Aggregation Network Design Methodologies for Triple Play Services

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***Abstract*—Triple-play services and P2P IPTV have not only led to an increasing demand for bandwidth in broadband access networks, but also to the need for new service delivery architectures. The choice of an appropriate architectural approach and sizing model for the aggregation network is studied in this paper through cost optimization models, which encompass aspects of non-stop delivery, service flexibility, policy management and cost allocation. We propose two independent quantitative programming models that identify the cost of each architecture and the corresponding effect of each of the hardware constraints and traffic flows. We show that due to the next generation applications, the ISPs will need to re-engineer the broadband access infrastructure to accommodate intelligent aggregation and optimize for QoS-sensitive services.**

I. Introduction

The recent proliferation of multiplay services has dramatically increased the bandwidth requirements in broadband networks. According to several studies, the annual global IP traffic will exceed a half of a zettabyte in the following years, therefore doubling in value every two years [1][2]. A more detailed study of those traffic profiles indicates that Internet Video is approximately one-quarter of all consumer internet traffic. Moreover, with the increasing demand for High Definition (HD) video broadcasting and Peer-to-Peer (P2P) Internet Protocol Television (IPTV), the current architectures face new challenges related to flexibility, scalability and efficiency. In this paper, we specifically focus on developing the tools that the Service Providers (SP) may use in order to design efficiently the edge and aggregation part of the network, while meeting those challenges.

Telecommunication network planning has been for several years a fundamental research problem in the design of computer networks, leading to different kinds of network models and optimization algorithms, as shown in the chapters of [3][4]. In the operation research literature [4][5], the problem of the location of the L2 and L3 devices is regarded as an hierarchical two-level location problem, under the limitation that a tree architecture exists between them. Moreover, due to the evolution towards P2P, IPTV and IP multicast, several other studies have focused on capacity analysis over next-generation networks [6][7]. However, the recent changes in traffic patterns and applications add new aspects to the planning process that have so far not been adequately studied. Therefore, the choice of an appropriate architectural approach and sizing model for the aggregation and edge part of the network, remains complex and multi-dimensional, encompassing new aspects of non-stop delivery, service flexibility and policy management [8].

Considering the above perspectives, we perform in this paper a comprehensive study of the two major aggregation topologies. The paper discusses the problem of where to place certain functions mainly focusing on subscriber termination versus transport functions, multicast replication point and routing of P2P traffic. Specific attention is given to methodologies for designing and comparing IP Carrier Ethernet topologies taking into account multiplay services and satisfying the requirements of [9]. Our multi-parameter optimization models are fed by databases of service flows and hardware values, create the corresponding constraints and determine the optimum allocation of the network elements. The models are evaluated with a combination of service traffic profiles and hardware values.

The paper is organized as follows: In the next section, the two investigated topologies are explained and in Section III, the traffic flows and the two optimization approaches are presented. In Section IV, the evaluation of the approaches is provided by modeling a multiplay scenario over a Digital Subscriber Line (xDSL) metro area network.

II. Architectural Comparison

A. Centralized Edge Design

In this type of architecture, the L2 Metro Ethernet aggregates the traffic from multiple access points before the IP Edge network, as shown on Fig. 1. Some of the characteristics of this architecture are: 1) all types of traffic are backhauled to the Broadband Network Gateways (BNGs) and then to a single P-Router or PoP (Point of Presence) location, which is connected to the ISP backbone; 2) subscriber termination functionality, multicast replication and IP QoS policies are executed in the BNG deeper in the network; 3) IP Multicast traffic for broadcast video is transmitted from the edge router over L2 multicast Virtual Local Area Networks (VLANs) to all customer premises.

B. Distributed IP Edge Design

A distributed IP Edge approach is being considered by many SPs as an alternative architecture to satisfy the bandwidth requirements for future applications. As shown in Fig. 2, the

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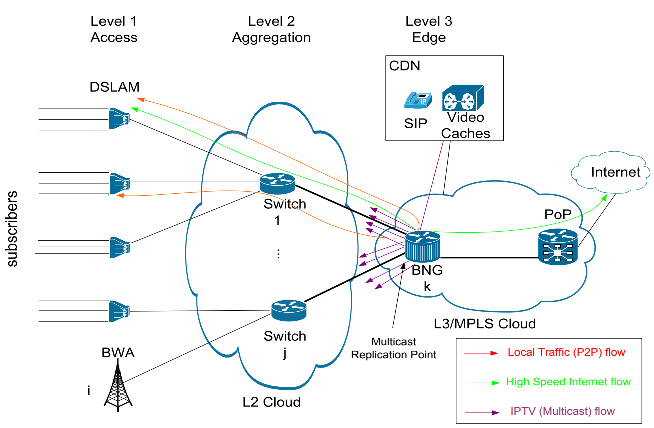

Fig. 1. Centralized Single Edge Overlay Architecture

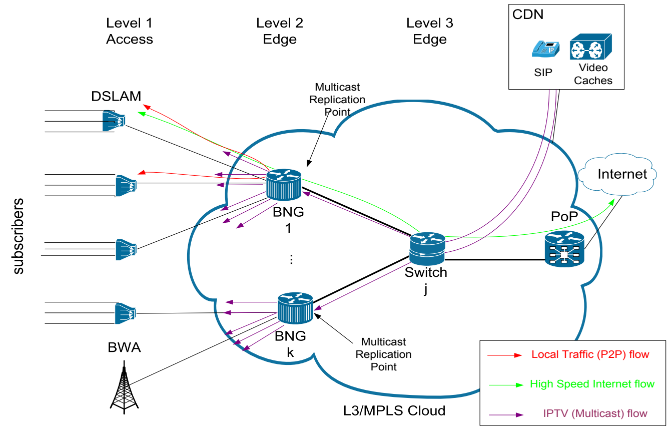

Fig. 2. IP Distributed Single Edge Overlay Architecture

edge network is comprised by both L2 and L3 routers. Video and High Speed Internet (HSI) are backhauled over VLANs to the Edge Routers, where services and access to the IP network is controlled. The scalability is increased, since the amount of state information in the BNG is decreased (less subscribers are terminated per BNG) and IP QoS is enforced closer to the last mile. IP multicast routing is used across the L2/L3 Carrier Ethernet network for delivery of broadcast video services.

III. Building a quantitave model

In this section a Linear Integer Programming (LIP) model is proposed for each architecture. A tree topology is assumed for the overlay network. Each L2 access location (e.g. DSLAM, Wireless BS) is connected to a level 2 location, and correspondingly the level 2 location is connected with a level 3 location, as shown on the above figures. The last level is the P-Router (or multiple P-Routers for resiliency) which is the gateway to the ISP's backbone. In each location there can be more than one device, but the traffic flows passes through a single device in every location. The Content Delivery Network (CDN) is comprised of a Video on Demand cache server from which the IPTV flow is transmitted to the subscribers. The replication point is assumed to be the edge router, since it is the point where the Customer VLAN (C-VLAN) is terminated.

The devices that are located at each access node location i are assumed to be able to handle a finite number of subscribers, based on the corresponding broadband technology (such as DSL, FTTx, BWA). The presented models are scaled per access node location, and not per subscriber, because 1) the multiplication of the number of subscribers with the access nodes would make the problem huge; 2) the ISPs are usually interested in aggregate numbers of traffic volumes, rather than keeping a separate database for every user's profile; and 3) specific groups of people have similar traffic patterns based on the product offered, geographical region and social structures (e.g., wireless users, business subscribers and residential customers).

A. Definition of Constants and Variables

Assume that the ISP has identified I Access locations, J (or K) aggregation switch (or edge router) locations with maximum device capacity of $L2$ for level 2, and K (or J) Edge Router (or aggregation switch) locations with maximum device capacity $L3$ for level 3. Each location has specific factors that affect the total number of elements it can handle (e.g., size, power availability, and cooling).

For each network element the vendors provide to the ISP the following set $\bar{N}_n = \{co_n, C_n, sub_n, port_n, size_n\}$, with the corresponding characteristics of each devices, where $n \in \{i, j, k\}$ and a similar set for the interfaces $\bar{N}_{n'} = \{co_{n'}, C_n\}$ where $n' \in \{ij, jk, ik, kj\}$. The elements of the vector are the cost, co_n; the capacity, C_n; the number of subscribers terminated in the edge router and number of VLANs switched per aggregation switch, sub_n; the number of ports, $port_n$; the physical size, $size_n$. Two more binary constants are defined per topology:

- $u_{1,2} = 1$ if the network element located in level 1, is connected with the element located in level 2; 0, otherwise. For the centralized topology $u_{1,2} \rightarrow u_{i,j}$ and for the distributed topology $u_{1,2} \rightarrow u_{i,k}$
- $u_{2,3} = 1$ if the network element located in level 2, is connected with the element located in level 3; 0, otherwise. For the centralized topology $u_{2,3} \rightarrow u_{j,k}$ and for the distributed topology $u_{1,2} \rightarrow u_{k,j}$

The objective function of the optimization problems can be expressed as, given the appropriate locations, to optimally allocate the network elements and to identify the number of interfaces (since each interface is associated with a link both terms are used interchangeably). Therefore, the variables are:

- The vector $\bar{Y}_{switch} = [Y_j]$ for the number of aggregation switches installed per location j.
- The vector $\bar{Y}_{BNG} = [Y_k]$ for the number of edge routers installed per location k.
- The matrix $\bar{Y}_{1,2}$ for the number of interfaces that are required to connect the elements from level 1 to level

2. For the centralized case, $\bar{Y}_{1,2} \rightarrow Y_{i,j}$ and for the distributed case, $\bar{Y}_{12} \rightarrow Y_{i,k}$.
- The matrix $\bar{Y}_{2,3}$ for the number of interfaces that are required to connect the elements from level 2 to level 3. For the centralized case, $\bar{Y}_{2,3} \rightarrow Y_{j,k}$ and for the distributed case, $\bar{Y}_{23} \rightarrow Y_{k,j}$.
- The vector $\bar{Y}_{3,P}$ for the number of interfaces that are required to connect the elements in the level 3 locations to the P-Router. For the centralized topology, $\bar{Y}_{3P} \rightarrow [Y_k]$, and for the Distributed topology, $\bar{Y}_{3,P} \rightarrow [Y_j]$.

B. Traffic Flows

1) IP Multicast (IPTV): Multicast IPTV traffic flow is coming from the CDNs cd and is replicated at the Edge Router. The streaming bit rate is usually between $IPTV_c$ =1Mbps for Standard Definition (SD) and $IPTV_c$ =10Mbps for HD channels. Several studies [10] have shown that the selection of IPTV channels $c \in \{1, ..., Ch\}$, where Ch are the total number of channels, follows a Zipf Law distribution $p_c = \alpha/c$ (where α is a constant), given that the channels are arranged by channel popularity. It is also assumed that the percentage of users per i access locations (e.g. DSLAM or Wireless Base station) that are being connected to the IPTV program is w_i. Therefore the bandwidth of the flows from the CDN to the first L3 router is, $x_{cd,k} = \sum_{c=1}^{Ch} IPTV_c, \forall k \in \{1, ..., K\}$. The IPTV traffic flow in the access locations is associated with the number of viewers, popularity of the channels, and multicast flows. Hence at each access location

$$x_{cd,i} = w_i \cdot sub_i \sum_{c=1}^{Ch} p_c \cdot IPTV_c \tag{1}$$

2) Peer-to-Peer (IPTV) and Local Traffic: The traffic flows that remain local are either those in the same geographical area (e.g. P2P or a business unit that has a local server) or in the same routing domain, and are highly dependent on how users are interconnected. For this case, we introduce $p_{d,i}$ as the portion of subscribers, in an access node i, that will communicate with another subscriber and are interconnected through the d level (e.g. if $d = 2$, the access nodes belong to the same level 2 network element). Without loss of generality, that portion can be associated with the Joint Degree Distribution (JDD) of a customer in access node i to communicate with another peer in d overlay hops. Several studies [11] have shown that the JDD is closely related to the investigated application. For example P2P applications like Gnutella and eDonkey show much higher average degree distribution compared to BitTorrent. Thus, for the centralized topology the routing for the P2P traffic flow is done on level 3. Customers generating this type of traffic are assumed to be located at DSLAM location $i' \in [1, ..., I]$. Hence the traffic flow can be expressed as follows

$$x_{i',i} = \lceil \sum_{d=1}^{3} p_{d,i} \cdot sub_{i_1} \rceil \cdot P2P_{up} \tag{2}$$

and for the IP distributed edge topology, the routing of the P2P flow is done on the 2nd level. Therefore d goes up to 2 (not 3). For the P2P download, changes are related to the direction of the flows, e.g. $P2P_{up}$ becomes $P2P_{dn}$.

3) Internet and non local traffic: Non local upload traffic is generated by the subscribers and is send to the ISP's backbone over all levels. For the centralized case, the Non local flow includes the Internet traffic, as well as part of the P2P flow that is not local.

$$x_{i,p} = \lceil HSI_{up} + (1 - \sum_{d=1}^{3} p_{d,i}) P2P_{up} \rceil \cdot sub_i \tag{3}$$

Again for the distributed case, d goes up to 2. For the opposite direction of the flow, the changes are: HSI_{up} to HSI_{dn} and $P2P_{up}$ to $P2P_{dn}$.

Therefore the set of all traffic sources is defined as $S = \{i, i', p, cd\}$ and the set of destinations $D = \{i, i_2, p\}$.

C. Centralized Edge Design Cost Optimization

The objective function is to minimize the deployment cost and can be expressed as a Linear Integer Programming model

$$min \sum_j co_j Y_j + \sum_k co_k Y_k +$$
$$\sum_i \sum_j co_{i,j} Y_{i,j} + \sum_j \sum_k co_{j,k} Y_{j,k} + \sum_k co_{k,p} Y_{k,p}$$

and the constraints are the **capacity of each of the network elements**, which can switch or route finite number of traffic flows. For the aggregation switching and edge routing capacity the following holds, $\forall n \in \{j, k\}$, $\forall j \in \{1, ..., J\}$ and $\forall k \in \{1, ..., K\}$

$$\sum_i (x_{p,i} + \sum_{i_2} x_{i_2,i} + x_{cd,i} + \sum_d x_{i,d}) u_{i,n} \leq Y_n C_n \tag{4}$$

where $u_{i,k} = u_{i,j} u_{j,k}$. The first three terms on the left side of the inequality correspond to the download traffic, the HSI flows from the P-Router, the local traffic flows (e.g. P2P) that come down to the subscribers and the IPTV multicast traffic. The last term corresponds to the upload traffic flows, which are divided into internet upload traffic and local traffic that will be routed back from the edge router to another subscriber at the same metro area. All these are summed over the access locations i that are connected to the aggregation location j (or edge router location k).

Each aggregation switch has a finite **number of VLANs**, each edge router has a finite **number of IP termination capacity** capabilities, and each location has a finite **size**. Such types of constraints can be expressed as a linear set and can be easily extended for other network element characteristics. Therefore, $\forall n \in \{j, k\}$, $\forall j \in \{1, ..., J\}$ and $\forall k \in \{1, ..., K\}$

$$\sum_i X_i u_{i,n} \leq Y_n X_n \tag{5}$$

where, in our case X_n takes the values from the set $X_n \in \{sub_n, size_n\} \subseteq N_n$. As for the required ports, the elements must be able to accommodate all the incoming interfaces

$$\sum_i Y_{i,j} u_{i,j} \le Y_j port_j \quad \forall j \in \{1, ..., J\}$$
$$\sum_j Y_{j,k} u_{j,k} \le Y_k port_k \quad \forall k \in \{1, ..., K\} \qquad (6)$$

Moreover, enough interfaces much be installed since each one has finite **capacity**. More specifically for the links that connect the edge routers with the P-Router the following constraints apply, $\forall k \in \{1, ..., K\}$

$$\sum_i (x_{p,i} + x_{i,p}) u_{i,k} \le Y_{k,P} C_{k,P} \qquad (7)$$

For the links that connect the aggregation switches with the edge routers, $\forall j \in \{1, ..., J\}, \forall k \in \{1, ..., K\}$

$$\sum_i (x_{p,i} + \sum_{i_2} x_{i_2,i} + x_{IPTV,i} + \sum_d x_{i,d}) u_{i,k} \le Y_{j,k} C_{j,k} \quad (8)$$

and finally for the link that connects the access nodes and the aggregation switches, $\forall i \in \{1, ..., I\}, \forall j \in \{1, ..., J\}$

$$(x_{p,i} + \sum_{i_2} x_{i_2,i} + x_{IPTV,i} + \sum_d x_{i,d}) u_{i,j} \le Y_{i,j} C_{i,j} \quad (9)$$

Finally, an interface of a link is used only, when there is a device (line card) that can support it. Such constraint is expressed as follows

$$Y_i \cdot u_{i,j} \le Y_{i,j} \quad \forall i \in \{1, ..., I\}, \forall j \in \{1, ..., J\}$$
$$Y_j \cdot u_{j,k} \le Y_{j,k} \quad \forall j \in \{1, ..., J\}, \forall k \in \{1, ..., K\} \quad (10)$$

D. Distributed Edge Design Cost Optimization

In this scenario, the edge routers are placed in the location of aggregation switches and vice versa. Some other changes include the characteristics of the links (since the links are now from access nodes to edge routers etc), IP functionalities are one level after the access links and the traffic flows are totally different. Hence the objective function is

$$min \sum_j co_j Y_j + \sum_k co_k Y_k +$$
$$\sum_i \sum_k co_{i,k} Y_{i,k} + \sum_k \sum_j co_{k,j} Y_{k,j} + \sum_j co_{j,p} Y_{j,p}$$

The traffic that passes through an aggregation switch are the download and upload HSI traffic plus a single flow of IPTV, $j \in \{1, ..., J\}$

$$\sum_i (x_{p,i} + x_{i,p}) u_{i,j} + \sum_k u_{k,j} x_{IPTV,k} \le Y_j C_j \qquad (11)$$

As seen in the above constraint the aggregation switch carries only a single unicast flow which is dependent on the selection of the IPTV channel, Eq. (**??**). Moreover, for the edge router locations, $k \in \{1, ..., K\}$

$$\sum_i (x_{p,i} + \sum_{i_2} x_{i_2,i} + x_{IPTV,i} + \sum_d x_{i,d}) u_{i,k} \le Y_k C_k \quad (12)$$

The constraints related to the number of ports, subscriber capacity, size and minimum number links, (5)-(6), have a similar linear form as in the centralized topology. However, the constraints of the links have differences due to the flow allocation. For all the interfaces of the distributed architecture the following holds $\forall k \in \{1, ..., K\}, \forall j \in \{1, ..., J\}$

$$[\sum_i (x_{p,i} + x_{i,p}) + x_{IPTV,k}] u_{k,j} \le Y_{k,j} C_{k,j} \qquad (13)$$

and $\forall i \in \{1, ..., I\}, \forall k \in \{1, ..., K\}$

$$(x_{p,i} + \sum_{i_2} x_{i_2,i} + x_{IPTV,i} + \sum_d x_{i,d,a}) u_{i,k} \le Y_{i,k} C_{i,k} \quad (14)$$

$$\sum_i (x_{p,i} + x_{i,p}) u_{i,j} \le Y_{j,p} C_{j,p}, \forall j \in \{1, ..., J\} \qquad (15)$$

TABLE I
INPUT PARAMETERS FOR HARDWARE AND LOCATIONS

Subscribers per Metro Area	sub	100K/200K
Level 3 Locations	K (J)	1
Level 2 Locations	J (K)	5
DSLAM Locations	I	20
Subscribers per DSLAM	sub_i	100
Agg. Switch VLAN capacity	sub_j	16K
Edge Router Termination capacity	sub_k	24K-128K
Agg. Switch capacity (Gbps)	C_j	280/560
Edge Router capacity (Gbps)	C_k	20/40
Level 1 to Agg. Switch link capacity (Gbps)	C_{ij}, C_{ik}	1
Level 2 to Level 3 (Gbps)	C_{jk}, C_{kj}	1
Level 3 to P-Router link capacity (Gbps)	C_{kp}, C_{jp}	10
Ports per Aggregation Switch	$port_j$	280
Ports per Edge Router	$port_k$	96
Cost ($) per Aggregation Switch	co_j	90K
Cost ($) per Edge Router	co_k	150K
Cost ($) per interface DSLAM to Agg. Switch	co_{ij}	1K
Cost ($) per interface DSLAM to Edge Router	co_{ik}	2K
Cost ($) per interface Agg. Switch to Edge	co_{jk}	3K
Cost ($) per interface Agg. Switch to P-Router	co_{jp}	3K
Cost ($) per interface Edge Router to P-Router	co_{kp}	4K
Number of IPTV Channels from CDN	Ch	100
Percentage of subscribers watching IPTV	w_i	50 %

IV. EVALUATION AND RESULTS

The implementation of the above optimization models was done in ILOG OPL Development Studio IDE, and Branch and Cut algorithm was used by calling CPLEX 11 engine. The model is fed by three independent databases: a) $\bar{N}_n$, for each edge router, aggregation switch and access locations, $n \in \{i, j, k\}$; b) the corresponding databases with the interface properties $\bar{N}_{n'}$, where $n' \in \{ij, jk, ik, kj\}$; and c) the traffic flows. This enables the use of different characteristics of devices per location, a case when the ISP is selecting different vendors, multiple access technologies per access node location and multiple traffic profiles. The problems are LIP with size of $O(max\{ij, ik, jk\})$ and $O(max\{ik, kj, ij\})$. For the evaluation an xDSL network has been modeled, with the values from Table I.

In Fig. 3 multiple values were chosen for multicast traffic and HSI. For HSI traffic, the users tend to download 10 times more packets than upload, and they exchange files through P2P only with subscribers in the same metro area, with a rate of $1/1$. As shown on Fig. 3, the cost for the centralized architecture is lower for low multicast traffic, irrespective of

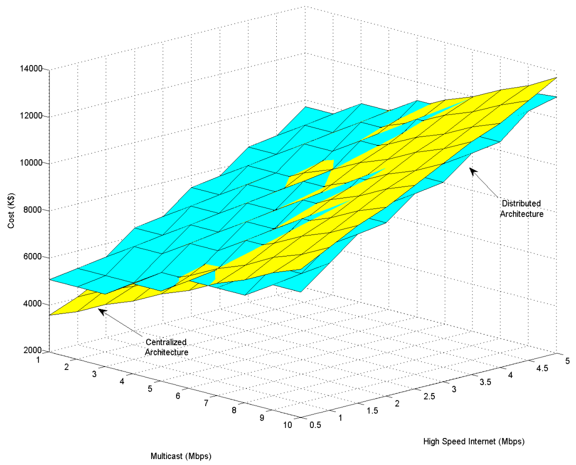

Fig. 3. Optimal cost comparison of Centralized (yellow) vs Distributed (blue) architecture for 100K subscribers and constant P2P traffic of 0.2Mbps per user.

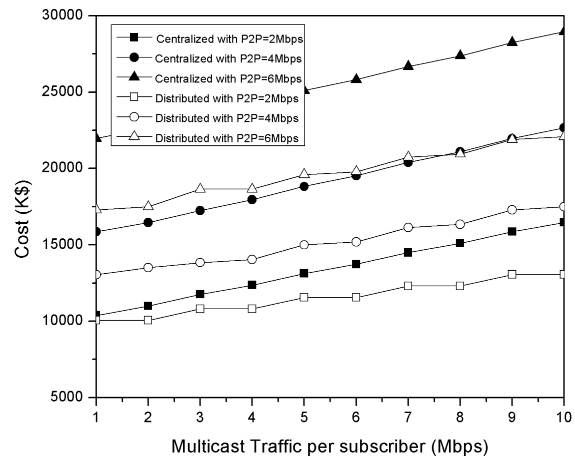

Fig. 4. Optimal cost comparison between Centralized and Distributed Edge Design for 100K subscribers and Internet traffic 1Mbps/user.

TABLE II
COST PER TOPOLOGY WITH 200K SUBSCRIBERS

Traffic Scenario	Network Element	Centralized Cost in K$	Distributed Cost in K$
$HSI_{dn} = 0.5$	Aggregation Switch	1350	1170
$HSI_{up} = 0.05$	Edge Router	13200	13500
$P2P_{dn} = 6$	Link Level 1 to 2	3520	7040
$P2P_{up} = 6$	Link Level 2 to 3	10530	345
$IPTV$=10	Link Level 3 to PoP	352	39
	Total	13124	11554

what happens to HSI traffic. However, as the bandwidth for multicast IPTV increases the distributed topology becomes cheaper. Therefore, if the SP wants to offer HD channels through C-VLANs, distributed architecture is the optimum.

In Fig. 4 we assume that HSI_{dn} =0.5 and HSI_{up} =0.05 and the values of P2P and multicast traffic are alternated. While for low multicast and relatively low P2P the cost for both topologies is similar, the cost for the centralized topology is increasing significantly, when either P2P or multicast are proliferating. Thus, if the SP has noticed increasing demand for multicast and P2P (file sharing or IPTV) with high degree of locality, then pushing the L3 closer to the subscribers seems to be a better option. Finally in Table II, an example traffic scenario has been used in order to showcase the distribution of costs between the two topologies. From the sensitivity analysis, it is proven that for higher values of IP termination capacity, the cost does not change.

V. CONCLUSION

In this paper, we presented the two prevailing aggregation architectures and showcased that the ISPs will need to redesign their aggregation topologies, because of the increasing demand for Video on Demand, multicast and P2P traffic. Two integer programming models were built, that took into account hardware and location input data as well as multiservice traffic flow data. A branch-and-cut combinatorial algorithm was used in order to prove that moving the IP layer functionalities closer to the last mile will have significantly lower deployment cost. Yet the paper focused only on developing the methodologies to calculate the Capital Expenditures (CAPEX), since Operation Expenditures (OPEX) is a dynamic problem and depends on exogenous factors.

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