Routing and Resilience in AWG Based WDM Networks

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Contents

- Arrayed Waveguide Gratings
- Classification of AWG based networks
  - Single Hop Networks
  - Multihop networks
- Failure types in AWG-based networks
- Protection in Single Hop networks
  - Homogeneous protection
  - Heterogeneous protection
- Protection in Multihop networks
- Routing in Multihop networks
  - How advantageous is wavelength conversion?
  - Cayley graphs for network construction and routing
Arrayed Waveguide Grating based networks

- We are considering a physical star topology
  - AWG instead of a Passive Star Coupler
- Spatial wavelength reuse
  - Use the same wavelength N times in an NxN AWG
  - No sender collisions (receiver collisions possible)
- Passive wavelength router
  - AWG is robust and can be made athermal
  - Inexpensive OAM
  - Distributed control and management of the network
Classification of AWG Based Networks

Single-hop networks

- Route = AWG output port
- Routing is done by means of $\lambda$ tuning
- Tx and Rx tunable
Resilience: Failure Types

- Failure can be at node, fiber, and hub (AWG) level
- AWG represents a **single point of failure**:  
  - In case of AWG failure **entire connectivity is lost**
  - Holds not only for **single-hop networks** but also for all **logical multihop topologies** embedded on a physical AWG based star network
  
  ⇒ **Protection needed**
- Link and node failures have only **local effect**
Resilience in Single-Hop Networks: Protection Types

Homogeneous protection
• Backup system is a **copy** of the working system
• **Conventional** schemes:
  • 1+1
  • 1:1
  • 1:N

Heterogeneous Protection
• Backup system **differs** from the working system
• **AWG** works in parallel to a passive star coupler (PSC)
• Combining respective strengths of both devices
Heterogeneous Protection

- During normal operation both AWG and PSC are used for communications
- Rationale:
  - **Broadcast** control, **multicast** data, and „overflow“ **unicast** data is sent over PSC
  - **Unicast** data is sent over AWG benefitting from **continuous** spatial wavelength reuse
  - **Mutual** protection of AWG and PSC
- Each node has 2 transceivers attached to AWG and PSC via two pairs of fibers ⇒ Node and fiber protection
Classification of AWG Based Networks (cont.)

Multihop networks

- Route = multiple passing the AWG
- Each node equipped with a 2 x 2 space switch per wavelength
Classification of AWG Based Networks (cont.)

- **PrimeNet** - A special kind of multihopping
  - Number of input ports of the AWG has to be prime
  - Number of rings between 1 and (N-1)
  - All nodes connected to all rings
  - No wavelength conversion in the nodes
    - A packet stays on the ring until it reaches its destination
- **Other multihop architectures are possible**
  - Spatial wavelength reuse reduces total number of wavelengths
    - E.g. (2,2) ShuffleNet uses 5 wavelengths instead of 16 in a PSC
  - Band limited amplifiers support a larger number of nodes
Protection in Multihop Networks

- AWG protection could be 1+1 or 1:1
  - Homogeneous protection
  - Heterogeneous protection using Cayley graphs follows
- Node or link failure
  - All rings affected, but the position of the failed node is different in each ring
  - Different mechanisms
- Unidirectional ring
  - “Bridge” the failed node
    - Outband signalling required!
    - Neighboring working nodes tune to the wavelength 
      \( (2\lambda) \mod N \)
      - Relatively slow tunable devices can be used 
        (tuning time < 50 ms)
Protection in Multihop Networks (cont.)

- **Bidirectional ring**
  - No LOS alarm possible (because there is no continuous signal in optical packet switching)
    - Timeout for SRP usage packets
  - Either re-routing similar to RPR
  - Or re-tuning when Rx/Tx are (slowly) tunable
    - If the next wavelength is not already in use
Routing in Multihop Networks (here: PrimeNet)

- Routing depends on the capability of the nodes
  - Nodes w/ or w/o wavelength conversion
    - Wavelength conversion means to receive and reroute
  - Example: 2 rings (=wavelengths), Diameter $\Delta$
    - Without wavelength conversion: (bi-directional)
      - $N/2$
    - With wavelength conversion: (FLBH rings)
      - Forward loop (+1 node), backward hop (-a nodes)
      - $\Delta = \lceil N/(a+1) \rceil + (a-1)$ for $1 \leq a \leq \sqrt{N}$
      - Which is smaller for all $a > 1$
Routing in Multihop Networks (here: PrimeNet)

- Mean hop distance w/ and w/o wavelength conversion
Routing in Multihop Networks (here: PrimeNet)

- Does it pay off?
  - Quotient of total network capacities w/ and w/o conv.
  - Assuming a uniform load distribution
Routing in Multihop Networks (here: PrimeNet)

- What happens if the AWG breaks (or my fibre)?
  - Or: interconnecting PrimeNets
- Cayley graphs
  - Highly regular structures based on permutation groups, introduced 1986
  - A Cayley graph $G=(V,G)$ with vertex set $V$ and generator set $G$
  - Two vertices (nodes) $v_1$ and $v_2$ are adjacent if $v_2 = v_1 * g$
  - Example:
    - $g_1 = 312$
    - $g_2 = 213$
Why Cayley Graphs?

- The AWG itself makes up a Cayley graph
  - Example: A 5x5 AWG can be represented as a cyclic permutation generator for each wavelength:
    - g1=51234
    - g2=45123
    - g3=34512
    - g4=23451
    - g5=12345 (this one maps the same wavelength from input to output)

- Hierarchical Cayley graphs show maximum fault tolerance (d-1)

- Every Cayley graph is vertex-symmetric (balanced load over all links, unlike other multihop networks like deBruijn, Kautz)
Routing in Cayley Graphs

- Routing has to be done once for all packets.
  - Set of generators has to be closed under inverses (\(g_1\) and \(g_1^{-1}\) have to be in the generator set)
- Packet from \(n_1\) to \(n_2\) takes the same route through the graph as a packet from \((n_2)^{-1} \cdot n_1\) to \(e\) (identity).
- Routing steps:
  - Transform myself using the inverse of the destination node
  - Either sort the permutation using the available generators or
  - build routing tree with the identity element as root of the tree and find myself in there

\[\begin{align*}
g_1 &= 21534 \\
g_2 &= 21453 \\
n_1 &= 12453 \\
n_2 &= 12534 \\
n_2^{-1} \cdot n_1 &= 12453 \cdot 12453 = 12534
\end{align*}\]
Conclusions

- Networks based on AWG offer increased capacity due to spatial wavelength reuse
- However, AWG is single point of failure
  - Protection can be done in single hop networks
    - Homogeneous
      - Copy of the working system
    - Heterogeneous
      - Use PSC to protect AWG and vice versa
      - Separate unicast/multicast traffic in normal operation
  - Protection in multihop systems by re-routing or re-tuning
- Routing in multihop networks depends on node structure
  - Wavelength continuity constraint costs most capacity for low number of rings and large number of nodes
- Using Cayley graphs for network construction guarantees maximum fault tolerance and fast routing