All-Optical Paths across Multiple Hierarchical Levels in Large Metropolitan Area Networks

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Abstract: This paper proposes a procedure for node-to-level path computation and applies it to a semi-synthetic huge MAN of 2,800 nodes. Results show key practical average and worst-case target references useful for MAN technology designers.

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1. Introduction and problem statement

Although FTTH and corporative traffic are the largest sources of traffic in a MAN, the advent of new 5G services like URLLC (Ultra-Reliable Low-Latency Communication) and the popularization of C-RAN (Cloud-Radio Area Network) fronthaul have put latency and jitter in the forefront of the interest of MAN network designers. For instance, 3GPP recommends a 250 μsec network latency budget for *intra-phy* split fronthaul traffic for 5G C-RAN [1], including propagation delay, which would allow for a maximum of 50Km if no other latency components existed. However, nowadays, the aggregation and distribution of traffic is mostly performed at the electronic layer by means of packet switches (either routers, ethernet bridges or MPLS-TP switches) which consume tens of μsecs after several hops in the path. Furthermore, forecasts of traffic growth will soon make >10Tb/s packet switching a requirement, with consequent added costs for a type of traffic which just needs aggregation and distribution.

One possibility to meet stringent latency targets at long distances and reduce IP layer costs is to maximize the use of the optical layer, as optical aggregation and distribution avoids packet queuing and store-and-forward delays in routers. EU project PASSION [2], is developing a technology that enables such functionality by means of cost-effective ROADMs and high capacity Sliceable Bandwidth-Variable Transceivers (SBVT) of up to 16 Tb/s per fiber [3][4]. This makes it possible to go beyond today's optical aggregation constrained to the WDM ring, and enable the traversal of arbitrary topologies and hierarchical levels. This paper identifies the types of path in a large future MAN that should be the target for IP-offloading by all-optical interconnection. Then, based on the selected topology, we discuss a procedure for worst-case path selection, an important datum that should be the taken as a design goal for future switches and transceivers toward an all-optical next generation MAN.

2. Insights of a large MAN topology and traffic requirements

At the optical layer a MAN network can be seen as a layered composition of ring and star topologies (usually ring within the same layer and a star when aggregating). This basic scheme is progressively evolving to mesh-like topologies as ROADMs with degrees greater than 2 are deployed. Table 1 shows the statistics of a semi-synthetic topology based on real sub-topologies of a huge MAN (over 2,800 nodes) projected for 2030.
As it can be seen, five hierarchical levels (HL) are defined, with differentiated functionalities. The average nodal degree mostly grows from the lowest HL (2) to the highest one (6). HL1 and HL2, connected in a mesh topology, make up the top level in the hierarchy and are treated as a single level, because HL3 nodes connect directly to either HL1 or HL2 nodes to reach the core, where the traffic is routed to/from either service gateways (e.g. IPTV or CDN caches at HL2, carrying 40% of the core traffic) or to the appropriate WAN routers (at HL1) for Internet and other global connectivity services, estimated as 60% of the core traffic. At the next level, HL3 are fast aggregation and transit nodes. HL5 consists of Base Stations and small COs (Central Office) hosting OLTs and DSLAMs, whereas HL4 are bigger COs that aggregate/distribute HL5 traffic, deal with traffic conditioning and have subscribers attached as well. The table also includes a peak traffic forecast for year 2030 based on the deployment of 5G and the assumption of global spread of symmetric 1Gb/s FTTH services in the next decade with moderate oversubscription ratios. Non-hierarchical traffic is not shown in the table as, in practice, only 10% of the traffic is of this kind.

Table 1. Hierarchical Levels, Nodal Degrees, Aggregation ratios and Traffic in a large MAN by 2030

Hierarchical Level (HL)	Nodal Degree (Physical Layer) Min/Avg/Max	Aggregation Ratio (n_{HLi+1}/n_{HLi})	Uplink Traffic per node UP (Tb/s)	Uplink Traffic per node DOWN (Tb/s)
HL5: Access	1/2/4	-	0.15	0.15
HL4: Aggregation Stage 1	2/4/10	2432/380=6.44	1	1
HL3: Aggregation Stage 2	3/3.2/5	380/33=11.51	11	12
HL2: Service gateways	4/6/7	33/6=5.5	73	80
HL1: WAN gateways			55	60

At the IP layer, the logical topology hides the physical layer topology and the aggregation/distribution hierarchy becomes more evident as shown in Fig. 1. In general, an IP level n node is connected to a pair of nodes of level $n-1$ (for protection purposes) by means of physically disjoint optical paths. In general, it can be assumed that a HLn node consists of a packet switch attached to a ROADM controlled with an SDN control plane, except in the lower level of the hierarchy (in our case HL5), where, for cost reasons, the topology usually consists of multiple rings of packet switches.

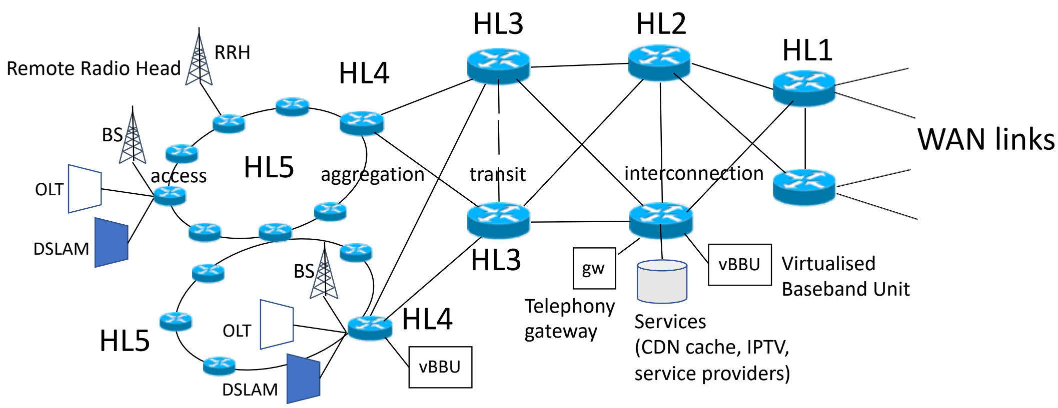

Fig. 1. Schematic IP Layer view of the hierarchy of routers

2. All-optical paths for IP offloading

An analysis of both topologies and the traffic per node can identify the target scope of all-optical paths, according to the use case. To minimize the number of IP hops in the case of transport of fronthaul traffic, the objective is the setup of direct circuits from HL5 nodes to HL4, and eventually up to an HL2 hosting the BBU (BaseBand Unit) of CRAN. This means adopting cost-effective ROADM metro-access technologies, as the scheme shows that HL5 is responsible for most opto-electronic conversions. On the other hand, if the use case is reducing the expenses in high-end packet switches and WDM optical circuits only set up for higher traffic, the network operator may find more convenient to enable all-optical paths from HL4 (aggregating 1 Tb/s of traffic) to the core HL2/HL1, thus off-loading HL3 routers, which would only forward non-hierarchical traffic dropped by a few wavelengths at the HL3 router's SBVT.

A relevant question is how these optical paths can be characterized in terms of fiber length and traversed OADM nodes. Fig. 2 illustrate a definition of distance from a given node to a hierarchical level n. The scheme shows the distances from node $HL4_A$ to the set of HL3 nodes. The distance from node $HL4_A$ to $HL3$, $d(HL4_A, HL3,1)$ is defined as the shortest path from a node $HL4_A$ to the closest HL3 node which in the example is $HL3_2$. This is the primary path from $HL4_A$ to HL3. The secondary path from $HL4_A$ to HL3 is the path to the second closest HL3 node (in the figure, $HL3_3$), which is computed after removing all nodes of the primary path. Its length is denoted by $d(HL4_A, HL3, 2)$.

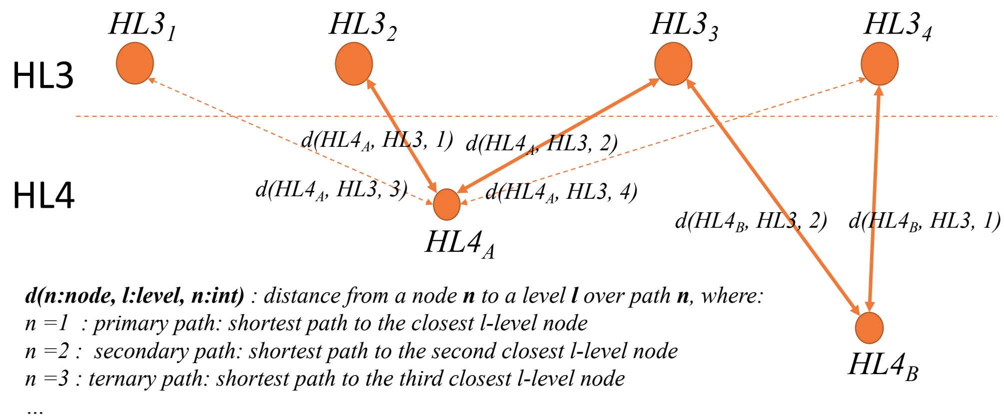

Fig.2 Distance node-level at the optical layer for primary and disjoint secondary paths

Then, path lengths can be computed taking as metric the aggregated fiber length or the number of hops. An optimization tool can easily obtain the optimum combination of span lengths and nodes. For lack of space, and trying to provide an illustrative worst-case path for the topology described in Table 1, in Table 2 we show only the more challenging secondary paths lengths.

Table 2 Path lengths between a node and its second closest (in number of hops) node of a higher Hierarchical Level (HL): **Secondary Path**

Connected HLs	Path Length (Km)			Path Length (# of hops)			Ratio of *no paths*
	Min	Mean	Max	Min	Mean	Max	
HL5 - HL4	0.5	7.0	29.7	1	5.1	10	526/2546
HL5 - HL3	9.1	44.6	86.7	4	11.0	23	1537/2546
HL5 - HL2/1	9.9	77.4	161.8	5	12.9	26	1548/2546
HL4 - HL3	7.7	45.4	78.7	2	5.8	9	0/380
HL4 - HL2/1	16.2	74.7	148.4	3	7.6	14	8/380
HL3 - HL2/1	5.1	43.9	102.2	1	2.5	5	0/33

For example connecting any HL4 node to the second closest HL2 or HL1 node over the hop-shortest disjoint path takes on average 74 Km of fiber and traversing 7.6 nodes, whereas the worst path has 15 hops and 150Km. Primary paths are obviously shorter (not displayed in the table). The same connection for a primary HL4-HL2/1 path has on average 4hops/36 Km with a standard deviation of 1.4hops/25Km and a maximum of 8hops/131Km.

4. Conclusions

All-optical by-passing of IP routers in a large MAN yields advantages such as lower latency, jitter and cost of IP equipment if a technology providing flexible super-channels with fine granularity is in place. We proposed a procedure for path characterization and applied it to a semi-synthetic huge MAN in order to obtain reference average and worst case paths useful as design targets. Results show that both HL5-HL4 primary/backup and HL4-HL2/1 primary all-optical interconnection are viable with technologies such as [2][3][4], based on 50Gb/s channels. More challenging worst-case secondary paths can be split at intermediate routers to keep QoT up in those specific cases.

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