Differential Delay Compensation Techniques for Multipath Routing in Optical Networks

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Outline

• Introduction
• Related Works
• Main contributions
• Optimization Models
• Numerical Results
• Conclusion
INTRODUCTION (I)

Problem

• Popular Services: Video on Demand (VoD), online gaming, multimedia contents, inter-data centers communications
  • High Bandwidth and QoS

• Challenge for capacity limited network

• Traffic carried over optical networks is increasing.

Current situation

• Today’s networks provide Multiple Path (MP)

• But legacy protocols prevents its exploitation (shortest path-based)

Solution

• Multipath (MP) routing + Differential delay compensation (DDC)
INTRODUCTION (II)

MP Routing

Advantages

- More bandwidth, Resource utilization efficiency, Load balancing, and with disjointness: reliability and protection

Disadvantages:

- Differential Delay (DD): Maximum delay difference between the MP set.
  - Large DD increases: packet reordering, buffer sizes, buffer overflow & complexity of nodes
RELATED WORKS (I)

How to Minimize DD in MP routing?

1. To find paths with similar delay [1][2]
   - Differential Delay Routing (DDR) problem [1]
     - VCAT – SDH, Ethernet/SONET networks
     - Find $K$ paths of unit capacity from source $S$ to destination $T$ such that their differential delay $DD$ is upper bounded by a given constant $\Delta$
   - NP-Hard [2]
   - Disjointness was not considered
   - Disjoint Differential Delay Routing Problem [3]
     - Transparent optical network.

Drawbacks:
   - It is limited by network topology
   - The size of centralized buffers

How to minimize DD in MP routing?

2. To use differential delay compensation techniques (DDC)
   - Distributed electronic buffers for VCAT [4]
   - Controlled routing cycles for transparent optical networks [3]

Main contributions

DDC techniques for MP routing in Transparent and translucent Optical Netw.

1. Jointly place electronic-DDC (buffers) and Optical Regeneration
   - Reduce Optical-Electrical (OE) conversion

2. Include Fiber Delay Lines (FDL) in the DDC process
   - Transparent device
   - Discrete delay: multiple of Module length \(G\)

3. Optimization model

![Diagram showing electronic buffers, Fiber Delay Line (FDL), and Regeneration nodes.]

R. Alvizu, DDC for MP routing, INW January 13° 2016
Optimization Models (I)

“Find link-disjoint MP sets for all demands \( d \in D \) in an optical network represented by the bi-directed graph \( G(V,E) \)”

• Such that each MP set realizing demand \( d \in D \) complies with:
  • Given upper bound on DD (\( \Delta_d \))
  • Requested Bandwidth volume \( h_d \) (normalized as the number of required wavelengths)

Multi-objective optimization problem:
1. Minimize the path delay: Propagation + DDC
2. Minimize the use of electronic buffer for DDC
3. Minimize the use of OE conversions

Based on DDC techniques
• Transparent-DDC: FDLs
• Electronic-DDC: Jointly with Optical Regeneration
## Optimization Models (II)

<table>
<thead>
<tr>
<th>Models</th>
<th>Electronic-DDC (Buffer)</th>
<th>Transparent-DDC (FDL)</th>
<th>WCC</th>
<th>Regeneration placement</th>
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<tbody>
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<td>C</td>
<td>D</td>
<td>CR</td>
<td>Discrete</td>
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</table>

C: Centralized  
D: Distributed  
CR (*): Continuous Relaxation of FDLs  
WCC: Wavelength Continuity Constraint
Optimization Models (III): FDL-RDBuff

\[
\min \sum_{d \in D} \sum_{p \in P_d} (\sigma_{dp} x_{dp} + T_{dp} + \alpha B_{dp} + \Omega \gamma_{dp})
\]  

(1a)

- \(\sigma_{dp} x_{dp}\): Propagation delay per path \(p \in P_d\) and demand \(d \in D\)

- \(T_{dp}\): Transparent-DDC (using FDLs) per path \(p \in P_d\) and demand \(d \in D\)

- \(\alpha B_{dp}\): Electronic-DDC (using buffers) per path \(p \in P_d\) and demand \(d \in D\)
  - \(\alpha > 0\)

- \(\Omega \gamma_{dp}\): Maximum electronic DDC
  - \(\Omega < 0\)

R. Alvizu, DDC for MP routing, INW January 13° 2016
Optimization Models (III): FDL-RDBuff

\[ \sum_{p \in \mathcal{P}_d} x_{dp} = h_d, \quad d \in \mathcal{D} \]

\[ \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}_d} \delta_{edp} x_{dp} \leq WF_e, \quad e \in \mathcal{E} \]

\[ x_{dp} \sigma_{dp} \leq \sigma_{d}^{\text{max}}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d \]

\[ \sigma_{d}^{\text{max}} - x_{dp} \sigma_{dp} - T_{dp} - B_{dp} - \phi_{d} (1 - x_{dp}) \leq \Delta_{d}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d \]

\[ g_{edp} G \leq \psi, \quad d \in \mathcal{D}, p \in \mathcal{P}_d, e \in \mathcal{E} \]

\[ x_{dp} \omega_{sdp} + \sum_{e \in \mathcal{E}} \Pi_{sedp} g_{edp} \leq L (1 + \sum_{v \in \mathcal{V}} \Gamma_{svdp} R_{vdp}) \]

\[ b_{vdp} \leq \sum_{s \in \mathcal{S}} \phi_{d} \Gamma_{svdp} R_{vdp}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d, s \in \mathcal{S} \]

\[ b_{vdp} \leq \gamma_{dp}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d, v \in \mathcal{V} \]

\[ \sum_{v \in \mathcal{V}} b_{vdp} = B_{dp}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d \]

\[ \sum_{e \in \mathcal{E}} \delta_{edp} g_{edp} G = T_{dp}, \quad d \in \mathcal{D}, p \in \mathcal{P}_d \]

\[ x_{dp}, R_{vdp} \in \text{binary}, \quad b_{vdp}, B_{dp}, g_{edp}, T_{dp} \in R^+, \quad g_{edp} \in Z^+ \]

Solenoidality C.
Capacity C.
Differential. Delay C.
FDL length C.
Optical Regeneration Placement C.
Electronic-DDC placement C.
Results

• Real topologies that were used to test the proposed models:

**Polish**
- Short Network:
  - Average Link length 189.16 Km
  - Nodes: 12
  - Links: 18

**NSFNET**
- Large Network:
  - Average Link Length 1299.04 Km
  - Nodes: 14
  - Links: 21
Results – Impact of FDLs’ Discrete nature

\[
\Delta_d = 0, \quad d \in D
\]
for \( G=1:1:200 \)

\[
FDL-\text{RDBuff}(G, DD, Net)
\]

end
Results – Impact of FDLs in Electronic-DDC (Buffer size)

- CBuff: Centralized Buffer
- DBuff: Distributed Buffer
- RDBuff: Distributed Buff with regeneration

Polish

- NSFNET

- 10% of All Demands
- 30% of all demands
- 50% of all demands
Results – Transparent DDC (FDL size)

![Bar chart showing the total transparent DDC (FDL size) for various network topologies and demand percentages.](image)

- FDL-CBuff
- FDL-DBuff
- FDL-CBuff (Polish)
- FDL-RDBuff (NSFNET)

Legend:
- □ 10 % of All Demands
- □ 30 % of all demands
- □ 50 % of all demands
Conclusions

1. The discrete nature of FDLs is a negligible drawback.

2. When applying distributed DDC for MP routing FDLs successfully allow to:
   • Reduce size of electronic buffers by more than 70% compared to benchmark
   • For transparent optical networks FDLs reduce the use of OE conversions

3. The best approach for electronic-DDC depends on the network size:
   • Small network: FDL-CBuff
   • Large network: FDL-RDBuff
Grazie

Gracias

Thanks

Questions?
Elastic networks: modulation-format (MF) vs. symbol-rate (SR) adaptation

In a metro network both modulation-format and symbol-rate adaptation can be exploited with no intermediate regeneration.

**MF adaptation**

- 25Gb/s
- 50Gb/s
- 75Gb/s
- 100Gb/s

**SR adaptation**

- 25Gb/s
- 50Gb/s
- 75Gb/s
- 100Gb/s

Elastic networks: variable Data-rate, how to?

- Elastic TXPs considered in this study are based on 100G PDM-QPSK OE-device, that can be tuned elastic as:
  - Modulation format adaptation (*MF or ELASTIC*):
    - symbol rate is kept fixed, modulation variation -> data-rate variation;
  - Symbol-rate adaptation (*SR*):
    - modulation is kept fixed, symbol rate variation -> data-rate variation.

- Optical reach is “independent” of the symbol-rate and equal to 1200km;
  - By lowering the data-rate no regenerator bypass is done.

- Optical reach is highly dependent on the modulation format used;
  - By lowering the data-rate we are able to reduce 3R regenerations.