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Conference Paper

Total Service Long-Run Incremental Cost Modelling in Broadband FTTx Architectures

ITS Online Event, 14-17 June 2020

Provided in Cooperation with:
International Telecommunications Society (ITS)

Total Service Long-Run Incremental Cost Modelling in Broadband FTTx Architectures

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ABSTRACT
This paper proposes an approach for the estimation of the cost contribution that FTTx broadband access networks make to the total service long-run incremental costs (LRIC) of the information services carried on these networks. The approach is applicable to the analysis of the techno-economic efficiencies of the business models enabled by the disaggregation/unbundling of the access network infrastructure. This is achieved by dimensioning first the access network for an expected service demand. The corresponding capital and operational expenditures are then calculated and apportioned to the services. The goal is to quantify the dependency of the LRIC on the architecture and the technologies used to deploy the access network. For selected business models, results are discussed for a case study that considers the provisioning of IPTV, VoIP and Internet services over FTTx networks implemented by active and passive optical networking technologies. The results show that the disaggregation of the access network may result in service cost savings compared to the traditional vertically integrated business model. Furthermore, different FTTx solutions based on active and passive technologies attain similar service costs.
Keywords: Fixed broadband access networks, FTTx, Lon-Run Incremental Cost, Cost Allocation to Services.

1. INTRODUCTION

Fixed broadband access networks are key to the delivery of high-speed, low latency and reliable connectivity towards the end user. A variety of architectures have been proposed for these networks, such as fibre to the curb (FTTC), fibre to the building (FTTB) and fibre to the home (FTTH) [1]. From these variants (commonly referred to as FTTx), FTTC and FTTB define hybrid infrastructures that combine optical and copper access networks, whereas FTTH defines a full optical network. In all FTTx architectures, the optical segment of the access network is implemented either by passive (PON) or active (AON) optical networking technologies, whilst the copper-based segment (in FTTC and FTTB architectures) may be based on technologies such as digital subscriber line (xDSL) - including G.fast - or data over cable service interface specification (DOCSIS).

The wide spectrum of architectures and technologies for the fixed access network enables novel business models such as bit-stream access and local loop unbundling [2-3]. This poses the challenge of formulating market policies for the identification - and adoption - of business models that promote the rollout of access networks that supply cost-efficient services. Such policies are necessary to steer the evolution from the traditional vertically integrated business model towards models based on disaggregated access. In this paper we study this issue by answering the following question: what is the techno-economic impact that the business model and the technologies adopted for the rollout of FTTx networks have on the delivery of cost-efficient services? To answer this question we propose an approach to analyzing the cost contribution of the access network to the total service long-run incremental costs (LRIC) of the services supplied. We focus on the modelling of the LRIC that stems from the operational processes required to supply the services, and on the capital (CAPEX) and operational (OPEX) expenditures caused by the acquisition and operation the access network. Further service cost factors originating from the metro/core network and the service management platforms are out of the scope of analysis, and thus, are not regarded in this paper.

To estimate the LRIC, we adopt a network dimensioning framework for the design of FTTx solutions that can be implemented by AON, PON and cooper-based technologies. These FTTx solutions consist of the infrastructure installed from the point of presence (PoP) of the operator to the customer premises equipment (CPE). The subscribers served are of three types: single family units (SFU), multi-dwelling units (MDU) and business dwelling units (BDU). The calculation of the LRIC of the services supplied to these subscribers is based on a bottom-up estimation of the total cost of network ownership (TCO). Although the literature provides a diversity of methods for LRIC calculation, e.g. [4-5], most of the existing models embrace ad-hoc approaches applicable to reduced sets of networking scenarios. There is no consensus on a comprehensive method that regards all relevant factors that influence the efficiency of the service costs. With this contribution, the intention is to narrow down this gap by focusing on the impact that the capital (CAPEX) and operational (OPEX) expenditures of the access network have on the LRIC. Special attention is given to the operational processes that need be implemented to guarantee an operational access network, and the processes used for the marketing, provisioning and pricing & billing of the services supplied to SFU, MDU and BDU subscribers.

This paper is organized as follows. In Section 2, we formulate a generic model for the calculation of the LRIC in fixed broadband FTTx networks. Applications of the approach to selected business models are discussed. Section 3 presents a case study and Section 4 concludes the paper.

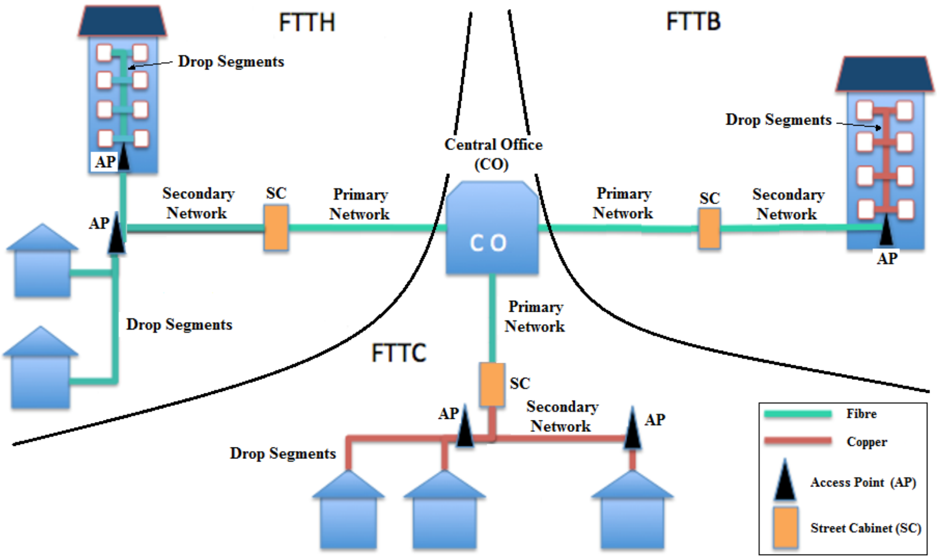


Figure 1. Generic structure of a fixed broadband access network. Selected FTTx architectures are shown.

2. BOTTOM-UP APPROACH TO SERVICE COSTING

2.1 Generic Structure of a Fixed Broadband Access Network

Fixed broadband access networks consist of the networking infrastructure (i.e. active and passive) deployed to connect subscribers to the central office (CO) of a communications service provider (CSP). The access network is split into three network segments as shown in Fig. 1. The first segment is the primary network which interconnects the CO to street cabinets (SC) strategically installed within a service area. From the SCs, a secondary network is deployed to further extend the network footprint towards access points (AP) that serve specific zones in the service area. Drop segments are installed to connect subscribers to the nearest AP. Different network architectures are defined by the technologies used to implement the network segments. In FTTC the primary network is optical, whereas the secondary network and the drop segments are copper-based. On the contrary, in FTTB the primary and secondary networks are optical with drop segments made up of copper pairs that connect users to APs. FTTH deploys all network segments with optical fibres.

2.2 Bottom-Up Calculation of the Network TCO

Consider a CSP that in year t_0 plans to offer K services over a planning period of T years. The expected service demand is $\bar{\mathbf{y}} = (y_1, \dots, y_k, \dots, y_K)$, with y_k being the foreseen number of demands or contracts of service type k. To fulfil this service demand, the CSP has to invest in a fixed broadband access network that connects users to its core network. The cumulative TCO of this access network over T is forecast to be:

$$TCO(\bar{\mathbf{y}}) = \sum_{t \in T}[CAPEX(t) + OPEX(t)] \quad (1)$$

where $CAPEX(t)$ and $OPEX(t)$ are the cash outflows expected in year $t \in T$ with:

$$CAPEX(t) = C_{Inf}(t) + C_{Ins}(t) + C_{ntsi}(t) \quad (2)$$

$$OPEX(t) = O_{CC}(t) + O_{OP}(t) + O_{ntsi}(t) \quad (3)$$

The cost contributors to the CAPEX in year t consist of network infrastructure costs $C_{Inf}(t)$, which includes the network software, the costs $C_{Ins}(t)$ incurred to install the infrastructure, and non-telco specific infrastructure costs $C_{ntsi}(t)$, e.g. buildings for personnel. The OPEX contributors include continuous costs of infrastructure $O_{CC}(t)$, which are caused when the network is in failure free mode of operation, the costs $O_{OP}(t)$ of the operational processes implemented to keep the network and the services up and running, and non-telco specific ongoing costs $O_{ntsi}(t)$, e.g. leasing of premises for personnel [6-7]. The continuous costs $O_{CC}(t)$ in year t are calculated as:

$$O_{CC}(t) = O_{EC}(t) + O_s(t) + O_L(t) \quad (4)$$

where $O_{EC}(t)$ is the energy consumption cost incurred by the network infrastructure in year t, $O_s(t)$ is the cost for leasing space to host proprietary network equipment, and $O_L(t)$ is the cost for leasing network infrastructure (e.g. dark fibre for the provisioning of unbundled access). The costs of the operational processes $O_{OP}(t)$ in year t are:

$$O_{OP}(t) = O_{SP}(t) + O_{ONP}(t) + O_{MK}(t) + O_{MR}(t) + O_{PB}(t) \quad (5)$$

where the annual costs of five operational processes are regarded, namely, service provisioning $O_{SP}(t)$, operational network planning $O_{ONP}(t)$, marketing $O_{MK}(t)$, maintenance & reparation $O_{MR}(t)$ and pricing and billing $O_{PB}(t)$.

The estimation of $TCO(\bar{\mathbf{y}})$ follows a bottom-up approach to network dimensioning. For a given service area, the access network is designed to cope with the service demand $\bar{\mathbf{y}}$ from the expected number of SFU, MDU and BDU subscribers over the planning period T. The design involves the dimensioning of the passive and active components of the access network (e.g. fibre, copper links, switches, splitters, etc.). This design provides the list of materials of the networking elements to be acquired, configured and installed. This information suffices for the calculation of the CAPEX cost contributors $C_{Inf}(t)$ and $C_{Ins}(t)$. Concerning OPEX, the following procedure is used:

- **Continuous Costs $O_{CC}(t)$.** This annual cost, as defined in (4), is derived from the technical specifications of the components in the list of materials. The energy consumption specifications are used to estimate $O_{EC}(t)$. Furthermore, $O_s(t)$ is estimated by calculating the annual renting costs caused by the space needed to host network equipment (e.g. renting costs in street cabinets). Regarding the leasing of networking infrastructure, the annual cost $O_L(t)$ is defined by the active and passive networking elements leased from third parties. Notice that it is not a necessity for the CSP to fully deploy and own the access network. Instead, it can rely on active/passive infrastructure supplied by other CSPs. The cost of this infrastructure is accounted for by $O_L(t)$.
- **Operational Processes $O_{OP}(t)$.** This cost is the sum of the annual costs incurred to run the operational processes of the CSP. The five processes summarized in (5) are defined as follows. Service provisioning is a process executed whenever a new subscriber is added to the network or when existing subscribers negotiate contract modifications (e.g. the cancellation, upgrade, downgrade or an extension of an existing service contract). The cost $O_{SP}(t)$ equals the average cost of running the process multiplied by the estimated number of new contracts and contract modifications expected in year t. Operational network planning is the process that involves day-to-day planning, management and re-optimization (i.e. upgrades, downgrades and/or migrations) of the network infrastructure. The cost $O_{ONP}(t)$ of this process is given by the wages of the personnel (e.g. engineers) responsible for the planning activities. Marketing is a process that includes promotion and advertisement of services in the market. The cost $O_{MK}(t)$ of this process includes the wages of the personnel responsible for the process (e.g. account managers) and the costs of service advertisement campaigns. Maintenance and reparation is a process executed whenever a failure occurs in the network. The annual cost $O_{MR}(t)$ can be calculated as the product of the annualized network failure rate into the average cost incurred to run the maintenance and reparation process. The network failure rate is determined by the mean time between failures (MTBF) of the network components. Maintenance and reparation also includes a cost component that stems from the continuous monitoring of the network which is implemented to assess when preventive maintenance work is needed. Pricing and billing is the process of charging subscribers. This process involves the calculation of charges, the generation and distribution of bills to the subscribers as well as making sure the subscribers pay. The cost $O_{PB}(t)$ is estimated by multiplying the number of expected contracts in year t by the average cost incurred to run the pricing and billing process.

Observe that for the calculation of $O_{SP}(t)$, $O_{MR}(t)$ and $O_{PB}(t)$, it is necessary to determine first the average cost incurred to execute each process. That cost is derived from activity-based diagrams that represent each process as a sequence of actions. An in-depth definition of these diagrams is found in [6] where it is shown that the cost of a process follows from the costs of the actions executed in the process. Such actions have costs that depend on their durations, the wages of the personnel involved, and the costs of resources required. The average cost of running a process is derived from the activity-based diagram of the process by applying the activity based costing (ABC) method outlined in [6], [8]. In this paper we embrace that method and assume all processes to be defined as in [6].

2.3 Total Service Long-Run Incremental Cost (LRIC) Calculation

The network cost $TCO(\bar{\mathbf{y}})$ can alternatively be expressed as [9]:

$$TCO(\bar{\mathbf{y}}) = \sum_k DC(y_k) + \sum SC + CC \quad (6)$$

where from the perspective of the K services offered by the CSP, the TCO is split into three cost components, namely, direct, shared and common costs. The direct cost $DC(y_k)$ for service type k is the expenditure incurred if and only if service type k is supplied over the network, i.e. if $y_k > 0$. If the service is not supplied (i.e. $y_k = 0$), there is no direct cost causation. Shared costs SC are the costs of a group of resources which are shared among different services. Shared costs must be apportioned to the services using rules that fairly reflect the resource usage from each service type. Common costs CC, or overhead costs, are the expenditures of activities (e.g. such as CEO

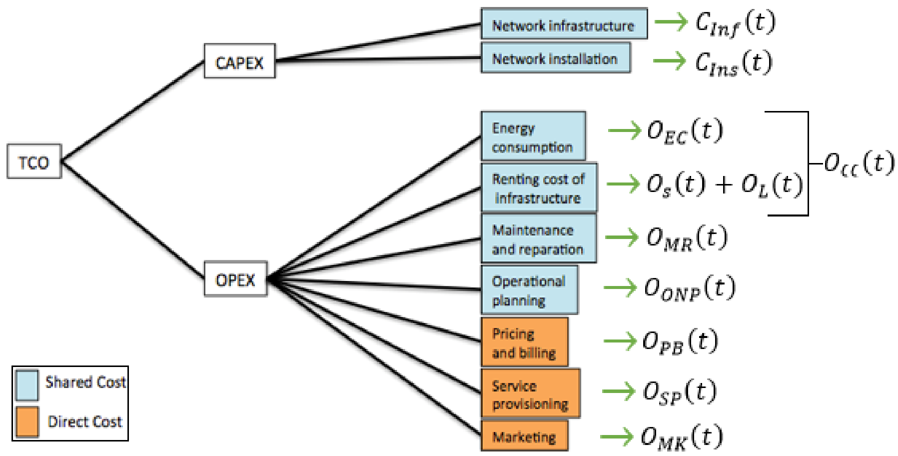


Figure 2. Mapping of CAPEX and OPEX cost contributors into direct and shared service costs.

salary) that are common to all functions of the business. In (6), the term $\sum_k DC(y_k)$ represents the total direct costs caused by the set of K services, whilst $\sum SC$ is the total cost that stems from all groups of resources being shared. From (1) and (6) it follows that:

$$TCO(\bar{\mathbf{y}}) = \sum_k DC(y_k) + \sum SC + CC = \sum_{t\in T}[CAPEX(t) + OPEX(t)] \tag{7}$$

The CAPEX and OPEX contributors define the following direct, shared and common service costs (see Fig. 2):

$$\sum_k DC(y_k) = \sum_{t\in T}[O_{SP}(t) + O_{MK}(t) + O_{PB}(t)] \tag{7.1}$$

$$\sum SC = \sum_{t\in T}\left[C_{Inf}(t) + C_{Ins}(t) + O_{CC}(t) + O_{ONP}(t) + O_{MR}(t)\right] \tag{7.2}$$

$$CC = \sum_{t\in T}[C_{ntsi}(t) + O_{ntsi}(t)] \tag{7.3}$$

The non-telco specific expenditures $C_{ntsi}(t)$ and $O_{ntsi}(t)$ define the common costs. The shared costs include the CAPEX incurred to acquire and install the network and the OPEX from the continuous costs of infrastructure and the maintenance & reparation and operational network planning processes. The direct service costs are caused by the service provisioning, marketing and pricing & billing processes [7]. The direct cost of service type k is:

$$DC(y_k) = \sum_{t\in T}\left[O_{SP_k}(t) + O_{MK_k}(t) + O_{PB_k}(t)\right] \tag{7.4}$$

with $O_{SP_k}(t)$, $O_{MK_k}(t)$ and $O_{PB_k}(t)$ being the operational costs incurred, respectively, for the provisioning, marketing and pricing & billing of service k. Notice that:

$$O_{SP}(t) = \sum_k O_{SP_k}(t) \tag{7.5}$$

$$O_{MK}(t) = \sum_k O_{MK_k}(t) \tag{7.6}$$

$$O_{PB}(t) = \sum_k O_{PB_k}(t) \tag{7.7}$$

Let $LRIC(y_k)$ be cost of offering service k with expected demand y_k over the access network with cost $TCO(\bar{\mathbf{y}})$. This network is optimized for the provisioning of K services with demand $\bar{\mathbf{y}} = (y_1, \dots, y_k, \dots, y_K)$. An approach to calculating $LRIC(y_k)$ is to design another network optimized for $K-1$ services with demand $\bar{\mathbf{y}}' = (y_1, \dots, y_{K-1})$, where service k is not offered over this network (i.e. $y_k = 0$). The cost of service k is then given by:

$$LRIC(y_k) = TCO(\bar{\mathbf{y}}) - TCO(\bar{\mathbf{y}}') \tag{8}$$

The $LRIC(y_k)$ can therefore be interpreted as the additional cost - or equivalently the cost increment - incurred to add a new service k (with expected demand y_k) to a network that has been optimized for the provisioning of $K-1$ services. This service cost is a long-run increment added to $TCO(\bar{\mathbf{y}}')$, where *long-run* points out that the increment considers the cumulative TCO incurred to supply the new service over the planning period of T years.

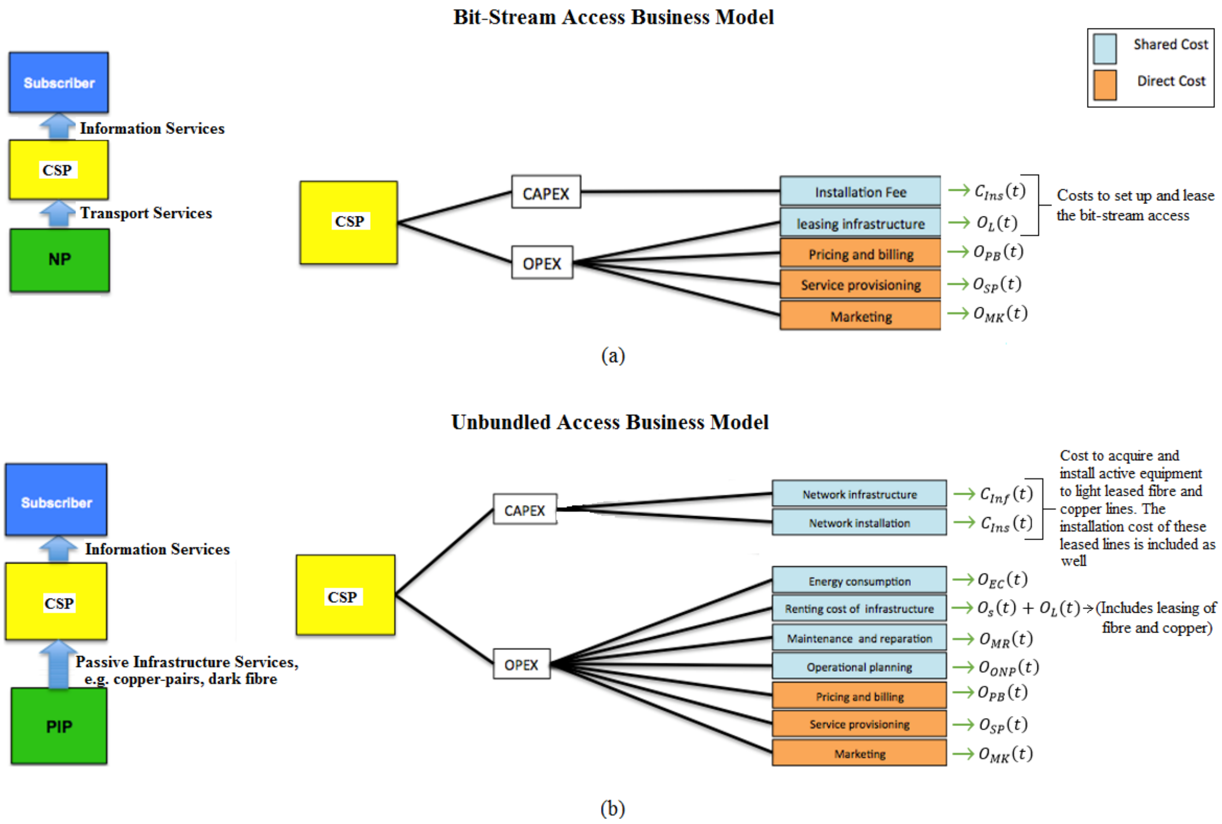


Figure 3. Mapping of CAPEX and OPEX costs into direct and shared service costs for two business models: a) Bit-stream access; b) Unbundled access.

By solving (8) with the aid of Equations (7), it follows that the $LRIC(y_k)$ is given by:

$$LRIC(y_k) = DC(y_k) + \Delta SC(y_k) \tag{9}$$

which according to (7.4) simplifies to:

$$LRIC(y_k) = \sum_{t \in T}\left[O_{SP_k}(t) + O_{MK_k}(t) + O_{PB_k}(t)\right] + \Delta SC(y_k) \tag{9.1}$$

The assumption is made that the common costs are the same for the networks with costs $TCO(\bar{\mathbf{y}})$ and $TCO(\bar{\mathbf{y}}')$. Therefore, the $LRIC(y_k)$, in addition to the direct costs $DC(y_k)$, includes the cost increment $\Delta SC(y_k)$ required to upgrade the resources which are shared among the new service k and the existing $K-1$ services. The estimated LRIC of a single service demand unit (or contract) is calculated as:

$$LRIC(k) = LRIC(y_k)/y_k \tag{9.2}$$

2.4 LRIC Calculation for Selected Business Models

The bottom-up method for TCO calculation provides a generic description of the calculation of the cost factors that contribute to $TCO(\bar{\mathbf{y}})$. To calculate $LRIC(y_k)$, i.e. to solve (9.1), it is necessary to explicitly define the CAPEX and OPEX contributors in (2)-(5) that are actually contributing to the direct, shared and common service costs. This depends on the business model under which the CSP offers its services. To illustrate this, let us consider three business models, namely, a vertically integrated CSP, a CSP that leases bit-stream access and a CSP that leases passive infrastructure in an unbundled access network model - see Fig. 3.

2.4.1 Vertically Integrated CSP

In this business model the CSP owns the entire access network infrastructure, which includes all passive and active networking components. Therefore, to offer K services over a planning period of T years, the CSP is expected to invest in a TCO that includes all CAPEX and OPEX cost contributors listed in (2)-(5). The service cost $LRIC(y_k)$ is given by (9.1) with $\Delta SC(y_k)$ containing upgrades to the shared cost contributors defined in Fig. 2.

2.4.2 Bit-Stream Access

In this business model the CSP provides its services through transport capacity or bit-stream access leased from a network provider (NP) that owns the access network. In this case, as shown in Fig. 3a, the shared costs consists of

Cost	Calculation	Definition
TCO	$TCO(\bar{\mathbf{y}}) = \sum_{t\in T}[CAPEX(t) + OPEX(t)]$	Total cost of ownership for a planning period of T years
Capex	Total cumulative CAPEX over T: $\sum_{t\in T} CAPEX(t) = \sum_{t\in T}\left[C_{Inf}(t) + C_{Ins}(t) + C_{ntsi}(t)\right]$	$C_{Inf}(t)$: Costs to acquire network infrastructure in year t $C_{Ins}(t)$: Installation costs of the network infrastructure $C_{ntsi}(t)$: Non-telco specific infrastructure costs in year t
Opex	Total cumulative OPEX over T: $\sum_{t\in T} OPEX(t) = \sum_{t\in T}[O_{CC}(t) + O_{OP}(t) + O_{ntsi}(t)]$	$O_{CC}(t)$: Continuous costs of infrastructure in year t $O_{OP}(t)$: Costs of operational processes in year t $O_{ntsi}(t)$: Non-telco specific ongoing costs
	Continuous costs of infrastructure in year t: $O_{CC}(t) = O_{EC}(t) + O_s(t) + O_L(t)$ with: $O_{EC}(t) = 365 \cdot 24 \cdot C_{kwh}(t) \cdot \sum_i P_i$ The sum is over all active network components	$O_{EC}(t)$: Energy consumption costs in year t $O_s(t)$: Costs for leasing space to host network equipment $O_L(t)$: Costs in year t for leasing network infrastructure -- P_i: Power in kW of the i*th* active network component $C_{kwh}(t)$: Cost per kWh in year t
	Costs of operational processes in year t: $O_{OP}(t) = O_{SP}(t) + O_{ONP}(t) + O_{MK}(t) + O_{MR}(t) + O_{PB}(t)$	$O_{SP}(t)$: Service provisioning cost $O_{ONP}(t)$: Operational network planning cost $O_{MK}(t)$: Marketing cost $O_{MR}(t)$: Maintenance and reparation costs $O_{PB}(t)$: Pricing and billing costs
	▪ Service Provisioning: $O_{SP}(t) = (x_t + y_t) \cdot C_{SP}$	x_t: Expected number of new contracts in year t y_t: Expected number of contract modifications in year t C_{SP}: Cost incurred to execute the service provisioning process
	▪ Maintenance and Reparation: $O_{MK}(t) = 365 \cdot 24 \cdot C_{MR} \cdot \sum_i \frac{1}{MTBF_i}$ The sum is over all network components	$MTBF_i$: MTBF in hours of the i*th* network component C_{MR}: Cost to execute the maintenance and reparation process
	▪ Pricing and Billing: $O_{PB}(t) = z_t \cdot C_{PB}$	z_t: Expected number of contracts active in year t C_{PB}: Cost incurred to execute the pricing and billing process
	▪ Operational Network Planning and Marketing: In year t these costs are approximated by the salaries of the personnel involved in the processes. Marketing includes the costs of service campaigns as well	**Remark about operational processes:** The process costs C_{SP}, C_{MR} and C_{PB} are calculated by applying the ABC method in [6], [8] to the activity-based diagrams that define the processes. Such diagrams are defined in [6]
LRIC	$\sum_k DC(y_k) = \sum_{t\in T}[O_{SP}(t) + O_{MK}(t) + O_{PB}(t)]$ $\sum SC = \sum_{t\in T}\left[C_{Inf}(t) + C_{Ins}(t) + O_{CC}(t) + O_{ONP}(t) + O_{MR}(t)\right]$ $CC = \sum_{t\in T}[C_{ntsi}(t) + O_{ntsi}(t)]$	$\sum_k DC(y_k)$: Total direct costs, consist of the OPEX that stems from service provisioning, marketing and pricing & billing $\sum SC$: Total shared costs, consist of the costs of acquisition and installation of infrastructure and the OPEX from the continuous costs of infrastructure, operational network planning and maintenance and reparation CC: Common costs, consist of non-telco specific costs
	$LRIC(y_k) = \sum_{t\in T}\left[O_{SP_k}(t) + O_{MK_k}(t) + O_{PB_k}(t)\right] + \Delta SC(y_k)$ $LRIC(k) = LRIC(\mathrm{y}_k)/\mathrm{y}_k$ In the *vertically integrated model*, $\Delta SC(y_k)$ may contain cost increments in all cost contributors in $\sum SC$, including passive and active infrastructure. In *bit-stream access*, $\Delta SC(y_k)$ contains cost increments in the installation and leasing costs of the transport capacity leased from a network provider (NP) In the *unbundled model*, $\Delta SC(y_k)$ contains cost increments in all cost contributors in $\sum SC$. The CSP leases dark fibre and/or copper pairs from a PIP to reach the customer premises. The leasing costs of these passive links are included in $O_L(t)$	$LRIC(y_k)$: LRIC of service k with demand y_k $LRIC(k)$: LRIC of a single service contract $O_{SP_k}(t)$: Service provisioning cost incurred by service k $O_{MK_k}(t)$: Marketing cost incurred by service k $O_{PB_k}(t)$: Pricing and billing cost incurred by service k $\Delta SC(y_k)$: Cost incurred to upgrade shared resources so as to add service k. The resources not only refer to infrastructure, but to additional resources that contribute to the network OPEX, e.g. resources for the upgrade of operational processes **Note:** The LRIC referred to in this table only regards long-run incremental costs that originate from the access network and the operational processes implemented for service supply. Hence, cost increments caused by the metro/core network and service management platforms are not included

Table 1. Calculation of the LRIC caused by the access network and the operational processes for service supply.

the CAPEX and OPEX caused by the installation and leasing of the bit-stream access. These cost factors contribute to the cost increment $\Delta SC(y_k)$ of the $LRIC(y_k)$ in (9.1). The direct service costs are determined by the operational processes for service provisioning, marketing and pricing & billing.

2.4.3 Unbundled Access

In this business model the CSP provides its services through dark fibre and, if required, copper pairs leased from a passive infrastructure provider (PIP) - see Fig. 3b. Besides the installation and leasing costs of these fibres and copper lines, the shared cost $\Delta SC(y_k)$ in (9.1) includes CAPEX and OPEX increments incurred to acquire, install and maintain active equipment of the CSP. The direct costs are the same as for the bit-stream access model.

2.5 Cost Model Summary

Table 1 summarizes the cost model for LRIC estimation. The calculation of the OPEX processes is shown in more detail. Notice that the equations in Table 1 refer to the $TCO(\bar{\mathbf{y}})$ and the LRICs expected over a planning period of T years. It is assumed that the planning of the network and the cost calculation is performed in year t_0, i.e. at the beginning of T. Thus, $TCO(\bar{\mathbf{y}})$ and the LRICs are predicted costs for an expected demand $\bar{\mathbf{y}}$. The cost model does not regard cost factors originating from the metro/core network and the service management platforms. The focus in this paper is on the LRIC caused by the access network and the operational processes required to supply services.

3. CASE STUDY

3.1 Problem Definition

We consider the problem of service costing for the delivery of information services in the urban area of the city of Bogotá D.C, Colombia. The area has size 307,4 km^2 with a population of 7.412.566 inhabitants [10]. In Colombia fixed broadband access has predominantly been supplied by vertically integrated CSPs. Local-loop unbundling has not been regulated in the country and most entrants have opted for the deployment of their own access infrastructure. Before 2013, fixed broadband access had predominantly been deployed through ADSL2+ solutions installed over legacy copper access networks. Since 2014 the market has witnessed a steady changeover towards the rollout of FTTH networks by vertically integrated CSPs in large urban areas. In this case study, besides the vertically integrated model, we analyse service costing in this market under the hypothetic implementation of the - not yet existing - disaggregated bit-stream and unbundled access business models. For that, we use reference data available for a CSP with significant market power in the city of Bogotá [11]. Based on that information we define the scenario in Table 2 which considers an access network that consists of coexisting FTTC, FTTB and FTTH networks deployed within the urban area.

Three services are regarded as shown in Table 3, namely, IPTV, VoIP and Internet. Relevant quality of service (QoS) and technical specifications are listed. The bandwidth of the internet service is an average over the internet offerings found in the market [11]. The costs of these three services are calculated for the FTTx architectures summarized in Table 2. We assume that each subscriber has a contract for each of the three services.

3.2 Network Designs

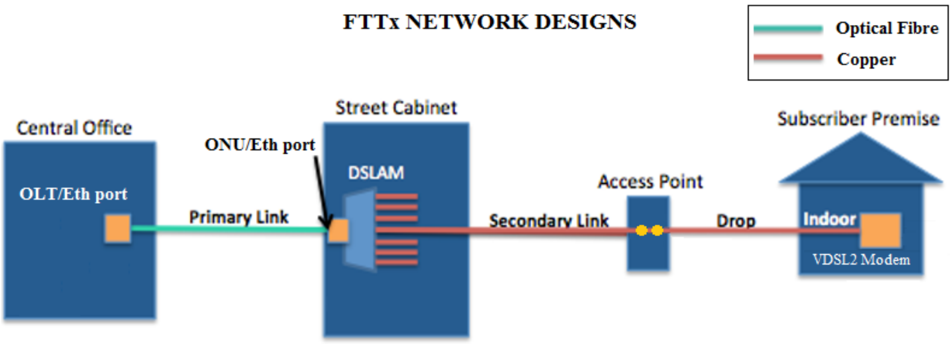
For each FTTx architecture, Fig. 4 and Fig. 5 show relevant technical specifications used in the network designs. Notice that according to Table 2, these network designs consist of coexisting FTTC, FTTB and FTTH solutions in the service area. This is a realistic scenario in most telecom markets in which the access network is a heterogeneous infrastructure combining different architectures. In this case study we assess the LRICs for the subscribers in Table 2 by implementing the FTTx solutions either with GPON/VDSL2 or AON/VDSL2 technologies. For both options, the FTTx networks are designed so as to guarantee the QoS specifications in Table 3. As seen in Fig. 4, each FTTx

Architecture	SFU		MDU		BDU		Summary	
	Subscribers	%	Subscribers	%	Subscribers	%	Subscribers	%
FTTC	35.284	10,2	15.878	4,6	222	0,1	51.384	14,8
FTTB	0	0,0	37.049	10,7	3.645	1,0	40.694	11,7
FTTH	94.904	27,4	142.356	41,0	17.455	5,0	254.715	73,5
Total	130.188	37,6	195.283	56,3	21.322	6,1	346.793	100,0

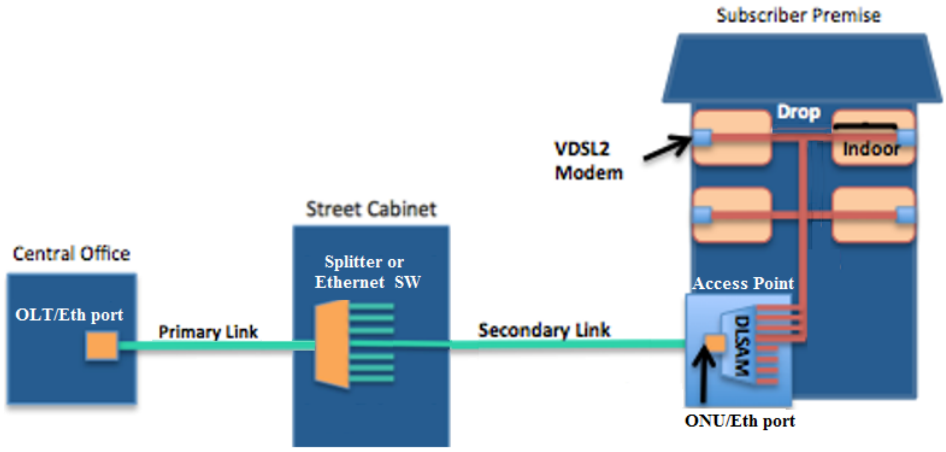
Table 2. Number of subscribers classed by user type and architecture.

Services	Codec	Bandwidth BW [kbps]	Round-Trip Delay [msec]	Packet Loss Rate	Jitter [msec]
IPTV	MPEG-4	8.000	< 10	$\leq 2\cdot10^{-4}$	< 2
VoIP	G.711	64	< 10	$\leq 2\cdot10^{-3}$	< 2
Internet	-	32.000	Best Effort	Best Effort	Best Effort

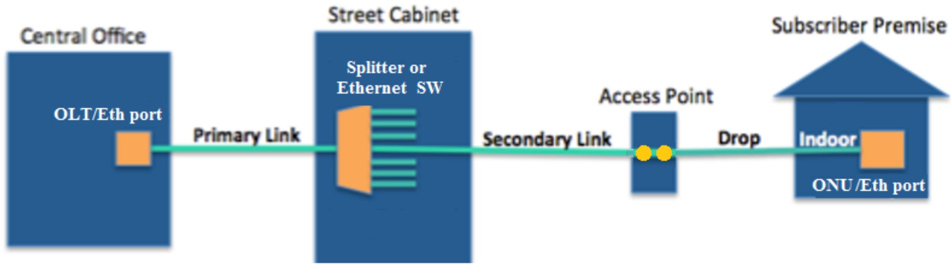
Table 3. Definition of Services.



a) FTTC



b) FTTB



c) FTTH

Figure 4. FTTx network designs. The networks are designed as P2MP topologies.

Subscriber Type	Architecture/ Technology	Central Office	Primary Link	Street Cabinet	Secondary Link	Access Point	Drop Segment	Premise
SFU & MDU & BDU	FTTH GPON	OLT ports	optical fiber	Splitter	optical fiber	Handhole	optical fiber	ONU ports
SFU & MDU BDU	FTTH AON	Eth GE ports Eth 10GE ports	optical fiber	Eth GE & FE ports Eth 10GE & GE ports	optical fiber	Handhole	optical fiber	Eth ports
SFU & MDU & BDU	FTTB GPON/VDSL2	OLT ports	optical fiber	Splitter	optical fiber	ONU ports DSLAM VDSL2	copper segment	VDSL2 modem
SFU & MDU BDU	FTTB AON/VDSL2	Eth GE ports Eth 10GE ports	optical fiber	Eth GE & FE ports Eth 10GE & GE ports	optical fiber	Ethernet ports DSLAM VDSL2	copper segment	VDSL2 modem
SFU & MDU & BDU	FTTC GPON/VDSL2	OLT ports	optical fiber	ONU ports DSLAM VDSL2	copper segment	Handhole	copper segment	VDSL2 modem
SFU & MDU BDU	FTTC AON/VDSL2	Eth GE ports Eth 10GE ports	optical fiber	Eth GE & FE ports DSLAM VDSL2 Eth 10GE & GE ports	copper segment	Handhole	copper segment	VDSL2 modem

Figure 5. Infrastructure specifications for the considered implementation variants.

network defines a point-to-multipoint (P2MP) topology with the optical network segments in FTTC, FTTB and FTTH implemented either by GPON or active Ethernet (i.e. AON). In FTTC and FTTB the copper network segments are based on VDSL2. Technical information regarding the port types and the type of infrastructure used in the network designs is shown in Fig. 5. Port types include Fast Ethernet (FE), Gigabit Ethernet (GE) and 10GE for AON solutions, and GPON – OLT ports with down/upstream bit-rates of 2,5/1,25 Gbps in the PON scenarios.

3.3 Cost Model Assumptions

We apply the cost model in Table 1 to assess the network TCO and the service LRICs for the GPON/VDSL2 and the AON/VDSL2 implementation variants. In both cases the access network is designed by applying the bottom-up approach in Section 2.2. A planning period of $T = 2$ years is regarded, with $t_0 = 2019$, i.e. the assumption is made that the network is planned and designed in 2019 so as to serve the number of subscribers shown in Table 2, which are the subscribers expected till the end of year $t = t_0 + T = 2021$.

To apply the cost model, a CAPEX price book has been defined with the unit costs of network components (e.g. switches, OLTs, ONUs, fibre/copper cables, ducts, DSLAMs, modems, etc.) and their technical specifications (e.g. energy consumption, MTBF). The unit costs are average values of prices surveyed in the market from different equipment vendors. Moreover, an OPEX price book is used for OPEX cost factors such as energy costs per kWh, rental and manual labour costs (i.e. the wages of the personnel that execute the processes). The durations of the activities of all operational processes are included as well. The CAPEX and OPEX price books, the definition of the activity diagrams of the operational processes as well as the derivation of the formulae used to calculate their costs can be found in [12]. We do not include such information here given that it is too voluminous. A detailed description of the network designs can also be found in [12]. Common costs are not regarded in the calculations.

3.4 Results and Analysis

In this section the results are expressed in cost units (cu), with 1 cu $=$ 150 EUR. Furthermore, the results refer to the $LRIC(k)$ calculated with (9.2), i.e. the LRIC of a single service contract.

We study first the case of the CSP in the vertically integrated business model. Table 4 shows the service costs for the GPON/VDSL2 and AON/VDSL2 implementation variants. To keep the notation simple, these variants are respectively denoted as GPON and AON. (Notice that VDSL2 is common to both FTTB and FTTC.) From Table 4 it is seen that for a given service $k = \{IPTV, VoIP, Internet\}$, the $LRIC(k)$ is approximately the same across all subscriber types (i.e. SFU, MDU, BDU), FTTx architectures and technology implementation variants (i.e. GPON, AON). Equivalently this means that for all subscriber types, regardless of the technology used, all FTTx solutions attain comparable cost efficiencies for a given service over the planning period T. Concerning the cost comparison across all services, Internet is the most costly, followed by IPTV and VoIP. These cost differences can be understood from the definition of LRIC in (8), i.e. $LRIC(y_k) = TCO(\bar{\mathbf{y}}) - TCO(\bar{\mathbf{y}}')$. For example, for IPTV, we have that: $k = IPTV$, $\bar{\mathbf{y}} = (y_{IPTV}, y_{VoIP}, y_{Internet})$, $\bar{\mathbf{y}}' = (y_{VoIP}, y_{Internet})$. Therefore, the service cost is: $LRIC(y_{IPTV}) = TCO(y_{IPTV}, y_{VoIP}, y_{Internet}) - TCO(y_{VoIP}, y_{Internet})$, which is the additional cost incurred to add the IPTV service (with demand y_{IPTV}) to an existing access network optimized to serve the VoIP and Internet services. Following the discussion in Section 2.3, such increment is given by the direct costs of the IPTV service and the costs incurred to upgrade the shared resources. (These resources contribute to the CAPEX and OPEX.) The upgrade of these resources grows in proportion to the service bandwidth. This explains why IPTV, which requires 8 Mbps, is more costly than VoIP (64 kbps) and cheaper than Internet (32 Mbps).

For the service costs in Table 4, Fig. 6 presents the CAPEX and OPEX cost breakdowns. CAPEX is the dominant cost contributor to the LRIC of IPTV and Internet - more than 70%. This result follows from the capacity upgrades required to add these services to the network, i.e. their bandwidth requirements involve infrastructure upgrades that increase the overall network CAPEX. On the contrary, the light bandwidth needs of VoIP require marginal capacity upgrades, and therefore, most of the effort involved in adding this service arises from OPEX-related costs.

Service	**Subscriber Type**	**LRIC [cu] - FTTH**		**LRIC [cu] - FTTB**		**LRIC [cu] - FTTC**	
		GPON	**AON**	**GPON**	**AON**	**GPON**	**AON**
IPTV	SFU	2,07	2,05	2,07	2,05	2,72	2,70
	MDU	2,12	2,09	2,05	1,91	2,39	2,37
	BDU	1,98	2,03	1,93	1,96	2,54	2,26
VoIP	SFU	0,22	0,22	0,22	0,22	0,23	0,23
	MDU	0,22	0,22	0,22	0,22	0,22	0,22
	BDU	0,22	0,22	0,22	0,22	0,22	0,22
Internet	SFU	5,06	5,02	5,06	5,02	6,75	6,70
	MDU	5,20	5,10	5,00	4,64	5,88	5,83
	BDU	4,83	4,96	4,69	4,78	6,29	5,55

Table 4. Total service long-run incremental costs $LRIC(k)$ in the vertically integrated business model.

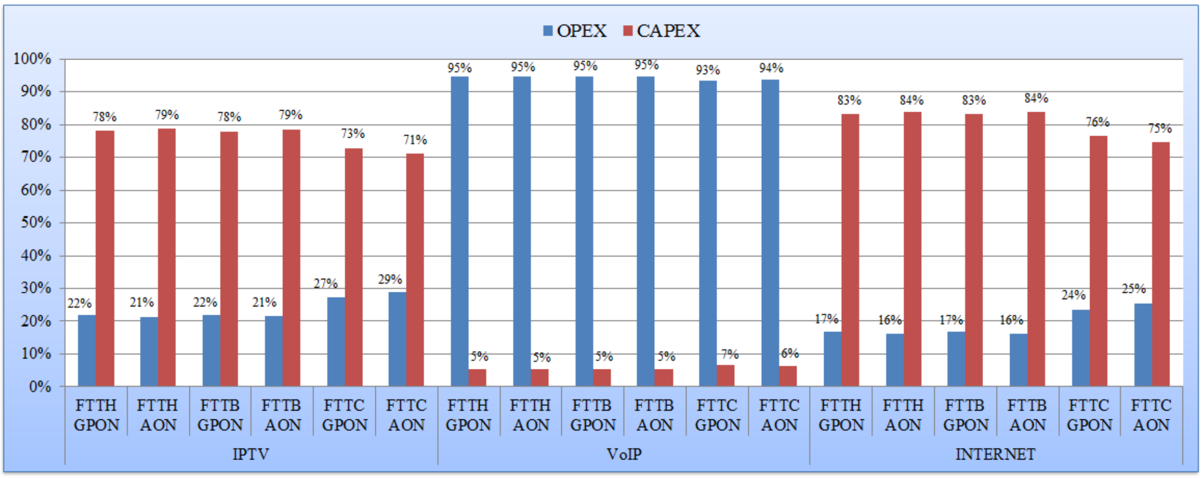


Figure 6. CAPEX and OPEX percentage contributions to $LRIC(k)$.

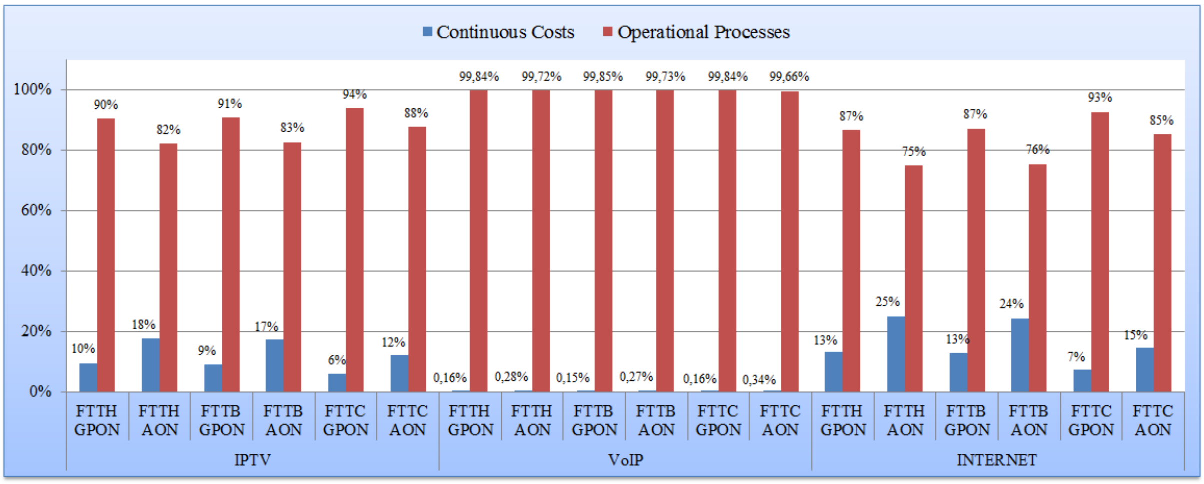


Figure 7. Percentage contributions of continuous costs and operational processes to the OPEX of $LRIC(k)$.

To further explore these findings, in Fig. 7 we present the percentage contributions of the continuous costs of infrastructure (i.e. energy consumption, space and leasing of infrastructure) and the operational processes to the overall service OPEX. In all cases, the OPEX of the LRIC is driven by the costs of the operational processes. As with CAPEX, the continuous costs of infrastructure have negligible impact on VoIP. The LRIC of this service is mainly driven by the operational processes. For IPTV and Internet, the continuous costs - although minimum contributors - are non-negligible. These costs are required to keep the capacity upgrade operational over the planning period. Since this upgrade is proportional to the service bandwidth, these costs are higher than VoIP.

Figure 8 shows the LRIC breakdown for the overall cost of the operational processes. For IPTV and Internet, the dominant process is maintenance and reparation. This cost is incurred to maintain/repair the capacity increment installed to supply these services. Such cost, as with CAPEX and the continuous costs of infrastructure, grows in proportion to the service bandwidth. This explains why maintenance and reparation is negligible for VoIP. The contribution of this process to FTTC is higher than FTTB and FTTH since the copper network requires more maintenance work than the optical segment. Moreover, pricing & billing, marketing and service provisioning are relevant contributors to the overall processes costs. Recall that, as discussed in Section 2.3, these processes define the direct service costs. These costs are dominant in VoIP and are the actual drivers of the LRIC of this service.

The findings in Fig. 6 - 8 can further be summarized as follows. The LRIC of a service depends on the capacity upgrades required to add the service. Such upgrades are proportional to the bandwidth requirements of the service and increase the cost factors that directly originate from the network infrastructure, i.e. the costs to acquire and install infrastructure and the OPEX from the continuous costs of infrastructure and maintenance & reparation. Therefore, in shared networks, services with high bandwidth requirements attain LRICs that are mainly dominated by these cost factors. The direct costs of these services (i.e. pricing & billing, marketing and service provisioning) have a minor contribution. On the contrary, for services with low bandwidth requirements, the LRIC is driven by these direct costs. As an example, from Fig. 6 - 8, it can be verified that for IPTV in the FTTH/GPON scenario the LRIC breakdown is 10% direct costs and 90% shared costs. In the same scenario, for VoIP the breakdown is 90% and 10% from direct and shared costs respectively. The results in Fig. 6 - 8 also evince that for a given service and

Figure 8. Breakdown of the LRIC costs caused by the operational processes.

FTTx architecture, the LRIC cost breakdowns for the GPON and the AON alternatives are comparable. This shows that, as seen in Table 4, both technologies attain similar service cost efficiencies.

3.4.1 Service Costing for Disaggregated Access

In the Colombian market, local loop unbundling has not been regulated yet. Relevant CSPs in the country argue that the poor quality of the existing copper-based access networks does not justify the implementation of an unbundled access model [13]. Instead, CSPs have opted to migrate their networks towards FTTH. The rapid rollout of FTTH networks may however enable the disaggregation of the access infrastructure to facilitate the entrance of new business actors. To study this scenario, let us consider the LRIC that results when the CSP supplies the services under the bit-stream access (BSA) and the unbundled (UN) access business models. In both cases the focus is on FTTH networks implemented with GPON and AON technologies. The cost model in Table 1 is applied with the following assumptions. In BSA, as defined in Section 2.4.2, the CSP does not own the access network. Instead, it pays a monthly fee to a NP for the transport capacity required from the FTTH network. To determine this fee, we apply the cost model in Table 1 for the calculation of the TCO of the FTTH network owned by the NP. From the TCO, the monthly cost is derived for the delivery of a unit of transport capacity over the network. The product of this unit cost into the capacity requirements of the CSP determine the fee charged by the NP. A similar approach is used in the UN case: the cost model in Table 1 is used to estimate the TCO of a PIP that deploys and owns the fibre infrastructure. From this TCO, the leasing fees payable by the CSP are determined. In both business models

Service	Subscriber Type	LRIC [cu] - GPON			LRIC [cu] - AON		
		VI	BSA	UA	VI	BSA	UA
IPTV	SFU	2,07	1,51	1,74	2,05	1,49	1,72
	MDU	2,12	1,76	1,99	2,09	1,73	1,94
	BDU	1,98	1,60	2,16	2,03	1,52	2,25
VoIP	SFU	0,22	0,16	0,22	0,22	0,16	0,22
	MDU	0,22	0,16	0,22	0,22	0,16	0,22
	BDU	0,22	0,16	0,22	0,22	0,16	0,22
Internet	SFU	5,06	3,69	4,20	5,02	3,65	4,16
	MDU	5,20	4,35	4,85	5,10	4,27	4,72
	BDU	4,83	3,94	4,41	4,96	3,72	5,53

Table 5. Long-run incremental costs $LRIC(k)$ for the VI, BSA and UA business models.

Service	Subscriber Type	Savings (%) - GPON		Savings (%) - AON	
		BSA	UA	BSA	UA
IPTV	SFU	27,0	16,01	27,20	15,93
	MDU	16,9	6,11	17,21	7,25
	BDU	18,9	-9,21	25,11	-11,00
VoIP	SFU	27,3	0,73	27,34	0,79
	MDU	26,4	-0,12	26,53	0,06
	BDU	27,0	-0,70	27,24	-1,01
Internet	SFU	27,0	17,09	27,38	17,23
	MDU	16,4	6,72	16,37	7,55
	BDU	18,5	8,65	25,04	-11,59

Table 6. Cost savings percentage of BSA and UA with respect to the vertically integrated business model.

the assumption is made that the CSP interconnects with the NP and the PIP at the CO. (The PIP provides fibre from the CO to the subscriber premises.) Having estimated the fees charged by the NP and the PIP, the cost calculation approach in Table 1 is used to estimate the LRICs for the CSP. Further details on the technical designs and the cost calculations of the network solutions for the NP and the PIP are available in [12].

Table 5 shows the LRICs attainable by the disaggregated business models. The service costs of the vertically integrated (VI) case are presented as well. (The VI results correspond to the FTTH scenarios in Table 4.) As with the findings previously discussed for the VI case, it is verified that for a given service, each disaggregated model yields service costs that are similar across all subscriber types (i.e. SFU, MDU, BDU) and technology variants (GPON, AON). Likewise, the costs exhibit the same dependency on the bandwidth requirements, i.e. the higher the bandwidth the more costly the service. A cross-comparison of the business models reveals, however, that the disaggregated scenarios may become more cost-efficient than the VI model. By disaggregating the infrastructure, network sharing is enabled amongst different business actors. This introduces economies of scope that reduce the costs incurred by the CSP to provide information services. By leasing infrastructure from PIPs and NPs, the CSP alleviates the investments caused by the rollout of the access network. Table 6 shows the cost savings percentage attained by the disaggregated models w.r.t the VI case. These savings are calculated as: $(LRIC_{VI} - LRIC_i)/LRIC_{VI}$, i ={BSA, UA}, with the LRIC values taken from Table 5. As seen, the savings are more noticeable in the BSA case since the CSP significantly reduces the investment in passive and active infrastructure. The savings in the UA case are less than BSA and in some cases comparable to VI. This is explained by the fact that UA solely leases dark fibre links and not transport capacity that involves the leasing of active network elements.

Figure 9 presents the cost breakdowns of the LRICs in Table 5 for the SFU subscribers. (The MDU and BDU subscribers have similar breakdowns.) For services with high bandwidth requirements, such as IPTV and Internet, the LRIC is driven in the VI case by the CAPEX from the acquisition and installation of infrastructure. This result is the same observed in Fig. 6 – 8. In the UA case these CAPEX contributors dominate as well and are followed - unlike VI - by the continuous costs of infrastructure, which include the leasing costs of the dark fibre supplied by the PIP. (Notice that in the VI model the continuous costs contribute less to the LRIC than in BSA and UA since the infrastructure is owned by the CSP, and therefore, the leasing costs are zero.) In the BSA model the LRIC is dominated by the continuous costs of infrastructure caused by the leasing of the BSA and by the installation costs of this access. For all business models, the operational processes have small impact on the service costs. However, the cost breakdown changes for services with low bandwidth requirements such as VoIP. In this case, it is observed that in all business models the LRICs are driven by the direct costs, i.e. the costs of the service provisioning, marketing and pricing & billing processes. The costs for acquisition, installation, leasing and maintenance of infrastructure are minimum since the bandwidth requirements of the service are marginal.

Figure 9. LRIC cost breakdowns for SFU subscribers in the VI, BSA and UA business models.

It is worth noting that, as seen in Fig. 9, for all services, the service provisioning process is less costly in the BSA model as compared to VI and UA. The reason is that in BSA, the CSP does not have to intervene the network when a subscriber requests a new service, which reduces the provisioning costs. Nevertheless, the CSP has to pay a fee to the NP for the setup of the capacity of the bit-stream access. This fee is accounted for by *the installation of bit-stream access* cost factor shown in Fig. 9.

The cost reductions attainable by BSA and UA suggest that these business models facilitate the market entrance of new CSPs with limited infrastructure. It is however the responsibility of the regulatory authority to formulate policies that guarantee that new entrants commit to the gradual rollout of their own infrastructure. This encourages not only competition with existing NPs and PIPs, but the rollout of networks in areas with low service coverage.

3.4.2 Further Remarks

The previously discussed findings show that for all subscriber types, under a given business model, the FTTx solutions achieve comparable service costs regardless of the technology used. It is however important to emphasize the underlying limitations inherent to the FTTC/FTTB solutions. The deployment of copper in these networks may severely limit their scalability in terms of coverage and performance. For the service area and the set of services regarded in this study, both FTTC and FTTB meet the QoS requirements. If the CSP intends to increase its coverage and/or add new services with more stringent QoS needs, these solutions may face technical limitations that may render them infeasible. According to the body of European regulators for electronic communications (BEREC), a fixed access network can be regarded as a very high capacity network if it is capable of supplying fixed-line services (under usual peak-time conditions) with downlink/uplink data-rates > 1000/200 Mbps [14]. This boundary can easily be outperformed by FTTH and certain FTTB implementations (e.g. based on DOCSIS 3.1), but not by FTTC. Therefore, the results of the case study suggest that the rollout of FTTH networks yields service cost efficiencies similar to well established legacy solutions, with the advantage that FTTH adds the flexibility to easily grow in coverage and capacity. This justifies the introduction of FTTH by both the deployment of Greenfield FTTH solutions and the gradual migration of FTTC and FTTB networks towards full fibre-based infrastructures [15-17].

4. CONCLUSIONS

The delivery of information services by the implementation of bit-stream access and unbundled access may reduce the LRIC attainable in the traditional vertically integrated business model. This stems from the economies of scope introduced by the infrastructure sharing enabled by these business models, which sheds light on the benefits that future networking paradigms, such as network virtualization, might bring for the rollout of FTTx infrastructures. The case study reveals that, for a given service and business model, the LRIC is comparable across different FTTx architectures and technology implementations, such as PON and AON. Concerning the LRIC cost breakdown, the contributions of direct and shared costs are determined by the bandwidth requirements of the services. In particular, for low bandwidth services, the LRIC is driven by the direct costs, i.e. the costs of the operational processes for service provisioning, marketing and pricing & billing. On the contrary, high bandwidth services have LRICs driven by the shared service costs which originate from the acquisition and installation of infrastructure and the OPEX due to continuous costs of infrastructure and maintenance and reparation. The causation of these shared costs results from the upgrade of resources required for the introduction of the service. The service cost efficiencies of FTTH and the superiority of this architecture over FTTB and FTTC justify the rollout of FTTH networks that may easily scale in capacity and coverage.

ACKNOWLEDGEMENTS

We acknowledge the support of Albert Raventos Roca with the implementation of the techno-economic models used for the derivation of the results presented in this paper.

REFERENCES

[1] Fibre to the Home Council Europe, “FTTH handbook,” Edition 8, 2018.

[2] B. Lannoo, S. Verbrugge, K. Casier, and J. V. Ooteghem, “Business aspects related to NGOA,” ACP 2010 workshop, December 2010.

[3] Fibre to the Home Council Europe, “FTTH business guide,” Edition 5, 2016.

[4] International Telecommunication Union, “Telecommunications regulation handbook,” ITU, Geneva, http://handle.itu.int/11.1002/pub/807b5608-en, 2011.

[5] Analysys Mason, “2010/11 upgrades to the NITA LRAIC,” in Report for National IT and Telecom Agency, Cambridge, 2010.

[6] S. Verbrugge, S. Pasqualini, F. J. Westphal, M. Jäger, A. Iselt, A. Kirstädter, R. Chahine, D. Colle, M. Pickavet, and P. Demeester, “Modeling operational expenditures for telecom operators,” In proceedings of the 9th Conference on Optical Network Design and Modeling (ONDM), pp. 455-466, February 2005.

[7] K. Casier, S. Verbrugge, R. Meersman, J. V. Ooteghem, D. Colle, M. Pickavet, and P. Demeester, "A fair cost allocation scheme for CapEx and OpEx for a network service provider," In proceedings of the 5th Conference of Telecommunication, Media and Internet Techno-Economics (CTTE), June 2006.
[8] C. Courcoubetis and R. Weber, "Pricing communication networks," John Wiley & Sons, 2003.
[9] R. Romero-Reyes and T. Bauschert, "Bottom-up framework for cost allocation to services in telecommunication networks," NETNOMICS: Economic Research and Electronic Networking Journal, vol. 18, pp. 81-105, May 2017.
[10] National Administrative Department of Statistics of Colombia, "Statistics of the population in the city of Bogotá D.C," https://www.dane.gov.co/files/varios/informacion-capital-DANE-2019.pdf, 2019.
[11] Colombian ICT Ministry, "ICT quarterly report Q4 2019 in Colombia – (Informe Trimestral de las TIC Cifras 4T 2019)," https://colombiatic.mintic.gov.co/679/w3-article-135691.html, April 2020.
[12] A. Raventos and R. Romero-Reyes, "Cost allocation schemes to services for fixed broadband access networks," Bachelor thesis manuscript, Chair for Communication Networks, Technische Universität Chemnitz, July 2014.
[13] Communications Regulation Commission of Colombia (Comisión de regulación de comunicaciones de Colombia), "Review of the regulatory framework for access and interconnection – (revision del régimen de acceso, uso e interconnexión," https://crcom.gov.co/es/pagina/revision-regimen-acceso-uso-interconexion, December 2019.
[14] Body of European regulators for electronic communications (BEREC), "Draft BEREC guidelines on very high capacity networks," Report for the definition of high capacity access networks, March 2020.
[15] R. Romero-Reyes, R. Zhao, and C. M. Machuca, "Advanced dynamic migration planning toward FTTH," in IEEE Communications Magazine, vol. 52, pp. 77-83, January 2014.
[16] W. Kun, C. Mas Machuca, L. Wosinska, P. Urban, A. Gavler, K. Brunnstroem, and J. Chen, "Techno-Economic Analysis of Active Optical Network Migration Toward Next-Generation Optical Access," Journal of Optical Communications and Networking 2017.
[17] J. Rendon-Schneir and Y. Xiong, "Cost analysis of network sharing in FTTH/PONs," in IEEE Communications Magazine, vol. 52, pp. 126-134, August 2014.