Availability of Optical Network with Self-Healing Nodes Designed by Architecture on Demand

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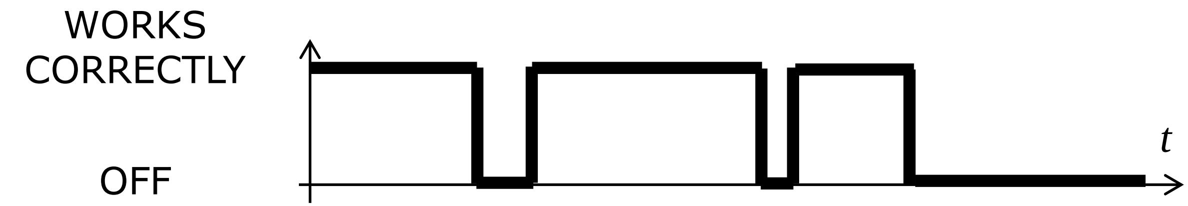
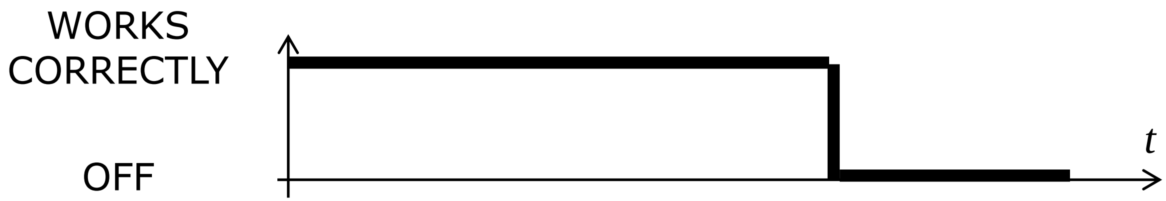
RELIABILITY
AVAILABILITY
SECURITY

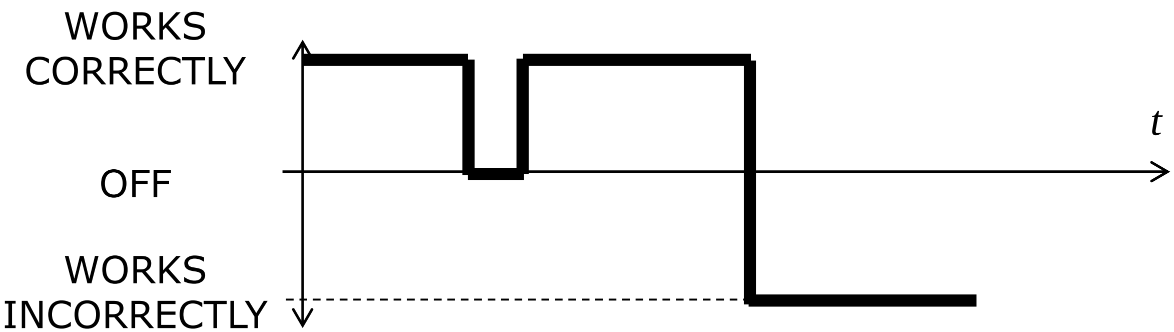
What kind of quality do we expect from a system?



to work correctly required time, tolarating failures



to work correctly required time without failure



to work correctly or to be in idle secure state in required time

Internet

Train

Computer

Aircraft

Elevator

Traffic lights

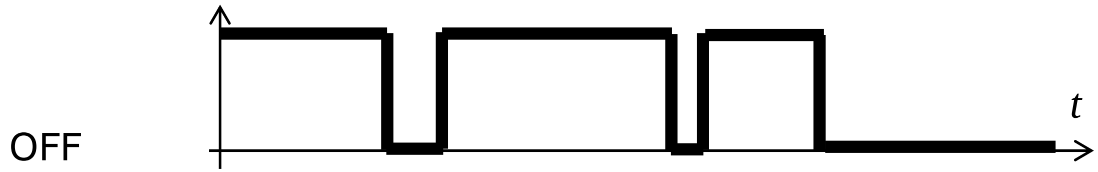
Pace maker

Internet

Computer

Money transfer

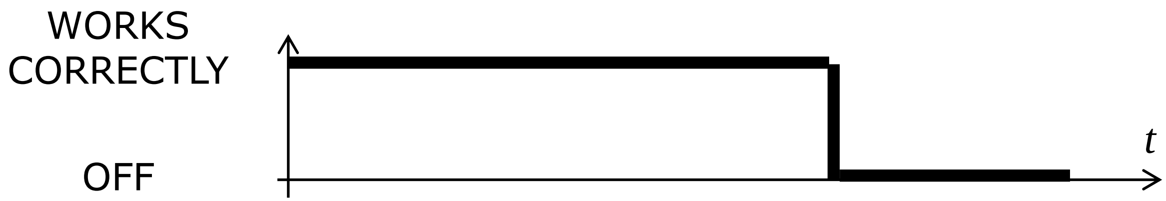
What kind of quality do you expect from a system? (2)



to work correctly required time, tolarating failures

Internet

Computer



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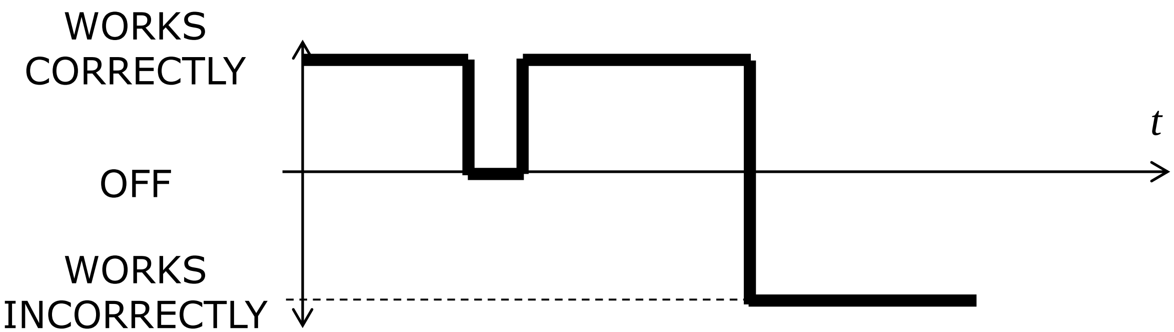


to work correctly or to be in idle secure state in required time

Elevator

Train

Traffic lights

Money transfer

Reliability / Availability / Security

- System **reliability** $R(t)$ is the probability that the system works correctly in the period of time t under defined environmental conditions.

- System **availability** $A(t)$ is the probability that the system works correctly at the time point t.

- System **security** (**safety**) $S(t)$ is the probability that the system works correctly or does not work at all in the period of time t under defined environmental conditions.

Why Survivability?

- Large volume of traffic is carried over transmission networks
- Loss of service means loss of income:
  - Direct losses, service cannot be charged
  - Indirect losses
    - Penalties – "***SLA*** not fulfilled"
    - Loss of clients

    - ***SLA*** *– Service Level Agreement*

Availability – **proper quality measure** in communications?

Availability → Is it proper quality measure for ***communication systems and networks****?*

The most important question:
What are the **consequences** of an **outage** of a communication system or network?

→ loss of money for operator and some troubles for subscribers → **but not a catastrophic event**.

- ***Low*** availability → **high** traffic losses
- ***High*** availability → **low** traffic losses, but **high** development, manufacturing and spare capacity costs.
- ***Optimal*** availability → **compromise** of quality and cost

For special communication services → other requirements could be specified (i.e. real time remote control (*R*) or money transfer (*S*).

An example: Availability of optical transport system?

Example: **1** optical cable/**24** fibres/**32** λ per fibre, **60%** utilization

Single wavelength (λ) (**40** Gbit/s): SDH transport network

1×STM-**256** = **256** STM-1 **= 256**×**63** E_1 =

= **256**×**63**×**30** E_0 **= 483,840 ch**/λ (E_0=**64** kbit/s)

Assuming channel (E_0) interconnection price: C_{ch}= **0.01 €/ch/min**

1 minute of a wavelength (λ) unavailability (***LOR****per ***min*** per λ)

$\boldsymbol{LOR_{min/\lambda}}$ **=483,840×0.01 ≈ 5,000 €/min/λ**

For entire cable: ×24×32×0.6 = 2,229,534.72 ≈

$\boldsymbol{LOR_{min/cable}}$ **≈ 2 M€/min/cable**

Availability of ***A***=**0.99999** (**unavailability** ***U***=$\mathbf{10^{-5}}$) amounts

MDT**=**5.256 min/year** (service unavailability per year)

$\mathbf{LOR_{year/cable}}$ = **11,718,434.49 € ≈ 12 M€/year/cable**

LOR* – Loss of Revenue

MDT** – Mean Down Time, (***MDT*** = ***U***×**525,600 min/year)**

RELIABILITY & AVAILABILITY OF COMMUNICATION NETWORK

Definitions of communication network availability

$A_{s,t}$ ***s,t*–availability** the most common measure: "**communication network availability**" (non-linear measure)

***s,t*-availability** of communication network is the worst node pair (s, t) availability among all pairs of nodes.

A_g ***g*–availability** probability that all n nodes in a network are connected (k=n)

$A_{i,j}$ *i,j*–availability node pair (i, j) availability (**basic measure**)

A_{av} *av*–availability average availability (**linear measure**)

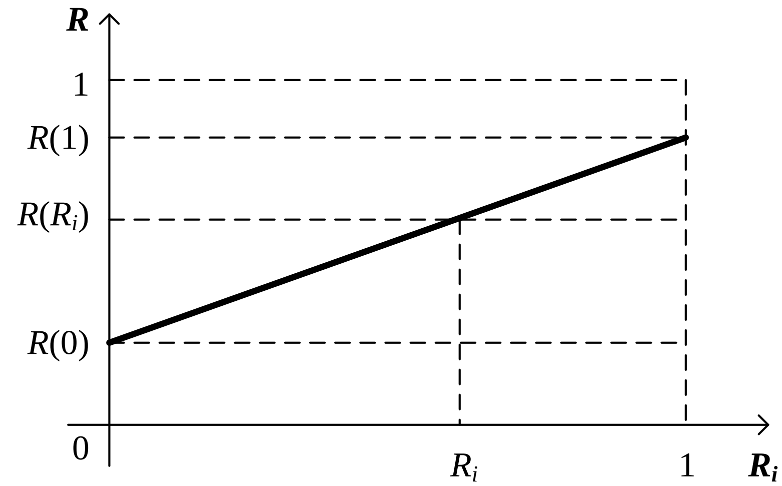
A_k *k*–availability probability that k nodes in a network are connected (if k=2 $\rightarrow$ *s,t*-availability) (**the most general measure**)

Reliability sensitivity

Taylor's formula

$$R(R+\Delta R_i) = R(R_i) + \frac{dR}{dR_i}\Delta Ri + \frac{1}{2}\frac{d^2R}{dR_i^2}\Delta R_i^2 + \cdots$$

Each complex reliability function is linear function of a single element reliability.



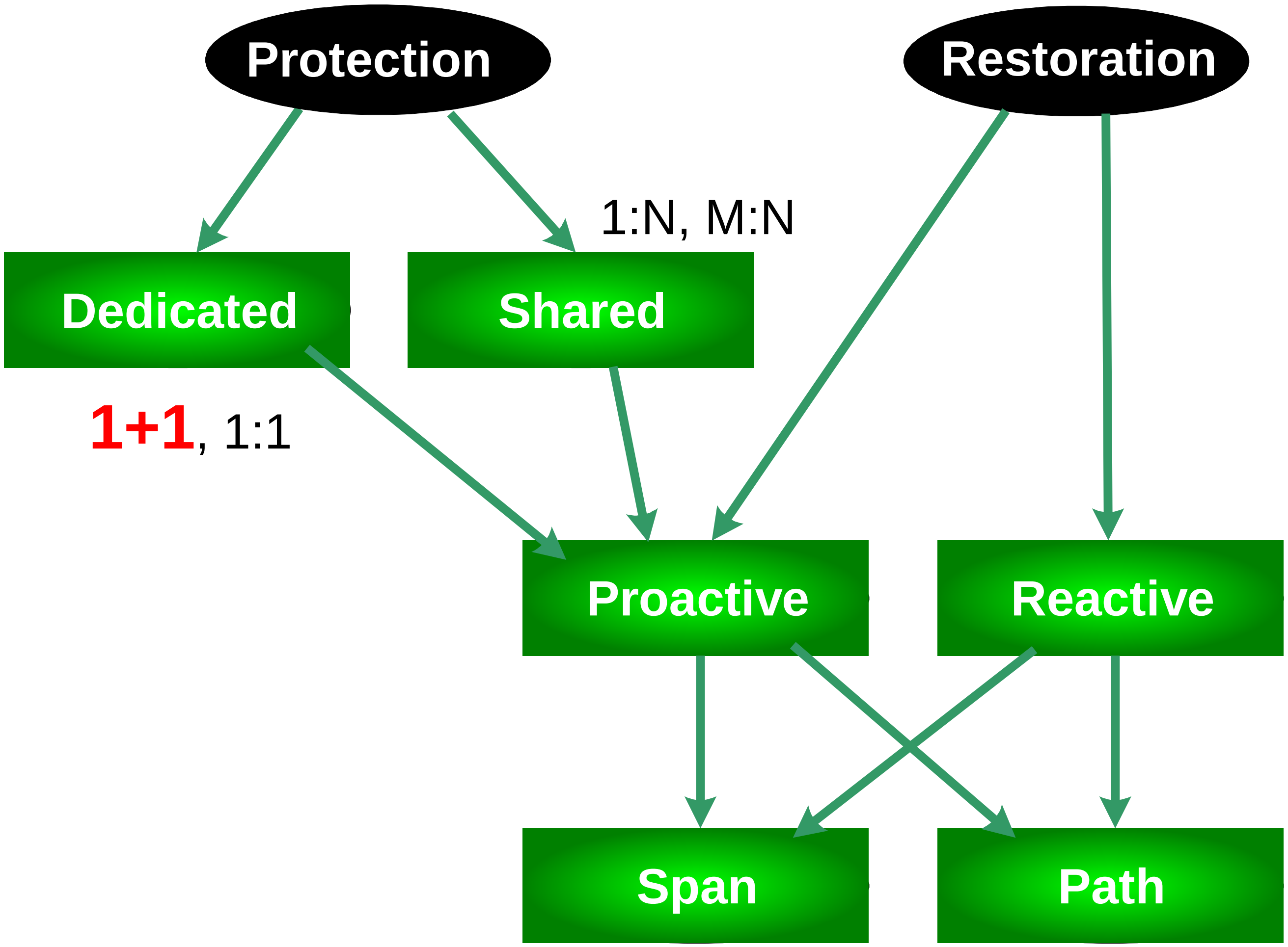
$$R = SiRi + K \qquad \frac{dR}{dR_i} = S_i$$

$$R(R+\Delta R_i) = R(R_i) + S_i\Delta Ri$$

Reliability sensitivity S_i on changes of reliability R_i of the component i:

$$S_i = \frac{dR}{dR_i} = \frac{\Delta R}{\Delta R_i} = \frac{R(R_i)-R(0)}{R_i} = \frac{R(1)-R(R_i)}{1-R_i} = \frac{R(1)-R(0)}{1-0} = R(1)-R(0)$$

Protection & restoration scenarios



Case study:
Availability of Optical Network with Self-Healing Nodes Designed by Architecture on Demand

Can be Architecture on Demand Nodes Used to Improve Availability of Optical Networks?

Joint project of
University of Zagreb and University of Bristol

Hard-wired optical nodes

Hard-wired (HW) optical node architectures

- Low level of architectural flexibility and scalability.
- Unnecessary components in the chain ➡ lower availability

Recovery after any node component failure is possible only on the network level

- there is a need for **number of protocol steps**
- switchover time in the range of **seconds**.

Architecture on Demand (AoD) in optical nodes

Usage of **additional switching elements**

(e.g. mirrors in 3D MEMS or collimator arrays in piezo electric switch)

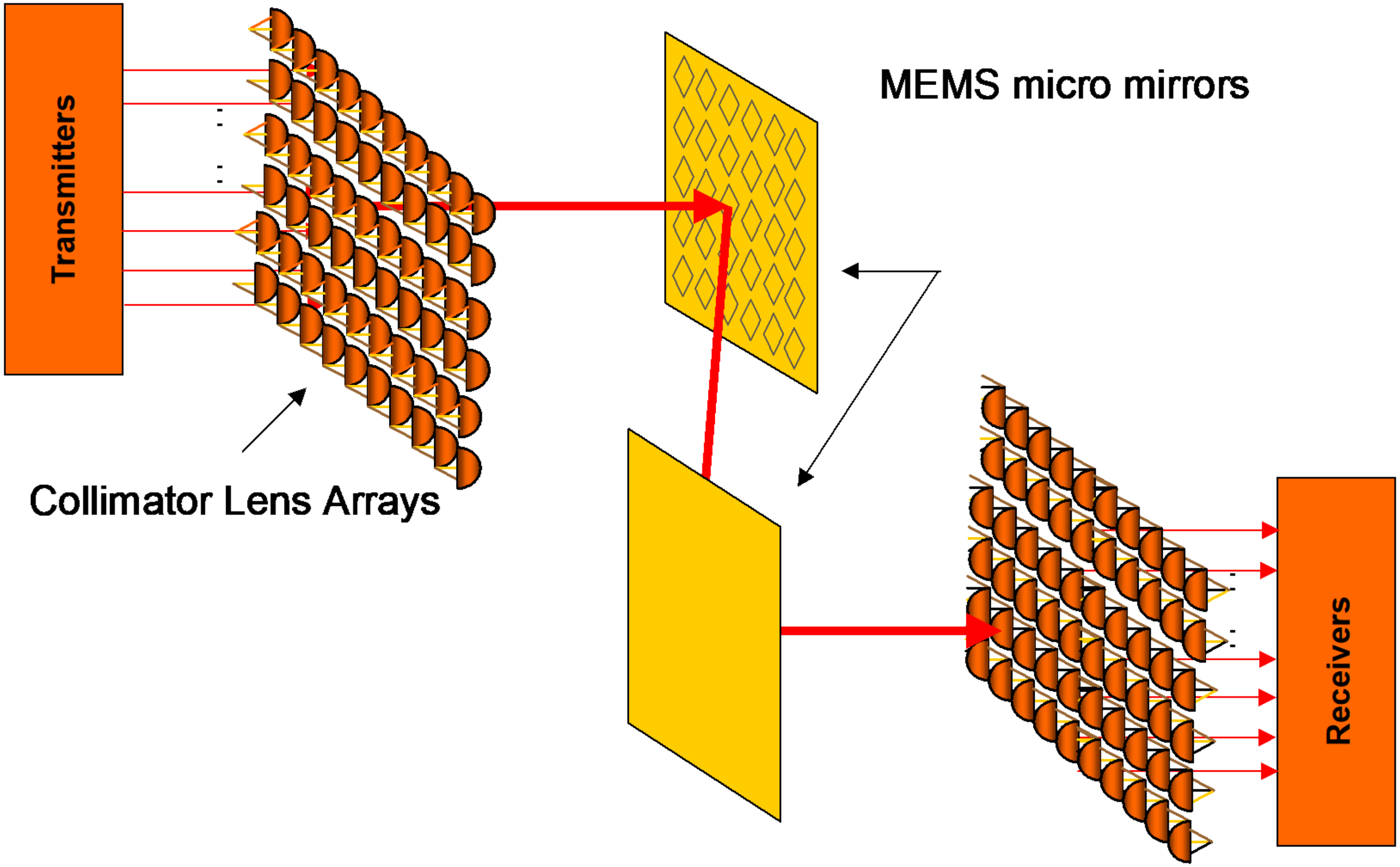
Disadventage:

- ⬇ Additional switches ➡ **higher node cost** ➡ **lower availability**

Adventages:

- ⬆ **arbitrary interconnection** of optical components
- ⬆ **additional functionality**
- ⬆ **different switching granularities**, *fibre*, *waveband*, *wavelength* and *sub-wavelength* (time)

3D MEMS



Transmitters
MEMS micro mirrors
Collimator Lens Arrays
Receivers

Additional adventage: Self-healing in AoD nodes

Self-healing after a failure of AoD node component is based on switchover to the **node redundancy**:

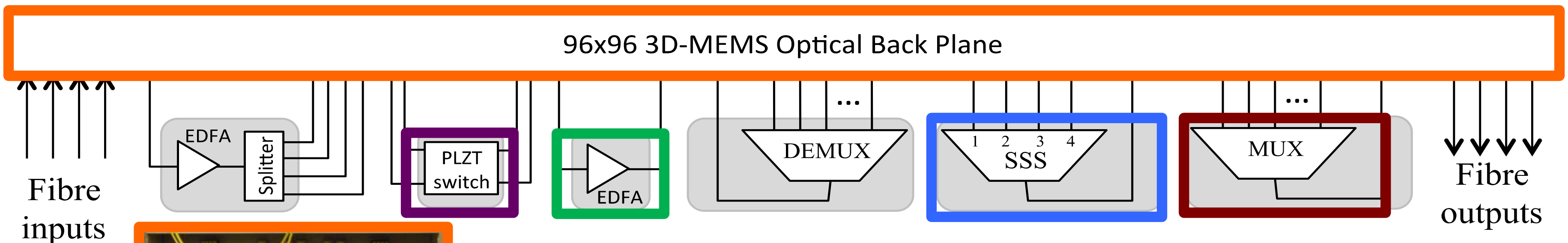
- **intentionally added for survivability enhancement**
- **created by releasing unused components**
  - At lower traffic load in a node ➨ surplus of components are released and used as **redundant**
  - By grouping of wavelength or waveband paths into **fibre-switched paths** ➨ node components are released and used as **redundant**.

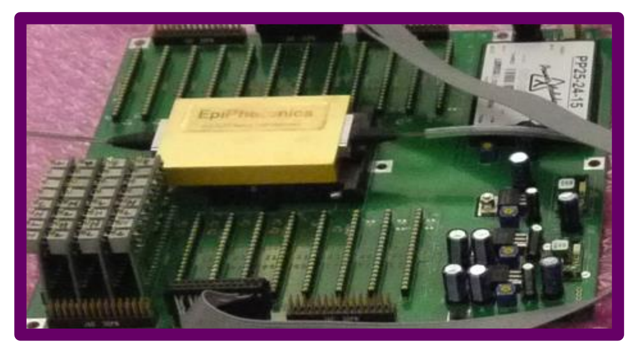
Basic question: If the redundancy + self-healing ➨ ➨ higher availability?

Architecture on Demand (AoD) experiment

University of BRISTOL
highperformancenetworks group

- Backplane provides connectivity and reconfiguration
- Modules provide required functionality, e.g. **amplification**, **spectral demultiplexing**, **subwavelength switching**, etc.





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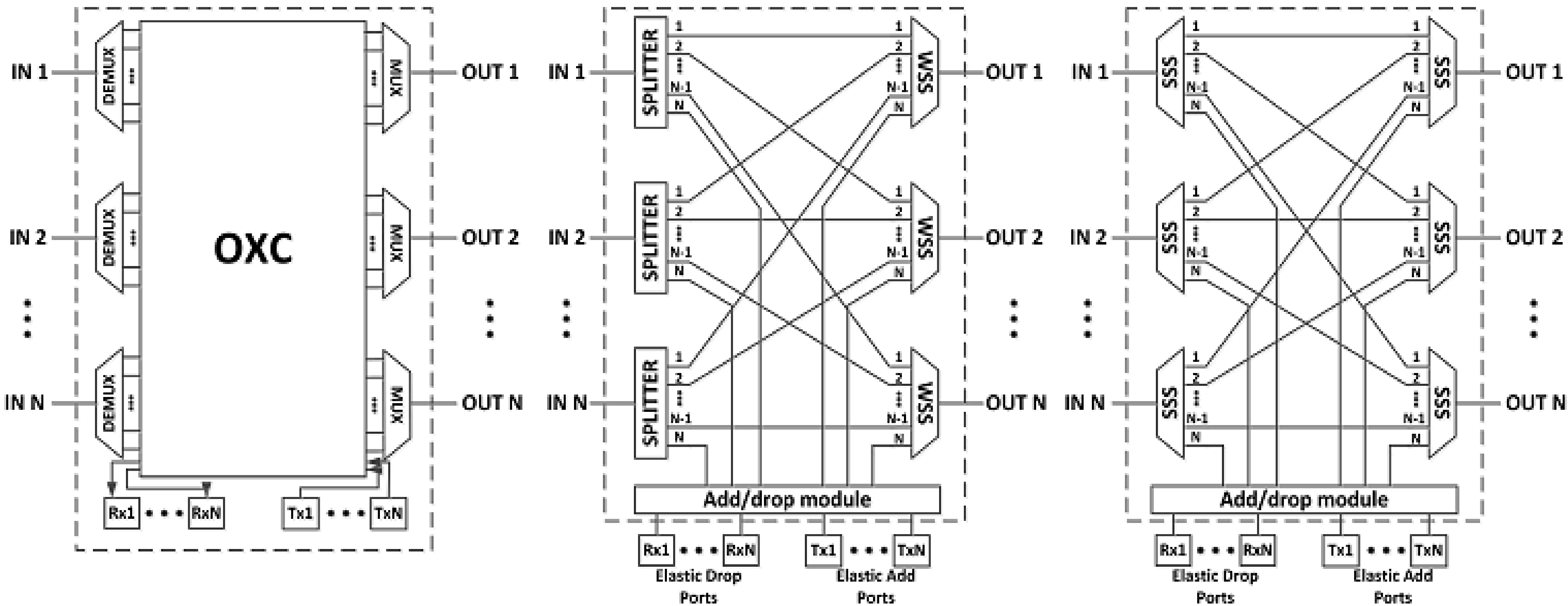
Hard-wired nodes

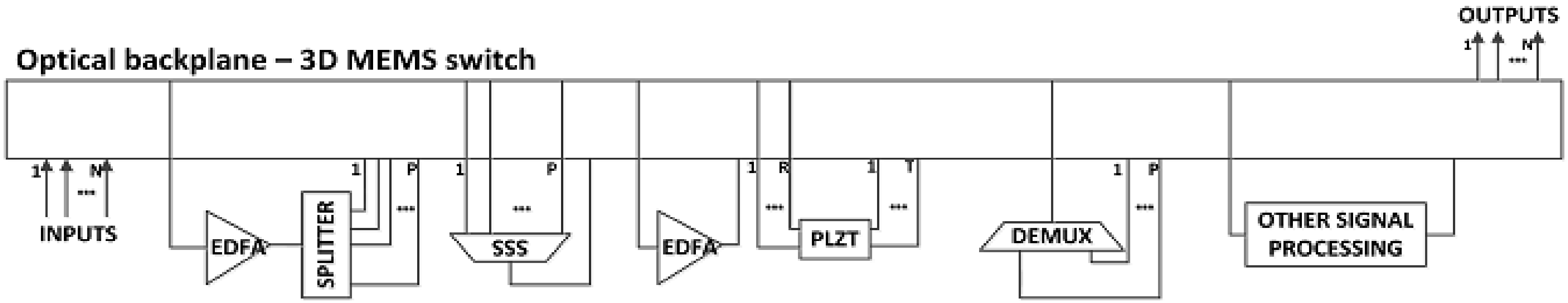


(a) Wavelength selective architecture

(b) Broadcast and select architecture

(c) Spectrum routing architecture

Node with Architecture on Demand



(d) Architecture on Demand

Use of redundancy

- All redundant components can be used on-the-fly for self-healing
  - provide backup resources for paths on the **optical node level -** switchover time at node level ➡ **10 milisecond** range (when 3D MEMS is applied)
  - no necessity for path rerouting on the **optical network level** - path recovery at network level - switchover time in **second** range.
- Only necessary components are traversed by a path ➡ **less components** ➡ **higher path** and **network availability**

Main trade-offs at AoD

Additional switches	vs.	Redundancy & Self-healing

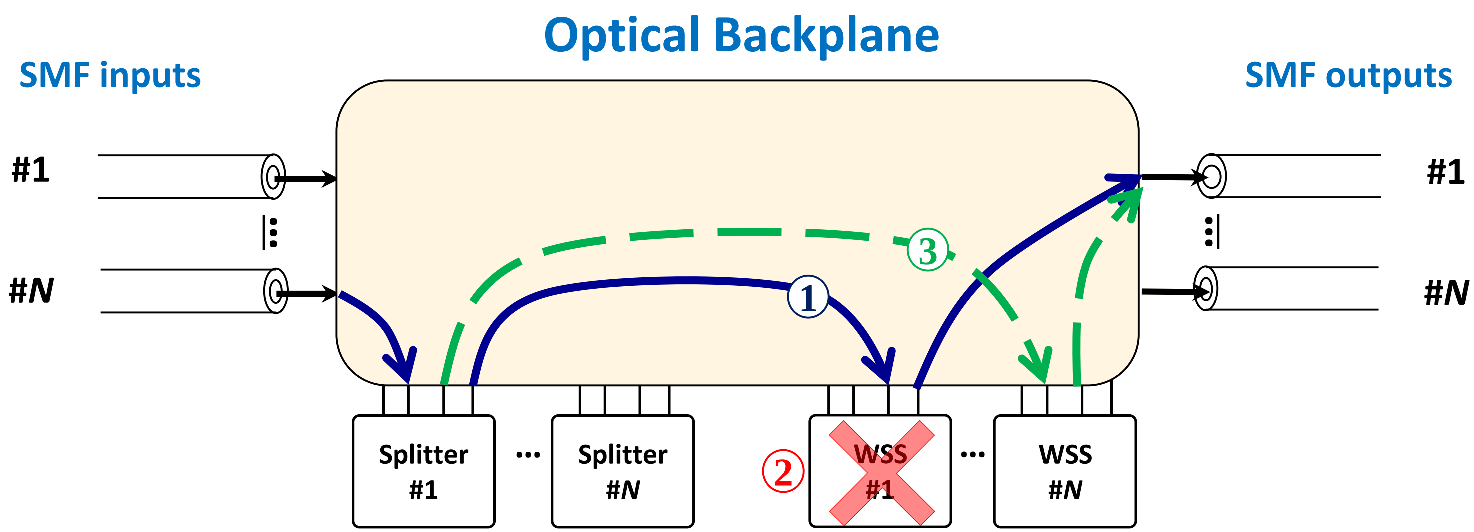
☹ Lower availability & High AoD cost ➡ Higher operator's revenue losses

☹ Higher power consumption

☺ Higher availability ➡ Lower operator's revenue losses

☺ Lower no. of active components ➡ Lower power consumption

Experimental setup –AOD ROADM with additional redundancy



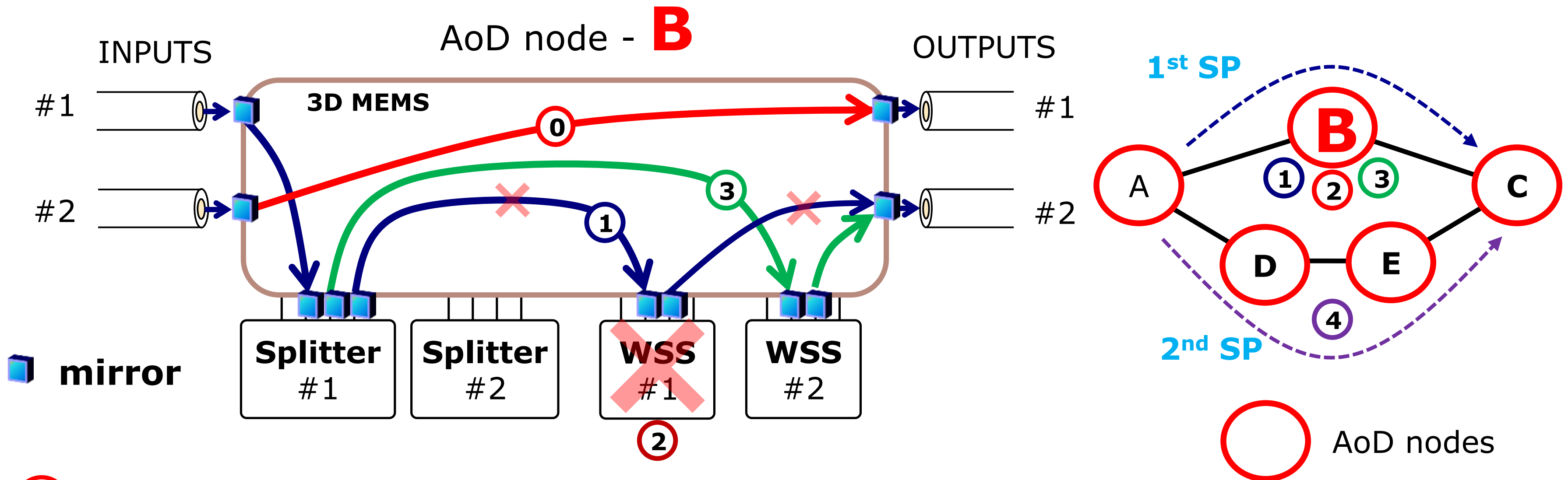
① **Original cross-connection from input *N* to output 1**

② **Component WSS#1 goes to a failure**

③ **Self-healing: New cross-connection to use idle WSS#*N***

- Restoration time ≈ 20 ms ✓
- Redundancy for any type of component without disturbing the existing connections ✓
- Capable of utilizing idle working components as redundant ✓
- Usage of expensive optical backplane (3D-MEMS) ✗

Self-healing procedure



0 **Fibre switched connection**

1 **Initial cross-connection (within 1st SP) from input 1 to output 2 at node B**

2 **Component WSS#1 fails**

3 **Self-healing: New cross-connections can use idle (redundant) WSS#2**

4 **If self-healing at B is not possible ➡ backup path (2nd SP) = protection path**

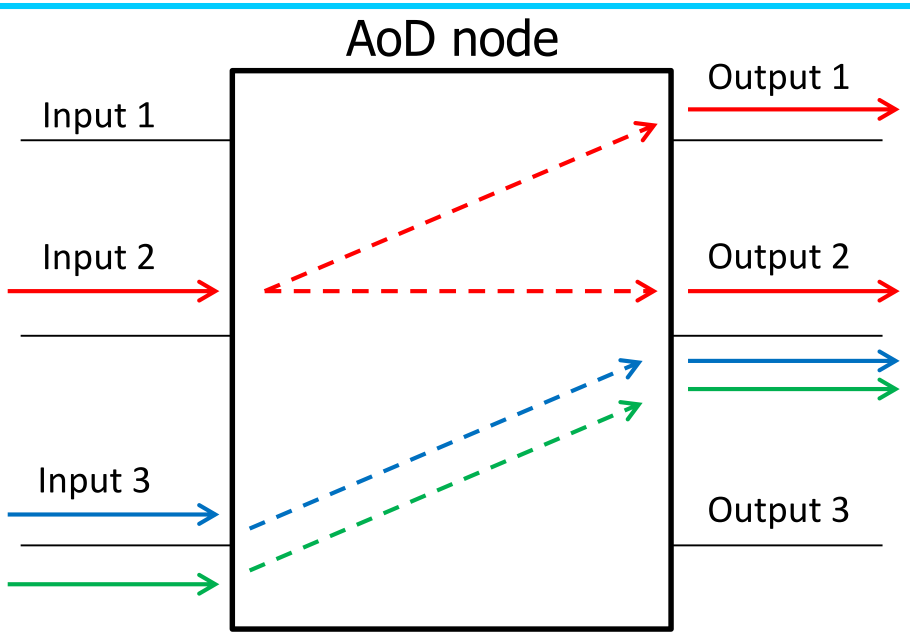
Availability measures

- *HWnet* and *AoDnet* are compared using availability measures:
- ***s,t-availability ($A_{s,t}$)*** - **minimal** value of all ***i,j-availabilities ($A_{i,j}$)*** among all node pairs - represents the worst end-to-end connection in a network.
- ***g-availability (A_g)*** is the probability that **all** end-to-end connections are in working state.
- ***Mean down time (MDT_g)*** is the time, in minutes per year, when at least one end-to-end connection is broken: $MDT_g=(1-A_g)\times 525{,}600$ minutes/year.

Availability evaluation

- **1st shortest and 2nd shortest paths** are found for each source and destination node pair of connection requests.
- Each node is reconfigured for all paths which fulfil the requirements for **fibre switching (*FS*)**. A ***SPL*** and one ***WSS*** are released and placed in the node **spare bank**.
- For reconfigured network, **Monte Carlo** failure/repair simulation is carried out.

Enforced fiber switching (EFS)



Fibre switching POSSIBLE!

Fibre switching NOT POSSIBLE!

- **Fibre switching** can be enforced via **careful routing on the network level**
- Main idea: Allow for fibre switching in nodes by rerouting the extra lightpaths

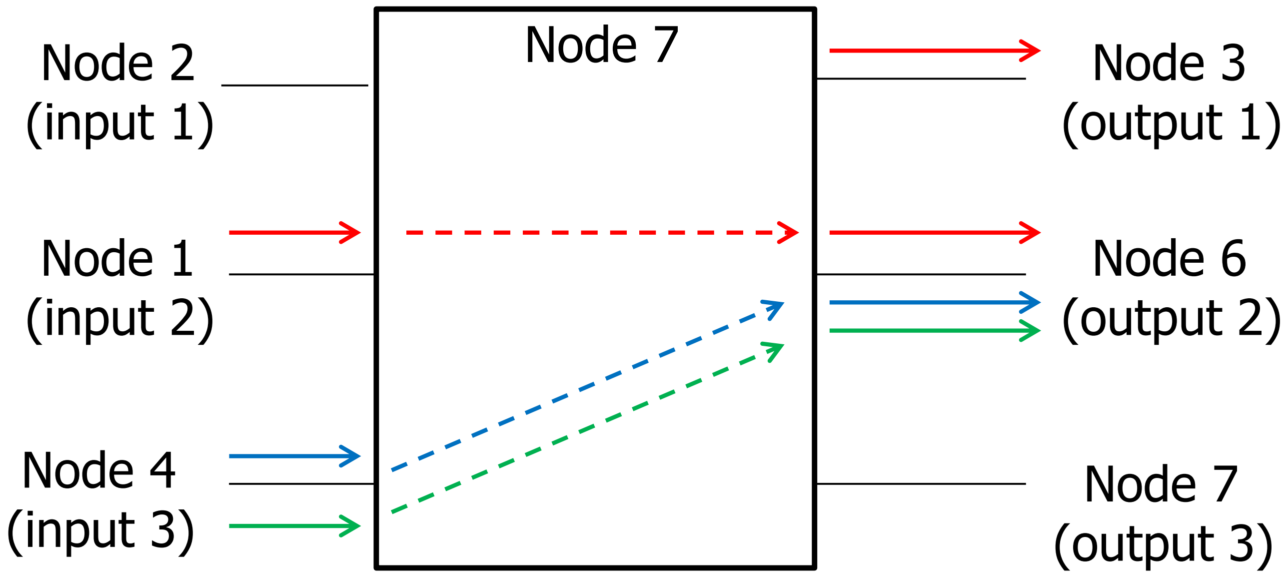
fs_ratio (node *n*, input port *i*, output port *j*)	=	#lightpaths which use port *i* **and** port *j* / #lightpaths which use **either** port *i* **or** port *j*

Must be rerouted to allow for fibre switching

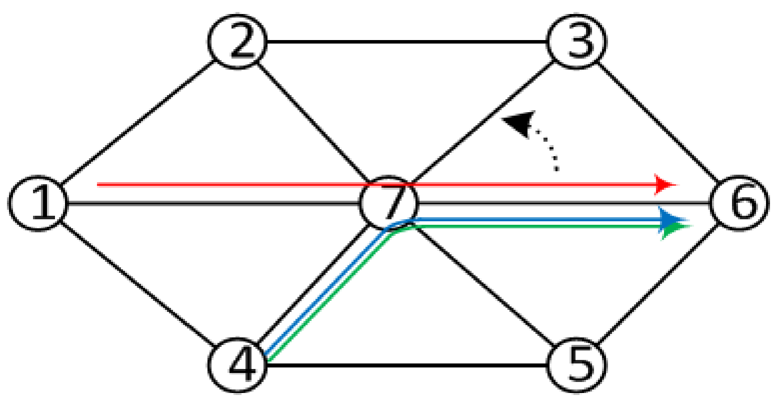
Can be fibre-switched between ports *(i,j)* in node *n*

$$fs\_ratio = \frac{2}{1} = 2$$

Enforcing fibre switching – network level

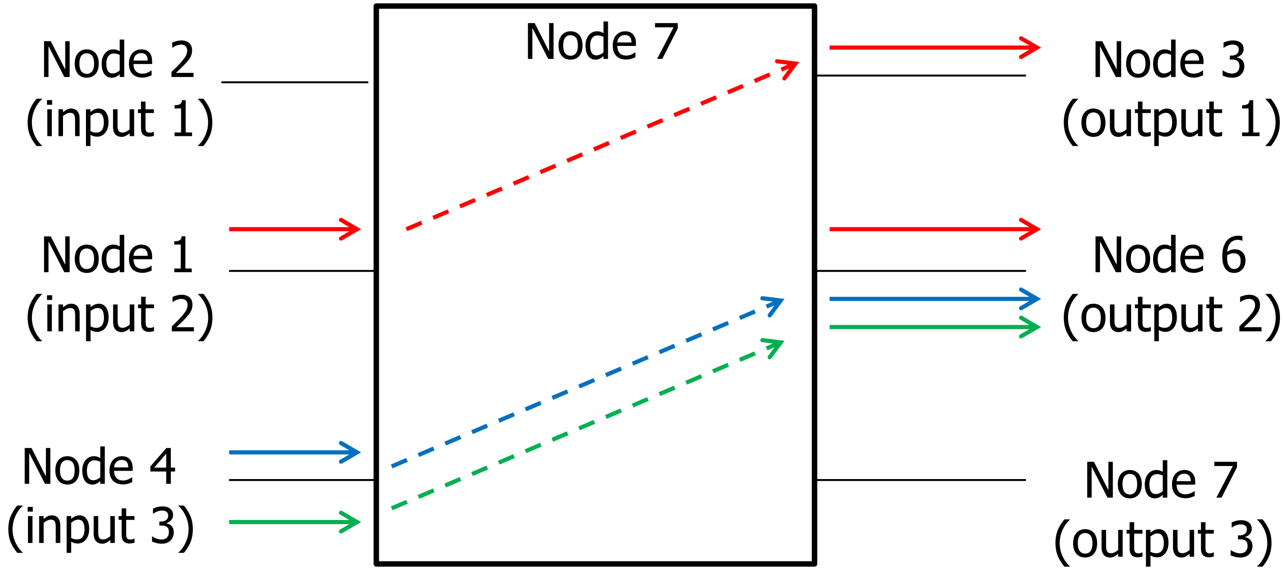


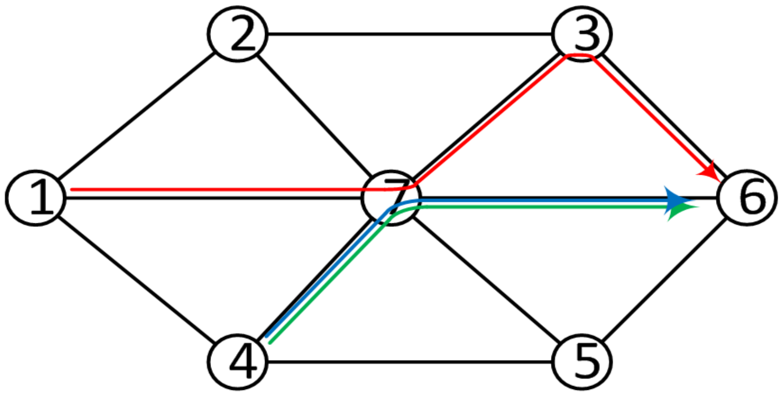
Red lightpath needs to be re-routed in node 7!



Fibre switching NOT POSSIBLE in node 7!

Enforcing fibre switching – network level





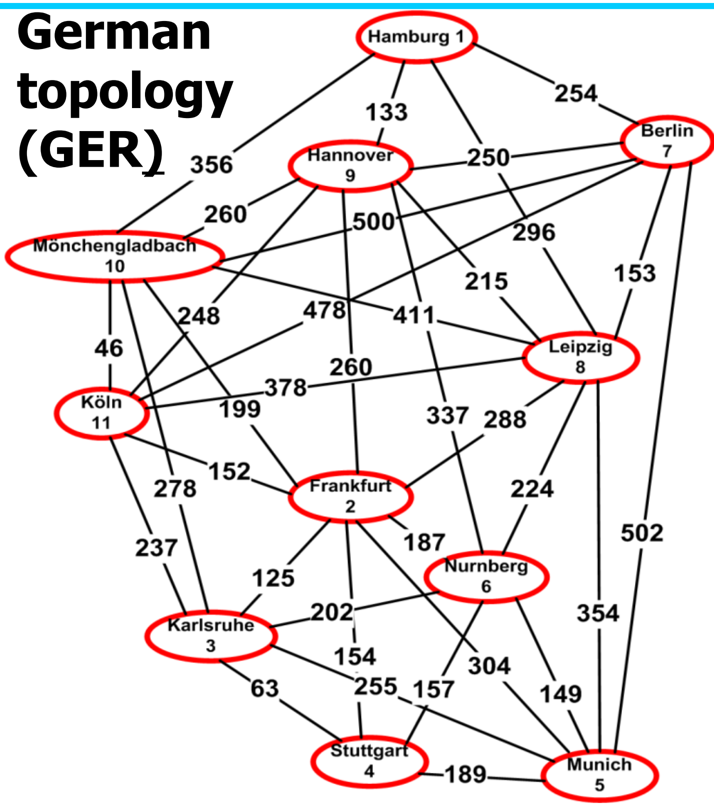
Fibre switching POSSIBLE by routing on the network level!

An example network – assumptions

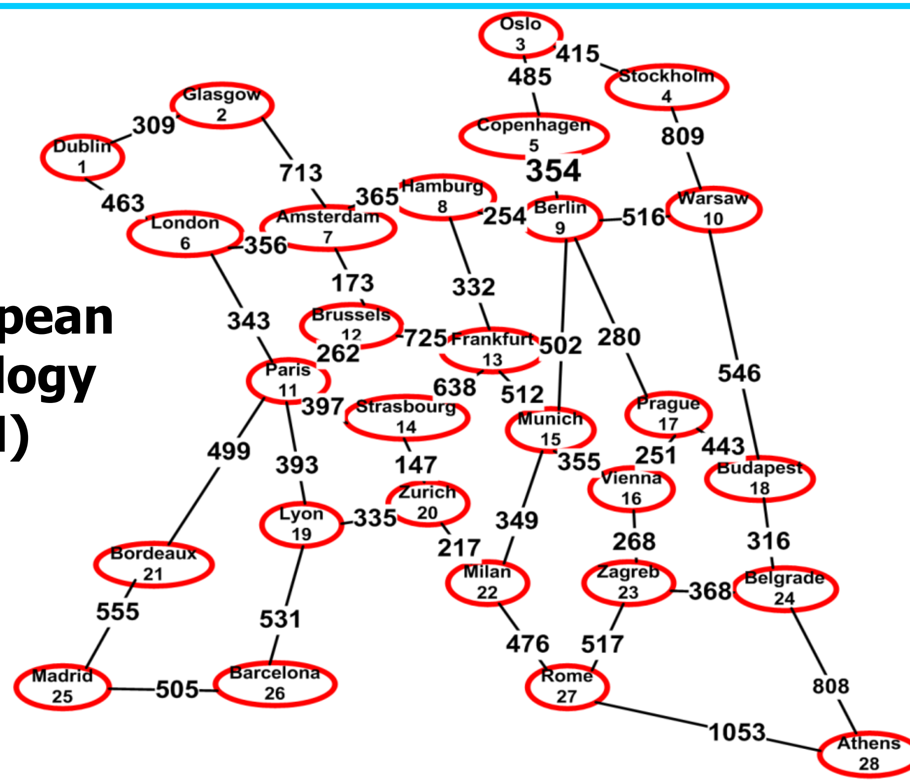
- **German topology** (11 nodes and 34 links).
- Network protection scheme: **1+1**.
- The traffic load in the network is assumed to be **static**.
- **Populations & distance** traffic calculus for each node pair.
- Traffic requirements are fulfilled by multiples of **10 Gbit/s** lightpaths.
- No. of *SPLs* or *WSSs* **=** node degree.
- Each optical end-to-end connection ➡ pair of paths:
  - first shortest path (1^{st} SP) - working path and
  - second shortest path (2^{nd} SP) - backup path (independent of the working path).

Networks used in simulations

German topology (GER)



European topology (EON)



	Min. ND	Max. ND	Avg. ND
GER	4	8	6.18
EON	2	5	2.93

Higher ND (node degree) → more routing possibilities

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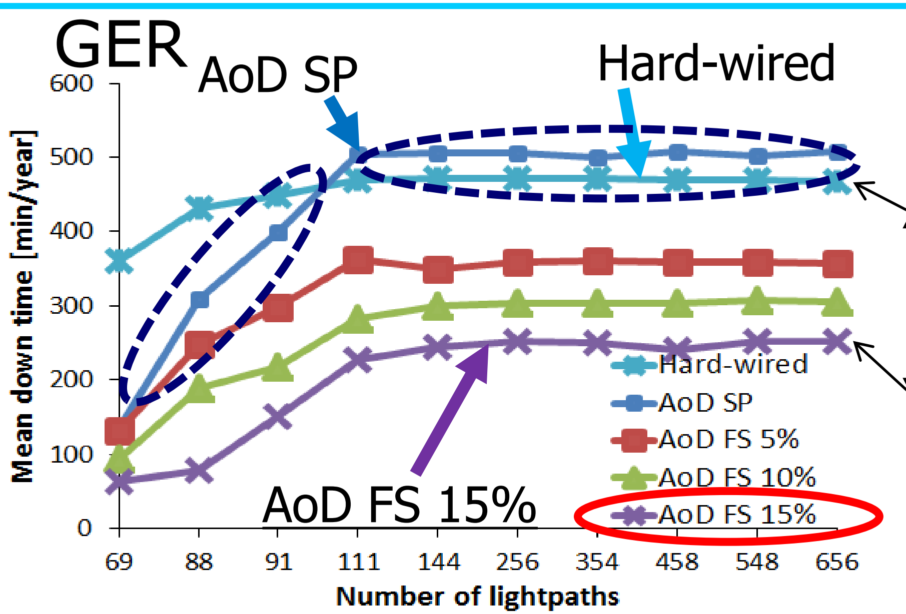
Simulation setup

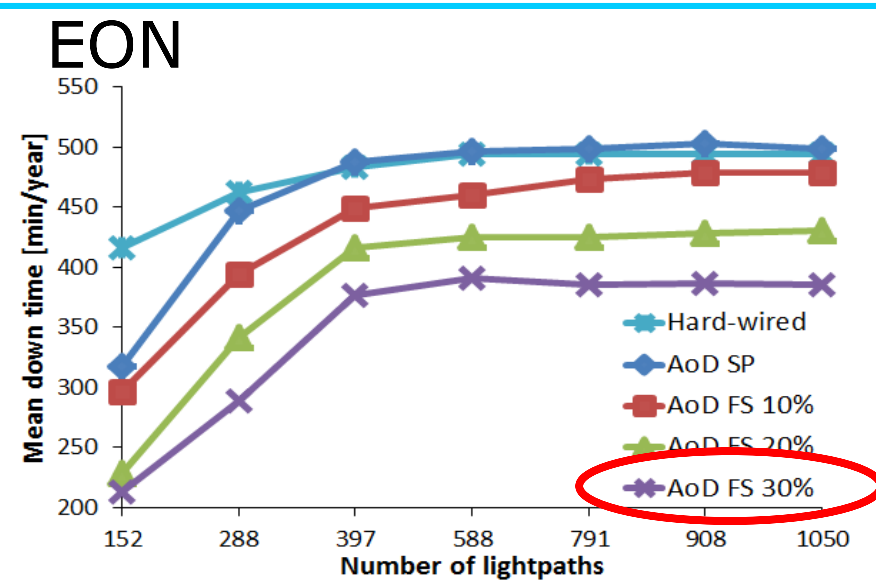
- Monte Carlo failure/repair simulation
  - C++ custom build simulator
  - Goal: evaluate availability and associated revenue losses
  - Traffic generation → population-distance based method
  - We simulate failures and repairs of MEMS mirrors, splitters and WSSs based on component failure (repair) rates
  - Simulated time = 10^9 hours, encompassing over 5,000,000 simulated events
  - We consider two cases:
    - Shortest path (SP) routing algorithm when hard-wired nodes are used
    - Enforced Fibre Switching (EFS) routing algorithm when AoD nodes are used.

Monte Carlo simulation

- Evaluation of **end-to-end connections'** successfulness for different total **traffic loads**.
- Using Monte Carlo simulation exponential distributed **times to failure/repair** of nodes and links are generated .
- When an AoD node component fails, node **spare bank** is checked for idle component identical to the failed type.
- If there is no idle component in the spare bank or in the case of a link failure, the recovery procedure is switched over to the **network level**, using **1+1 protection**.
- Simulated time = **10^9 hours**, with **10^5 simulated events**

Results – Mean down time (MDT)



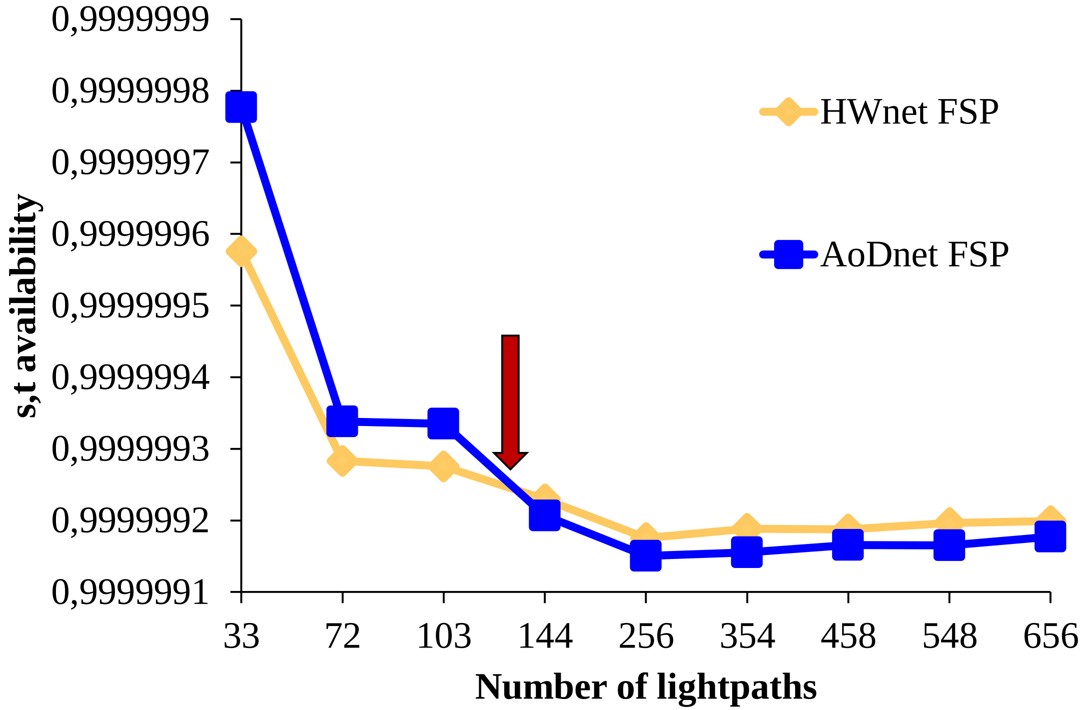


- The MDT obtained for following cases:
  - Hard-wired nodes with the shortest path (SP) and AoD nodes with SP/EFS
- Under low traffic – AoD with SP achieves lower MDT
  - Some components remain idle – used as redundancy
- Under high traffic– all components used
  - MDT of AoD with SP surpasses MDT of the hard-wired architecture
  - When SP is replaced with EFS, the MDT for AoD significantly decreases

Simulation results – HWnet vs. AoDnet

At **low traffic** loads ➡ logical topologies are **not fully connected** ➡ higher no. of idle components.

At **high traffic** loads ➡ logical topologies are **fully connected** ➡ lower no. of idle components.

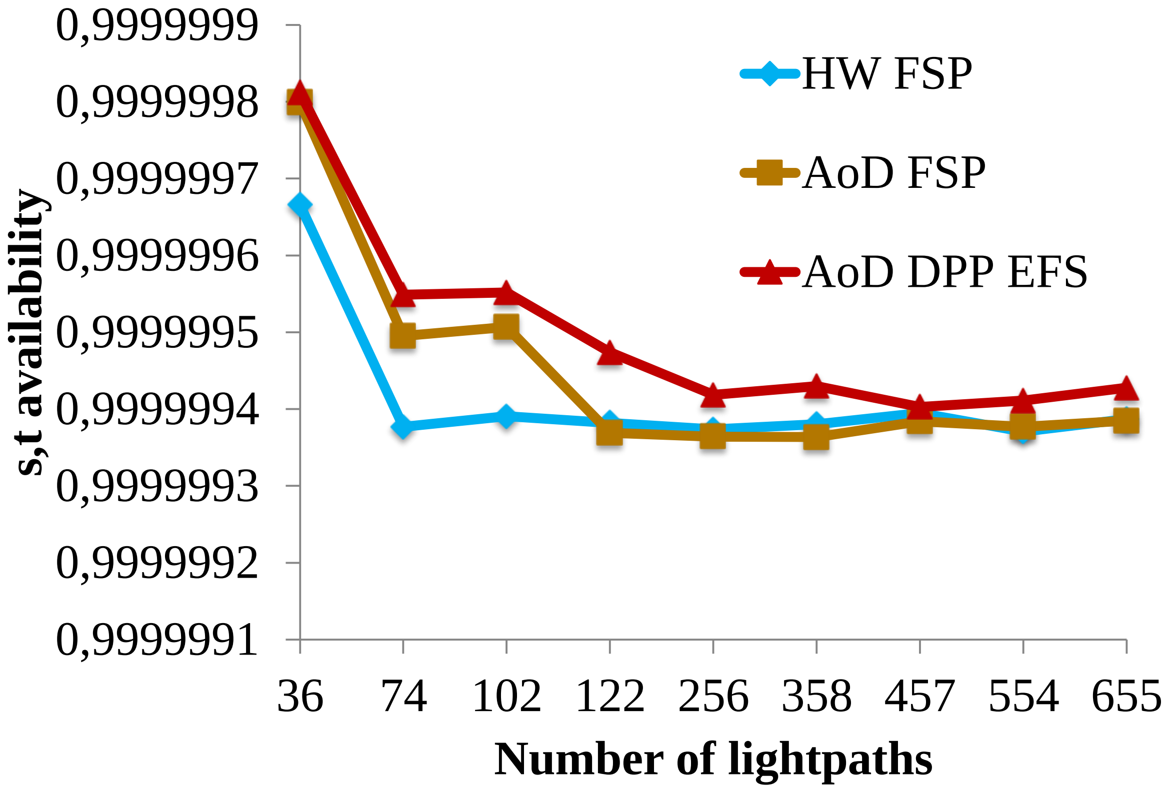


HWnet FSP – HW network – with fixed shortest path routing

AoDnet FSP – AoD network – with fixed shortest path routing

Simulation results – Enforced fibre switching (EFS)

DPP EFS (dedicated path protection) **+ enforced fibre switching**

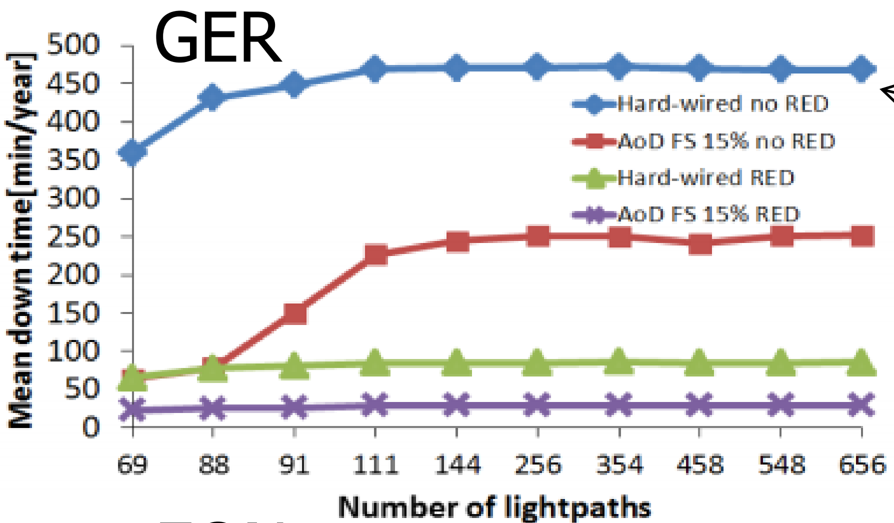


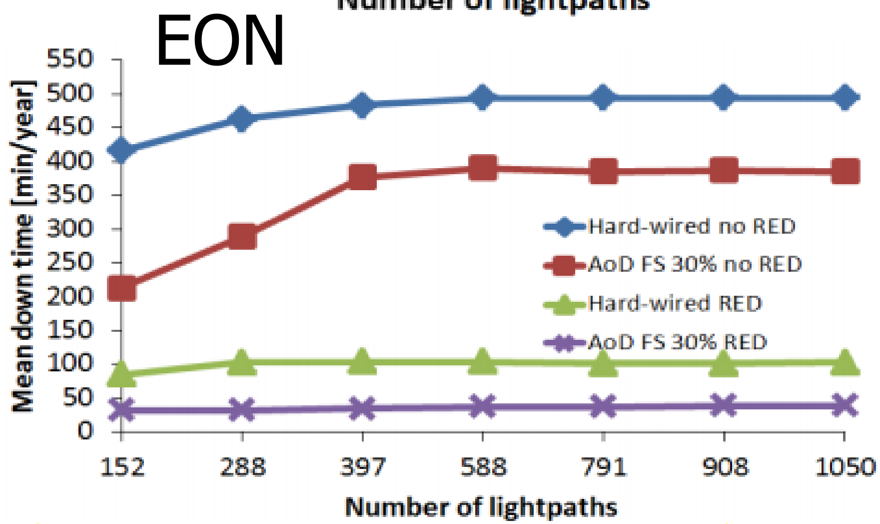
EFS - Initial **shortest** path layout ➡ transformed to **optimised** path routing in order to increase no. of fibre-switched (**FS**) paths ➡ increase no. of redundant components.

Trade off

⬇ Availability of **prolonged** paths **vs** ⬆ Availability of **FS** paths

Results – **added redundant** components





Without redundancy

HW 6x lower MDT

AoD 9x lower MDT

With redundancy

Without redundancy

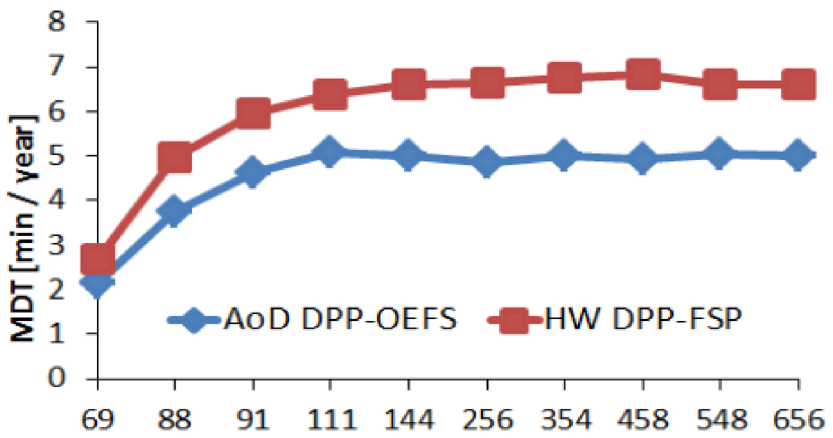
HW 5x lower MDT

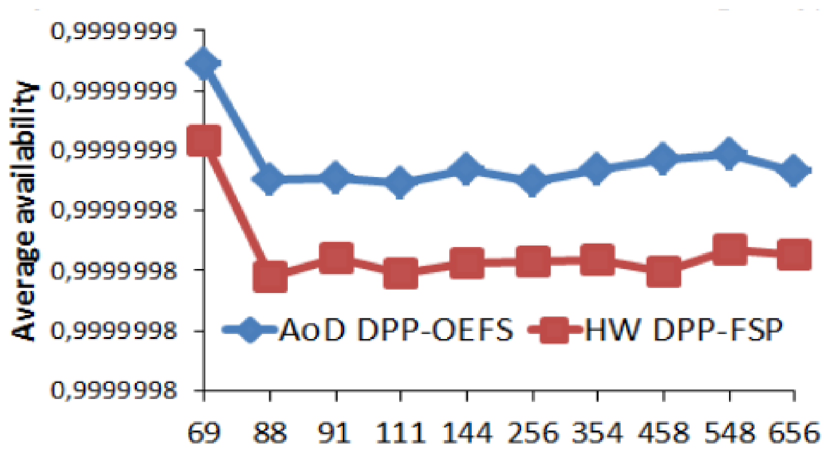
AoD 10x lower MDT

With redundancy

Results – **GER** topology

- Average link distance 242 km
- MDT for AoD with DPP-OEFS is lower 25%



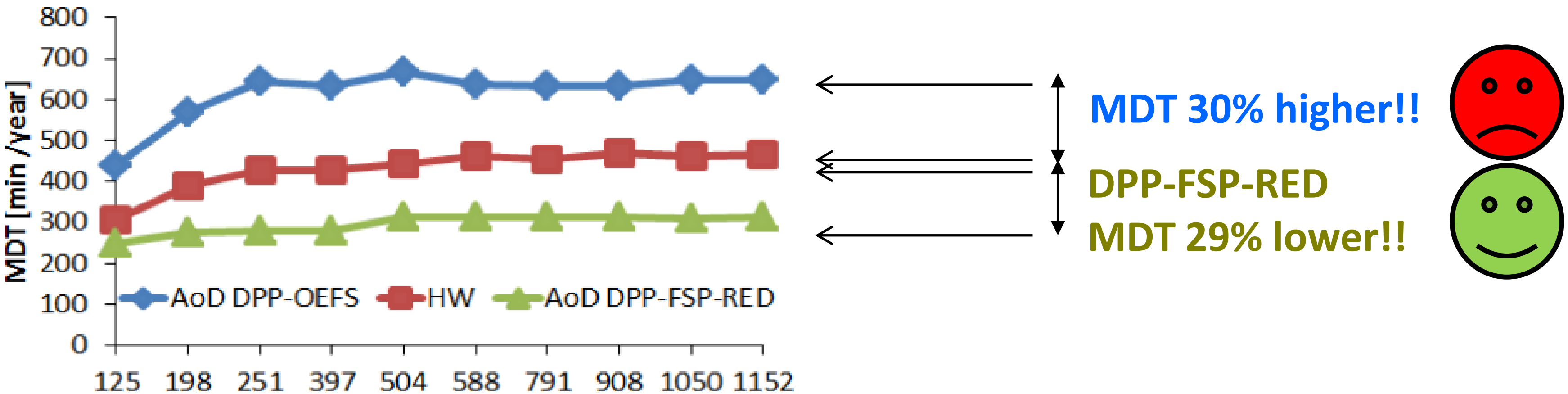


Results – **EON** topology

- Average link distance 432 km
- In most cases, re-routed lightpaths can **NOT** compensate failure rate increase caused by extension of lightpath length.
- MDT approximately higher 30% over all test cases

PROBLEM? HOW TO DECREASE MDT??

- **DPP-FSP-RED - added redundant WSS in 8-out-of-28 nodes**
- **Cost increased 9%, while MDT was decreased 29%**



Conclusion

- The availability benefit of using AoD nodes with self-healing capability, compared to HW nodes, is evident at lower traffic loads using fixed shortest path (FSP) routing without additional investments in redundancy.
- If a tailored routing algorithm, with enforced fibre switching (EFS), is used, benefit of AoD deployment is extended to higher traffic loads.

- **Always exists the possibility - AoD self-healing capability can be improved by investement in redundant node components dedicated for failure recovery.**