On the Optimum Topology of a Nationwide Aggregation and Core Network

Carsten Behrens, Ralf Hülsermann & Monika Jäger
Telekom Innovation Laboratories
Berlin, Germany
BehrensC@telekom.de

Christian Raack
atesio GmbH
Berlin, Germany
raack@atesio.de

Abstract—In this paper we assess the sensitivity of the most important topological parameters of an all-IP network with WDM transport planes with respect to a capital expenditure (CAPEX) optimization. We consider conservative and progressive traffic growth scenarios applied to several access network architectures in an effort to identify optimum metro and core router locations.

Keywords—Optimization; IP networks; Telecommunication Network Topology

I. INTRODUCTION

Faced with exponentially increasing traffic [1] and tough competition [2] reducing costs as well as raising efficiency remain top priorities among telecommunications service providers. As a consequence, service providers are looking to migrate from their historically grown, heavily service-centric network architecture to a drastically simpler IP-centric production model [3]. As architectural migration to a leaner production model seems inevitable, the network topology is the next important lever with significant cost reduction potential.

In this paper we aim to assess the sensitivity of the network structure in feeder, metro and core domain with respect to capital expenditures (CAPEX). By employing a comprehensive optimization approach spanning across those three domains, we analyze the structural interdependencies between the different network layers: What is the impact of a structural change in one layer on the total network cost and how does it affect the structure and the cost of the other layers?

We build on a two-level hierarchy of the metro/core network with a lower hierarchy Metro IP Router (MR) and a higher hierarchy Core IP Router (CR) as well as coarse wavelength division multiplex (CWDM) transport in the feeder and dense WDM (DWDM) transport in metro/core domains. We consider two access network architectures: full fiber-to-the-cabinet (FTTCab), where the last mile to the subscriber is bridged with the copper network and full fiber-to-the-home (FTTH), with fiber running all the way to the subscribers home. Finally, we identify the most economical number of MR and CR sites, considering two different traffic demand scenarios for the year 2020: conservative and progressive traffic growth.

II. NETWORK ARCHITECTURE & TOPOLOGY

Across all studies we assumed the access network attached to ~8,000 central offices to be constant. In particular, we ignored its cost in the optimization, since access network cost and structure can be optimized separately [4]. Consequently, the objective of our work is to optimize feeder, metro and core network, considering an existing FTTCab access network architecture as well as a potential FTTH roll-out (see Figure 1 for the network model).

![Network architecture with respect to nodes and links in the Feeder, Metro and Core domain](image-url)

Figure 1: Network architecture with respect to nodes and links in the Feeder, Metro and Core domain

In the FTTH architecture, Optical Line Terminals (OLT), which terminate the customers’ passive optical network (PON) connections, are situated in ~8,000 central offices. Generally, traffic needs to be protected when a link or equipment failure would affect more than a certain number of customers. In this case the relatively large number of customers served per OLT, requires the traffic backhauled via CWDM systems to be 1+1 protected with a dual homing approach. In case of the FTTCab architecture, Multi-Service Access Nodes (MSANs), which terminate the customers’ digital subscriber line (DSL) connections, are located in ~330,000 street cabinets across the country. In this scenario, the relatively small number of customers per MSAN as well as the cost associated with the high number of feeder links renders protection for the CWDM...
Communication networks are dimensioned with respect to the peak traffic that is expected during the busy hour of the day (typically between 8:00 and 9:00 p.m.). Since the dominant portion of the traffic is download traffic and interfaces in the metro and core network have symmetrical capacity, it is justified to dimension the network according to the peak hour download traffic as displayed in Figure 3. The expected network traffic in 2020 was projected into two scenarios: conservative and progressive traffic growth, subdivided into 4 different service classes:

- Internet Access (Webbrowsing,…)
- Cloud Computing (File storage applications,…)
- TVoD/VoD (Video streaming applications)
- IP-TV (Multicast traffic)

Multicast IP-TV traffic originates in IP-TV backend systems, which span two separate multicast trees across the core and metro network for survivability reasons. TVoD/VoD and Cloud Computing traffic originates in data centers (ISP offerings) and peering points (OTT offerings). Note that, Internet Access traffic enters the network entirely via peering points.

The traffic is distributed towards the traffic sinks in the access network by employing realistic traffic matrices. These traffic matrices take into account the number of customers, their regional distribution and the service penetration as well as realistic peering point and data center ratings.

Each MR node houses at least one IP Router with colored interfaces and CWDM Multiplexer/Demultiplexer southbound, as well as grey interfaces that connect to 10G and 100G transponders in an optical add-drop multiplexer (OADM) northbound. Each metro link collects the traffic from a restricted number of metro nodes, connecting two core routers (dual homing) with an open-ring structure [5]. These links are protected by a 1+1 ring protection to combat link failures. Depending on the required capacity, the metro nodes are interconnected with 40 or 80 channel DWDM systems using a drop and waste approach (no wavelength reuse). The ROADMs are equipped with booster amplifiers to combat insertion loss and fiber attenuation; however, additional OLAs have to be inserted in links longer than 80km. On the IP-layer each metro router is exclusively connected to its two core routers to form a star like network.

The open ring on the WDM layer is terminated with 10G and 100G transponders in DWDM Multiplexer/Demultiplexer on both ends of the link. The transponders are directly connected with grey interfaces to the IP Core Routers at the CR locations. Northbound, the CR connect via grey interfaces to multi-degree reconfigurable optical add-drop multiplexers (ROADMs) that offer increased flexibility on the optical layer. The ROADMs are physically interconnected with 80 channel DWDM systems employing 10G and 100G transponders to form a mesh network. Each connection features a 1+1 path protection with a dedicated backup path to protect against single link failures. On the IP-layer the core network is fully meshed. Note that, some of the CR locations are connected to peering points, data centers and IP-TV backend systems that represent the traffic sources in this model.

III. TRAFFIC & SERVICE MODEL

Each MR network are ink failures (red and - oce the dominant d Computing traffic originates in data centers optimum OADM R.- 8000 -e -wo -two (dual homing) with an open ring strucure 10G and 100G transponders in DWDM Multipliexer/Demultiplexer (OADM) northbound. Each metro link collects the traffic from a restricted number of metro nodes, connecting two core routers (dual homing) with an open-ring structure [5]. These links are protected by a 1+1 ring protection to combat link failures. Depending on the required capacity, the metro nodes are interconnected with 40 or 80 channel DWDM systems using a drop and waste approach (no wavelength reuse). The OADMs are equipped with booster amplifiers to combat insertion loss and fiber attenuation; however, additional OLAs have to be inserted in links longer than 80km. On the IP-layer each metro router is exclusively connected to its two core routers to form a star like network.

The open ring on the WDM layer is terminated with 10G and 100G transponders in DWDM Multiplexer/Demultiplexer on both ends of the link. The transponders are directly connected with grey interfaces to the IP Core Routers at the CR locations. Northbound, the CR connect via grey interfaces to multi-degree reconfigurable optical add-drop multiplexers (ROADMs) that offer increased flexibility on the optical layer. The ROADMs are physically interconnected with 80 channel DWDM systems employing 10G and 100G transponders to form a mesh network. Each connection features a 1+1 path protection with a dedicated backup path to protect against single link failures. On the IP-layer the core network is fully meshed. Note that, some of the CR locations are connected to peering points, data centers and IP-TV backend systems that represent the traffic sources in this model.

III. TRAFFIC & SERVICE MODEL

Communication networks are dimensioned with respect to the peak traffic that is expected during the busy hour of the day (typically between 8:00 and 9:00 p.m.). Since the dominant portion of the traffic is download traffic and interfaces in the metro and core network have symmetrical capacity, it is justified to dimension the network according to the peak hour download traffic as displayed in Figure 3. The expected network traffic in 2020 was projected into two scenarios: conservative and progressive traffic growth, subdivided into 4 different service classes:

- Internet Access (Webbrowsing,…)
- Cloud Computing (File storage applications,…)
- TVoD/VoD (Video streaming applications)
- IP-TV (Multicast traffic)

Multicast IP-TV traffic originates in IP-TV backend systems, which span two separate multicast trees across the core and metro network for survivability reasons. TVoD/VoD and Cloud Computing traffic originates in data centers (ISP offerings) and peering points (OTT offerings). Note that, Internet Access traffic enters the network entirely via peering points.

The traffic is distributed towards the traffic sinks in the access network by employing realistic traffic matrices. These traffic matrices take into account the number of customers, their regional distribution and the service penetration as well as realistic peering point and data center ratings.

Each MR node houses at least one IP Router with colored interfaces and CWDM Multiplexer/Demultiplexer southbound, as well as grey interfaces that connect to 10G and 100G transponders in an optical add-drop multiplexer (OADM) northbound. Each metro link collects the traffic from a restricted number of metro nodes, connecting two core routers (dual homing) with an open-ring structure [5]. These links are protected by a 1+1 ring protection to combat link failures. Depending on the required capacity, the metro nodes are interconnected with 40 or 80 channel DWDM systems using a drop and waste approach (no wavelength reuse). The OADMs are equipped with booster amplifiers to combat insertion loss and fiber attenuation; however, additional OLAs have to be inserted in links longer than 80km. On the IP-layer each metro router is exclusively connected to its two core routers to form a star like network.

The open ring on the WDM layer is terminated with 10G and 100G transponders in DWDM Multiplexer/Demultiplexer on both ends of the link. The transponders are directly connected with grey interfaces to the IP Core Routers at the CR locations. Northbound, the CR connect via grey interfaces to multi-degree reconfigurable optical add-drop multiplexers (ROADMs) that offer increased flexibility on the optical layer. The ROADMs are physically interconnected with 80 channel DWDM systems employing 10G and 100G transponders to form a mesh network. Each connection features a 1+1 path protection with a dedicated backup path to protect against single link failures. On the IP-layer the core network is fully meshed. Note that, some of the CR locations are connected to peering points, data centers and IP-TV backend systems that represent the traffic sources in this model.

III. TRAFFIC & SERVICE MODEL

Communication networks are dimensioned with respect to the peak traffic that is expected during the busy hour of the day (typically between 8:00 and 9:00 p.m.). Since the dominant portion of the traffic is download traffic and interfaces in the metro and core network have symmetrical capacity, it is justified to dimension the network according to the peak hour download traffic as displayed in Figure 3. The expected network traffic in 2020 was projected into two scenarios: conservative and progressive traffic growth, subdivided into 4 different service classes:

- Internet Access (Webbrowsing,…)
- Cloud Computing (File storage applications,…)
- TVoD/VoD (Video streaming applications)
- IP-TV (Multicast traffic)

Multicast IP-TV traffic originates in IP-TV backend systems, which span two separate multicast trees across the core and metro network for survivability reasons. TVoD/VoD and Cloud Computing traffic originates in data centers (ISP offerings) and peering points (OTT offerings). Note that, Internet Access traffic enters the network entirely via peering points.

The traffic is distributed towards the traffic sinks in the access network by employing realistic traffic matrices. These traffic matrices take into account the number of customers, their regional distribution and the service penetration as well as realistic peering point and data center ratings.
IV. Cost Model

The cost model covers the CAPEX of more than 40 items in feeder, metro and core domain on IP- and WDM-layer. Current costs have been discounted assuming an annual cost decline until the year 2020 and where topical costs were not available, the cost has been projected e.g. by taking into account costs of lower speed components. Table I shows an overview of the cost groups of the model differentiated by network domain and layer.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Layer</th>
<th>Cost Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder</td>
<td>Fiber</td>
<td>Optical interfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mux/Demux</td>
</tr>
<tr>
<td></td>
<td>CWDM</td>
<td>Fiber</td>
</tr>
<tr>
<td>Metro</td>
<td>DWDM</td>
<td>OLas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transponders</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OADMs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Terminal Equipment</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>Optical Interfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linecards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shelves</td>
</tr>
<tr>
<td>Core</td>
<td>DWDM</td>
<td>OLas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transponders</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ROADMs</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>Optical Interfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linecards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shelves</td>
</tr>
</tbody>
</table>

V. Optimization Approach

Instead of providing a single cost-optimal topology, our optimization framework has been designed to evaluate a series of optimized solutions in order to study the impact of design decisions such as the access/aggregation architecture (FTTH versus FTTCab) or the number of metro and core locations. To achieve this, we have chosen a three-level decomposition of the overall dimensioning problem.

In the first step we optimize the number and location of MR locations while assigning each access node to one MR node using the shortest fiber route (FTTCab) or to two MR using disjoint fiber paths (FTTH). This decision problem is a variant of the so-called facility location problem [6] and can be solved by using mixed-integer-linear-programming (MILP) techniques [7]. The computational difficulty mainly depends on the number of feasible assignments. In our case an assignment is feasible if the corresponding fiber path is below the 80km threshold. In case of FTTH there should be two such paths that are disjoint. For FTTCab we have to respect a maximum customer bound at each MR for limiting the failure penetration in case of MR outage, whereas in the FTTH scenario the dual homing concept assures full survivability in case of single MR failure events. The optimal metro node distribution strongly depends on the ratio of the assignment cost (the fiber cost) and the cost for the metro node. By artificially increasing/decreasing the latter we were able to generate a series of optimized metro node distributions and connected access nodes with 100 to 1000 MR locations. The different solutions are later combined with different CR distributions and cost-evaluated at the very end of the procedure.

In a similar manner we assign metro nodes to core nodes using a facility location model and control the number of core nodes by artificially varying its cost. However, in this case we have to find two CRs for each MR and we have to organize MR nodes in WDM rings. The rings have to be routed on disjoint paths in the fiber network and they have to respect the
capacity constraints of a restricted number of MR and at most 40/80 used channels in the same ring, as described in section II. We solve this problem by a combination of MILP techniques for the assignment part and a heuristic to organize the rings. For simplicity, we assume that two adjacent MR are connected by a shortest fiber path. For our study, we generated 5 to 100 core nodes together with optimized metro rings connecting the MR.

Once access nodes are assigned to metro nodes and metro nodes are assigned to core nodes, we solve the core dimensioning problem in the third step, taking into account the traffic matrix depending on the traffic scenario (see Figure 3) and the number of customers connected to the same core node. This results in a classical two-layer (IP-over-WDM) network design problem [8] with the restriction of a full mesh between the core nodes in the IP domain and with 1+1 protection (disjointedness in both layers). It is further left to the optimization how data center and peering points connect to the core. Again, we use an MILP to solve this problem.

VI. RESULTS

The results we present in this paper are grouped according to the number of metro locations, which are drawn from a series of 100 to 1,000 MR locations as described in the previous section. Similarly, each group for a given number of metro nodes is subdivided into the number of core locations which has been drawn from 5 to 100 core locations (see Figure 4, 5 and 6). CAPEX figures are given in % with respect to the FTTCab scenario with 972 MR and 74 CR locations.

A. Number of Metro Router Locations

Figure 4 shows the optimization results for the FTTCab scenario assuming a conservative traffic growth. In general, it can be seen that, regarding the number of MR locations, there are many solutions with similar costs, even though the contributions of isolated cost items change with the number of MR locations. With decreasing number of MR locations the cost of fiber and CWDM systems in the feeder domain increases, while WDM and IP costs in metro and core domain decrease accordingly. The cost of colored interfaces connecting access node and MR node remains constant, because their number and capacity depends on the amount of traffic and the access architecture. Eventually, it turns out that there is a relatively broad optimal range from 200 to 600 MR locations with similar total cost as indicated by the black line in Figure 4.

Figure 5 displays an extract of the optimization results with respect to the progressive traffic growth scenario. As expected the total costs increase with the amount of traffic, since they are largely dominated by interface and slotcard costs. The optimal number of MR shifts slightly to the range between 300 a 700 compared to the conservative growth assumption. This shift is due to higher CWDM and fiber costs in the feeder section, which can be explained by a massive increase in the number of required ports ultimately necessitating the deployment of more CWDM systems.

Comparing the results of the FTTCab scenario in Figure 4 to the FTTH scenario in Figure 6, it stands out that the FTTH scenario incurs significantly lower costs in the feeder section, which is due to a higher traffic aggregation by fewer access nodes. Furthermore this leads to less interface, CWDM and fiber costs in the feeder section as a result of shorter link lengths and finally to less MR locations. Assuming the conservative traffic growth and FTTH architecture the optimum number of metro locations lies between 170 and 550.
Considering the surprisingly broad CAPEX optimums the results are expected to be very robust against inevitable uncertainties associated to traffic and cost prediction, even though additional criteria e.g. operational expenditures may warrant further investigations.

B. Number of Core Router Locations

Considering Figure 4 and Figure 6 it appears that it is more cost effective to deploy only a few CR. A similar mechanism that has been already observed during optimization of the number of MR locations comes into effect here as well: With decreasing number of CR the cost of fibers in the metro domain increases, while WDM and IP costs in metro and core domain decrease accordingly. However, for a few reasons it is not advisable to reduce the number of CR below a certain number. The requirements for CR node equipment in terms of port and slot-count increase drastically. The survivability decreases below 10-20 CR nodes. Routing of node and link disjoint WDM is more complicated. The number of metro DWDM links increases in case of less than 10-20 CR locations leading to higher administrative costs. Furthermore, cost decreases below 30 CR nodes are not significant enough to compel the deployment of less than 10-20 CR.

VII. CONCLUSIONS

The results show a relatively broad optimum with insignificant differences in CAPEX, which reflects a surprisingly robust balance between feeder and metro costs. Ultimately 170 to 600 metro router locations may serve the underlying access network structure rather independently of the traffic and access network architecture. Considering these results, many solutions are expected to be robust against the inevitable uncertainty with respect to traffic and cost predictions. However, future work may be directed at including the impact of additional criteria e.g. increasing operational costs with increasing number of locations, into the design decisions. Finally, even though a trend to fewer and fewer core router locations is indicated, practical considerations such as survivability and node and link-disjoint routing requirements limit the minimum number of core router locations to approximately 15.

ACKNOWLEDGMENT

The authors wish to thank Michael Düser and Andreas Gladisch of Telekom Innovation Laboratories as well as Roland Wessäly of atesio GmbH for the fruitful discussions in the course of this work.

REFERENCES