Resource Allocation for Space-Division Multiplexing: Optical White Box Versus Optical Black Box Networking

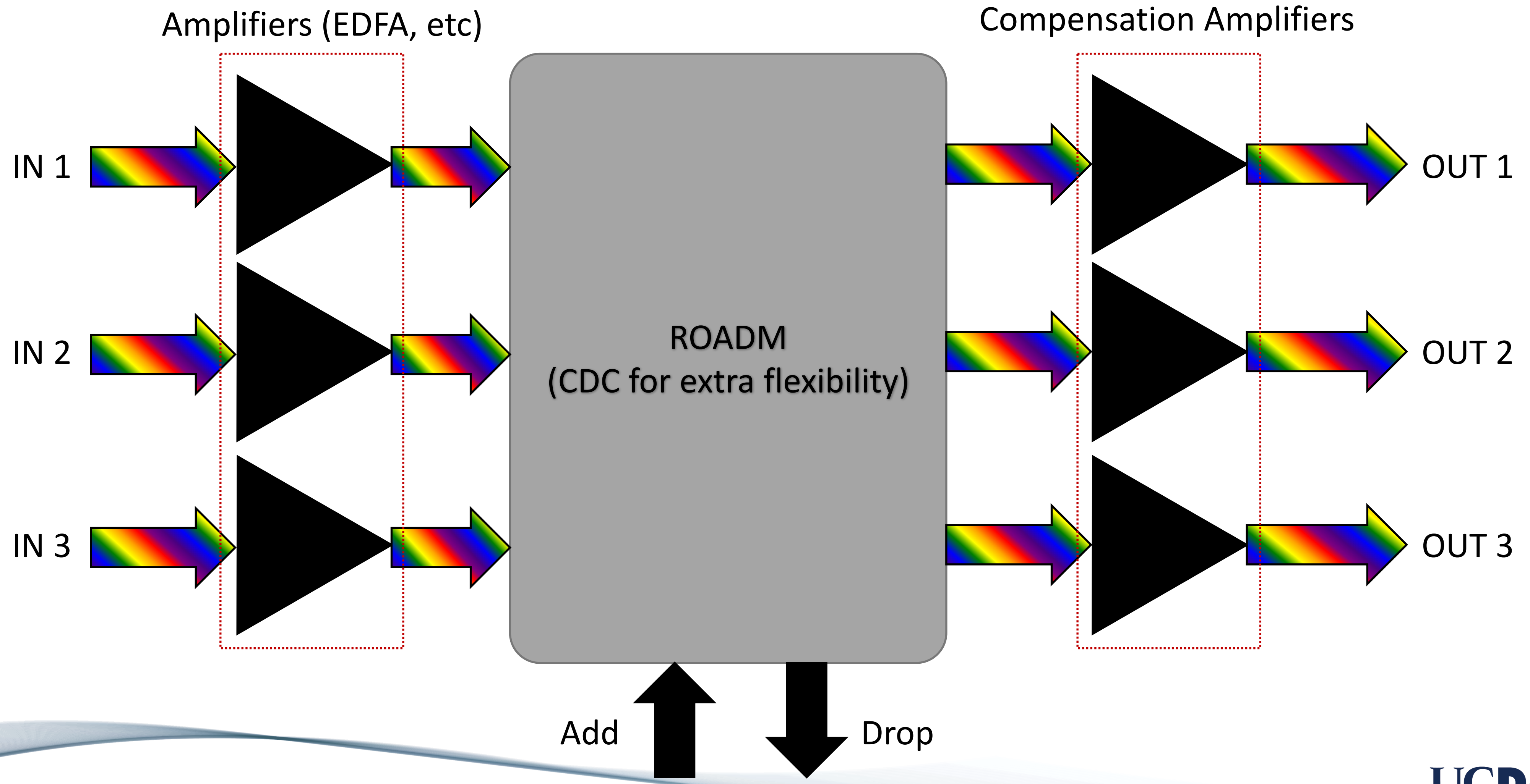
Ajmal Muhammad, Georgios Zervas, and Robert Forchheimer

Journal of Lightwave Technology – December 2015

Presented by: Rafael B. R. Lourenco in February 3rd 2017.

UCDAVIS
UNIVERSITY OF CALIFORNIA

Common Optical Node Architecture

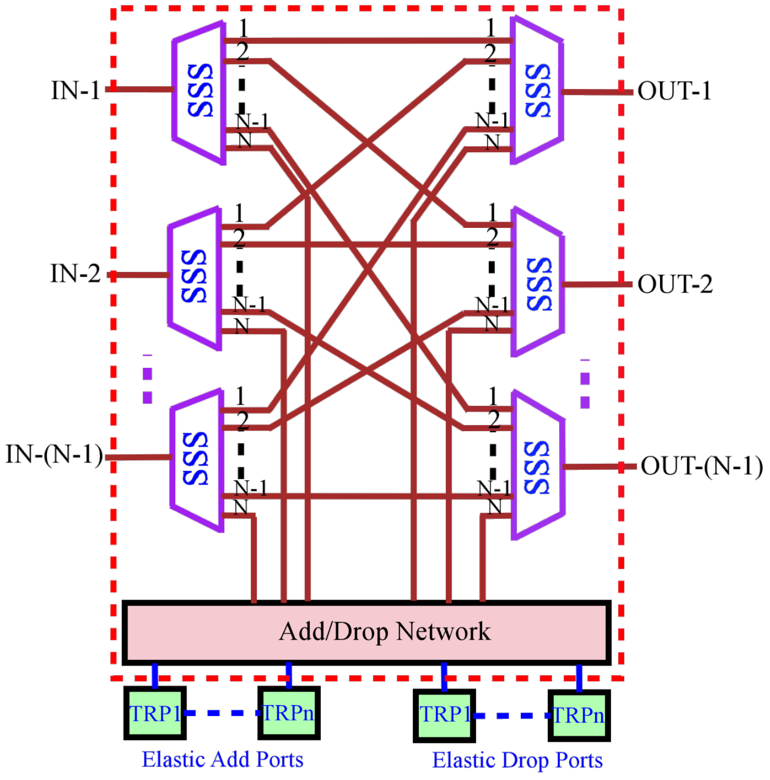


UCDAVIS

Optical Black Box Vs. Optical White Box

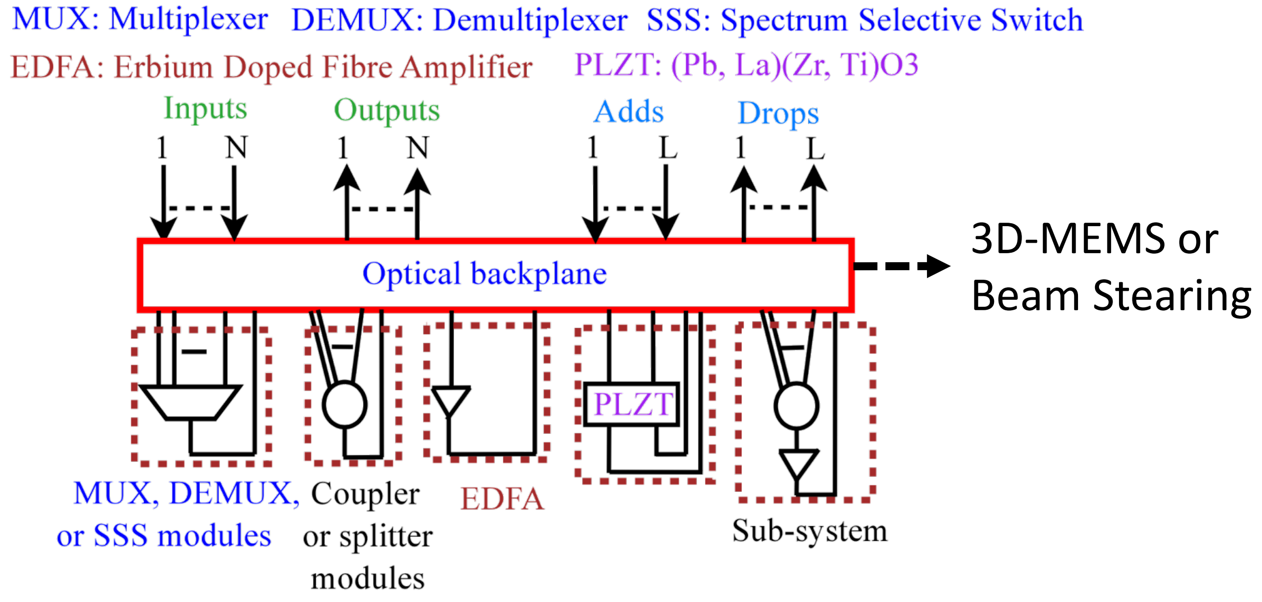
ROADM (Black Box)

Internal connections are hardwired.



Architecture on Demand Switch (White Box)

Dynamically reconfigurable backplane



Obs: 96x96 3D-MEMS is only 20% more expensive than 1x16 Spectrum Selective Switch (SSS)

Elastic Space Division Multiplexing (SDM) Networks

- Multi-Mode Fiber (MMF): different propagation modes
- **Multi-Core Fiber (MCF): different cores, each carrying a signal**
- Few-Mode Fiber (FMF): similar to MMF, but fewer
- Few-Mode Multi-Core Fiber (FM-MCF): FMF and MCF
- Single-Mode Fiber (SMF) Bundles: common long distance systems

- Spatial-spectral superchannels

UCDAVIS

Contribution and Considerations

- Investigate planning and dimensioning of MCF-based elastic SDM networks considering quasi-static traffic model. Propose an algorithm to solve the Routing, Modulation, Spectrum, and Core Allocation (RMSCA) problem in these networks considering Cross-Talk (XT)
- Compares optical white boxes (AoDs) and black boxes (ROADMs)
- Bandwidth Variable Transceivers (BVTs), weakly-coupled MCFs, no MIMO (it would require different signals to not be decoupled)
- BPSK, QPSK, 8...64-QAM and PDM
- ROADMs are Colorless, Directionless, and Contentionless

Cross-Talk (XT) and Multi-Core Fibers (MCF)

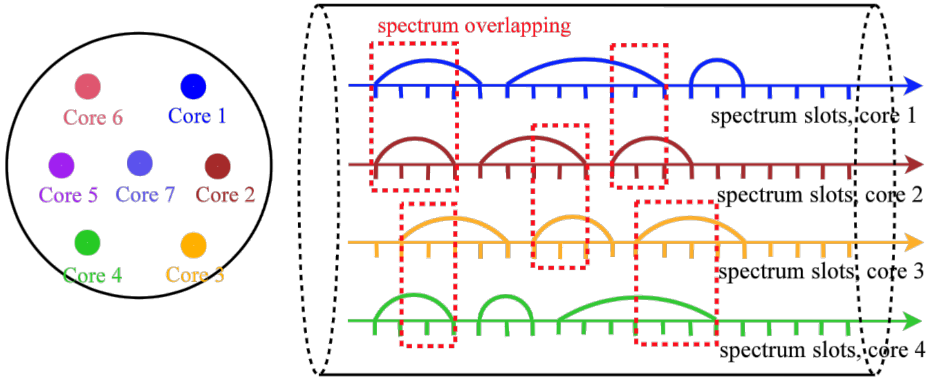


Fig. 5. XT unaware spectrum allocation.

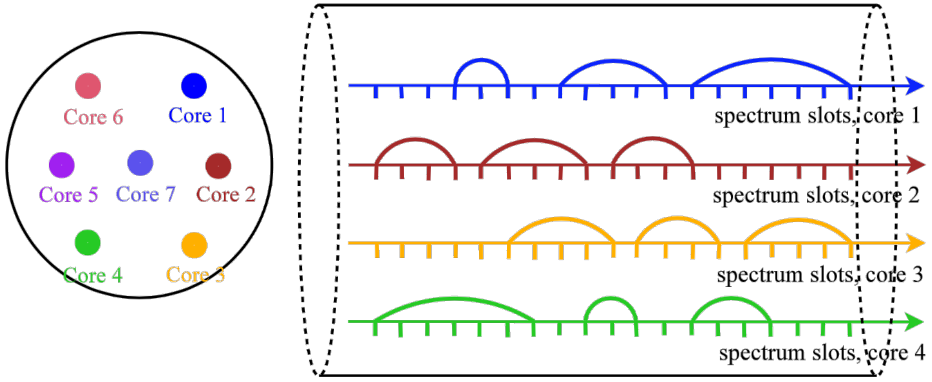


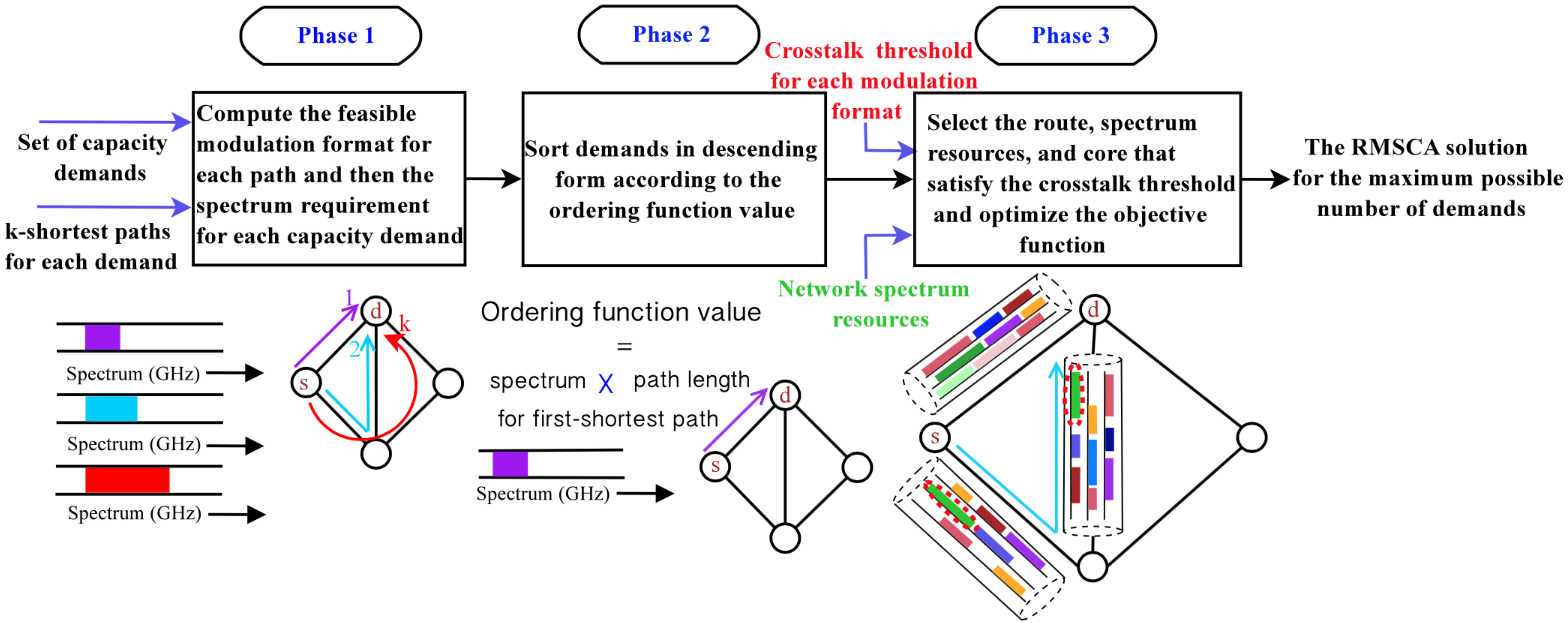
Fig. 6. XT aware spectrum allocation.

$$XT = \frac{n - n \cdot \exp(-(n+1) \cdot 2\frac{\kappa^2}{\beta}\frac{R}{\Lambda}L)}{1 + n \cdot \exp(-(n+1) \cdot 2\frac{\kappa^2}{\beta}\frac{R}{\Lambda}L)}$$

*N is the number of adjacent cores.
Proposed in the paper: T. Hayashi *et al.*, “Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber,” *Opt. Exp.*, vol. 19, no. 17, pp. 16576–16592, Aug. 2011.

UCDAVIS

Provisioning Algorithm



ROADM Ordering Function

- To reduce number of SSSs, focus on using already lit cores

$$\text{Cost} = (\#\text{ New link cores lit}) * (\text{XT value for path})$$

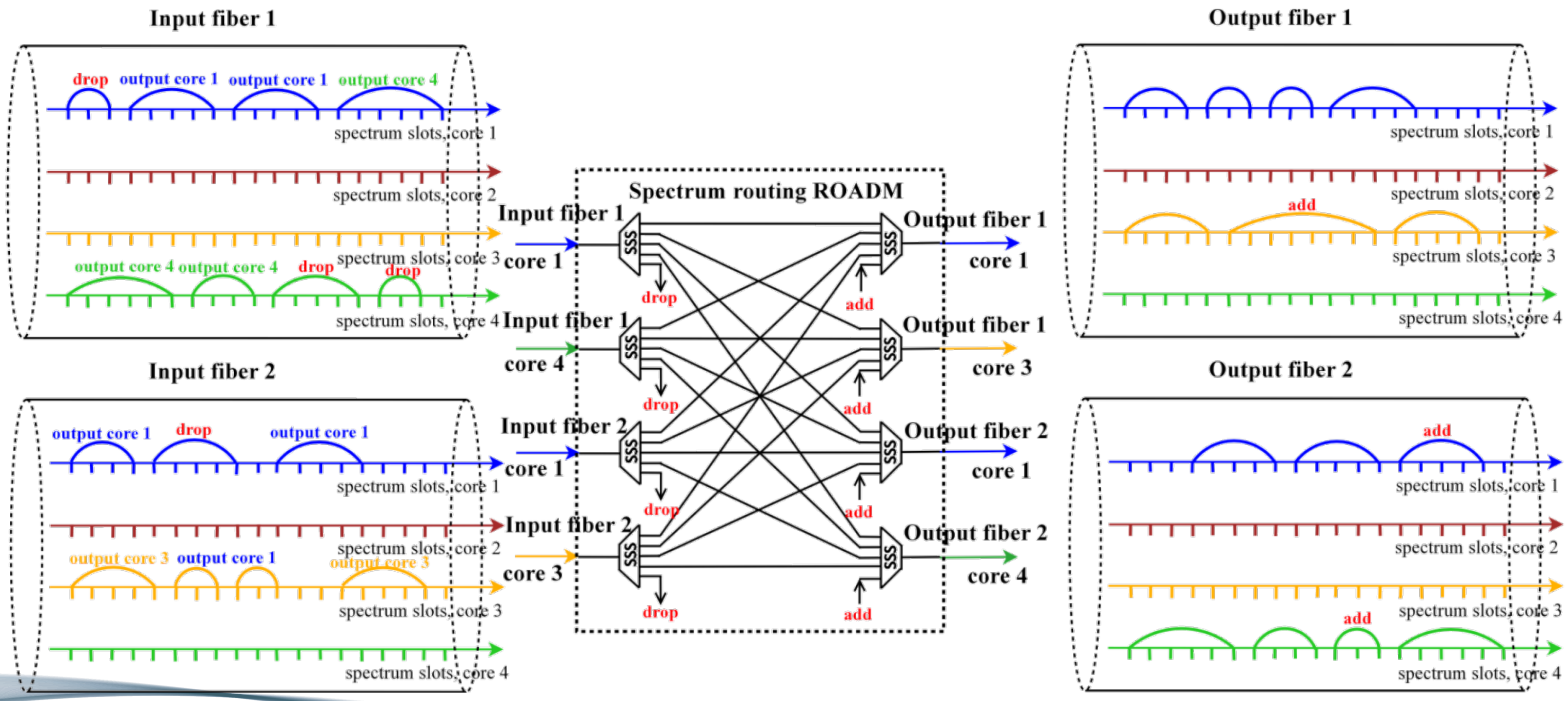


Fig. 9. ROADM for MCF-based SDM networks.

UCDAVIS

AoD Ordering Function

- AoD: reconfigure to remove unnecessary switch modules, and (more importantly) optical backplane can route input to output without SSS. Thus, spread demands through fiber to take advantage of that

Cost = (# Additional switching modules) * (XT value for path)

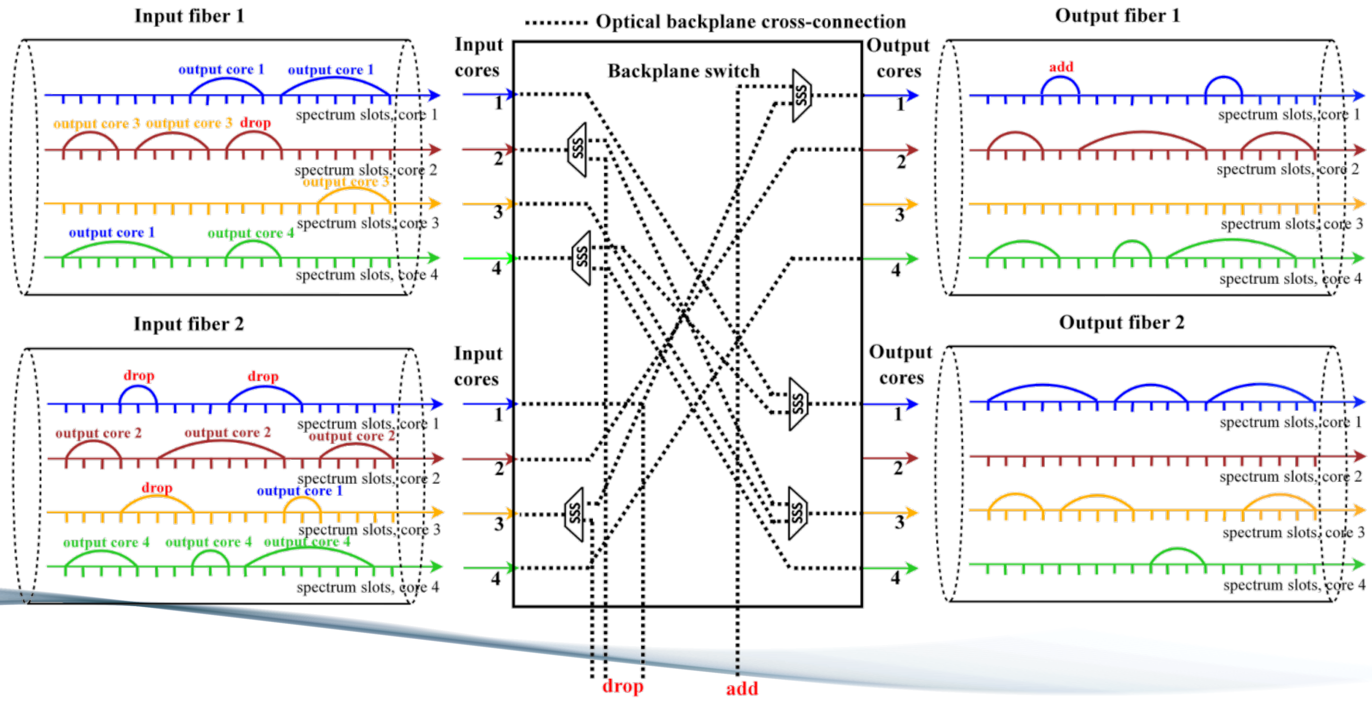


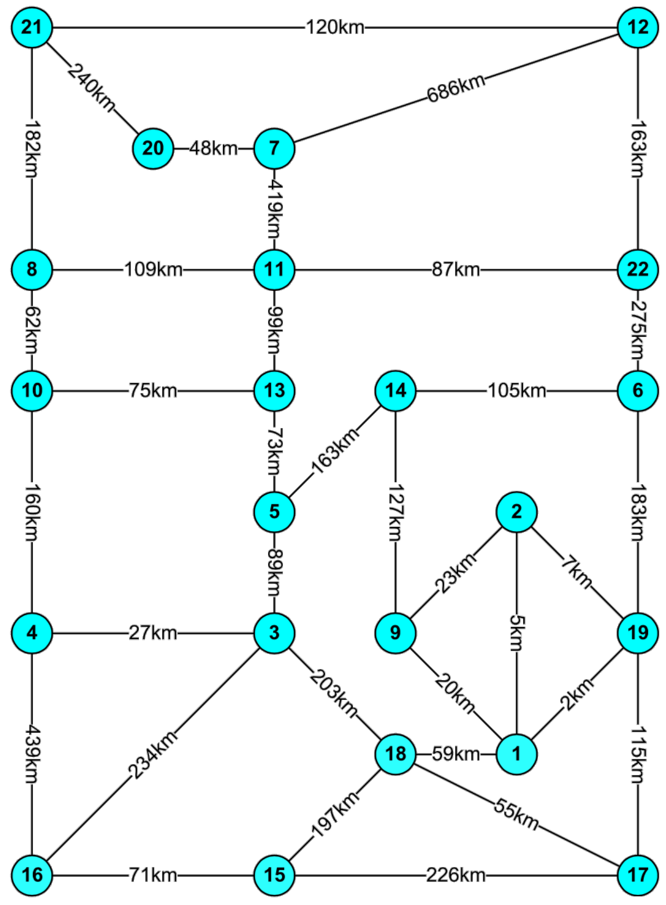
Fig. 10. AoD for MCF-based SDM networks.

Allocation Decision

- Two types:
  - Modulation Format Fixed (MFF) – if demand cannot be provisioned within XT threshold, it is dropped
  - Modulation Format Switching (MFS) – if demand cannot be provisioned within XT threshold, downgrades modulation level from the most spectral efficient to some lower modulation that passes the XT threshold test

Results – Overview

- BT Topology: 22 nodes, 70 unidirectional links
- Demands: uniform sd-pairs and bandwidths (from 10 to 500Gbps)
- Utilization increases by 30% every epoch besides new demands
- Confidence Level of 95%, Conf. Interv. < 5%



UCDAVIS

Results – Part 1

- Incorporating XT values while computing through cross-layer optimization helps (specially AoD)
- ROADM first seek spectrum resources on non-adjacent cores of network links, exploiting their dense intra-node connectivity. Once these are used up, allocated resources are reconfigured to demands to minimize the level of XT
- AoD occupies (spreading) resources on different link cores to maximize the fiber switching. Though disjoint spectrum slots are sought, chances of spectrum overlapping are still higher compared to ROADM
- MFS-AoD better than MFF-AoD for low traffic, but similar for higher traffic because modulation is lowered due to XT (widening bands)
- Prioritizing the cost function to minimize deployment of new switching modules (MFS-AoD (dif.)) hurts successful traffic

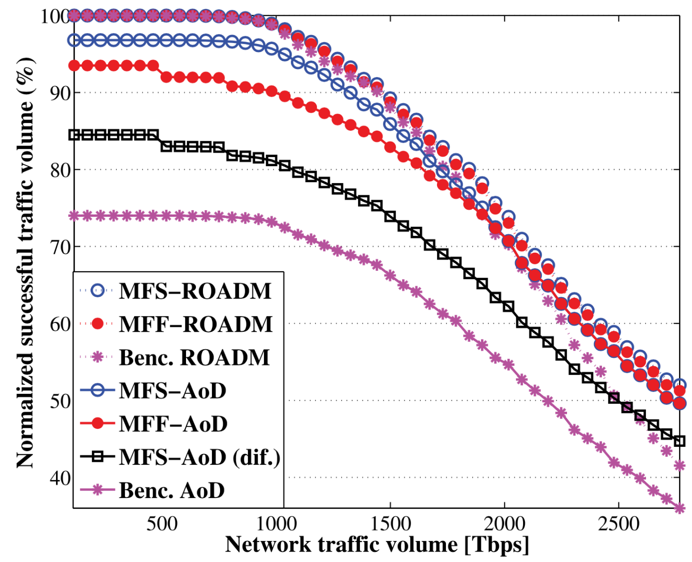


Fig. 12. Normalized provisioned traffic volume versus total traffic volume.

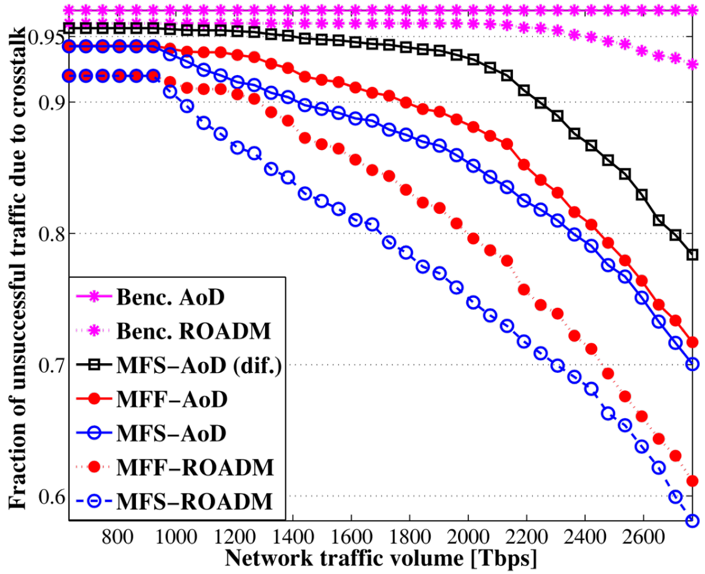


Fig. 13. Fraction of total unsuccessful traffic due to XT versus total traffic volume.

Results – Part 2

- Performance of MFS-ROADM approximately the same as benchmark. Both use same criteria: to use up spectrum resources of a core before lighting other cores (lit cores proportional to # of SSSs)
- AoD-based up to 60% less SSSs: achieved by enhancing fiber switching and relocating the prior installed modules
- For single-core (SC) amplifiers,
  - ROADM net: requires sum of inline plus the ones for compensating amplifiers
  - AoD net: fiber switching raises # of inline amplifiers considerably, compared to ROADM in low traffic. For high traffic, ROADM needs more (compensating amps) since most of the fiber cores are lit
- For Multi-core (MC) amplifiers, # of inline amplifiers becomes independent of the lit cores, enabling AoD nets to use less amplifiers

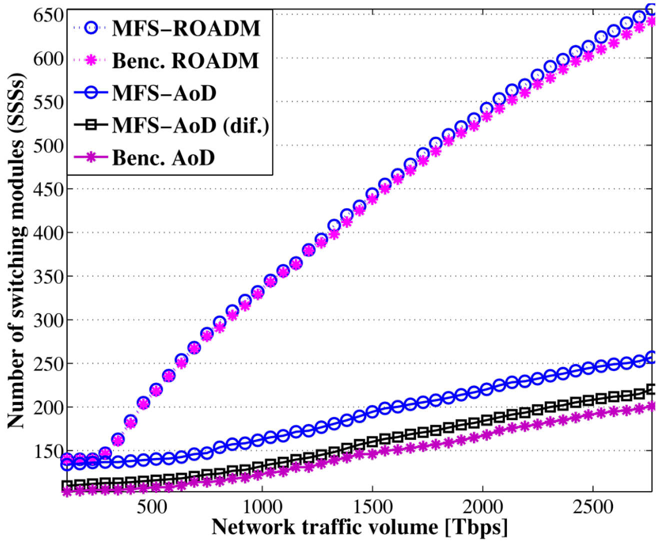


Fig. 15. Number of switching modules versus total traffic volume.

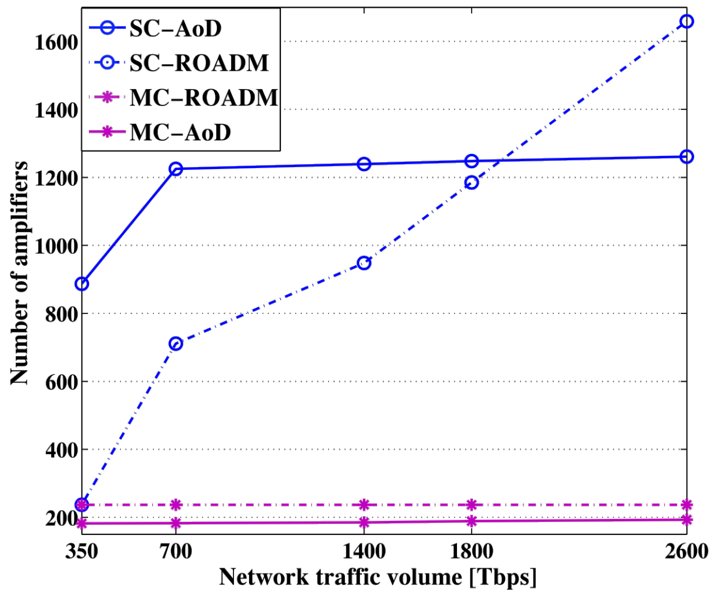


Fig. 16. Total number of SC and MC amplifiers for ROADM and AoD based networks.

UCDAVIS

Results – Part 3

- AoD-based network, in general, and MFF-AoD, in particular, have higher levels of XT (smaller value of dB) with respect to the ROADM scenario
- Modulation switching to lower levels enables MFS-AoD to alleviate the XT compared to AoD-MFF
- MFS-ROADM utilizes resources on non-adjacent cores of the fiber to minimize the impact of XT
- MFS-AoD use partial resources on all cores (with minimum spectrum overlapping among neighbor cores) to maximize fiber switching

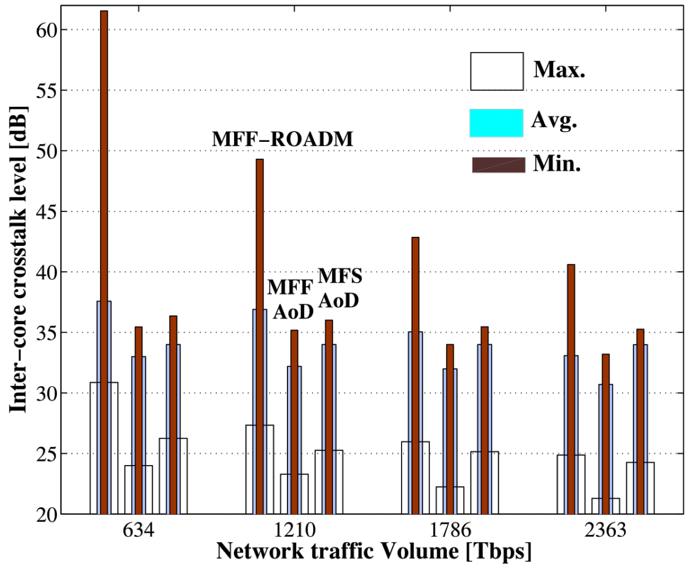


Fig. 17. XT for different provisioning strategies at different network loads.

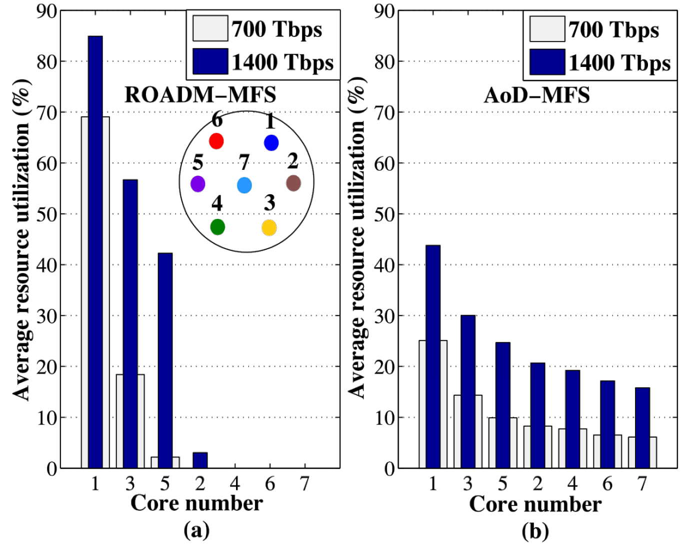


Fig. 18. Average spectrum resource utilization on different cores for MFS.

UCDAVIS

Results – Part 4

- For MFS-AoD, switching resources (and thus intra-nodal connectivity) grow with the increase in traffic volume. More intra-connected nodes improve chances of finding spectrum resources on shorter paths. Thus, the path length for MFS-AoD drops with the rise in network traffic
- For MFS-ROADM, path length goes up with the increase in network traffic volume. Because the cost function forces the selection of shorter paths (to achieve low XT) when network spectrum resources are partly occupied. As traffic increases, the candidate solution space shrinks, leading to the selection of longer paths
- Modulation level (for MFS strategy) not only depends on the path length but also on the XT. The ratio of provisioned traffic for MFS-ROADM is higher than for MFS-AoD, which indicates more likelihood of signal interference on longer routes for MFS-ROADM. Thus, the signal robustness to XT is enhanced by employing a relatively lower level of modulation compared to MFS-AoD

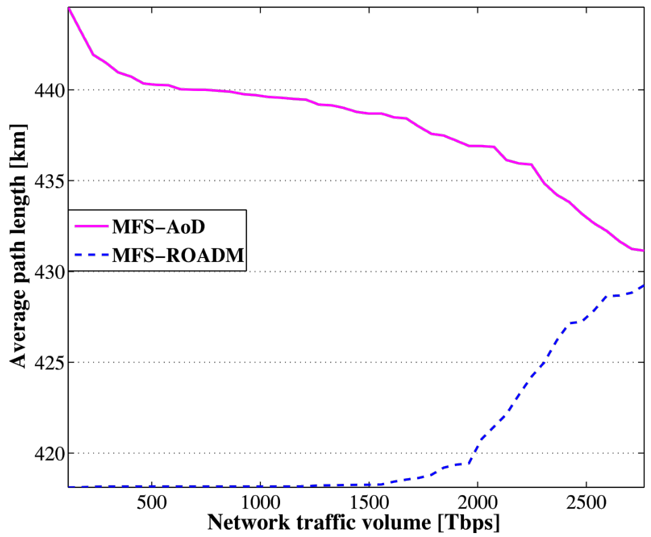


Fig. 20. Average path length versus total traffic volume.

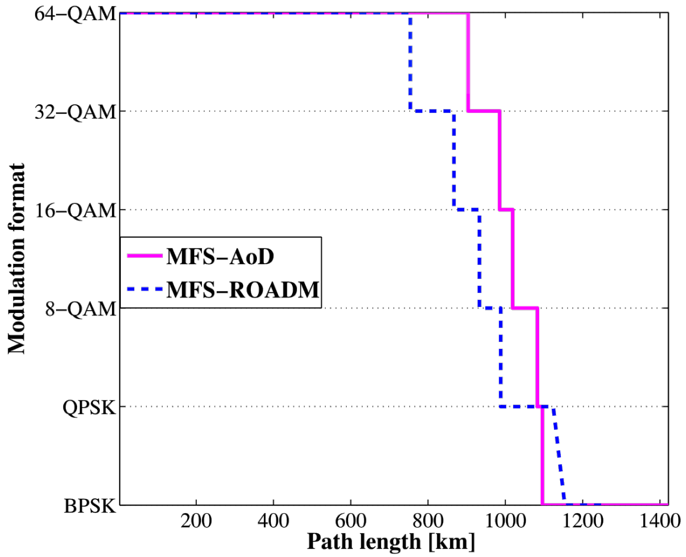


Fig. 21. Modulation format versus path length.

UCDAVIS

Extra Slides

Algorithm Pseudo-Code

Algorithm 1 XT Aware RMSCA

1: $\mathcal{G}(\mathcal{V}, \mathcal{E})$: network topology;
2: $\mathcal{C}$: set cores;
3: S: set available spectrum slots;
4: D: set demands sorted for ordering function;
5: P: path matrix; $\pi^d \in$ P set candidate paths for $d \in$ D;
6: M: set modulation levels; $\mathrm{m}_{\hat{\pi}^d} \in \mathrm{M}$ highest attainable level for d on path $\hat{\pi}^d \in \pi^d$;
7: $\aleph_{\hat{\pi}}$: set link core combinations for path $\hat{\pi}$;
8: Ω: set computed spectrum slots; $\omega_{\hat{\pi}^d} \in \Omega$ slots needed for d on path $\hat{\pi}^d$ using modulation level $\mathrm{m}_{\hat{\pi}^d}$;
9: $\mathcal{XT}$: set crosstalk thresholds; $\mathrm{xt}_\mathrm{m} \in \mathcal{XT}$ crosstalk threshold for modulation format m;
10: Initialization: $\widetilde{\mathrm{C}} = -1$;
11: **for** each demand $d \in$ D **do**
12: Initialization: $\widetilde{\mathrm{M}} = |\mathcal{XT}|$;
13: Initialization: $\widetilde{\mathrm{S}} = 0$;
14: **for** each path $\hat{\pi}^d \in \pi^d$ **do**
15: **for** each $l_c^{\hat{\pi}^d} \in \aleph_{\hat{\pi}^d}$ **do**
16: Let $\Lambda_{l_c^{\hat{\pi}^d}}$ be set of free contiguous slots for $l_c^{\hat{\pi}^d}$;
17: **if** $\omega_{\hat{\pi}^d} \le \Lambda_{l_c^{\hat{\pi}^d}}$ **then**
18: Increment $\widetilde{\mathrm{S}}$ by 1;
19: Compute xt for d and those prior established superchannels that are inflicted by $\Lambda_{l_c^{\hat{\pi}^d}}$;
20: **if** $\mathrm{xt} \le \mathrm{xt}_\mathrm{m}$ for d and all the affected superchannels **then**
21: Compute cost function $\mathrm{Ct}_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}$;
22: **end if**
23: **end if**
24: **end for**
25: **end for**
26: **if** $\widetilde{\mathrm{S}} \neq 0$ **then**
27: **Try_subroutine_xxx**;
28: **else**
29: Reject d;
30: **end if**
31: **end for**

Try_*subroutine*_MFF
Select $\hat{\pi}^d$, $l_c^{\hat{\pi}^d}$, and $\Lambda_{l_c^{\hat{\pi}^d}}$ with $\widetilde{\mathrm{C}} = \min\{\mathrm{Ct}_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}\}$;
if $\widetilde{\mathrm{C}} \neq -1$ **then**
Return $\hat{\pi}^d$, $\mathrm{m}_{\hat{\pi}^d}$, $l_c^{\hat{\pi}^d}$, and $\Lambda_{l_c^{\hat{\pi}^d}}$;
else
Reject d;
end if

Try_*subroutine*_MFS
Select $\hat{\pi}^d$, $l_c^{\hat{\pi}^d}$, and $\Lambda_{l_c^{\hat{\pi}^d}}$ with $\widetilde{\mathrm{C}} = \min\{\mathrm{Ct}_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}\}$;
if $\widetilde{\mathrm{C}} \neq -1$ **then**
Return $\hat{\pi}^d$, $\mathrm{m}_{\hat{\pi}^d}$, $l_c^{\hat{\pi}^d}$, and $\Lambda_{l_c^{\hat{\pi}^d}}$;
else
Decrement $\widetilde{\mathrm{M}}$ by 1;
Downgrade the modulation for d by one level and compute new values for Ω;
if $\widetilde{\mathrm{M}} \neq 0$ **then**
Repeat Steps 13–23;
else
Reject d;
end if
end if