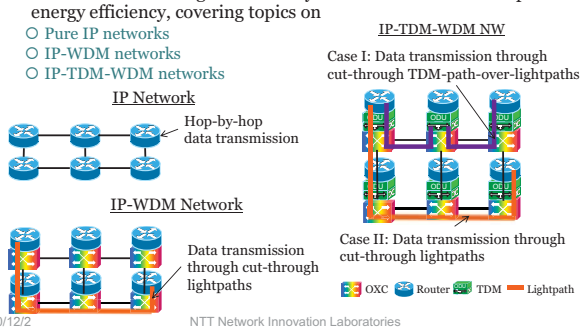
- The number of terminals is dramatically increasing.
- More multimedia services are expected.

⇒ An Internet traffic tsunami
⇒ An energy consumption problem



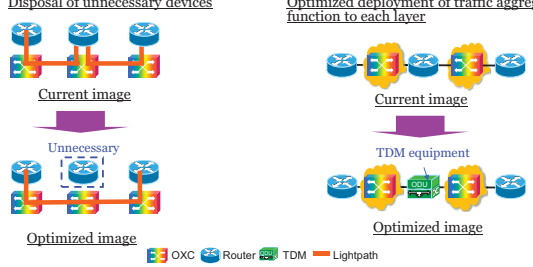
Our Focus

- Simultaneous multi-layer network design, has the potential to maximize the total network efficiency.
- We focus on the design of multi-layer network from the viewpoint of energy efficiency, covering topics on
  - Pure IP networks
  - IP-WDM networks
  - IP-TDM-WDM networks



Design Objectives

- The ideal power-efficient network design must meet the demands of traffic accommodation and QoS, while achieving the following objectives.
  - To employ minimal devices with the lowest specifications
  - To place the most suitable equipment in the most suitable locations



IP Network Design --Principles

- A router chassis has much higher power consumption than a line card, which, in turn, consumes more power than an interface.

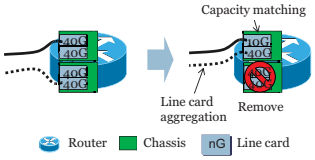
⇒ To aggregate more active line cards into each chassis and aggregate more active interfaces to each line card.

- Different types of chassis/line cards/interfaces have different process capabilities and consume different amounts of power.

⇒ To deploy the most suitable devices while satisfying the expected traffic load.

Typical power consumption of router components

Component	Power consumption
1-port 40G line card	≈80 (w)
1-port 10G line card	≈20 (w)
Chassis	≈250 (w)



IP Network Design --An ILP Formulation

Parameters and their explanation

- NC_i ···the number of chassis equipped at i
- $NL_{i,l}$ ···the number of line cards of type l at i
- P_l ···the power consumption of a line card of type l
- PC ···the power consumption of each chassis
- $T_{i,j}^{s,d}$ ···the traffic volume between s and d routed through link ij
- T_l ···the switching capacity of a line card of type l

Constraints

①The configuration relationship between line cards and chassis

$$NC_i \times NL \geq \sum_l NL_{i,l}, \forall i$$

②The accommodation relationship between line cards and traffic

$$\sum_s \sum_d \sum_j T_{i,j}^{s,d} \leq \sum_l NL_{i,l} \times T_l, \forall i$$

Objective function

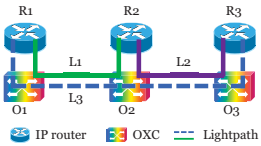
$$MIN \sum_i \left(\underbrace{\sum_l (P_l \times NL_{i,l})}_{\text{Line cards}} + \underbrace{PC \times NC_i}_{\text{Chassis}} \right)$$

IP-WDM Network Design --Principles

- Since optical equipment has not yet completely replaced electronic equipment, the IP-WDM network is seen as a candidate for the power-efficient network.

⇨ To establish as few lightpaths as possible in order to meet the traffic demand.

An optimization problem exists for establishing lightpaths to minimize power consumption.



A new request from R1 to R3 is received...

CASE I: No lightpaths in advance
L3 (cut-through) utilizes 2 interfaces, compared to L1&L2 (hop-by-hop) utilizing 4 interfaces.

CASE II: L1&L2 already established
Aggregating traffic to L1&L2 requires no more interfaces, compared to establishing L3 utilizing 2 more interfaces.

IP-WDM Network Design --An ILP Formulation

Parameters and their explanation

- $F_{i,j}^{m,n}$ ···The number of lightpaths between i and j routed through link mn
- $T_{i,j}^{s,d}$ ···The traffic volume from s to d routed through lightpaths ij
- $V_{i,j}$ ···The number of lightpaths between i and j
- $T^{s,d}$ ···The traffic demand between s and d
- C ···The capacity of each lightpath
- P ···The power consumption of each lightpath
- W ···The number of lightpaths multiplexed in a fiber

Constraints

①The multi-commodity equations for lightpath routing

$$\sum_m F_{i,j}^{m,k} = \sum_n F_{i,j}^{k,n}, k \neq i,j, \forall i,j,k \qquad \sum_{i,j} F_{i,j}^{m,n} \leq W, \forall m,n$$

②The multi-commodity equations for traffic routing

$$\sum_j T_{i,j}^{s,d} = \sum_m T_{i,k}^{s,d}, i \neq s,d, \forall i,s,d \qquad \sum_{s,d} T_{i,j}^{s,d} \leq V_{i,j} \times C, \forall i,j$$

Objective function

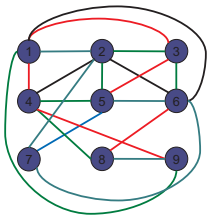
$$MIN \sum \sum_{i,j} \underbrace{V_{i,j}}_{\text{Lightpaths}} \times P$$

IP-WDM Network Design --A Heuristic

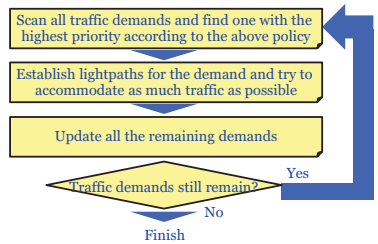
- The ILP formulation is only suitable for small networks due to its NP-complete feature, so in practice, a heuristic approach is necessary.

⇨ To introduce a policy that the traffic demand whose corresponding lightpath establishment accommodates the most traffic should be met first.

Complexity of the problem

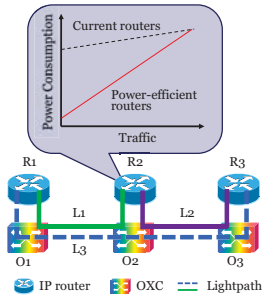


Flow chart of the proposed heuristic



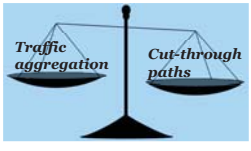
Introducing Power-Efficient Routers

- For power-efficient routers, a new parameter pertaining to the electronically processed traffic volume should be added to the objective function in addition to the interface number.



A new request from R1 to R3 is received...

CASE III: L1&L2 already established
Aggregating traffic to L1&L2 requires an additional electronic process in R2 (intermediate router) compared to establishing L3 (cut-through) which requires 2 more interfaces

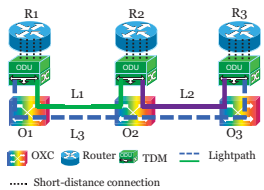


IP-TDM-WDM Network Design --Current Deployment Image

- Some facts may prevent the simple IP-WDM networks from prevailing.
  - The power consumption of high-end routers will remain high, processing traffic in units of single packets.
  - The capacity of optical transmission is increasing dramatically.

⇨ To introduce TDM-XCs may resolve this dilemma!

An IP-TDM-WDM network (full-deployment case)



IP-WDM Vs. IP-TDM-WDM

NW	Traffic	Power
IP-WDM	Packets/LSPs	Router IF
IP-TDM-WDM	Time slot	Router IF + TDM IF

It is hard to judge which architecture is more power efficient...

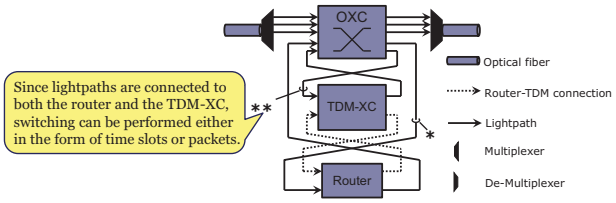
On one hand
①The coarse-granularity switching ⇨ Power ↓

On the other hand
①Low lightpath utilization
②Transformation between IP and TDM ⇨ Power ↑

IP-TDM-WDM Network Design --Partial Deployment of TDM-XCs

- To take the advantage of both packet switching and time-slot switching, one mechanism selectively switches traffic using either the router or TDM-XC.

The proposed node architecture



IP-TDM-WDM Network Design --An ILP Formulation (1/2)

Parameters and their explanation

Lightpath-related

IP-related

- $F_{i,j}^{m,n}$ ···The number of lightpaths between i and j routed through link mn
- $V_{i,j}$ ···The number of lightpaths between i and j
- C ···The capacity of each lightpath
- $T_{i,j}^{s,d}$ ···The traffic volume from s to d routed through lightpaths ij
- $T^{s,d}$ ···The IP traffic demand between s and d
- P_c ···The power consumption of a router interface of capacity c

TDM-related

- $P_{i,j}^{m,n}$ ···TDM's counterpart to the time slot traffic
- $U_{i,j}$ ···TDM's counterpart to the time slot traffic
- g ···TDM's grooming ratio
- $S_{i,j}^{s,d}$ ···TDM's counterpart to the time slot traffic
- $S^{s,d}$ ···The TDM traffic demand between s and d
- P_g ···The power consumption of a TDM interface of grooming ratio g

Power-related Traffic-related

Common

- $\Lambda_{s,d}$ ··· The total traffic demand from s to d
- W ··· The number of lightpaths multiplexed in a fiber
- P_d ···The power consumption of a router-TDM connection with capacity d

IP-TDM-WDM Network Design --An ILP Formulation (2/2)

Constraints

IP-related

①The multi-commodity equations that account for the routing of a lightpath for IP traffic

$$\sum_m F_{i,j}^{m,k} = \sum_n F_{i,j}^{k,n}, k \neq i, j; \forall i, j, k$$

②The multi-commodity equations that account for the routing of IP traffic

$$\sum_j T_{i,d}^{i,j} = \sum_j T_{s,d}^{j,i}, i \neq s, d; \forall s, d, i$$

$$\sum_{s,d} T_{s,d}^{i,j} \leq V_{i,j} \times C, \forall i, j$$

TDM-related

① TDM's counterpart to the time slot traffic

$$\sum_m P_{i,j}^{m,k} = \sum_n P_{i,j}^{k,n}, k \neq i, j; \forall i, j, k$$

② TDM's counterpart to the time slot traffic

$$\sum_j S_{i,d}^{i,j} = \sum_j S_{s,d}^{j,i}, i \neq s, d; \forall s, d, i$$

$$\sum_{s,d} S_{s,d}^{i,j} \leq U_{i,j} \times g, \forall i, j$$

Common

Constraints on the number of lightpaths within a fiber

$$\sum_j \left(F_{i,j}^{m,n} + F_{i,j}^{n,m}\right) \leq W, \forall m, n$$

TDM traffic IP Traffic Total Traffic

$$\Lambda^{s,d} \leq S^{s,d} \times \frac{C}{g} \leq T^{s,d}, \forall s, d$$

Objective function

$$Min \sum_{i,j} \left(U_{i,j} \times P_g + V_{i,j} \times P_c\right) + \sum_{s,d} \frac{\Lambda^{s,d} - T^{s,d}}{d} \times d$$

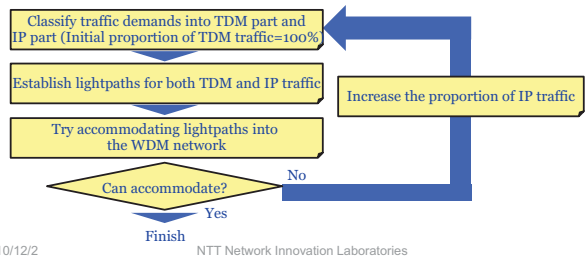
TDM IP Transformation between IP and TDM

IP-TDM-WDM Network Design --A Heuristic

- A heuristic has also been proposed to address this issue.

To initially assume that all traffic is in the form of time slots and then increase the proportion of IP traffic gradually until all the lightpaths can be accommodated.

Flow chart of the proposed heuristic



Evaluation --Environment

- In order to evaluate the power-saving effect, we conduct an evaluation based on the 13-node 15-link SINET3 topology.

Traffic

Parameters	Values
End-to-end traffic	Random number between 0 and T_{max} that increases in increments of 2.5G

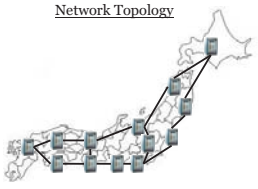
IP layer

Parameters	Values
Power consumption of a router interface (40Gbps)	1000W
Power consumption of a router interface (2.5Gbps)	60W

TDM layer

Parameters	Values
Grooming ratio	4
Power consumption of a TDM interface (g=4)	80W

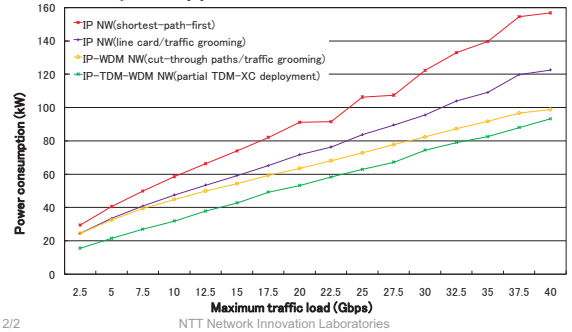
Network Topology



Parameters	Values
Lightpath number multiplexed in a fiber	16
Lightpath capacity	40Gbps
Power consumption of a transponder (40Gbps)	80W

Evaluation --Result & Discussion

- When the maximum traffic load reaches 40Gbps, we witness the great power conservation of approximately 60%, which equals to a saving of 10,000,000 yen every year.



Conclusion and Future Work

- Contributions
  - We discussed the popular topic of network power efficiency, focusing on the potential power savings achievable through multi-layer network design.
- Results
  - We see good potential for significant power savings, even though many challenges still remain.
- Future work
  - To study the important factors such as transmission delay and maintenance cost

We believe that this paper is the first step towards a power-efficient network!

Thank You!