Cost-effective Metro Optical Network Architectures

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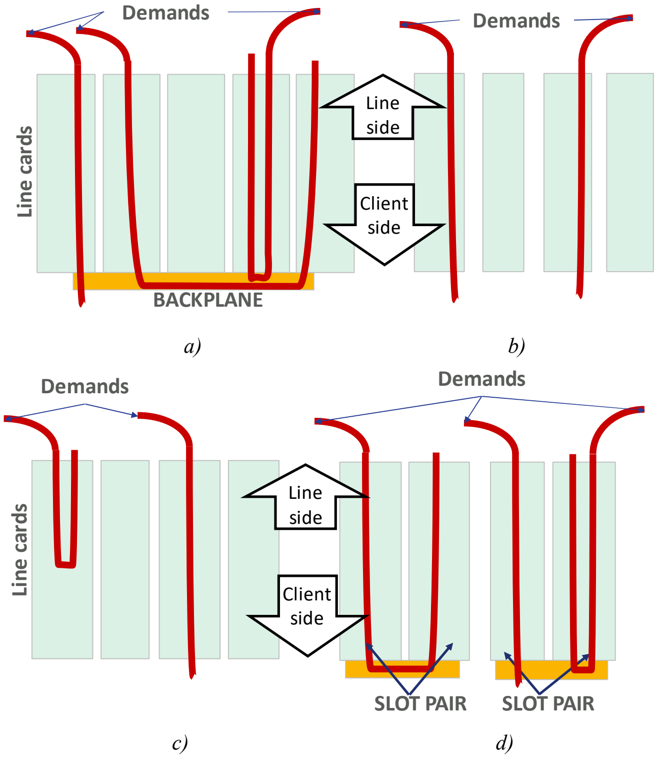
***Abstract*—We investigate cost-effective metro-optical network solutions using different building-blocks: full-fabric OTN switching, paired muxponder add-drop multiplexing (ADM), single muxponder ADM, and pure muxponder (no-ADM), and show that paired muxponder ADM functionality can give optimal results without the additional costs of full-fabric OTN switching.**

***Keywords*—switching architecture, metro network solutions, network cost optimization**

I. INTRODUCTION

Metro optical networks are one of the faster growing networking segments [1], seeing diverse applications such as in data center interconnects, mobile transport, and enterprise services. While there is a growing segment of packet centric metro networks, a significant number of operators still prefer OTN switched networks, leveraging the traditional advantages of OTN, such as multi-service transport, strong OAM capabilities, and Forward Error Correction [2]. Additionally, while line side carrier capacities now exceed 100Gbps with coherent interfaces, on the client side, most metro networks still have large numbers of sub-100G and sub-10G multi-service clients [3]. Therefore, multiplexing and grooming of low rate clients into the minimum number of waves and providing a low first-in cost and low overall cost network solution is critical to maintain cost competitiveness.

In this context, state-of-the-art metro optical solutions fall in the following broad categories (Fig. 1). First, complete fabric based OTN switching solutions where every node has an OTN switch that multiplexes and switches low rate client onto 100Gbps and above coherent line side interfaces. Second, muxponders which aggregate low rate clients onto 100Gbps above coherent line side interfaces, but do not perform any switching function. The full fabric based OTN switch solution ensures client traffic is carried by the lowest number of waves, at the expense of higher switch costs. This solution has the added advantage of network resiliency in the event of fiber cuts [4]. The muxponder-only approach generally has the highest number of waves but can be a lower first-in cost solution [5]. However, this solution rapidly becomes expensive as the network loading increases. Additionally, for the muxponder only solution, careful wavelength planning is required to ensure fiber spectrum is not fragmented and waves stay in the extended C band of transmission; otherwise, addition of L band amplifiers is required increasing network cost. A third solution exists that includes muxponders with ADM functionality where client traffic can be added, dropped, or switched between a pair of line interfaces on one muxponder. In a fourth solution, this ADM functionality is extended to a second muxponder paired with the first, such that client traffic is added, dropped, or switched between two line interfaces on either the first muxponder, or between the first and second muxponder (its pair). This ADM functionality on a single muxponder or paired muxponder can be thought as equivalent to mini-OTN switches with limited blocking. However, if the switching bandwidth within a single muxponder, or between a pair of muxponder is large enough to accommodate sub-100G and sub-10G clients, then such solutions can offer the right balance of flexibility and cost. While these solutions have been described individually, they can possibly be combined to provide an optimal solution.



a) b) c) d)

Fig. 1. Metro optical solutions: a) full-fabric OTN switch, b) muxponder (no switching), c) Add-Drop Multiplexer, d) paired Add-Drop Multiplexer

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Previous work was carried out to evaluate the impact of electrical cross connect sizes on network cost in terms of line interface count [6]. Further studies were conducted to evaluate the impact of node architecture interconnection restrictions in multi-period scenario with client traffic churn [7]. However, the studies were not targeted specifically at metro networks, which has its own characteristic topology and traffic pattern. Though the studies compared switching matrices of different sizes, ADMs and dual-slot ADMs, which can provide a cost-effective solution in metro network scenarios, were not investigated.

II. MODELING

A. Network models

Two reference networks are used for this study – i) LEARN and ii) CESNET. LEARN (Lonestar Education and Research Network) based in the state of Texas, USA, is depicted in Fig. 2 with 10 nodes and 12 links [8] [9]. The network can be looked upon as a conglomeration of two major rings and has a mean nodal degree of 2.4, mean number of hops for shortest path of 2.3. The mean link length is approximately 189kms. All these characteristics represent a typical metro network.

CESNET (Czech Education and Scientific Network) based in the Czech Republic is more meshed compared to LEARN topology [10]. The network as depicted in Fig. 3 has 12 nodes and 19 links with a mean nodal degree of 3.17. The mean number of hops for shortest path is 2. The mean link length is 91kms. All these characteristics also make CESNET represent a typical metro network.

All network modules are assumed to have two-line ports (at the top of each block scheme in Fig. 1), each carrying a coherent line interface. We assume there are enough client ports for all client demands. On the OTN switch, each client port is connected to all line interfaces in the switch. For the other three architectures, the client ports are assumed to be on the line cards. Consequently, on the muxponder architecture, the clients are connected to only the line interfaces on the same card. 1Gbps clients are, if necessary, aggregated to 10Gbps by an external aggregator, and we assume any changes in external aggregation costs between the different solutions is negligible. The bandwidth of the switching electronics in the OTN switch architecture, and between two paired ADM line cards, as well as within an ADM line card, is assumed to be sufficient for all traffic passing through, i.e. they are non-blocking.

With the assumption of two line ports, the distinct architectures in Fig. 1 lead to an observation about the flexibility of demand routing. With a full OTN switch, a demand passing through the node can be routed to any outgoing line interface, so it can potentially go through any subset of connected nodes to get to the destination. With ADM, the demand can go out on only one line interface, on the same card. Consequently, the route consists of the cards, not nodes, that are connected in the OTN layer. With a paired ADM, the demand can go out on up to three line interfaces: one on the same and two on the paired card. Thus, the number of nodes that can be reached with paired ADM is up to 3^{h-1}, where h is the number of hops through the OTN topology. With a pure muxponder, there is no passing through. These properties will affect network design and the results of our study.

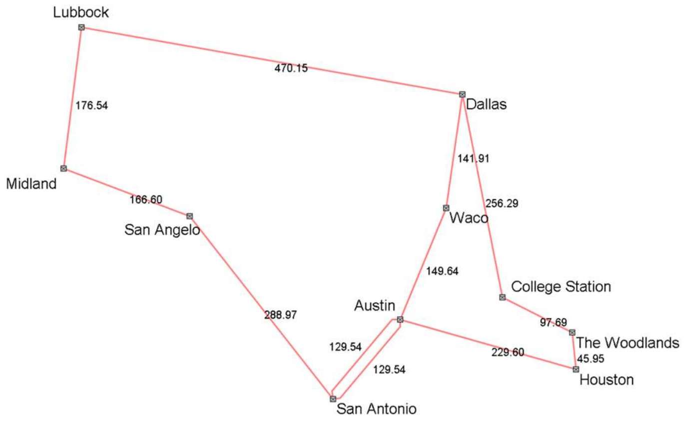

Fig. 2. LEARN topology

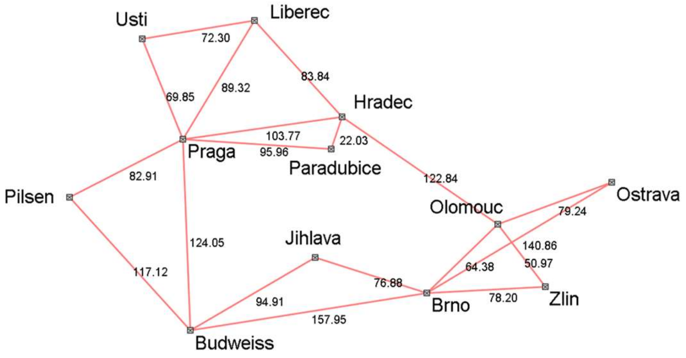

Fig. 3. CESNET topology

To keep the modeling consistent and the comparison fair, the main criteria of evaluating the efficacy of the solutions are the number of coherent network waves or network ports used. We ignore any chassis slot limitations or chassis sizes, as well as the costs of other chassis elements such as controller cards and power supplies, again assuming any differences in the same will be negligible when compared across the different switching/grooming schemes.

B. Traffic models

To adequately evaluate the advantages/disadvantages derived from the presence of muxponder in ADM/slot-pairing configurations, different sets of static traffic demands are considered in this study. As shown in Table I, a total of six distinct demand sets are contemplated in our network simulations. These sets are differentiated by the amount of bandwidth supported and/or the number of nodes which are exchanging traffic. While the former allows for identification if traffic saturation changes the outcome of the simulation, the latter is useful to understand if traffic diversity also bears any influence in the results. For all demand sets, the same demand type distribution is applied. Taking into consideration that this analysis focuses on metropolitan networks, the majority (50%) of the traffic demands are 10Gbps, while 1Gbps and 100Gbps appear on 30% and 20% of the occurrences, respectively. This demand type distribution is common to all demands sets. As depicted in Table I, the first two demand sets, *All_4T* and *All_8T*,

TABLE I. TRAFFIC DEMANDS

Traffic demands set name	Total Bandwidth Carried	Random selection of node pairs with demands	Max spectrum utilization (see text)
All_4T	4Tbps	Uniform distribution applied to all network nodes	Cesnet 7.55% Learn 10.41%
All_8T	8Tbps	Uniform distribution applied to all network nodes	Cesnet 31.25% Learn 39.84%
All_12T	12Tbps	Uniform distribution applied to all network nodes	Cesnet 35.67% Learn 42.44%
Partial_4T	4Tbps	Uniform distribution applied to six network nodes (see text)	Cesnet 7.55% Learn 10.41%
AllUneven_4T	4Tbps	3Tbps are uniformly distributed over nodes picked in *Partial_4T*, and 1Tbps are uniformly distributed over all the node pairs	Cesnet 13.02% Learn 19.53%
AllEven_4T	4Tbps	2Tbps are uniformly distributed over nodes picked in *Partial_4T*, and 2Tbps are uniformly distributed over all the node pairs	Cesnet 21.35% Learn 25.00%

uniformly select the node pairs which will exchange traffic from all the network nodes. While *All_4T* has a total of 4Tbps of traffic, *All_8T* increases this value to 8Tbps by doubling the demands between node pairs present in the *All_4T* set. We take this one step further with the 12Tbps *All_12T* traffic.

The next one, *Partial_4T*, is different from *All_4T* in the sense that the traffic demands are exchanged only between the node pairs, generally, with a higher number of nodal degrees. Specifically, in Learn, we select Dallas, Austin and Houston, and then skip every other node along the two rings in the network, thus adding San Angelo, Lubbock and College Station for a total of six nodes. In Cesnet, we select the nodes with a degree greater than two, again for a total of six nodes. Note that limiting the traffic to only these nodes does not preclude the usage of the other nodes for grooming/3R functions, if necessary.

AllUneven_4T and *All_Even4T* concentrate a part of the traffic demands (3Tbps or 2Tbps, respectively) between nodes selected in *Partial_4T* and the remaining bandwidth (1Tbps or 2Tbps) is uniformly distributed over all the other node pairs. Note that, to create a demand, the nodes in the source-destination pair are selected randomly among the six (e.g. in *Partial_4T*) or among all the nodes, depending on the traffic matrix.

To illustrate fiber link loading for each traffic pattern, we show the maximum network utilization in Table I. We derive the numbers by optimizing the network design as described in Section III using the muxponder architecture[1]. Then, on each fiber link F, for each pair of line modules $P_{lm}(i)$, we assume a channel width of 37.5GHz for each wave in the group (of one or two waves) on F belonging to $P_{lm}(i)$. We assume a guard band of 12.5GHz between $P_{lm}(i)$ and $P_{lm}(i+1)$ for each i on F, where indices i are assigned arbitrarily to the pairs of line modules transmitting over F. The resulting spectrum occupancy is divided by 4800GHz to get the utilization on F.

While our design tool can perform spectrum assignment (wavelength coloring), we will not investigate its impact here. We do not believe that, given the utilization numbers in Table I, coloring would change the conclusions of our study.

III. NETWORK DESIGN OPTIMIZATION

The network design process has two phases: optical express route (OTN link) generation and capacity planning. Such a layer-by-layer approach is common, e.g. [11]. For a survey or other multi-layer optimization strategies, see [12].

In OTN link generation, the input is the network physical topology. First, a shortest geographical distance path is found for each node pair. Along this path, a line system is modeled, with commercially available components, to give the best optical signal to noise ratio (OSNR) for the optical express route between the nodes. If the route passes an OSNR threshold, a corresponding link between the nodes is added to the OTN topology. We choose the line wave modulation format and baud rate so that the line bitrates are 100Gbps, 150Gbps, or 200Gbps. For each OTN link, the highest line rate that passes the OSNR threshold is chosen.

The OTN topology is now fed to the capacity planning phase, which is based on an integer linear programming (ILP) model. ILP has the advantage over other optimization methods in that it will produce the best possible solution for the modeled problem, although this comes at the expense of possibly long runtimes. Our ILP engine finds a route for each traffic demand. Each route will traverse chassis, client modules and ports, line cards, and OTN links. The ILP constraints are thus such that the chassis, blades and waves in the output of the coarse phase are sufficient to carry the demands assigned to them. In addition, we use the standard flow constraints used in many ILP networking models. The network resources and the demand routes traversing them are the output design.

For each pair of line cards, there is a wave variable, and the sum of these variables multiplied by their respective weights is the objective function. Recall that the model chooses the highest bitrate for each OTN link, so the wave variable weights in the objective function are arbitrary. The objective function thus minimizes the number of waves. As noted in Section II, we choose wave count as the quantity to observe, as it abstracts out other quantities such as the number of line cards and chassis, power and size. Also note that such quantities may vary with the platform or, for the equipment not yet available, are unknown. We are assuming the same line system is deployed across the different use cases, hence cost of the line equipment used to validate the OTN links is not used in our ILP program. Thus, for our purpose, optimizing only for the wave counts is justifiable.

The runs with the full-fabric OTN switch and the muxpunder architecture were with the stopping criterion of 5% target gap from the objective lower bound derived by the ILP solver (we used IBM CPLEX). We then used the wave count for the switch as a lower bound for the ADM and paired ADM runs, this time 12 hours runtime or 10% gap; we thus assume the 10% difference to be small enough to justify considering ADM as a replacement for the switch. In cases where the runs were very

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[1] In Section III it will become clear that with the muxponder, the utilization will not change between the two demand routings (shortest and any feasible path). This is because each demand uses the OTN link from source to destination (there is no intermediate switching), and each OTN link is a shortest distance path from source to destination.

fast (a few minutes for *Partial_4T* traffic), we tightened the target gap to 0-5% to see if the ADM wave count can equal that of the switch.

IV. NUMERICAL RESULTS

We will first show the result for the *All_4T* traffic. The results will show the adequacy of the paired ADM architecture. The remainder of the modeling scenarios then attempt to find situations where the performance of the ADM (paired and not paired) architecture is less comparable to the full OTN switch. To that end, we will a) double the traffic, b) reduce the number of nodes sourcing and sinking the traffic, c) change the destination nodes for the traffic demands and d) use cumulative planning. Two kinds of routing mechanism were used, first, shortest path routing where demands are routed over the shortest distances. In real networks, this routing is preferred when services need to be routed with the lowest latency. Second, any feasible path (AFP) routing, which generally results in the lowest cost network design, since existing wavelengths are filled first at the expense of latency. Real network deployments will in general have both types of routed client demands, depending on the service level agreements with end customers. Hence we modeled both kinds of routing to check consistency of results.

In Table II are the results for the base traffic, i.e. *All_4T*. Here, we observe that Cesnet benefits more from allowing the demands to take any path through the OTN layer. The Learn physical topology is ring-based, so most of the paths through the network in the shortest path run are already shortest, i.e. there are few alternatives. Consequently, going to AFP only saves one or two waves on Learn. As expected, the no-ADM muxponder does not benefit from changing the routing option, because each demand can only take the single OTN link (optical express route) from source to destination. This observation for the muxponder is true for all subsequent experiments as well. Next, ADM is shown as providing significant savings against the muxponder. Finally, for both networks, paired ADM is within 10% of the wave count (fractions rounded up) for the full OTN switch.

To test whether paired ADM can remain within 10%, we double the traffic in Table III. Here, the at most 10% performance gap between the paired ADM and switch architectures is present again. We believe this to be due to the following factors. First, the larger traffic generates extra line cards. Thus, at each card each incoming demand has more choices to get to the destination despite the lack of a nonblocking backplane. Second, the total traffic has grown but the demand types (1,10,100Gbps) have not, so the effective demand bandwidth granularity is finer with the 8Tbps traffic matrix. This in turn allows the effectively smaller demands to be re-routed more freely than with the 4Tbps[2].

The *Partial_4T* traffic matrix again tests the paired ADM 10% performance gap. As described in Section IIB, the traffic is exchanged between only six nodes in each network. The results in Table IV show that even non-paired ADM may replace the full OTN switch. This is because the amount of traffic that is groomed is small: in *All_8T* the ratio of add-drop to groomed traffic at each node is ~1:4, and with *Partial_4T* it is ~1:8. Since with *All_8T* the paired ADM achieved the 10% gap, and ADM only added a few waves to the count, with *Partial_4T* the much smaller groomed traffic can be expected to be easily handled even without the backplane. To verify this explanation, Table V shows the results for the 12Tbps traffic. Paired ADM is inside the 10% performance threshold, thanks to the even lower add-drop to groomed traffic ratio, which is now ~1:10. The satisfactory performance of the paired ADM with *All_12T* indicates that any further increase in traffic load would not yield a different conclusion.

TABLE II. WAVE COUNTS FOR ALL_4T TRAFFIC

Architecture	**Shortest Path**		**Any Feasible Path**	
	Cesnet	***Learn***	***Cesnet***	***Learn***
Switch	37	29	30	28
Muxponder	69	49	69	49
ADM	53	34	39	31
Paired ADM	41	32	33	30

TABLE III. WAVE COUNTS FOR ALL_8T TRAFFIC

Architecture	**Shortest Path**		**Any Feasible Path**	
	Cesnet	***Learn***	***Cesnet***	***Learn***
Switch	56	51	54	51
Muxponder	89	75	89	75
ADM	73	58	55	55
Paired ADM	62	53	55	52

TABLE IV. WAVE COUNTS FOR PARTIAL_4T TRAFFIC

Architecture	**Shortest Path**		**Any Feasible Path**	
	Cesnet	***Learn***	***Cesnet***	***Learn***
Switch	25	26	24	25
Muxponder	28	30	28	30
ADM	26	28	26	25
Paired ADM	25	27	24	25

TABLE V. WAVE COUNTS FOR ALL_12T TRAFFIC

Architecture	**Shortest Path**		**Any Feasible Path**	
	Cesnet	***Learn***	***Cesnet***	***Learn***
Switch	75	70	67	67
Muxponder	100	83	100	83
ADM	87	81	79	79
Paired ADM	83	76	74	74

The results so far lead us to believe that, to possibly disrupt the paired ADM performance record, we need a smaller rather than larger traffic matrix, and a large rather than small set of nodes that exchange traffic, i.e. the traffic must go in diverse directions. More precisely, after trying the two extremes – the diverse *All_4T* and the sparse *Partial 4T* – we use *AllUneven_4T* and *AllEven_4T*, whose diversities are in between. To illustrate this, we show in Table VI the traffic layer node degrees (for completeness, all the traffic patterns are shown). The result for

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[2] Each shortest path run, despite the fixed geographical route for each demand, still chooses, for each demand, between the multiple line cards at each node along the route.

AFP demand routing is in Table VII. Indeed, in two cases (*AllUneven_4T*:Cesnet and *AllEven_4T*:Learn), the paired ADM wave count is three and two waves greater than the 10% gap achieved earlier. We ran the two cases again for several days to improve the result but only achieved a 31.7% and 15.7% gap, respectively. Thus, for the two cases, even though we did not find them, there may exist networks whose wave counts fall within the 10% threshold.

Table VIII shows the numbers for the same cases as Table VII, except demand routing is on shortest distance paths. As before, changing the demand routing does not change the wave counts for the muxponder, because the underlying optical connections are on shortest distance paths. Paired ADM is within 10% of the OTN switch.

TABLE VI. DEMAND DIVERSITY

Network	Traffic	Min	Average	Max
Cesnet	*All_4T*	9	10.3	11
	All_8T	9	10.3	11
	All_12T	9	10.3	11
	Partial_4T	5	5	5
	AllUneven_4T	2	6	9
	AllEven_4T	7	9.6	11
Learn	*All_4T*	9	9	9
	All_8T	9	9	9
	All_12T	9	9	9
	Partial_4T	5	5	5
	AllUneven_4T	3	6.4	8
	AllEven_4T	8	8.6	9

TABLE VII. WAVE COUNTS FOR ALLUNEVEN_4T AND ALLEVEN_4T TRAFFIC WITH ANY FEASIBLE PATH DEMAND ROUTING

Architecture	AllUneven_4T		AllEven_4T	
	Cesnet	*Learn*	*Cesnet*	*Learn*
Switch	27	27	29	27
Muxponder	45	43	62	54
ADM	37	34	36	33
Paired ADM	33	30	32	32

TABLE VIII. WAVE COUNTS FOR ALLUNEVEN_4T AND ALLEVEN_4T TRAFFIC WITH SHORTEST DISTANCE DEMAND ROUTING

Architecture	AllUneven_4T		AllEven_4T	
	Cesnet	*Learn*	*Cesnet*	*Learn*
Switch	35	29	36	30
Muxponder	45	43	62	54
ADM	37	33	47	34
Paired ADM	36	31	38	33

Cumulative planning

The results so far for *All_4T*, *8T*, and *12T* were obtained by running the optimization from the beginning for each of the three. We now turn to multi-period, cumulative planning. More precisely, the planning is *brownfield*, so that the network resources (client ports, line cards, line ports, chassis, waves) for each demand found with *All_4T* are retained with *8T*, and then the same is done between *8T* and *12T*. This is a scenario where, to simplify operations, the resources assigned in one period cannot be changed in the next. The demands of *8T* are assumed to be not known at the time of planning for *4T*; ditto for *12T* and *8T*. The primary goal is to investigate whether paired ADM can still match the OTN switch, where the latter can accommodate demands more freely to cope with the adverse scenario.

In Tables IX and X, paired ADM is again within 10% of the OTN switch, except for one extra wave for Cesnet AFP in Table IX. However, unexpectedly in Table X for shortest path demand routing, worse than i) ordinary ADM or ii) even the muxponder[3]. We explain i) with our suboptimal assignment of linecards to paired slots, which is as follows. If, with *All_4T*, a card is not performing paired add-drop multiplexing (as it does in Fig. 1(d)), we assign it to a slot in such a way that facilitates coding, i.e. by choosing the first on the list of unoccupied slots. This is justified under the assumption of brownfield planning, which ignores future traffic demands. Then, with *8T* and later with *12T*, this choice may be suboptimal, because demands could otherwise traverse the card and its pair. Paired ADM may thus not always benefit from its architectural advantage over ADM.

For ii), note that for *All_12T* the wave counts are closer together than with any other set of runs. This closeness is due to the pinning of the demands to the network resources in *4T* and *8T*, which in our process is not re-optimized for *12T* and so two thirds of the traffic is pinned. The three switching architectures thus cannot benefit from their flexibility as much as they did with non-cumulative optimization. To verify this explanation, we ran a partial brownfield scenario, where *4T* and *8T* are

TABLE IX. WAVE COUNTS FOR ALL_8T TRAFFIC WITH CUMULATIVE NETWORK OPTIMIZATION

Architecture	Shortest Path		Any Feasible Path	
	Cesnet	*Learn*	*Cesnet*	*Learn*
Switch	64	56	55	54
Muxponder	89	75	90	75
ADM	73	65	68	59
Paired ADM	69	58	62	60

TABLE X. WAVE COUNTS FOR ALL_12T TRAFFIC WITH CUMULATIVE NETWORK OPTIMIZATION

Architecture	Shortest Path		Any Feasible Path	
	Cesnet	*Learn*	*Cesnet*	*Learn*
Switch	86	80 (77)	81	77
Muxponder	100	83	106	87
ADM	94	88 (80)	94	85
Paired ADM	97	84 (80)	89	82

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[3] Numerical results here have up to 5% gap from the numerically (theoretically) optimal due to our ILP solver stopping criterion.

greenfield, and only *12T* is brownfield. The resulting wave counts (in parentheses in Table X) from the all-brownfield scenario shows the explanation is correct. A lower wave count for the switching architectures can possibly be found by re-optimizing *All_4T* and then, again in brownfield manner, *8T* and *12T*. However, here we want to show a worst-case scenario where the future traffic is not known in advance and no old routes can be changed.

In Tables IX and X, the muxponder is affected less, because the OTN topology (one-hop) routes cannot change anyway, and there are enough client ports for all demands. Consequently, for the muxponder, there is little to no change[3] in the wave counts between non-cumulative and cumulative optimization. The switching solutions with AFP routing are also less affected, because the more flexible routing can partially compensate for the myopic optimization done under the brownfield scenario.

The close wave counts of cumulative *All_12T* lead to a final note on the generated network designs. As mentioned in the Section I, the four architectures can be combined to create the lowest cost network. For example, even though ADM architecture is allowed in the design process, some cards may only perform add-drop function, which implies the lower-cost and less complex muxponders can be used. Similarly, even though paired ADM is allowed, some cards may not have to communicate with their pairs, allowing for the ordinary ADM at some sites. This can be expressed as

OTN switch >> paired ADM >> ADM >> muxponder

The lowest cost network design thus has the allowed architecture and possibly those to the right of it. This may not be obvious, because the tables in this section imply only one architecture is used for each network design. The ideal network thus has, for example, a bundle of paired ADM and muxponder cards at each site, where the inclusion of paired ADM allows for a low wave count and the muxponder for a low CAPEX and operational complexity. The simpler architectures become even more attractive with the close wave counts of *All_12T* in our brownfield planning.

V. CONCLUSIONS AND FUTURE WORK

We used a fair comparison model-wise, realistic metro traffic matrices, representative physical topologies and strict ILP-based network design optimization to evaluate the four architectures. We found that paired ADM has a wave count within 10% of the full OTN switch in 30 out of 32 use cases. In two (out of 32) cases paired ADM wave counts are within 20% of the OTN switch wave counts, with a possibility to get within 10% after a very long runtime. Thus, despite the various attempts to disrupt it, in our measurements, paired ADM has performance comparable to the OTN switch.

If paired ADM cannot be used for some reason, single card traffic grooming of ordinary ADM provides significant savings over a muxponder only architecture. The more cost-effective architectures (including the muxponder) may also be more long-term feasible in brownfield scenarios where traffic increases by a large factor and demand routing is constrained; the flexibility of the full fabric OTN switch may prove insufficient. Ultimately, the choice of solution built by a hardware vendor or used by a network operator may depend on operational factors that are not considered in this study.

Future work will focus on increasing the client and line rates to 400G.

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